Promotor:	Dr. ir. R.A. Feddes Hoogleraar in de Bodemnatuurkunde, Agrohydrologie en Grondwaterbeheer
Co-promotoren:	Dr. M.W. Rosegrant Senior Research Fellow, International Food Policy Research Institute, Washington D.C., United States
	T. Rieu, IGREF Head, Irrigation Division, Cemagref, Montpellier, France

Analyzing Alternative Policy Instruments for the Irrigation Sector

An Assessment of the Potential for Water Market Development in the Chishtian Sub-division, Pakistan

Pierre Strosser

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Stellingen/Propositions

Behorend bij het proefschrift *Analyzing alternative policy instruments for the irrigation sector – An assessment of the potential for water market development in the Chishtian Sub-division, Pakistan* door Pierre Strosser

1. The notion of water scarcity is more related to financial issues than to water issues.
   This thesis
2. There is a potential for surface water market development in irrigation systems for which the interdependency in allocation between users and between time periods is reduced to a limited level.
   This thesis
3. Purchase at its very price the water you'll drink.
   Deuteronome, Chapter 2, Verse 6
4. Suggestions for improvement of irrigation system performance must take the current system as a given. For economists, this means recognizing the physical dimension of water resources in the search for better use of these resources.
   Gould (1989) ; this thesis
5. Ce qui est simple est toujours faux, ce qui ne l'est pas est inutilisable.
   P. Valery
6. To integrate disciplines leads to one discipline: but which one?
   Adapted from the English proverb: to form a couple is to become one: but which one?
7. Risk is like love: we all have a good idea of what it is, but we cannot define it precisely.
   J. Stiglitz
8. In the long term, we will all be dead.
   J.M. Keynes
9. Il vaut mieux allumer une seule et minuscule chandelle que de maudire l'obscurité.
   Chinese proverb
10. Mais voir un ami pleurer.
    J. Brel

Abstract

Strosser, P. 1997. Analyzing alternative policy instruments for the irrigation sector – An assessment of the potential for water market development in the Chishtian Sub-division, Pakistan. Ph.D. thesis, Wageningen Agricultural University, the Netherlands. 243 pp, 39 figures, 40 tables, 3 appendices.

The increasing scarcity of water and financial resources has made the economic dimension of water an important element of irrigation sector policies. Water pricing is the means traditionally used to incorporate economic issues into irrigation sector policies. More recently, water markets have been proposed as an alternative to water pricing. From a theoretical point of view, water markets are expected to lead to an efficient allocation of water among water users, as well as to improve water use economic efficiency. However, the discrepancy between theoretical requirements and the existing characteristics of the irrigation sector is significant. Therefore, the potential for water markets in managing water resources is questioned.

In Pakistan, consideration has recently been given to water markets as a means to improve the performance of irrigated agriculture. The present study investigates issues related to water markets in Pakistan using the example of the Chishtian Sub-division, an irrigation system located in the South-Punjab. Within the framework of an integrated approach that combines hydraulic, soil and economic issues, the study analyses the functioning and impact of existing surface and groundwater markets that have developed spontaneously within the tertiary units of the irrigation system. Although constraints remain on the functioning of these markets, water transactions significantly improve the flexibility in managing water resources without threatening significantly the sustainability of irrigated agriculture.

This study also discusses elements related to the technical feasibility of water markets at higher spatial scales in the irrigation system, and their potential impact on agricultural production and the physical environment. The potential for reallocation of surface water in terms of increased farm gross income is the highest within and between tertiary units. Also, the impact of reallocation on farm gross income is higher when volumes of surface water are transacted independently of the time of the year, as opposed to yearly reallocations that would affect proportionally the supply of canal water received each month. Constraints related to the existing conveyance infrastructure are not seen as a major obstacle to water transactions. Changes in the operational rules required to develop water markets at higher spatial scales, however, may represent an important constraint to water market development. Also, the absence of storage facility limit the potential for temporal reallocation of surface water, thus the overall impact of potential water markets.

The thesis concludes by emphasizing the importance of a combination of interventions to manage the irrigation sector, as well as to improve its performance in terms of agricultural production and sustainability. The need to analyze, compare and combine interventions, further stresses the relevance of an integrated approach that integrates disciplines, links decisional and bio-physical processes, and investigates the heterogeneity of these processes within the irrigation system.

Keywords: water markets, irrigation management, integrated approach, economic modeling, Pakistan

Contents

Abbreviations and glossary of local terms

Abbreviations

CCA	Culturable Command Area
Cemagref	French research center for agricultural and environmental engineering
DPR	Delivery Performance Ratio
FAO	Food & Agriculture Organization of the United Nations
GCA	Gross Command Area
GDP	Gross Domestic Product
GIS	Geographic Information System
ICWE	International Conference on Water and the Environment, Dublin, 1992
IIMI	International Irrigation Management Institute
MAD	Mean Absolute Deviation
MVP	Marginal Value Product
NESPAK	National Engineering Services of Pakistan
OECD	Organization for Economic Cooperation and Development
PIPD	Punjab Irrigation and Power Department
PTO	Power-Take-Off tubewells
RD	Reduced Distance
SCARPs	Salinity Control And Reclamation Projects
SDO	Sub-Divisional Officer
SIC	Simulation of Irrigation Canals, hydraulic model
SWAP93	Simulation of transport processes in the Soil-Water-Air-Plant environment, hydrodynamic model
UNCED	United Nations Conference on Environment and Development, Rio de Janeiro, 1992
WAPDA	Water and Power Development Authority, Pakistan

Glossary of local terms

Abiana	Area and crop-based water charges
Bildar	Laborer
Distributary	Secondary canal
Gur	Raw sugar
Kaccha warabandi	Flexible irrigation schedule, taking the variability in watercourse head discharges into account
Khal Barai	Time required draining the watercourse
Kharif	Summer cropping and irrigation season

Locals	Social group that settled in the study area long before the development of large scale irrigation
Mogha	Tertiary outlet
Nikkal	Time required filling the watercourse
Pakka warabandi	Irrigation schedule with turns being fixed for a specific time of the week
Rabi	Winter cropping and irrigation season
Settlers	Social groups that came in the study area at the time of the Sutlej Valley Project or at the time of the Independence in 1947
Warabandi	Roster of water turns developed for all landowners (official warabandi) or water users (agreed warabandi) along a given watercourse
Watercourse	Tertiary unit

Chapter 1

Introduction

The main objective of this introduction is to present three important elements that have been combined to form the present thesis. The first element relates to interventions and policies for the irrigation sector, and the assumption that *water markets* have an increasing role to play in the management of the irrigation sector. The second element is methodological, advocating for the need to develop a sound research framework, or *integrated approach*, to investigate the multiple dimensions of irrigation systems and their performance, and assess the potential for interventions in the irrigation sector. The third element relates to the location where most of the scenes presented in this thesis will take place, i.e. *Pakistan*, where a drastic institutional reform is currently being discussed for managing the irrigation sector.

1.1 Water scarcity and water sector policies

The history of the irrigation and water sectors in various countries shows that water sector policies are dynamic processes, often responding to changes in the physical, macro-economic, social and political environment. Although in the past policy changes took place at each country's pace, it is increasingly apparent that discussions on irrigation and water sector policies have moved from the national to the international arena and are part of a wider concern about issues and appropriate options. As will be discussed below, the failure of past policies and projects, inadequacy of existing interventions to tackle current issues of the water and irrigation sector, and increasing financial pressures on governments and economies are seen as the main causes explaining this *world-wide concern of the importance of water issues*.

In recent years, there has been a growing recognition from a large number of countries, as well as from international bodies such as the Organization for Economic Cooperation and Development (OECD, 1989), the International Bank for Reconstruction and Development (World Bank, 1993) and the Food and Agriculture Organization (FAO, 1994) of the need to move to more demand-oriented interventions that consider the economic value of water. This recognition is illustrated by the following citations:

> *Member countries develop and* ***implement effective water demand management policies*** *in all areas of water services through making greater use of: forecasting future demand for water;* ***appropriate resource pricing*** *for water services; appraisal, reassessment and transferability of*

> ***water rights; various non-price demand management*** *measures; and integrated administrative arrangements for demand management* (OECD, 1989)
>
> *Past failure to recognize the* ***economic value of water*** *has led to wasteful and environmentally damaging uses of the resource* (ICWE, 1992)
>
> *A prerequisite for* ***sustainable management of water as a scarce vulnerable resource*** *is the obligation to acknowledge in all planning and development its full costs. Planning considerations should reflect... investment, environmental protection and operating costs, as well as opportunity costs reflecting the most valuable alternative use of water...* ***The role of water as a social, economic and life-sustaining good*** *should be reflected in* ***demand management mechanisms****.* (UNCED, 1991)

The following paragraphs investigate the rationale that supports this wide consensus, which emphasizes the economic nature of water and promotes the integration of *demand management mechanisms* in water and irrigation sector policies. The objective here is not to identify solutions that will resolve all problems faced by the irrigation sector of any country. On the contrary, the complexity of the task of designing appropriate irrigation sector policies is fully recognized. Different objectives are specified simultaneously (for example, increasing agricultural production, restoring equity, or developing specific regions); are given different weights according to economic, cultural and political criteria; and are to be met under physical, socio-economic and political constraints that may vary in space and in time. The main thrust of the discussion presented below emphasizes the need to investigate the relationship between water scarcity and appropriate policy options.

Using the terminology developed by Randall (1981) in his analysis of the water economy, two stages can be distinguished in the development of the water economy, each requiring different interventions and policies. The first stage or *expansionary phase* is characterized by *supply-based* interventions (See Table 1.1) and the expansion of irrigation facilities, i.e. developing more area under irrigation, constructing new irrigation systems and storage facilities, and reaching a larger number of potential users. Priority is given to expansion of the irrigated area and increasing total agricultural production to respond to the needs of an increasing population and to reduce the risks of famine. Public intervention is predominant, partly due to the large investment costs involved in most of the irrigation infrastructure (natural monopoly), but also due to the social and political dimensions of water. Also, there is no structural shortage of water and water is supplied more or less free of cost to users.

The second stage, or *mature phase*, is characterized by water scarcity, with no extra supplies that can be tapped except at prohibitive costs, increasing pressure from the other sectors of the economy such as municipalities and industries, and significant environmental problems such as waterlogging, salinity and pollution. As water scarcity, both in terms of quantity and quality, increases, the irrigation economy enters into its mature phase. Supply-based interventions, such as constructing new irrigation infrastructure, that were favored during the expansionary phase are less well adapted to this phase. Supply-based approaches coupled with the failure to price water at an economic level induces short and long-term water problems: supplied at zero or low costs, water is seen by consumers as available in unlimited quantities with no incentive to use water efficiently.

Table 1.1. Supply-based versus demand-based interventions in the water sector.

Intervention	Supply-based	Demand-based
Modification of physical system	Construction Rehabilitation Changes in infrastructure	Development of new irrigation technology
Changes in management activities	Operation Maintenance Information management	Farm scheduling Information management
Changes in enabling environment	Institutional framework Legal system Budgetary policy	Water pricing, quota, water markets Legal system

To correct the imbalance between demand and supply of irrigation water, the economic value of water should be considered to influence water users' behavior. In short, there is a need to move from strictly supply-based to more *demand-based* interventions (see Table 1.1) or demand management mechanisms that become the least-cost methods to maximize benefits. With increasing water scarcity, efficient use of water and efficient allocation between users, whether within a sector or between sectors, become important objectives of water sector policies. Examples of demand-based instruments that have been widely discussed under different socio-economic and physical environments are *water pricing, quotas and water markets*. Box 1.1 presents some of the characteristics of these policy instruments. For presentation and discussion of a larger number of supply-based and demand-based interventions, see for example Bhatia et al. (1994), FAO (1994) and Winpenny (1994).

The distinction proposed by Randall (1981) between the *expansionary* and *mature* phases requires some comments. Going from the expansionary phase to the mature phase is a continuous process, with no clear separation between the two phases. According to the position of the irrigation sector within the economy, the overall economic development of the country, the physical characteristics of water supplies, and the existing infrastructure and institutional set-up, different levels of *maturity* may be expected, with only some of the problems highlighted above appearing in the water economy. Also, as new technologies develop, changes in the imbalance between supply and demand may be modified and excess supplies become again available, positioning the notion of maturity into a more dynamic context.

It is important to stress that policy choices are not limited to the decision to choose between supply-based and demand-based interventions (FAO, 1994). Whether to promote independent *projects* or integrate interventions into a general framework or *programs* is also part of the policy process (World Bank, 1993; FAO, 1994; Winpenny, 1995). Important choices should be made regarding the management mode that is going to accompany these interventions:

Box 1.1. Three examples of demand management mechanisms: Water pricing, quota and water markets (adapted from Montginoul and Strosser (1997)).

Water pricing

From a theoretical point of view, water pricing is the basic instrument that helps to distribute limited water resources to users and to determine allocation of these resources by providing appropriate signals or incentives. At the same time, water pricing is used for cost recovery purposes. Several conditions are required for water pricing to achieve allocative efficiency: demand for water being sensitive to water prices; water pricing mechanisms that are easily understood by water users; and, mechanisms stable enough over time to be in accordance with time horizons considered by farmers/water users to take their decisions. Other aspects to be considered for the establishment of water pricing include the enforcement of payments by users, the need to consider marginal cost issues and externalities, and financial issues such as the cost of implementing water pricing mechanisms and the financial autonomy of the managing agency.

Although water pricing is aimed at influencing farmers' decisions and the demand for water, demand and/or supply parameters may be considered while developing water pricing mechanisms. Objectives of demand-based pricing may be to appropriate part of the benefits made by water users, to maximize their total utility by putting users in competition, or to take into account more socio-political aspects (for example equity considerations). Supply-based water pricing considers the costs of delivering water to the crop (operation and maintenance costs, investment costs) and other (social) costs related to negative external effects and support by the society. The parameters used to develop and compute water prices, along with the water pricing structures, differ from country to country, and even from irrigation project to irrigation project. Extreme cases of water pricing structure (or water charge schedule) are flat-rate or fixed charge (whether area-based or user-based) and volume-based charge.

Quota

The main objective of the quota is to limit water use. Contrary to water pricing, quotas do not provide an incentive to water users but simply constrain their demand. A quota has an effect on the demand only if, for a given water price, the estimated demand for water would be higher than the quota imposed. Different types of quota may be proposed: quota in time, quota in volume and quota related to uses (for example type of crop). Quotas may be fixed over time or may vary according to the availability of water.

If the price elasticity of water demand is equal or close to zero, quotas are more efficient in constraining water users to save water than water pricing. If the demand is elastic with regard to prices, then economic theory shows that quota and water pricing lead to the same results in terms of water use when the demand for water is stationary. However, if increases in the demand for water are expected as a result of changes in other sectors of the economy, then quotas are the preferred option as they constrain the demand at the same level, while changes in water demand would be expected under water pricing.

Water markets

Water markets are an allocation mechanism based on an initial allocation of water rights. As a result of the confrontation between water supply and water demand, water is (re-)allocated between users at an equilibrium price established on the market. Requirements for well functioning water markets include water scarcity, well defined and transferable water rights, a large number of purchasers and sellers, no (or limited) transaction costs and the existence of an appropriate information system.

Existing water markets show a large diversity of functioning and organization. Water markets include permanent transfers of water rights, or lease of these rights and transfers of volumes of water. Water markets often function at the margin, i.e. involving only a limited portion of existing water resources. High transaction costs (as compared to the value of water and expected benefits), inadequate physical infrastructure and legal framework, or socio-political resistance are factors that explain this situation. Many difficulties arise as a result of potential externalities and third-party effects of water transactions, and lack of information to quantify these effects.

- *Decentralized or centralized management and control.* While in the past centralization has often been the first choice (especially in large irrigation systems in developing countries), the tendency in recent years has been towards decentralization of organization and decisions.

- Range of management styles polarized between *authoritarian and participatory.* Again, and as a result of the failure of past authoritarian management styles, participatory management has recently received a lot of attention in developing countries. Examples of experiences in the irrigation sector are summarized by Kloezen and Samad (1996).

- Identification of the relative importance of the *public and private sector.* The role of the public sector has always been very strong in the water sector, due to the special cultural and social value of water, its natural monopoly nature, the interdependency between users in a river basin or aquifer, and problems of externalities (World Bank, 1993; Winpenny, 1994). However, fragmented management, inefficiency of public agencies in managing water resources, and increasing financial problems of these agencies have highlighted the potential for private sector involvement in the water sector.

Finally, it is important to emphasize that consideration has to be given to the fit between demand-based instruments and the infrastructure available to support the implementation of these instruments. Thus, in most cases, the challenge remains *the identification of the right balance between water treated as an economic good and water considered as a social good, between supply-based and demand-based interventions, and between different management options or models.*

Many countries are moving towards policies that consider the economic value of water and emphasize proper incentives, pricing and regulation (Serageldin, 1993; FAO, 1994). Drastic changes in water sector and irrigation sector policies have been proposed and also implemented in numerous developing countries, often primarily as the result of financial pressure from donors and funding agencies and, secondarily, to respond to increasing water scarcity. Interestingly, however, the highest priority is often given to changes in the institutional framework and management mode (i.e. decentralization, participation, and higher private sector involvement) instead of changing incentives and implementing demand management mechanisms. The priority given to the reduction in budget deficit as compared to improving economic efficiency, along with the relative lack in popularity of these mechanisms (for example, increasing water charges) may explain this trend.

In developed countries, also, important modifications have taken place as a result of the imbalance between supply and demand, increasing competition between sectors, and water quality problems (pollution). Also, financial considerations play an important role as demonstrated by the recent reform of the water sector in the United-Kingdom. Table 1.2 presents examples of recent changes in water and irrigation sector policies in selected countries. The fact that changes have taken place under a large range of physical and socio-economic environments stresses the complexity of what is often casually defined as *water scarcity.*

Table 1.2. Recent changes in water and irrigation sector policies for selected countries (adapted from FAO (1994)).

Country	Justification for change and review of existing policies	Main thrust of policy review & reform	Final documents and action
Indonesia	Re-orientation of large public investments, with high water subsidy, deterioration of water resources infrastructure, regional supply-demand imbalance, water use changes.	De-centralized water administration based on river basins; privatization and cost-recovery; cross-sectoral analysis; regional water resources development.	Water Policy in 2nd 25-Year Plan and VIth Development Plan. Decentralized water administration.
Mexico	Growing regional imbalance between water demand and availability of water to cities and to irrigation	Promote water use efficiency; improve quality of water services through enhanced role of the private sector.	November 1992: Laws on National Waters enacted by Federal Congress.
England and Wales	1985: conflicting issues of financial management of public Water Authorities	Redraw boundary between the public and an integrated private sector. Control of a privatized water industry.	1988: Water Bill released. July 1989: Water Act enacted by Parliament.
France	Supply-demand imbalance worsened by drought	Manage water resources in an integrated and balance manner. Balance water resource development and conservation	January 1992: Laws on Waters enacted by Parliament.

In fact, as a conclusion to this section, it is important to look again at the analysis presented by Randall (1981) that emphasizes the link between water scarcity and water sector policies. Current examples of policy changes that promote demand management mechanisms in developing and, to a lesser extent, developed countries emphasize the importance of financial resources required to implement water and irrigation sector policies. In the case of the western United States, for example, Gould (1989) mentions that *the pressure for (water) reallocation is not simply a result of demand exceeding supply. Much of the pressure is financial.* The recent impetus for change in water and irrigation sector policies may be more the result of a financial crisis in the context of structural adjustment programs and reduction of budgetary deficits, than a pure water crisis. Of course, the importance of the latter is fully recognized, especially in the context of supplying basic water needs to the poorest in developing countries. But this view is supported by the simultaneous recognition in a large number of countries facing a large diversity of "water scarcity" situations, of the need for drastic changes in water and irrigation sector policies that promote demand based mechanisms.

The following section takes the example of the irrigation sector in Pakistan to illustrate what has been described so far in general terms. Some of the symptoms of the mature phase of the water economy as described by Randall (1981) are present in the irrigation sector in Pakistan, that is currently under scrutiny and pressure to undertake drastic policy and institutional reforms.

1.2 Main issues related to irrigation system management in Pakistan

The importance of the agricultural sector in the economy of Pakistan can be summarized in the following key figures: the sector accounts for 26% of the Gross Domestic Product (GDP) of the country, provides job opportunities for 55% of the labor force, and accounts for 80% of the total export earnings of the country (Strosser and Rieu, 1993). Within the agricultural sector, irrigation plays a predominant role as it provides 90% of the total agricultural production of the country, mainly within the 14.5 million hectares of the Indus Basin Irrigation System. Also, the irrigation sector plays a major role in the industrialization process of Pakistan with the production of cash crops such as cotton and sugarcane.

During the 1960s and 1970s, and similar to other countries that benefited from the technological improvements of the Green Revolution, Pakistan has been able to improve its self-sufficiency in agricultural and food product with significant increases in cropping intensities and crop yields. However, crop yields remain among the lowest in the world. Also, by the end of the 1980s, several signals suggested that the period of agricultural output growth was over, with the productivity per unit of land of the main crops becoming stagnant or even following a decreasing trend (World Bank, 1994; Bandaragoda and Firdousi, 1992).

With a population estimated at more than 130 million inhabitants today, that is expected to reach 150 million people by the end of the century and 400 million by the year 2050 (World Bank, 1994), the demand for food products is expected to continue growing. Thus, unless there are significant improvements in agricultural productivity and total production at least in the same order of magnitude as those recorded during the Green Revolution period, the imbalance between supply and demand of basic agricultural goods is expected to increase in the future and to threaten the self-sufficiency objective of Pakistan.

While the different actors involved in the management of the irrigation system may disagree on *the* main cause explaining the current low productivity level, the majority of them recognizes the problems faced by the irrigation system. Although the benefits of irrigation *per se* are fully recognized (under the semi-arid climate of Pakistan, little would grow without irrigation), the irrigation sector has become increasingly the target of criticisms and considered as the main cause for productivity problems in agriculture for the following reasons:

- *Poor performance of the public sector in supplying irrigation water to end-users.* Low conveyance efficiencies are obtained, with only 40 percent of the water diverted to the canal system reaching the root zone of the crops (John Mellor Associates, 1994)[1]. Canal water supplies are highly inequitable, variable and unreliable (Bhutta and Vander Velde, 1992; Kuper and Kijne, 1993; Ahmad et al. 1993). Public tubewells, also, have a poor operational performance, with low utilization rates and discharges lower than design (Malik and Strosser, 1994). Poor maintenance, lack of application of operational rules, no proper information system, local preference by operators that increase variability downstream, and interference by water users in

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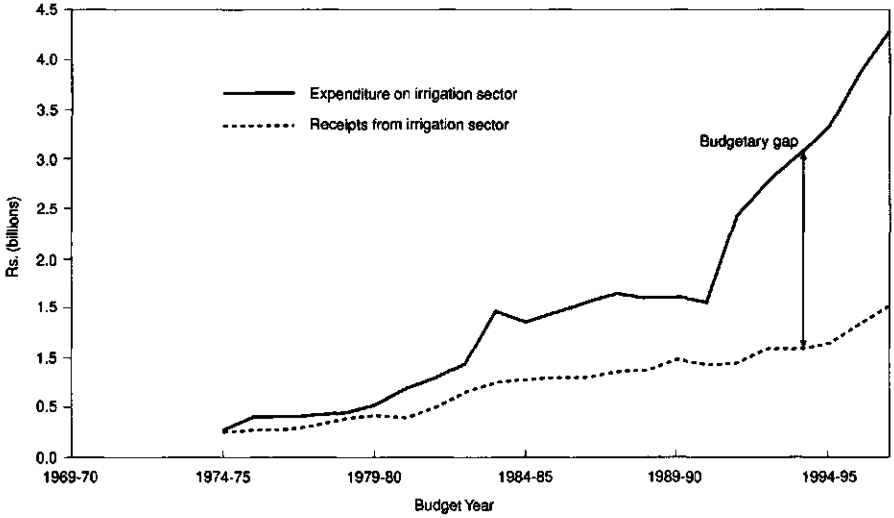
[1] In fact, low conveyance efficiencies are to be considered in the context of the overall efficiency of the Indus Basin. In areas with good quality groundwater, such losses will be reused via tubewell pumping.

the operation of the irrigation system, or lack of interest by government staff, are reasons explaining the poor performance of the public sector.

- *Severe environmental problems.* Although investments in drainage have been significant in Pakistan during the last 20 years, waterlogging still affects large tracts of land, with more than 22% of the total Gross Command Area (GCA) of the Indus Basin Irrigation System having groundwater tables within 1.5 meters of the soil surface (World Bank,1994). Also, salinity and sodicity constrain farmers and affect agricultural production, problems that may be further exacerbated by the use of poor quality groundwater (Kijne and Kuper, 1995). In areas with good groundwater quality, excessive pumping by private tubewells leads to mining of the aquifer (NESPAK, 1991).

- *Financial constraints.* Maintenance and operation of irrigation systems has been constrained by inadequate allocation of funds in the provincial budgets. The low level of funding is partly related to the existing gap between water charges collected from water users and operation and maintenance costs (influenced by the high operation and maintenance costs of public tubewells) as illustrated in Figure 1.1. However, the overall financial constraints faced by the different provinces largely explain the situation (John Mellor Associates, 1994). Inadequate financial allocation, along with the lack of appropriate methodologies to allocate these scarce financial resources optimally, and poor quality control and fraud associated with contract work (Vander Velde, 1990), has led to deferred maintenance, with negative impact on canal water supply performance.

Figure 1.1. Gap between receipt and expenditures in the irrigation sector for the period 1974 to 1996 (source: Government of Punjab, Pakistan)



There is a need to stress that some of these problems are not new in the irrigation sector in Pakistan. Dry tails, problems of maintenance, user's interference, and waterlogging and salinity, have always been part of the history of irrigation in Pakistan. For example, in 1895 already, measures were implemented to control waterlogging (Kuper, 1997). However, the negative impact of these problems could then be compensated at the macro level by the construction of new irrigation systems that constituted the major public intervention in the irrigation sector for a very long period.

1.3 The historical context to understand current policy changes in Pakistan

Looking back at history

Up to the end of the colonial period in 1947, the British administration promoted the construction of large irrigation schemes that resulted in the existing Indus Basin Irrigation System. Initial objectives of irrigation related policies included the relief of the population pressure existing in the congested districts of Central Punjab and the creation of model villages *superior in comfort and civilization to anything which had previously existed in the Punjab* (Farmer, 1974). Rapidly, the main objective of irrigation related policies became the mitigation of famines, especially after the severe famine that affected large parts of India in 1878, by spreading water resources thinly and equitably over large areas of land. Also, the establishment of a comprehensive hydraulic network and its related administration strengthened the control of the British over large areas and populations.

In irrigated areas, the British established a system of quota (still in use nowadays) to share limited canal water supplies. The quota, expressed as the combination of a duration of use at the farm level (i.e. the water turn of the *warabandi* schedule that shares canal water between users within the tertiary unit or *watercourse*) and a share of water flows (specified by the dimensions of the watercourse outlet) was enforced through social control and physical infrastructure. A limited number of control structures along the main canals were provided to minimize operational requirements. With imposed scarcity, efficient use of canal water was also expected. The British established a system of area/crop-based water charges (*abiana*) to cover mainly operation and maintenance costs and also to generate some revenue (Farmer, 1974).

Since Independence in 1947, most of the interventions in the irrigation sector have focused on water supplies to increase agricultural production, improve self-sufficiency in major food crops, and promote equity in water supplies. Major efforts were targeted towards replacing the supplies "lost" to India under the 1959 Water Treaty by building link canals to bring supplies from the Western to the Eastern part of the country, and constructing dams to increase storage capacity. However, cropping intensities increased more than irrigated areas during this period.

At the same time, further emphasis was given to mitigating the adverse effects of irrigation such as waterlogging and salinity. Large-scale Salinity Control And Reclamation Projects (SCARPs) have been implemented since the beginning of the 1960s, initially with the installation of large public tubewells that provided also extra irrigation water supplies in areas with good groundwater quality, and then with the construction of large surface drains. More recently, drainage facilities have included sub-surface (tile) drainage systems in limited areas. As will be discussed below, the end of the 1970s saw a shift in the focus of policies, with the development of the On-Farm Water Management projects aimed at reducing water losses taking place within tertiary units and farms.

The irrigation system to date: new pressures on water and financial resources

The Indus Basin Irrigation System today is the result of one century of supply-based policies. Surface water is supplied to more than 14.5 million hectares or 89,000 watercourses through an extensive network of main canals and secondary canals or *distributaries*. The system of quota and area/crop-based water charges is still in use, although discrepancies exist between official rules and rules in practice, with for example the development of localized canal water markets. The 1980s, however, have brought major changes that have stressed the inadequacy of the supply-oriented and engineering-driven interventions for projects implemented so far. In this context, two issues are seen as particularly important.

The *first issue* relates to *changes in water scarcity* that have taken place within the irrigation system. It is not clear that the quota initially imposed by the British administration played a role as the demand for irrigation water was rather minimal. During the last decade, however, the pressure on water has drastically increased, with more competition for quantity and quality of irrigation water within the irrigation sector, but also from other sectors of the economy.

- As a result of changes in the macro-economic environment, farmers have increased their cropping intensities from the original design figures of 50-70% to an average of 120% per year for the Indus Basin (John Mellor Associates, 1995). This has led to an increasing pressure on the (cheap) surface water resources, translated into a significant interference of water users into the operation of the irrigation system (Rinaudo et al., 1997a).

- As a result of inadequate canal water supplies, but also as a response to changes in the macro-economic environment, farmers have installed a large number of private tubewells to tap groundwater resources. However, current pumping rates have already led to mining of the aquifer in several canal command areas with good groundwater quality (NESPAK, 1991). In areas with poor groundwater, farmers still have installed tubewells and pumping leads to problems of salinity and sodicity (Kijne and Kuper, 1995).

- More recently, water needs by other sectors of the economy, such as industries and municipalities, are becoming more significant, although the overall quantity used by these sectors remain marginal as compared to water use by the irrigation sector, i.e. less than 5% of total water resources (World Bank, 1994). Competition over water resources between sectors has been limited to specific areas close to large cities and industrial complexes. The main issues presently at stake include competition on groundwater use (quantity), and problems of effluents and pollution of irrigation water (quality).

- There has been a recent recognition of the in-stream needs of the Indus River. Minimum discharges from the Indus to the sea are required to limit intrusion of seawater into the coastal area. However, little is known about the minimum flows required and how this would compete for surface water resources with the irrigation sector.

- Finally, the competition for surface water resources has intensified between the four Provinces, and mainly between the Sindh and the Punjab. After long negotiations, the Indus River System Authority was created in 1992 to implement the water apportionment accord that specifies surface water allocations to Provinces. However, confrontations between the Sindh and the Punjab regarding these allocations still arise periodically, mainly during periods of high water demand.

The *second issue* is linked with the level of *financial resources* available for the irrigation sector. Financial resources for the development of the irrigation sector are scarcer today than 20 years ago, both in absolute and relative terms. Several reasons explain this situation.

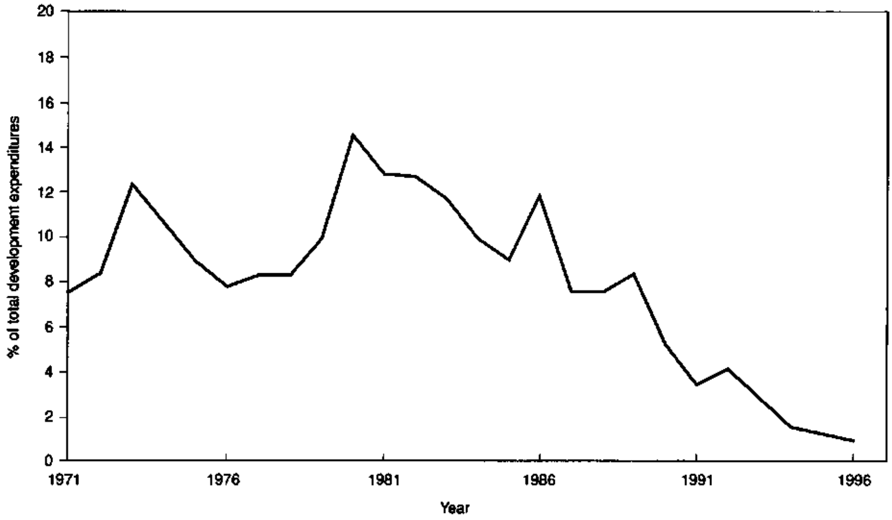
- Similarly to the general trend observed in the Sub-continent (Rosegrant and Svendsen, 1993), the development costs of irrigation projects per unit area today are significantly higher in absolute terms, as low-cost high-potential areas have already been developed. As a consequence, significant improvements in agricultural benefits will be required if acceptable economic returns are to be realized.

- In the context of structural adjustment programs and under pressure from international lending agencies, there is a political will to reduce subsidies to the irrigation sector. As shown by Figure 1.1, the irrigation sector has been (and still is) highly subsidized in recent years. Financial autonomy has become an important policy objective in Pakistan. The recent SCARP Transition Projects illustrate this concern. In order to eliminate the financial burden related to the high operation and maintenance costs of public tubewells, these projects aim at closing down public tubewells, selling them to farmers or group of farmers, or providing subsidies for the installation of private tubewells by individual farmers.

- The level of financial public resources available for the irrigation sector has drastically decreased in relative terms. This results from the disengagement of donors traditionally involved in the irrigation sector (the end of the US-Aid period in 1991 as a result of the Pressler amendment). The increasing importance of the total debt servicing of the country, presented in Figure 1.2 as a percentage of the Gross Domestic Product (GDP), is another element that limits the availability of financial public resources. Also, the competition from other sectors of the economy has increased: higher economic rates of return are in fact expected from investment in industrial and infrastructure development as compared to investments in the irrigation sector. Figure 1.3 illustrates the decreasing share of the agricultural sector (including irrigation) in the total annual development expenditures of the Government of Pakistan.

Figure 1.2. Total debt servicing in Pakistan for the period 1987 to 1996, expressed as a percentage of the Gross Domestic Product (GDP) of the country (Source: Government of Pakistan).

Figure 1.3. Annual development expenditures of the agricultural sector (including irrigation) in Pakistan for the period 1971 to 1996, expressed as a percentage of the total annual development expenditure of the Government of Pakistan (Source: Government of Pakistan).



With the increasing scarcity of water resources and financial resources described above, it is clear that highly expensive *supply-based engineering* approaches become less viable. This has been reinforced by the increasing recognition of the failure of past projects that did not yield the expected (lasting) benefits that were visualized, and could not solve problems in the irrigation sector (World Bank, 1994).

1.4 Proposed options for irrigation sector policy in Pakistan

In the 1980s in Pakistan, there was already recognition of the inadequacy of the purely supply-based engineering biased interventions for tackling the problems faced by the irrigation and agricultural sector. New approaches were proposed that included institutional components. Examples of such approaches include: the On-Farm Water Management Projects that promote the development of water user associations at the watercourse level (Colorado State University, 1976); the SCARP Transition Projects that aim at reducing public involvement in the groundwater sector by closing down or transferring public tubewells to water users (World Bank, 1988); or the Command Water Management Program that promoted water users' involvement in the maintenance of the irrigation system up to the distributary head (World Bank, 1996a). Also, under the pressure of donors, there have been discussions on the need to increase water charges to decrease the gap between revenues from the irrigation sector and operation and maintenance costs. Although conditional to loans for several projects, the political decision to increase water charges has been postponed. Only recently have some of the provinces decided to increase water charges.

However, despite the apparent change in philosophy that guided interventions in the irrigation sector, the engineering components only of these new approaches were successfully implemented. A typical example is the On-Farm Water Management Projects cited above, where watercourse lining (the engineering component) has been implemented in large number of watercourses while few water user associations (the institutional component) have been developed in a sustainable manner. Reasons explaining this lack of success may be related to inadequate approaches for local conditions; the absence of real needs for water user associations within the watercourse command area; the lack of local support and appropriateness of changes brought by outsiders; the meager qualified human resources (i.e. technical staff from engineering wings of government departments trained as social organizers) allocated to the implementation of these projects; and the incentives for implementation staff closely tied to construction progress rather than to institutional progress and development impact (World Bank, 1996a).

More recently, in recognition to the current problems in the irrigation sector and under pressure from international lending agencies, drastic changes in irrigation sector policies have been proposed (World Bank, 1994). These changes, in line with the worldwide recognition of the economic value of water illustrated above, included the *privatization of the irrigation sector and development of water markets* in order *to achieve financial autonomy of the sector and economic efficiency*. Several rounds of discussions were held between the major stakeholders of irrigation systems in Pakistan, i.e. government departments at the provincial and federal levels, farmer organizations, politicians and donors to discuss the proposed and highly controversial changes. The different stakeholders eventually agreed on the need to decentralize, instead of privatize, irrigation system management and to promote a participatory management mode. In short, the final proposal opted for an increasing involvement of water users and the development of financially autonomous irrigation authorities at the Provincial level and Area Water Boards at the canal command area level.

Although there has been a political decision to proceed with these changes, it is surprising to realize that very little is known regarding the details of the proposed changes and of their implementation, and their expected impact on water supply, agricultural production and sustainability of the resource base. The approach selected for implementation includes the development of selected canal command areas as pilot projects that are expected to provide information on constraints and limitations of proposed changes and lead to a successful implementation for other irrigation canal commands. It is important to note that pilot projects will impact on large areas of no less than 300,000 hectares, thus on a large number of farmers that may eventually pay for an ill-designed project or unsuitable options.

1.5 Justification of the study

Analysis of policy interventions in the irrigation sector shows that little effort is generally made to adequately appraise alternative interventions and estimate their economic impact. This aspect has been recently emphasized in a study reviewing irrigation projects funded by the World Bank that *noted a very high level of unsatisfactory planning and design in irrigation projects* (Jones, 1994). In fact, policy and project appraisal may take place too often under the conditions described more than 25 year ago by Ingram (1971) with *benefit-cost analysis* (or as a matter of fact other studies used to appraise interventions)*.... used to clothe politically desirable projects in the figleaf of economic respectability*. Often, interventions are justified theoretically, ideologically or politically, or because similar experiences have successfully taken place in other countries.

Although the political nature of policy decisions may limit the need for appraisal of new projects and policies, other causes explain the lack of comprehensive appraisal and analysis of proposed interventions in the irrigation sector. Firstly, well-specified appraisal methods that analyze and integrate the multiple facets of irrigation in an effective way are rare. Due to the *complexity of the irrigation system*, there is no simple cause-effect relationship between an intervention and its impact. It may be necessary to analyze the complexity of decisional and biophysical processes to identify and quantify the impact of a given intervention. Also, as other external interventions may take place at the same time and influence these processes, it is sometimes difficult to identify the *marginal* impact of given interventions. In some cases, methodologies may be available with researchers, but have not been operationalized to integrate constraints existing in most of the appraisal processes related to availability of time, financial resources and information.

Secondly, the appraisal process in itself is often mono-disciplinary oriented, without due consideration given to the integration of disciplines. Priority is often given to technical aspects. And environmental, social and economics issues are considered at a later stage of the appraisal process once major technical choices are made. In fact, although the need for integration between disciplines in appraisal and evaluation processes is increasingly recognized, the effective integration of economics and technical issues in these processes remains rare (Goldsmith, 1986; Srinivasulu et al., 1997; Faisal et al., 1997).

Thirdly, the appraisal process is hampered by a lack of information. Little is often known on the functioning of the existing irrigation system and good information is particularly scarce in developing countries. Pakistan provides a good illustration of information-related issues in the irrigation sector; information is scattered between institutes, is collected for different time and spatial scales, lacks accuracy, and is often outdated. The following sentence mentioned by Gould (1989) in the context of water right issues remains valid for the appraisal of new irrigation sector policies in Pakistan and stress the importance of good information on the existing situation: *suggestions for improvement must take the current system as a given. It can be improved, but it will not be replaced. This, too, is a reality, which must guide the search for better use of water resources.*

Also, information on the impact of policy interventions in other countries and irrigation systems is lacking in most of the cases. Proper monitoring and evaluation of past experiences is often inadequate. The large literature on privatization or turn-over of irrigation systems, for example, focuses on the processes and the organizational dimensions of privatization, while results showing that these experiences have effectively produced the desire benefits are lacking (Seckler, 1993). Thus, lessons from past interventions are generally insufficient to support current appraisal processes. New policies are then only justified by the existence of similar interventions in other countries or irrigation systems, and not by the effectiveness of these interventions to reach specific objectives and tackle well identified issues.

1.6 Objectives of the study

Most of the issues mentioned above explain the lack of adequate appraisal of current proposals for decentralization and water market development in Pakistan and provide the rationale for the present study. The main thrust is that further research on the functioning and constraints of the irrigation systems to date will provide necessary information and understanding of the complexity of these systems and lead to a more appropriate design of alternative policy instruments. This research requires a specific framework to analyze in an integrated manner the technical, economic and environmental dimensions of the irrigation sector, to understand the relationships between these dimensions, and to analyze tradeoffs between policy options.

In this context, the present study has two objectives:

- **The development of a methodology or *integrated approach* to assess the potential for policy interventions in the irrigation sector.**

The proposed methodology will be used to analyze irrigation systems in an integrated manner, and provide information on the impact of various interventions on irrigation system performance in terms of water supply, agricultural production and the physical environment. Also, the technical feasibility of these interventions is assessed as part of this integrated approach. The methodology has been developed jointly for the present study and for the analysis of the relationship between main system management and salinity and sodicity presented by Kuper (1997).

- The application of this methodology to one case study, the assessment of the **potential for water market development in irrigation systems in Pakistan.**

The application investigates one component of the current policy proposals in Pakistan, i.e. the development of water markets to improve economic efficiency and increase agricultural productivity and agricultural production. Of interest in this application will be the analysis of *existing water markets*. As mentioned above, informal water markets have already developed within the tertiary units of the irrigation system, but little analysis has been carried out regarding their organization, impact and constraints. Also, the *potential for water market development* at different levels of the irrigation system (between tertiary or secondary units) will be investigated.

The structure of the thesis is as follow. Based on a literature review, Chapter 2 investigates issues related to water markets. The main objective of this review is to identify important issues related to water markets, in general, that are to be addressed in the context of water market development in Pakistan. Chapter 3 presents the general methodology or integrated approach that has been developed to assess the impact of interventions in the irrigation sector on irrigation system performance. Chapter 4 presents the irrigation system selected for the application of the integrated approach to the analysis of existing and potential water markets, while Chapter 5 summarizes the elements combined into the economic component of the integrated approach.

Selected elements of the integrated approach are applied to the analysis of the functioning and impact of existing water markets, and to the analysis of the potential reallocation between tertiary and secondary units of the irrigation system. The results of both analyses are presented in Chapter 6 and Chapter 7, respectively. Based on the application of the integrated approach to the analysis of water markets, and also on results obtained in the companion study by Kuper (1997) on the link between main system management and salinity and sodicity, Chapter 8 concludes with a preliminary assessment of the added value, potential and perspective of the integrated approach.

Chapter 2

Understanding water markets: a literature review

The main objective of this chapter is to better define water markets and identify the main issues that are related to their functioning and impact, based on a review of literature. The conditions for perfectly functioning water markets are first defined, and then discussed in the context of the intrinsic characteristics of water resources. The important role given to the definition of water rights is then discussed, theoretically and in the context of existing water markets. An attempt is made to investigate the economic impact of existing and potential water markets. The final section of the chapter summarizes the main issues related to water market functioning and impact that are relevant to the analysis of existing and potential water markets in Pakistan.

2.1 Water markets from an economic theory perspective

Generalities

Markets are traditionally defined as the place or context in which buyers and sellers buy and sell goods, services and resources. The confrontation between supply and demand of a given product results in a market equilibrium price when the forces of market demand and market supply are in balance. Apart from the confrontation between supply of, and demand for, given commodities and inputs, and as highlighted by the definition given above, markets are also an institution and organization that links potential sellers and purchasers. Specific arrangements are required to obtain appropriate information and provide it to potential sellers and purchasers, to organize and implement transactions, and to control and enforce transfers of products between sellers and purchasers.

The definition used to define markets for water is similar to the ones presented above. Quoting Katz and Rosen (1994), *water markets generally refer to a group of independent voluntary decisions (transactions) by consumers and producers taking place continuously over a period of time.* From the theoretical point of view, the sale of irrigation water by a centralized agency (whether private or public) to individual customers may be seen as a water market, with the producer (the irrigation agency) and consumers (farmers) entering into a series of voluntary transfers. The particularity of this example, however, would be the monopoly power of the (single) producer. In this case, the supply curve would be mostly based on cost-related considerations that would lead to the establishment of specific prices or water charges. The demand curve depends on farmers' strategies and constraints and on the equalization of the marginal value product of, and proposed price for, water. Importantly, however, are the *independent* and *voluntary* aspects of the *transactions* that limit cases of water markets to irrigation systems where users can specify and modify their demand according to water prices and their own water requirements.

In the literature, the term water market is mostly used to describe situations where users with specific rights over water sell or lease these rights to other users, whether permanently or temporarily. Water markets can be considered in terms of the access to water or irrigation services (a quantity received for example) or in terms of transfers of water rights. The main benefits expected from water markets are an optimal allocation of available resources between users and uses, and an increased water use economic efficiency.

In the case of irrigation, the decisions to sell water or water rights are not related to marginal cost considerations, but to opportunity cost issues; irrigation water has an utility for farmers and can be alternatively used on the farm or sold on the market. Thus, the development of an irrigation water market is expected to improve the allocation of resources, while also impacting the efficiency of water use of *both* purchasers and sellers. The main advantage of water markets as compared to efficient water pricing remains their flexibility and ability to respond to temporal changes in demand from different uses by reallocating water from low-value to high-value uses. In a well-functioning market, the marginal benefit of using water is the same for all consumers and users, so that general economic welfare cannot be increased by re-allocation. This is referred to in the economic literature as the *pareto-optimum* condition

Necessary conditions for market perfection

An important issue related to markets in general, and water markets in particular, relates to the above-mentioned pareto-optimum and the notion of *market perfection.* This notion relates to the ability of markets to promote an optimal and efficient allocation of resources, not only for individual users that participate in market transactions, but also for the society as a whole. From a theoretical point of view, necessary conditions that lead to market perfection include (Brajer et al. 1989):

- A large number of sellers and purchasers, so that the action of any individual does not affect the price of the water;
- Sellers and purchasers free to participate in water transactions;
- The homogeneity of the product transacted on the market;
- Transparent and perfect information available to all potential participants in the market, unbiased and free of cost;
- A perfect mobility of resources, thus absence of transaction costs;
- The absence of externalities or third-party effects.

The characteristics of water resources themselves make the above-mentioned conditions valid in only a few very specific cases. These characteristics, described in the following paragraphs, lead to cases of *market failures* to express markets' limitations for achieving (optimal) economic efficiency. In fact, market failures are (or have been) the main justification to public interventions into the water sector.

- Water has the *nature of a public good.* The essence of a public good is that it is available to all and no one can be denied access to it (Winpenny, 1994). Investments in the water sector yield common products such as flood control, electric power, recreation and irrigation, which makes pricing and allocation decisions difficult. However, many argue that water is not bound to remain a public good (Vaux, 1986; Winpenny, 1994). In fact, inappropriate and outmoded institutions that lead to under-pricing of water and locking water into existing usage confer a public good nature to some water services that did not originally have this nature.

- There are rarely a large number of sellers and purchasers. On the supply side, decreasing return to scale for large investments often leads to situations of *natural monopoly*. Most of the irrigation managers of large irrigation systems are, in fact, in a situation of monopoly towards their customers. Similarly, tubewell owners in Pakistan may be in a situation of monopoly towards neighboring farmers that do not have choices among several sellers. On the demand side, situations of *monopsony,* with a single buyer facing a large number of potential sellers, are also frequent. This is the case, for example, for most of the water transactions taking place between the agricultural sector (large number of farmers) and the urban sector (usually one city).

- There is a high interdependency between water users. This interdependency usually leads to high *externalities* or *third-party effects* resulting from the reallocation of water resources. From the economic point of view, an externality is a divergence between private costs and social costs or between private gains and social gains. Examples of direct externalities include users sharing the flows of a common stream with some users depending on return flows of upstream users, or aquifer where each user pumping from the aquifer is affecting other users that pump in the same aquifer. In both cases, the transfer of water rights between two users may threaten the water right of other users. Indirect externalities take place when the reallocation of water resources affect sectors of the economy that do not have a direct use of water, but that are economically dependent from the actors involved in water markets.

- Water is not an homogeneous product and is characterized by a *bundle of attributes*. Apart from the quantity or volume that is usually considered in market analysis, those attributes include timing of water supplies, reliability of water received, location, and water quality. Although the different facets of water may be integrated into the definition of water rights and eventually translated into the price of water, it remains difficult to define and easily compare water rights. This, in turn, may affect the development of water transactions and also their overall efficiency. In most of the cases, however, this may be more a problem of information collection or higher transaction costs (see below) to assess existing rights, than a problem affecting market perfection in itself.

- *High transaction costs* are expected in water transfers. These costs include collecting appropriate information on existing rights and potential third-party effects, searching for transaction partners, and organizing transfers. It also includes contractual and enforcement costs, costs required to manage the physical and legal hardware to ensure that rights are transferred, and to confirm the absence of third-party effects. As a result of the numerous attributes of water, the mobility of water resources and their unreliability, and the existing legal system, large efforts are spent on collecting information related to the rights to be transacted and to potential third-party effects that may result from the transaction. Transaction costs include, also, the potential physical losses that may take place as a result of the transfer. Transaction costs are often high in absolute terms, but also in relative terms as compared to the low value of water per unit of volume resulting from the bulkiness characteristic of water.

Water rights, precondition for efficient allocation of water resources

An important part of the discussion on water markets focuses on water rights seen as the basic requirement for efficient functioning of water markets (Coase, 1960; Rosegrant and Binswanger, 1994). Coase (1960) reduces the market perfection conditions to two issues and demonstrates that market allocation will be efficient given *well-defined and non-attenuated water rights* and *no transaction costs*. Completely specified, exclusive, transferable and enforceable water rights, that combines security and flexibility (Livingston, 1995), are then a requirement for efficient allocation of water resources through market mechanisms (Brajer et al., 1989; Rosegrant and Binswanger, 1994). More practically, water rights must be defined in a readily understood and measurable way, so everyone knows what the right is and can monitor its transfer (Simpson, 1994).

Water rights may be defined as riparian water rights, appropriative water rights, or usufruct rights related to a concession or contract with a water company (Colby, 1990). Water rights may be linked to land ownership, as it is in the case of riparian water rights and most of usufruct water rights in irrigation systems. The entitlement attached to the right can be defined in terms of volume of water, share of a flow, share of a storage capacity (Dudley, 1991), or time of use for the simplest usufruct water rights. Also, different levels of priority of use may be attached to water rights. For example, appropriative water rights in California are fully defined by 5 distinct elements, i.e. the diversion entitlement, the point of diversion, the purpose of use, the location of use, and the priority date.

According to the type of water right, it may be more difficult to develop water markets. For example, the definition of riparian water rights limits the possibility of reallocation to other users. In some cases, only a component of the water right may be transacted, as illustrated by changes in location and transfers of the consumptive portion of appropriative water rights.

In a large number of situations, water rights are not properly defined and enforceable as specified above. The inherent heterogeneity in appropriative water rights may be a reason limiting water transfers, or at least increasing the information requirements and transaction costs (see below). Ill-defined water rights that do not internalize third-party effects are also problematic, as they will require complex procedures to ensure that third parties are not affected by transactions. In most of the cases, for example, information on the consumptive use portion of water rights would not instantaneously be available and would need to be collected. And water rights mostly concentrate on water quantities and neglect water quality issues, an important element to be considered in reallocation of water resources (Howe et al., 1986). Also, transactions may carry a certain level of risk, as there is no certainty attached to the output of the purchase (Frederick, 1986).

Sufficient conditions for water market functioning and improved economic efficiency

The preliminary, maybe obvious, condition for water markets to develop is water scarcity, i.e. a demand for water higher than water supply. The level of water scarcity specifies the marginal value product of water, i.e. the marginal increase in output expressed in financial or economic terms that is obtained by increasing water allocated to a user by one unit. Water transactions will develop only when differences exist between the marginal value product of water for different users or uses. And water will then be transferred from lower-valued to higher-valued uses. It is important to note that scarcity may be a temporary condition only, with different arrangements being required to develop water markets under conjectural or structural scarcity conditions.

Other necessary conditions for water markets to function include sellers and purchasers free to enter or to leave the market, and the possibility for establishing links between potential sellers and potential purchasers in terms of information and infrastructure to exchange water (Rosegrant and Binswanger, 1994). It is important to note that the infrastructure may not be a problem, as a simple infrastructure may be sufficient for water markets to function (Rosegrant et al., 1995). Also, a tradable margin that can be accommodated by the existing infrastructure may already provide the required flexibility and lead to an efficient allocation of water resources (Howe et al., 1986). In fact, the infrastructure becomes an issue when transfers between uses, or at high spatial scales, are considered (Simpson, 1992).

The fact that transactions between individuals do not consider third party effects and externalities is an important limitation for water markets to achieve overall economic efficiency. A particular (market-based) water allocation is efficient relative to another (non market-based) allocation if those who benefit from the reallocation of water are able to fully compensate those who lose water or income as a result of the transfer. Several alternatives may be proposed to limit externalities:

- To develop a legal and institutional framework to control water transactions;
- To incorporate externalities into the definition of the water right itself, as discussed in the previous section;
- To limit water transfers to the consumptive use part of the water right or user's entitlement (Rosegrant et al., 1995); and,
- To promote market-related organizations that would internalize externalities related to water reallocation taking place within the boundaries of the organization.

Although the theoretical requirements for well-functioning water markets are rarely met in reality, water markets have been reported under a large range of physical and socio-economic environments. The following section concentrates on the description of *existing* water markets, and stresses the diversity of functioning of these water markets.

2.2 A large diversity in existing water markets

The increasing interest in water markets mechanisms, whether by policy makers or researchers, is rather recent and has its origin in the 1980s as a result of the recognition of the poor performance and inadequacy of past policies to manage water scarcity (see Chapter 1), possibly accentuated in some regions and countries by recent periods with temporarily high water scarcity such as the 1987-91 drought period in the State of California. However, water markets already existed long before this more recent surge of interest. Although not very well reported in the literature, historical examples of water markets include transactions of surface water rights in traditional irrigation systems in the South of Spain (Maas and Anderson, 1978), accounts of water trading dating from the first-half of the twentieth century in irrigation systems in the western United-States (Hutchins, 1936; Anderson, 1961; Gardner and Fullerton, 1961, cited in Reidinger, 1994), or groundwater transactions reported in the State of Gujarat, India for more than 60-80 years (Shah, 1985).

Water markets within irrigation systems are probably the most common cases of water markets, although they have not been the focus of intensive research and are not often reported in the literature. The term *water markets* covers a large range of highly diverse situations and organizational arrangements. It is used to characterize varied situations such as the exchange of canal water turns between neighboring farmers in North-India (Reidinger, 1980), the transfer of water rights from the agricultural sector to the urban sector, and reallocation of water resources between countries as proposed for an efficient management of water resources in the Middle-East (Becker, 1996). More specific terms are used to distinguish some of these transactions: *water transfer* when there is a change in use or place of use (Gould, 1988); *water marketing* when prices for water are attached to the transaction (Reidinger, 1994); *water trading* for transactions that do not involve prices (Reidinger, 1994); and *water farming* to describe the sale of farm land to cities as a means to purchase groundwater rights attached to land in order to provide required water supplies to urban customers (Charney and Woodard, 1990).

The main characteristics of, and differences between, water markets are summarized in the following paragraphs. Water markets can be classified according to three important dimensions:

- *The object of the transaction*
- The definition of the product that is transacted: whether volume of water or water rights, or a specific component of the water right such as the consumptive use portion of appropriative water rights.
- The duration of the transaction: ad-hoc or seasonal transfers of volumes, temporary or permanent transfers of water rights (most of the transfers from the agricultural sector to other sectors).
- The resource considered: surface water flowing along a stream or stored in a reservoir, groundwater.

- *The actors involved in the transaction*
- Individual users, user's groups or local communities, private companies, governmental departments, or states.
- Within sectors or between sectors: In some cases, water transactions mean change in use. A large number of water transactions exist within irrigation systems and involve individual farmers or groups of farmers. However, water markets may involve changes in use as illustrated by water right transfers from the agricultural sector to municipalities or industries.

- *The organization of the transaction*
- Informal or formal water transfers: informal water transfers usually take place within irrigation systems. Formal water transfers exist when the legal system of water rights is more developed to take into account third party effects or mitigate negative effects to third parties.

- Centralized or decentralized: water transfers are mostly decentralized. And potential sellers and purchasers are put in contact directly and bear the entire transaction costs. In some cases, however, a centralized body may be involved in controlling and recording existing transactions. Such an organization plays the role of water broker that makes the link between demand and supply of water, but without a direct confrontation between suppliers and purchasers.
- Auction or bilateral negotiation: in auctions, water rights or volumes are proposed to a large number of potential purchasers and allocated to the highest bidders. Bilateral negotiation usually takes place when one single purchaser (most of the time a municipality) negotiates water purchases from individual farmers or an irrigation district.

Box 2.1 illustrates the functioning of three different types of water markets that have developed under different characteristics of the socio-economic and physical environment, namely:
- Groundwater markets in the State of Gujarat, India;
- Institutionalized water markets in Chile; and,
- The emergency 1991 Drought Water Bank in the State of California, United-State.

Also, existing and potential water markets in Pakistan are described in Chapter 6 and Chapter 7 of this thesis.

Two important conclusions can be drawn from the review of existing water markets reported in the literature. Firstly, the majority of the literature on water markets focuses on two types of water markets:
- The transactions of well-defined water rights from the agricultural sector to the urban sector that have been reported in the western states of the United-States (and also in Australia and Chile); and,
- Informal groundwater markets that take place in South-Asia and have been reported mainly in India, Bangladesh and also Pakistan.

The importance of the literature on water transactions from the agricultural sector to the urban sector may be explained by the indirect economic effects related to changes in use, with larger socio-economic and political issues being involved in such transfers. As specified by Gould (1989), *changes in use, not changes in ownership, are responsible for problems in water transfers.* This results mainly from changes in the consumptive use portion of water rights that often accompany changes in use and that lead to direct third-party effects.

Secondly, the literature mainly focuses on legal and statutory remedies to promote water markets and explain limitations in their current functioning. Little attention has been given to the existing functioning of these markets and *the role of water organizations in water transactions*. In fact, local agricultural water organizations often promote water transfers within their borders and may provide local flexibility that does not exist in the law and operational rules with reduced transaction costs. At the same time, these organizations appear to limit external transfers (Thompson, 1993).

Box 2.1. Three examples of water markets: India, Chile and California

Groundwater markets in Gujarat (Shah, 1985; Shah, 1994)

Groundwater markets have been recorded for more than 60-70 years in the State of Gujarat, India. These markets take place within the irrigation sector and are in fact lease markets for irrigation equipment, as tubewell owners sell volumes of water to other farmers. In some cases, tubewell owners become solely water sellers. There are not groundwater rights in the State of Gujarat. Groundwater resources are common property resources that are privatized as soon as access to the aquifer is secured through the installation of pumping devices. There is no control over groundwater extraction and tubewell owners are free to sell as much as they want to other farmers. Volumes of water are sold in a spot market or less often as part of a seasonal contract. Prices are usually in cash and per hour of tubewell operation. Price per hectare of given crop and contract with payment in kind are also encountered. Extensive networks of underground pipes have been installed by competing tubewell owners in agriculturally advanced areas of Gujarat to reach a higher number of potential customers. This help reducing losses between sellers and purchasers, but in itself impose some rigidity in the way the system can allocate groundwater. Also, problem of monopoly may occur and reduce market efficiency.

Institutionalized water markets in Chile (Gazmuri, 1994; Hearne and Easter, 1995)

Chile is often cited as *the* country where water markets have effectively and practically been included in water sector policies. The cornerstone of these policies has been the Water Code of 1981 that includes a clear definition of water rights for surface and groundwater. Although water remain a public good and the property of the State, individuals can receive a grant for new supplies or prescription for existing supplies based on historical use. Those are equivalent to *de facto* property rights that are transferable by law among users and between sectors. Water rights for surface and groundwater are expressed in volumes per unit of time, and are proportional to the stream flow if supplies are insufficient. Water rights are consumptive or non-consumptive, permanent or contingent to available supplies in waterways, or alternate between users. Specific *ad-hoc* and location-related regulations have been specified for groundwater rights to take into account the exhaustibility nature of groundwater resources. As many uses do not involve return flows, third party effects are minimal. The definition of water rights has been accompanied by the development of strong and compulsory user organizations that include all users of the same source. Transfers within the agricultural sector are the most frequent transfers taking place. These transfers are short-term transactions and consists in water rental, water swap or permanent transfers of water rights between farmers. Second are transfers from the agricultural sector to the urban sector that usually involve transfer of water rights. Although the legal framework that favor water markets have been implemented more than 15 years ago, there has been so far no comprehensive study on the functioning, problems and impact of these markets.

The 1991 Drought Water Bank in California (Howitt, 1993; Bhatia et al. 1995)

The Water Bank in California was established in 1991 as a means to tackle supply problems occasioned by the severe drought that was taking place since 1987.The Water Bank was created very rapidly (around 4 weeks) as an emergency institution and played the role of a short-run water market at relatively low operating cost (8% of the water purchase costs). The Bank purchased water at a fixed price of US$ 100 per 1000 m^3 from February to April 1991. The main sources of water purchase were fallowing of land, exchange of surface rights for groundwater rights and purchase of water that was in excess in some districts. The water purchased (in fact, equivalent to an temporary expropriation of water rights with financial compensation) was then sold by the Water Bank at a fixed price of US$ 140 per 1000 m^3 plus transportation costs. Analyzing exporting sites and time of trade minimized environmental externalities. Farmers were the main water sellers, but also participated in water transactions as purchasers. However, municipalities were the major purchasers. The Water Bank allocated some water to environmental use and instream flows. All water initially purchased by the Water Bank was not sold and a portion was left in storage and carried over to 1992.The transfers of water from the agricultural sector to the urban sector mainly has led to an overall economic benefit. However, negative indirect economic impact of water transfers have been estimated for districts that had been exporting water, mainly due to the high concentration of selling areas within the State of California. Also, negative indirect effects on soils and wetlands were reported.

Possible reasons advocated to explain the constraints developed to limit external transfers include:

- The respect of community cohesion and indirect negative economic impacts;
- Equity concerns with water seen as a common resource to be shared equitably among members of the organization, and that cannot be transferred outside of the community;
- The avoidance of transfers that would lead to conservation or long-term loss of water for members of the community;
- Inadequate incentive structures that make the sharing of transfer benefits difficult among the members of the organization;
- Technical problems in the operation of the irrigation system with lower water supplies;
- The need to cover the organization's fixed costs with a lower number of members;
- Members' interest in preserving restrictive markets and low prices; and,
- Managerial opposition related to the self-interest of managers and boards of organizations that favor large organizations and budgets and avoid controversial issues such as external water transfers.

In summary, the large number of transactions that take place within many irrigation systems without a complex legal system defining water rights shows that there may have been an overemphasis in the literature on problems related to the legal aspects and definition of water rights. It is important to note that the definition of water rights does not necessarily mean actual ownership right (Simpson, 1992). Usufructuary rights or contractual rights of use may already provide enough certainty in water entitlements required to develop water transactions. Although the importance of well-defined and enforceable water rights is recognized for the development of long-term water markets, they are probably not a necessary condition for short-term water markets to function and still yield relatively high efficiency gains (Howe et al., 1986).

2.3 Existing water markets: a diversity of situations for a single objective?

The purpose of this section is to investigate the impact of (existing) water markets that function under various physical and socio-economic environments. From the theoretical point of view, as discussed in the first section of this chapter, water markets are expected to promote allocative efficiency and increase economic efficiency. However, the presence of market failure could lead to private gains for participants in water transactions, but negative overall benefits for the society, that would justify the legal constraints that are often put on water transactions.

Studies that have analyzed existing water markets in terms of their overall economic impact are rare. In fact, the importance of the legal and statutory issues in the literature is rather surprising as compared to the limited economic analysis of existing markets. Market analyses include information on the type and intensity of transactions, and often specify prices that have been paid for purchased water, but usually fail in assessing the benefits of existing water markets. Those are usually investigated in analyses that focus on the potential for water market development in areas that currently restrict these transactions (Saliba, 1987). Table 2.1 (see next page) summarizes economic-related information that has been gathered from the literature for mostly institutionalized water markets. The relationship between localized and informal water markets and economic impact is further investigated below, using the example of water markets in irrigation systems in Pakistan.

Table 2.1 clearly shows how little information is available for the analysis of the economic impact of water transactions. Also, economic gains reported in absolute terms make difficult a comparison between the case studies presented. And market prices are often reported in different units that are difficult to homogenize because of the lack of information on the quantities of water effectively reallocated. For example; prices in the Chile case are expressed in US$ per $l.s^{-1}$, thus per unit of flow rate; while prices in the Colorado-Big Thompson project are reported for an allocation share defined for average years but with a reported temporal variability. Overall, however, market prices reported in the literature appear significantly higher than water charges reported for the different sectors of the economy and paid by water users to government departments, public authorities or private companies (Bhatia et al., 1994).

The analysis of the functioning of water markets in the Southwestern States of the United-States by Saliba (1987) is probably one of the few studies that discusses the efficiency of existing water markets. The study concluded that existing water markets in these States were functioning relatively well in allocating water between agricultural, municipal and industrial uses. However, little information was provided regarding the economic impact of the reallocation of water resources through market mechanisms. In a few studies, the impact of water markets on economic efficiency was questioned, because of the involvement of speculative investors in water transactions (Michelsen, 1994), or because of the low water use efficiency of water purchasers (Thompson, 1993).

Another study (Howitt, 1993) investigated in detail the direct and indirect impact of water transfers that took place within the framework of the 1991 Drought Water Bank in California. In the case of Chile, that is often cited as *the* example of institutionalized and well-functioning water markets, information on the impact of water markets is scanty. Increases in agricultural production and productivity that have been observed for the last 10 years are claimed to result from water market development (Gazmuri, 1994). However, the significance of drastic input and output price changes and the general liberalization of the economy that took place in Chile simultaneously make the estimate of the marginal impact of water market impossible with aggregated economic information for the country. Moreover, recent studies (Hearne, 1995; Bauer, 1997) have shown that existing water markets were not as developed as what had been described in most of the publications on water markets in Chile.

In the case of Pakistan, where localized water markets have developed within the irrigation system, the impact of tubewell water markets on agricultural production and productivity have been investigated in a few cases. Most of these studies are micro-level studies that have emphasized the positive impact of tubewell water use (whether for tubewell operators or tubewell water purchasers) on agricultural production and productivity. In the 1970s, for example, Freeman et al. (1978) estimated that tubewell water purchases increased crop yields by 17%, 50% and 43% for wheat, rice and cotton, respectively, as compared to canal water use only. Renfro (1982) also stressed that tubewell water purchases influence cropping intensities, the percentage of cultivated are under crops with high water requirements, and gross farm income per unit area. More recently, Meinzen-Dick (1996) showed that each extra purchased groundwater irrigation application increased wheat yield by 44 $kg.ha^{-1}$, versus a marginal impact of only 31 $kg.ha^{-1}$ for canal irrigation application, but still less than 48 $kg.ha^{-1}$ obtained from an extra application of tubewell water by the tubewell owners. The same study stresses the significant impact of tubewell water purchases, especially in conjunction with canal water use, on household gross margin per season.

In all studies on water markets in Pakistan, however, the agricultural productivity of tubewell water remained lower for tubewell water purchasers than for tubewell owners that control water resources. This may reflect the existence of inefficient existing water markets, with issues at stake related to unreliability of canal water supplies, monopoly power of tubewell owners, lack of information, high transaction costs that would be involved to develop transactions with farmers from other social groups, or limited infrastructure that reduce the potential for sales. Recent studies, however, have shown that the gap between tubewell owners and tubewell water purchasers is decreasing over time (World Bank, 1996b).

Overall, it is important to re-emphasize that literature on the functioning and impact of *existing* water markets is rare. The focus on potential and hypothetical water markets needs to be balanced by research on already functioning markets (Howe et al., 1986; Saliba, 1987), to better assess the potential of water markets under real-life situations.

Variable	Chile (Hearne and Easter, 1995; Gazmuri, 1994)	Australia (Pigram et al., 1992)	South-western States of US (Saliba, 1987)	Water auction in Victoria, Australia (Simon and Anderson, 1990)	Colorado Big-Thompson project (Michelsen, 1994)	Rio Grande Valley, Texas (Chang and Griffin, 1992)	1991 Drought Water Bank (Howitt, 1993)
Type of transfer	intra- and inter-sectoral trade	Intra-irrigation sector, permanent and temporary	From agriculture to urban sector	Auctions of new supplies to irrigators	Sale of shares within agri and between sectors	Water right sales and rental, mainly from agri. to urban sector	Inter-sectoral temporary transfers
Intensity, volumes	Limited general information	620 temporary & 46 permanent transactions in 87/88, for total of 157 $10^6 m^3$ (5-10% of total use)		2300 Megalitres sold in 6 sales (= 75% of total proposed for sale)	For 1970-1993, 30 percent of total shares sold in 2700 transac. 30% of volumes leased yearly	152 change in use for 1971-90 (3% of total water) 10% of volume leased yearly	1,013 MCM purchased and 0.488 MCM sold by the Water Bank
Price/value of water	US$ 400-4000 per l/s between farmers Average US$ 950 per l/s from agri. to cities, up to 4000	Aus$ 0.05 to 0.135 per m^3	US$ 300-1300 per ac-ft, few cases up to 3500-400 /ac-ft	Average price per sale from Aus$ 100 to 330 per megalitre (maximum 775)		Change in use: US$ 0.4-0.5 per m^3 Lease: US$ 0.007-0.035 per m^3	Purchase price: US$ 0.1 per m^3 Sale price: US$ 0.14per m^3
Net economic gains	US$ 1.65 to 2.85 per m^3					US$ 10 per m^3	US$ 106 millions
Other economic gains and losses							Negative impact on soils and wetlands (long-term losses)
Comments	High financial benefits but low economic gains to society for some transfers		Market prices reflect values in marginal use + expectations on growth and future values	Constraints on potential purchasers keeping price low	Only 17% of the total water resources potentially transferable among users	Rough calculations based on transfers involving 2 cities	Local concentration of water sales lead to economic losses in exporting regions

2.4 Conclusion of the literature review on water markets

Although the importance of market failures is fully recognized, markets may still represent the best options available to address existing issues in the water sector (Howe et al., 1986; Young, 1986). In fact, market failures are to be weighted against failures of other approaches or interventions developed to reach specific objectives and more particularly economic efficiency. Large public systems and government intervention, for example, have been prone to what the literature defined as *non-market organizational failure* resulting from their monopoly position, but also from *internalities* related to private goals of agents in a public organization (Young, 1986; FAO, 1994). Examples of rent-seeking behavior, poor management efficiency, large third-party effects of public policies, such as environmental damages in large irrigation systems, are well illustrated in the literature on publicly managed irrigation systems. Also, the high transactions costs required for water markets to function may still be lower than transaction costs that would be required for public centralized institutions to collect information to implement efficiency pricing and reach economic efficiency.

The fact that water markets have failed to develop in many areas (Gould, 1989) or function at the margin with a low number of transactions and small volumes transacted (Young, 1986), is often stressed in the literature. In this context, the importance of impediments on water market development, such as high negative third party effects, hurdles imposed by the legal system to water transactions, the absence of well-defined water rights, or high transaction costs, is fully recognized. Also, high initial transaction costs may be required to establish the environment that would favor water market development (Young, 1986; FAO, 1994). However, it is important to stress that water markets still function under conditions that are seen as unfavorable by the economic theory, and can be a viable alternative for managing water resources (Rosegrant and Gazmuri, 1994).

The literature review has stressed the importance of issues that will be further investigated in the context of the analysis of existing and potential water markets in Pakistan, that include:

- The potential for water reallocation among users through market mechanisms, illustrated by *differences in the marginal value product of water* for different users.
- The definition of *water rights* that is expected to influence market reallocation.
- The importance of *direct or indirect externalities* that would result from the reallocation of water within an irrigation system.
- The *adequacy of the existing infrastructure* to reallocate water according to the market. There is little evidence that various infrastructures are constraining existing water markets, whether because markets are localized, or because low volumes of water are effectively transferred. However, existing infrastructure may be an important factor constraining the development of water markets when changes in infrastructure required for these markets to operate would be too costly

To analyze the functioning and impact of existing and potential water markets in Pakistan, and address the research issues proposed above, a methodological framework is developed and presented in Chapter 3. This framework considers the economic dimension of irrigation water, the physical constraints that may arise as a result of the existing infrastructure, the interdependency between water users, and the relationship between water and the physical environment.

Chapter 3

An integrated approach to assess the potential for water market development in the irrigation sector

The main objective of this chapter is to present the analytical framework that has been developed to assess the potential for water market development in the irrigation sector in Pakistan. The proposed framework, or *integrated approach*, has a larger scope than the analysis of water markets, as it aims at *assessing the impact of a wide range of interventions in the irrigation sector* (Garin et al., 1996). This results from the combination of research efforts to investigate the relationship between irrigation management and salinity and sodicity (Kuper, 1997) and the present study to analyze the functioning and impact of existing and potential water markets. This chapter presents the main elements that compose the integrated approach, and discusses the application of the approach to the analysis of water markets in Pakistan.

3.1 Main elements of the integrated approach

The terms *integrated management*, *integrated approach* or *integrated models* have recently received much attention in the field of water resources, and further attention on integration is expected in the future (Shaw and Bellamy, 1996). This phenomenon has its roots in increasing environmental concerns, competition over water resources among different uses (Witter and Bogardi, 1994), the high degree of interdependency between users (Glasbergen, 1990), and the recognition of failures of past non-integrated approaches that did not yield the expected impact (Margerum and Born, 1995). The three terms share the same *multi-disciplinary and holistic* dimensions. They heavily draw on systems theory and its use for identifying and implementing new policies. They promote the investigation of the *complexity of a system*, defined as a network of objects or sub-systems that are in interaction with each other (Le Moigne, 1995), each sub-system transferring mass, energy or information inputs into specific outputs (Belouze, 1996).

The differences between these terms can be structured into a hierarchy, where integrated tools are developed in the context of an integrated approach to support the integrated management of water resources. The integrated tool is a means to investigate a complex system and simulate the impact of interventions on the output of the system. Individual process-based models are integrated to provide a means to examine the overall consequences of various *what-if* scenarios before management options are implemented (Shaw, 1996).

The integrated approach aims at the development of a platform or shared understanding and knowledge between actors and researchers to identify potential interventions and evaluate these interventions. It relies on the requirements of integrated management and actors to investigate a complex system, and includes the development of multi-disciplinary integrated models to identify more appropriate policy options than those drawn from personal preference and expert advise (Shaw, 1996).

Integrated water management aims at the implementation of those interventions that have been accepted by all (or a large number of) users. It relies heavily on the analysis of institutions, actors, and natural and utilitarian functions of water resources systems (Glasbergen, 1990; Witter and Bogardi, 1994). Information technologies, conflict resolution and negotiations, institutional and legal arrangements between actors are the main elements of an integrated management framework. The systems approach to water management provides a method of gaining a comprehensive insight into the processes to be managed and clarify for all actors how their various interests are intertwined (Glasbergen, 1990).

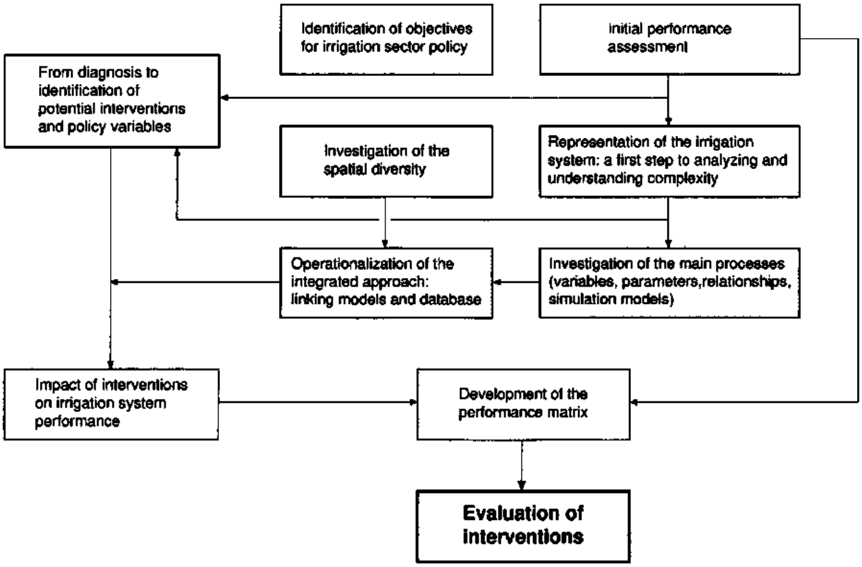
Without making an exhaustive review of examples of integrated approaches and models applied to water resources and irrigation management, it is important to note that they represent a large heterogeneity of approaches according to the system analyzed (a farm, an irrigation scheme, a country), the disciplines considered (hydrology, hydraulics, agronomy, economy, sociology), and the models developed (simulation, optimization, stochastic, empirical).

Integrated approaches reported in the literature, however, have difficulties in integrating disciplines effectively. Often, one discipline is favored over other disciplines that are then summarized into a limited number of constraints to the processes of interest for this discipline. More particularly, the effective integration between hydrology and economics, that requires an early involvement of both economists and biophysical experts in research planning and option development, remains rare (Goldsmith, 1986; Srinivasulu et al., 1997; Faisal et al., 1997). Also, integrated approaches are often applied to limited geographical areas or aggregated areas, as a result of the limited availability of information and difficulties to investigate the spatial variability of the processes investigated.

The elements of the integrated approach as developed and used in the present study and in Kuper (1997) are presented in Figure 3.1. Among those, five elements (gray boxes in Figure 3.1) are seen as essential and will be detailed in the following sections of this chapter:

- The *representation of the irrigation system* is the first step to investigating the complexity of a system where a large number of inter-linked biophysical and decisional processes take place;
- The investigation of the *main bio-physical and decisional processes*, by analyzing the existing situation and developing simulation tools to test the impact of different interventions on the output of these processes;
- The analysis of the *spatial variability* of the main variables and parameters that intervene in these processes;
- The *operationalization of the integrated approach*, by linking simulation models, optimization models, and databases that take into account the spatial diversity, into an integrated model; and,
- The development of a *performance matrix* that considers the multiple dimensions of irrigation system performance that result from proposed interventions in the irrigation sector, that is used to compare and evaluate potential interventions.

Figure 3.1. The *integrated approach*: analytical framework to assess the impact of management interventions on irrigation system performance.



As mentioned above, interactions with actors involved in the management of the irrigation system are an important element of the integrated approach (Garin et al. 1996). Such interactions are required:

- To build the representation of the irrigation system;
- To assess current irrigation system performance;
- To identify constraints and potential options for improvements (interventions);
- To identify the major biophysical and decisional processes that are to be investigated by researchers; and,
- To spell out information requirements for potential users of the integrated approach.

However, interactions with actors that have taken place during the development of the integrated approach are not described in the present thesis. The same holds true for the institutional set-up required for implementing the integrated approach in a real-life situation. For the two case studies undertaken so far, potential users of information are: policy makers to support the selection of appropriate irrigation sector policies and allocate scarce financial resources in an optimum way; and irrigation system managers whose objectives are the improvement of the operation of the canal system or the minimization of complaints from water users.

The following sections describe the application of the integrated approach to the analysis of water markets in one irrigation system in Pakistan. This application, along with the case study by Kuper (1997), verifies the pertinence of the proposed framework to investigate issues related to assessing the impact of interventions in the irrigation sector on irrigation system performance.

3.2 Representation of an irrigation system in Pakistan

Since the construction of the first irrigation system by the British in 1867, irrigation development in Pakistan has concentrated on the construction of large scale irrigation systems in the plain of the Indus River and its tributaries, namely the Sutlej, Beas, Ravi, Chenab, and Jhelum Rivers. After Independence in 1947 and the Indus Basin Treaty signed with India in 1961, the Government of Pakistan continued to further develop the Indus Basin Irrigation System, resulting in the largest contiguous irrigation system in the world. Overall, around 90% of the irrigated area of the country are part of the Indus Basin Irrigation System, the bulk of which is contained in the Punjab and Sindh Provinces. The remaining area is irrigated through small-scale traditional irrigation systems, mainly located in the Balochistan Province and the North-West Frontier Province.

Although there is a large variability in the social, economic and physical conditions within the Indus Basin Irrigation System, the canals and infrastructure are similar with homogeneous rules, regulations and institutional setup for the operation and maintenance of the irrigation network. The irrigation system as defined here includes processes taking place *from the canal water inflow* point of the irrigation network *up to the production of agricultural products,* which is the main objective or purpose of the system defined.

Referring to the nested representation of an irrigation system developed by Small and Svendsen (1990), both the irrigation and irrigated agriculture systems are considered. Higher levels of the nested representation, such as the economic system, are not included in this study, as those would require investigating processes related to input and output markets, household decisions not directly related to agricultural production, and general economic development and welfare of the area. Also, the spatial boundaries of the irrigation system are defined here as the limits of the area commanded by one main canal. Thus, other storage and conveyance infrastructure, such as dams and link canals located upstream in the Indus Basin Irrigation System, are not considered here.

Figure 3.2 presents a schematic representation of an irrigation system with *biophysical processes*, *actors*, *decisional processes*, and factors from the *external environment* influencing these processes. The figure is further explained in the following paragraphs. Information and financial flows between sub-systems that are considered in systems approaches and economic and financial analysis, have not been represented in Figure 3.2 for the purpose of clarity.

Biophysical processes

Following the flow of water, the inflow at the head of the main canal (CW_{Main}) is delivered to the head of secondary canals or *distributaries* (CW_{di}, CW_{dj}). Canal water is then distributed to tertiary canals or *watercourses* (CW_{wci}, CW_{wcj}, CW_{wck}) through ungated outlets. Below the watercourse head or *mogha*, surface water is shared between farmers (CW_{Fi}, CW_{Fj}, CW_{Fk}) through a 7-day rotation of water turns or *warabandi*. Water is distributed based on the warabandi schedule with one farmer only using the full canal water supply at a time. Each farmer uses his own water turn, or trades water turns (+/-) with other water users.

As a result of the inadequacy and unreliability of canal water supplies, farmers also use groundwater (TW_{Fi}), whether pumped by their own tubewell or purchased from neighboring tubewell owners. During the season, canal and tubewell water are allocated to the various fields of the farm ($(CW, TW)_{fi}$, $(CW, TW)_{fj}$, $(CW, TW)_{fk}$) based on previous irrigation events, rainfall, characteristics of the fields, and farm strategies and priorities. Eventually, water is applied to fields and crops. Irrigation practices along with capillary rise from the shallow groundwater (CR_{fi}, CR_{fj}, CR_{fk}) will result in a specific evapotranspiration (ET) and crop yield at the field scale. At the same time, the use of irrigation water has an impact on the physical and chemical processes that take place within the soil profile and influences the evolution of salinity and sodicity.

From the head of the main canal system to the field, losses take place at different levels: seepage along the main canal (L_{Main}) and distributaries (L_{di}), operational and seepage losses along watercourses (L_{wci}), seepage losses along the farm channels and percolation losses at the field level ($L_{F,f}$). These losses directly feed the underlying aquifer from which tubewell water is pumped. Other non-beneficial losses (NBET) directly evaporate to the atmosphere and are lost to irrigation (Perry, 1996). Also, infiltrated water carries salts that directly influence the quality of groundwater, and eventually farmers' irrigation practices, field salinity and agricultural production.

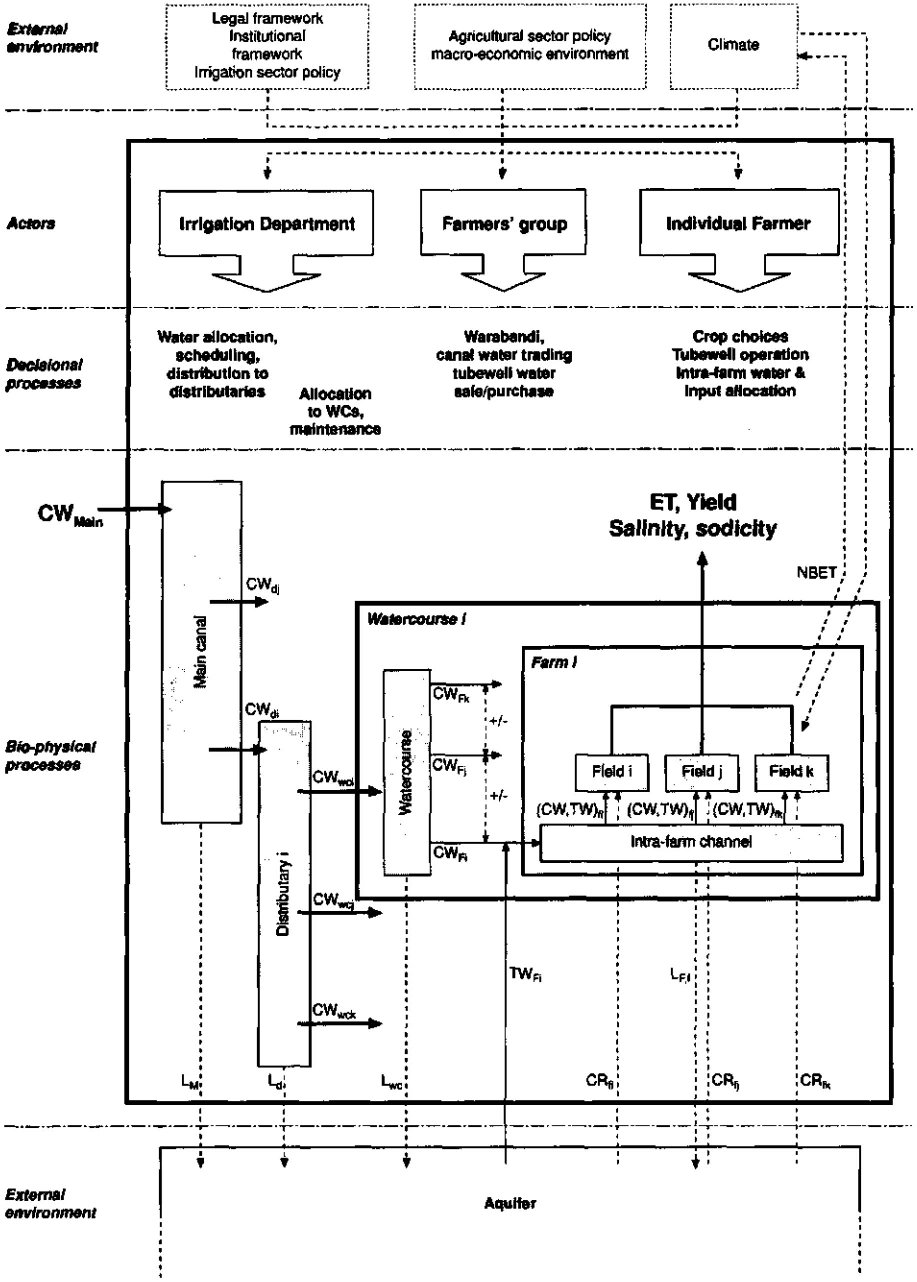
An important element of all water-related variables specified at different scales of the irrigation system is their multi-dimensional nature. Water supplies can be defined in terms of quantity, variability, timeliness, reliability or quality (Svendsen and Small, 1990). These dimensions are to be considered simultaneously as they influence the biophysical and decisional processes that take place within the irrigation system.

Actors and decisional processes

Allocation, scheduling and distribution of surface water at the main canal are organized by officers of the provincial irrigation departments, with local gate operators manipulating cross regulators and distributary head gates to follow allocation and scheduling plans. At the distributary level, maintenance activities such as desilting of the canal or remodeling of watercourse outlets are the main tasks performed or supervised by staff from the irrigation department to ensure equitable canal water supplies to outlets. In some cases, farmers intervene also in the management of the main system, whether in its operation or by modifying part of the physical infrastructure (Rinaudo et al., 1997a). These interventions, however, are illegal and may lead to court cases and fines for concerned farmers. For more information on the operation and maintenance of irrigation systems in Pakistan, see Kuper (1997).

Below the mogha, the warabandi schedule has usually a 7-day period, with water turns being fixed for a specific time of the week for each farmer (*pakka warabandi*) or following a more flexible schedule that takes into account the variability in water flows in the distributary (*kaccha warabandi*). The warabandi can be official and recorded in the irrigation department records. However, the warabandi schedule is often updated and agreed upon by farmers at the beginning of each season as a result of regular negotiations among water users of a given watercourse command area (Bandaragoda and Rehman, 1995).

Figure 3.2. Representation of an irrigation system in the Indus Basin – Biophysical processes, actors, decisional processes and the external environment (adapted from Garin et al. 1996).



The tasks of irrigation department officials below the mogha remain limited to the assessment of area and crop-based water charges (*abiana*), and to the resolution of conflicts that may emerge between farmers regarding the allocation of canal water turns or the path of the watercourse within the command area of tertiary units.

Other water management activities undertaken by farmers below the mogha include canal water distribution, trading of canal water turns, watercourse maintenance, drainage of surplus water whenever required, tubewell installation, operation and maintenance of private tubewells, and sale and purchase of tubewell water. These water management activities involve different levels of informal organization, from a single individual for the installation of a private tubewell, to all farmers cultivating land within the watercourse command area for the determination of the warabandi schedule at the beginning of each season.

At the farm level, decisions are numerous regarding the use of water and other inputs (Strosser and Rieu 1997). At the planning stage, based on expected water supplies and production strategies, farmers identify an appropriate cropping pattern for the coming cropping season or year. Then, water and other farm inputs such as labor, fertilizers and pesticides are applied to the fields according to crop requirements and farm constraints. In some cases, non-farm activities may significantly influence farming practices and farm strategies.

Biophysical and decisional processes are closely inter-related. By their nature, decisional processes influence the state of the biophysical irrigation system. At the same time, biophysical variables and parameters influence actors' decisions. Examples of such *feedback loops* include the role of water levels in the main canal for operational decisions of gauge readers, or the influence of salinity and sodicity on farmer's choices in terms of crops and appropriate irrigation practices. In fact, from a systems analysis point of view, the importance of feedback loops is a fundamental element influencing the level of complexity of a system (Le Moigne, 1995; Belouze, 1996). For concerns of simplicity and clarity, although their importance is recognized, these feedback loops have not been included into the representation of the irrigation system presented in Figure 3.2.

External environment

Along with feedback loops, the importance of interactions with the external environment influences the level of complexity of a system and the difficulty in comprehending this system (Le Moigne, 1995; Belouze, 1996). In the case of the irrigation system considered, decisional processes are influenced by the external environment, defined here as all what is not the irrigation system itself but influencing processes within the system. The institutional and legal framework, irrigation sector policies and agricultural sector policies influence farmers' decisions regarding cropping pattern, and the implementation of rules and regulations by irrigation department officials. At the same time, the climate, as well as the status of the aquifer, influence decisional and physical processes. Rainfall may influence the operation of the irrigation system, as the irrigation department staff may follow specific (emergency) distributional rules under high rainfall situations. Also, changes in the level of the aquifer, resulting from water movements that take place at scales larger than the irrigation system considered, will have an impact on tubewell pumpage costs and farmers' decisions regarding tubewell water use. And changes in the groundwater-table depth will impact on capillary rise and directly influence the accumulation of salts within the root zone.

Summary

A representation of the irrigation system is proposed, taking into account biophysical and decisional processes, actors and the external environment. The representation facilitates an understanding of the complexity of the irrigation system and the identification of relationships between individual processes and variables. The representation provides an adequate basis to select the main processes that will be investigated for the analysis of the functioning and impact of existing and potential water markets. These processes are presented and discussed in Section 3.3. Section 3.4 further emphasizes the importance of the economic dimension of water in the analysis of water markets for the analysis of the processes selected.

3.3 Main biophysical and decisional process for analyzing water markets in Pakistan

The basis for the selection of processes is the confrontation between the representation of the irrigation system presented in Figure 3.2 and the specific research objectives identified for the case study being considered. As specified at the end of Chapter 1, the present study focuses on the following elements:

- The *functioning of existing and potential water markets,* in terms of volumes of water exchanged and market equilibrium prices. Factors that may constraint/promote water markets are identified in this context.
- The *impact* of water markets *on agricultural production,* and the potential role of water markets for increasing agricultural productivity;
- The *impact* of water markets *on the (physical) environment,* for example the soil or the aquifer underlying the irrigation system; and,
- The *technical feasibility* of potential water markets, in terms of infrastructure, organizational and operational requirements.

Table 3.1 summarizes the different processes selected for the analysis of water markets in Pakistan. Each process is then described in the following paragraphs of this section. It is important to specify that the main emphasis of the case study is on long-term planning decisions and allocation of surface water and groundwater among different users. The analysis of the impact of existing and potential water markets is undertaken by comparing separate equilibrium situations. However, the analysis of the functioning of existing water markets will also investigate short-term decisions related to the distribution and use of both canal and tubewell water.

3.3.1 Analysis of *existing* water markets

Allocation and distribution of irrigation water within the watercourse command area

Canal water supply is initially allocated to individual farmers through the warabandi schedule. This schedule may already include specific canal water transactions that are taking place for longer time periods, such as the season or the year. Once a specific farmer receives canal water, the farmer may need longer water turns, or may be in a position to give or sell his turn to other farmers.

Table 3.1. Decisional and physical processes selected for the analysis of existing and potential water markets in Pakistan.

		Process	Type	Scale	Input	Factors influencing these processes	Output
Potential water markets	Existing water markets	Water allocation and distribution within the watercourse command area	Decisional	Tertiary unit	Initial canal water allocation (water turn), inflow to tertiary unit	Official allocation rules, market-based rules related to farm characteristics, tubewells (number, water price), water supply & demand curves	Reallocation of canal water turns, volumes of canal water received at farm level
		Water flow: from the watercourse head to farmer's fields	Biophysical	Tertiary unit	Water inflow at the head of tertiary units	Seepage and operational losses	Water flow at the farm and field scales
		Impact of canal water on farm decisions and agricultural production	Decisional	Farm	Canal water allocation at the farm	Farm characteristics and production objectives, access to land, labor, credit, and groundwater resources, crop gross margins, tubewell water price	Cropping pattern, gross income, tubewell water use, marginal value product of irrigation water
		Relationship between water and crop yield	Biophysical	Field	Irrigation applications (quantity, timing, quality)	Soil type, salinity level, crop type, input use (fertilizers, pesticides, farm-yard manure, etc)	Crop yields
		Impact of water supply on salinity and sodicity	Biophysical	Field	Irrigation applications (quantity, timing, quality)	Soil type, soil chemical composition, groundwater table depth	Changes in salinity, sodicity
		Water allocation and distribution at the main system level	Decisional (operation)	Main canal	Water inflow at main canal head	Allocation and distributional rules Physical characteristics of main canal, water supply & demand curves	Gate openings, canal water volumes received by secondary canals
		Water allocation and distribution at the secondary level	Decisional (maintenance)	Secondary canal	Water inflow at distributary head	Physical characteristics of secondary canal, water supply and demand curves	Outlet dimensions, canal water volumes supplied to tertiary units
		Water flows: from the main canal to the head of the tertiary unit	Biophysical	Main canal, secondary canal	Water inflow (main canal, secondary canal)	Physical canal characteristics, seepage losses, gate setting, outlet characteristics	Outflow to secondary canals, tertiary units

As a result of canal water transactions, each farmer will receive a given quantity of canal water at the farm that is not only influenced by his final canal water turn, but also by the watercourse head discharge and conveyance losses between the watercourse head and the farm. As both the discharge and the conveyance losses influence the final outcome of the transaction (i.e. the volume effectively received at the farm gate), they are expected to influence canal water transactions and farmer's willingness to participate in such transactions. To estimate quantities of canal water effectively received by farmers and transferred between water users is, however, a difficult task, because of the high variability in canal water discharges at the watercourse head or farm gate and the high information requirements to obtain accurate discharge estimates.

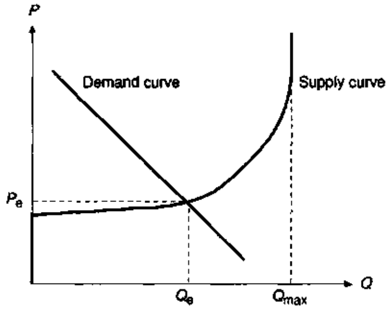
In practice, as will be described in Chapter 6, little sale and purchase of *canal water* take place within watercourse command areas. Limited canal water transfers may be related to small differences between the marginal value products of individual farmers that already use tubewell water extensively. The lack of reliability of the canal water, its better quality, the social role of canal water in local societies, and the link between water and land ownership that forbid the participation of non-land owners into the transfer of canal water turns are other aspects that may constraint canal water transactions. Thus, the analysis of existing canal water sales and purchases rapidly moves away from a purely technical analysis of allocation and distribution, to a more complex issue where socio-economic factors play an important role.

The analysis of allocation and distribution of groundwater within the watercourse command area requires a further move away from purely technical issues and greater insights into economic issues. Tubewell ownership, influenced both by the relative water scarcity in the area considered and farmers' potential to invest in tubewells, becomes an important factor explaining access to groundwater resources. It is clear that tubewell water markets have improved the access to groundwater resources for tubewell water purchasers. However, quantities effectively transferred through the market are not well known.

Supply and demand curves for tubewell water provides a powerful means of investigating the allocation and distribution of tubewell water. These curves relate the quantity of tubewell water a farmer or group of farmers is willing to purchase/sell to the price of this water. The comparison between the equilibrium point in terms of quantity and price estimated by the confrontation of these curves, and the current price and quantity transacted on existing markets, is a means to evaluate the allocative efficiency of these markets. Figure 3.3 presents examples of supply and demand curves for tubewell water.

Tubewell owners are not expected to sell water for a price below tubewell operation and maintenance costs. In fact, tubewell water prices equal to these costs have often been reported for existing tubewell water transactions (Strosser and Kuper, 1994). Although this would make the first part of the supply curve horizontal at the level of these operation and maintenance costs, a slight upward curve is kept in Figure 3.3 to account for increased service costs and probability of tubewell breakdown. If the demand increases, thereby boosting prices, tubewell owners will start reducing their own tubewell water use to increase tubewell water sales. Above a certain price, the technology and the capacity of the tubewells in the command area limit the total quantity of tubewell water that can be sold in the market.

Figure 3.3. Supply and demand for tubewell water in the command area of one tertiary unit – P is the tubewell water price, Q the quantity of tubewell water, Q_{max} the maximum quantity of tubewell water that can be pumped with the existing tubewell capacity, and Q_e the quantity sold on the market at equilibrium price P_e.



Relationship between irrigation water supply and agricultural production

The relationship between irrigation water supply and agricultural production are analyzed at two levels:

- At the *farm* level: based on expected canal water supply, a farmer will specify his cropping pattern to meet his objectives (auto-consumption, maximization of profit, etc). Access to, and cost of, other resources such as labor, tubewell water, credit, are considered in farmers' decisions.
- At the *field* level: water applied will influence crop growth and eventually crop yields. Other inputs such as fertilizer or pesticides, along with soil characteristics and proximity of the groundwater aquifer, are also expected to influence crop yields.

The analysis of the relationship between irrigation water and agricultural production is the backbone in the application of the integrated approach to the analysis of water markets. This analysis simultaneously supports the development of supply and demand curves for tubewell water required to investigate the allocation of tubewell water and the intensity of current tubewell water markets. Information is also provided about the impact of water transactions on agricultural production and productivity. Farmers' participation in water transactions will influence their expected irrigation water supply, thus their decisions related to cropping pattern. For tubewell owners, participation in canal water markets may also influence tubewell water sales and thus tubewell water markets.

According to the type of transactions, different dimensions of water supply performance may be modified, such as the total quantity available for the crops, the timeliness of irrigation water supplies, the quality of irrigation water applied to crops, etc. This may, in turn, affect the productivity per unit area for a given crop, influence the cropping pattern selected by farmers, or improve the overall irrigation application efficiency on the farm.

Linking water markets and the environment

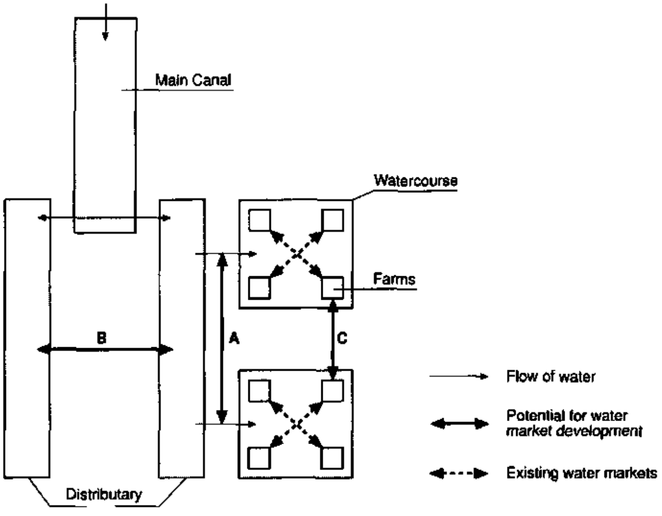
As they modify the allocation and distribution of canal water among users, and also the use of groundwater by non-tubewell owners, changes in the quantity and quality of irrigation water received by different water users will occur as a result of existing water markets. Under specific soil and groundwater table depth conditions, such changes may impact on the salinization and sodication process, i.e. redistribution of salts within the soil profiles, concentration or precipitation. High quantities of sodium in the soil profile will have a negative impact on the soil structure and aggregate stability, with possible degradation of the soil structure by physical and chemical processes that will negatively impact on the infiltration and hydraulic conductivity.

With the development of water markets, the balance between recharge to the aquifer and extraction from the aquifer through tubewell pumpage may also be modified. Although it is clear that tubewell water sales have increased tubewell water extraction without significantly influencing the various elements of the recharge to the aquifer, their impact on the net recharge to the aquifer is to be assessed. If the system is not in equilibrium and mining of the aquifer takes place, then the sustainability of the existing management of water resources is to be questioned. Tubewell pumpage costs will be expected to increase, thus mainly affecting resource-poor farmers. Also, shallow tubewells may become dry and require extra investments in tubewell bores that may be too expensive as compared with the financial resources of some of the current tubewell owners.

3.3.2 *Potential* for water market development

Existing water markets function within the command area of tertiary units only. The potential for water market will also be investigated at other scales of the irrigation system as illustrated on Figure 3.4. Water markets may develop between groups of farmers belonging to two different tertiary units (A), or between groups of farmers from two distributary command areas (B). Also, one may envisage water transactions taking place between individual farmers located along tertiary units off-taking from the same or different distributaries (C). In the scenarios developed for the analysis of potential water markets, canal water transactions only are considered between tertiary and secondary units of the irrigation system. It is assumed that tubewell water markets continue to function below the watercourse head, but that exporting tubewell water outside of the watercourse command area is not possible for technical and organizational reasons.

Figure 3.4. Potential for water market development in an irrigation system in Pakistan.



Impact of potential water markets on agricultural production and on the physical environment

The analysis of the potential for water markets development at higher levels of the irrigation system is also based on the analysis of the processes presented in Section 3.3.1. Central to the analysis is the establishment of the relationship between the quantity of canal water allocated and its marginal value product for different users and areas. The confrontation between such relationships will highlight the existing heterogeneity in the marginal value product of canal water within the irrigation system investigated, which will stress the potential for canal water reallocation through market mechanisms.

Processes that relate water to agricultural production described in section 3.1.1 will also be used for the analysis of the potential for water markets and their impact on agricultural production. Similarly, processes described in section 3.1.1 are used for the analysis of the potential impact of water markets on the sustainability of irrigated agriculture.

The reallocation of surface water among water users and the resulting changes in farmer's marginal value product of water may induce long-term changes in irrigation practices and the technologies developed and applied by farmers. The development of water markets is expected to increase farmer's incentives to save water to offer higher quantities for sales and thus increase the overall farm income. However, this change in technology and practices is not investigated in the present study.

Water allocation and distribution at main and secondary canal levels: investigating the technical feasibility of potential canal water markets

Although the analysis of the technical feasibility of water markets does not require specific attention within the watercourse command area, as a result of the system design and its simple allocation and distribution rules, the situation is different for the analysis of water market development between higher units of the irrigation system. As illustrated in Figure 3.4, transfers of canal water are proposed between and within distributaries, while the irrigation system has not been designed for such transfers. Thus, physical limitations are expected with the existing infrastructure.

The analysis of the physical process of water flow from the head of the irrigation system to the head of tertiary units is an important aspect that will provide information on the physical limitations of the existing irrigation system. Issues at stake relate to:

- The *capacity of the primary and secondary channels* to carry and distribute volumes of canal water reallocated through market mechanisms. This may be important for areas that have purchased extra canal water, and for areas that have sold part of their allocation and that may face technical difficulties in distributing the remaining water within the area. For example, the existence of freeboard constraints for some channels may limit the reallocation of surface water from one area of the irrigation system to another.
- The *adequacy of the control structures* to distribute canal water supplies according to the allocation through markets. At the main system, cross-regulators and gates at the head of the major distributaries provide some flexibility in reallocating water between distributaries. However, no such control structures exist along distributaries.

Changes in the operation of the canal system, or in the infrastructure, may be required to reduce or eliminate the major physical constraints on canal water reallocation between watercourses and distributaries. In fact, changes in infrastructure, operation of the irrigation system, and institutional arrangements may result in important initial transaction costs that are too high when compared with the potential benefits obtained from the reallocation of surface water supplies.

The following section further discusses some of the processes identified so far, emphasizing the economic focus that underlies the analysis of water markets. Overall, the analysis of water markets will put a greater emphasis on economic issues as compared to the analysis of more traditional supply-based interventions and irrigation management. While in the present setup, allocation decisions are taken by the manager of an irrigation system, the analysis of the potential for water market development starts from the water users.

3.4 Selected research issues related to the analysis of existing and potential surface and groundwater markets in Pakistan

Understanding the functioning and organization of existing water markets: actors

In theory, and with no or limited transaction costs, an efficient allocation of water through market mechanisms would lead to an equalization of the marginal value products of water between water users that participate in these markets. In practice, transaction costs may be significant, and specific socio-economic, organizational and physical constraints may limit the functioning of existing water markets. Issues related to the functioning of existing water markets within the command area of tertiary units, that will be investigated in the present study, include:

- *The factors that influence the functioning of water markets:* Variability in type and intensity of water transactions has been reported in the literature (WAPDA, 1990; Renfro, 1982; Meinzen-Dick, 1996; Rinaudo et al., 1997b). However, the factors explaining this variability have not been systematically identified. Those may include the composition of the farm population that influence the demand for irrigation water, and the characteristics of irrigation water supplies.

- *The identification of participants in water markets.* Participation in water transactions is an important issue that relates to the share of potential benefits related to such transactions among water users. In fact, the wealth concentration effect of water reallocation is central to controversies related to water market development (Shah, 1985; Carruthers, 1995, cited in Richard, 1996).

- *The organization of existing water markets.* Organizational issues relate to the type of contracts developed between participants that specify the terms of the transactions. These contracts may be formal or informal, for long-term or short-term transactions (Meinzen-Dick, 1996; Rinaudo et al. 1997b). Prices are an important element of these contracts. Their spatial and temporal variability in relation with changes in water scarcity is an important element in analyzing the efficiency of existing water markets.

An important issue relates to the relative monopoly power of tubewell water sellers. Although tubewell water prices equal to tubewell operation and maintenance costs have been reported in the literature (Strosser and Kuper, 1994), some tubewell owners offer tubewell water for sale at prices higher than the operation and maintenance costs of their tubewell. Whether the extra cost considers investment and replacement costs, or results from the monopoly power of tubewell sellers, is unclear. With a limited number of tubewells in a watercourse command area, a monopoly situation may develop, while a larger number of tubewells may lead to competition between tubewell owners. At the extreme, the number of tubewells/tubewell owners may be so high that tubewell water purchasers are in a monopsony situation.

Canal water purchaser or canal water seller?

The analysis of the potential for canal water reallocation among farmers starts from an initial canal water allocation, related to the duration of farmer's water turns, or to a given authorized discharge at the head of tertiary and secondary canals. According to the outcome of the market, farmers may decide to sell or purchase canal water. If the quantity allocated by the equalization of the marginal value products among users is lower than the initial allocation, the farmer would become a seller. At the opposite, he would become a purchaser if his final canal water allocation obtained through the market is higher than his initial allocation. Thus, a single relationship between the quantity of canal water allocated and its marginal value product is seen as more appropriate than separate supply and demand curves. The market allocation would be obtained by confronting such relationships developed for different water users.

An interesting issue relates to the *scale of the irrigation system that represents the highest potential for water markets* in terms of impact on agricultural production and overall economic efficiency gain. It is expected that differences between marginal value products aggregated for large areas (for example distributary command areas) will be smaller than differences between marginal value products estimated for individual farmers. In some cases, however, major differences may exist between farming systems found along two distributaries, thus leading to significant gaps between the aggregated marginal value products for these distributaries.

Canal water market, conjunctive use and impact on the physical environment

As emphasized in Figure 3.5, the presence of private tubewells in the command areas of specific hydraulic units influences the relationship between canal water allocation and its marginal value product.

Figure 3.5. Relationship between canal water allocation, Marginal Value Product (MVP) of canal water, tubewell water use and potential for canal water reallocation for two watercourse command areas WC_a and WC_b,. Q_a and Q_b = canal water allocation to WC_a and WC_b; Q_0 = initial canal water allocation to WC_a and WC_b; Q_e = market allocation to WC_a; Q_{tw} = tubewell water use; TWC_a and TWC_b = unitary tubewell operation and maintenance costs for WC_a and WC_b; $TWmax_a$ and $TWmax_b$ = maximum quantity of tubewell water available for WC_a and WC_b; P_e = equilibrium market price for canal water.

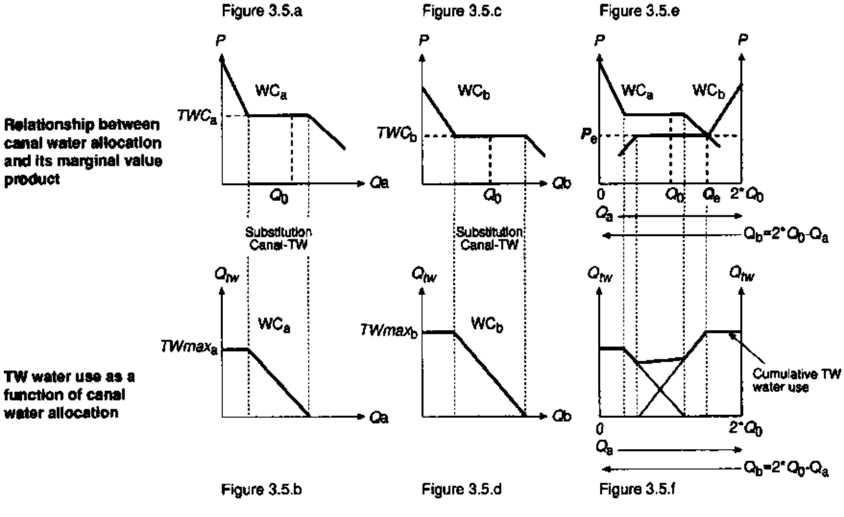


Figure 3.5.a presents the relationship between canal water allocation and marginal value product of water for a watercourse WC_a, where private tubewells have been installed and are operated with operation and maintenance costs per unit of tubewell water equal to TWC_a. Figure 3.5.b complements Figure 3.5.a with the relationship between canal water allocation and tubewell water use. The assumption made here is of a 1 to 1 substitution rate between canal water and tubewell water. Also, it is assumed that tubewell water is priced at tubewell operation and maintenance costs as long as tubewell water use is not constrained by the availability of tubewell water.

Starting from a high canal water allocation in Figure 3.5.a, the allocation is reduced and leads to an increase in the marginal value product of canal water. As soon as the marginal value product of canal water is equal to the tubewell operation and maintenance costs, TWC_a, farmers compensate any reduction in canal water by an increase in tubewell water use (Figure 3.5.b). Thus, the marginal value product of canal water remains constant and equal to TWC_a (Figure 3.5.a). However, once tubewell water is used at its maximum quantity, $TWmax_a$ (Figure 3.5.b), a reduction in the quantity of canal water is accompanied by a similar increase for the marginal value product of both canal water and tubewell water (Figure 3.5.a).

The transfer of canal water between two watercourses is also illustrated in Figure 3.5, using the example of two watercourses WC_a and WC_b with different average tubewell operation and maintenance costs, TWC_a and TWC_b, but the same initial canal water allocation, Q_0. The confrontation of the relationships between canal water allocation and its marginal value product shows that a reallocation of canal water would take place from WC_b to WC_a, as the marginal value product for WC_a at Q_0 (equal to TWC_a) is greater than the marginal value product for WC_b at Q_0 (equal to TWC_b). As illustrated in Figure 3.5.e, the market would allocate a quantity Q_e to WC_a, and a quantity 2^*Q_0-Q_e to WC_b, at a market P_e equal to TWC_b in this example. Figure 3.5.f shows that WC_b has compensated for the decrease in canal water allocation by an increase in tubewell water use. Overall, the reallocation of canal water would be expected from watercourses or distributaries with low tubewell operation and maintenance costs to watercourses or distributaries with high tubewell operation and maintenance costs.

The way Figure 3.5.e and Figure 3.5.f are constructed require specific comments, as it differs from what is usually presented in the economic literature. Figure 3.5.e presents the marginal value product of canal water for WCa and WCb as a *function of the allocation to WC_a*, while Figure 3.5.f presents tubewell water use for WC_a and WC_b as a *function of the same allocation to WC_a*. As it is assumed that the total canal water allocation to both watercourses is fixed at 2^*Q_0, the canal water allocation to WC_b is equal to 2^*Q_0 minus the canal water allocation to WC_a, and is read from the right to the left of the x-axis for both figures.

Figure 3.5 highlights also the impact that canal water markets may have on the environment via changes in tubewell water use. As a result of canal water reallocation, tubewell water pumping is modified in each watercourse (Figures 3.5.b, 3.5.d and 3.5.f), leading to an impact on salinisation and sodication for each watercourse. Also, the cumulative quantity of tubewell water pumped by the two watercourses will be modified as illustrated by Figure 3.6.f, influencing the net recharge to the aquifer.

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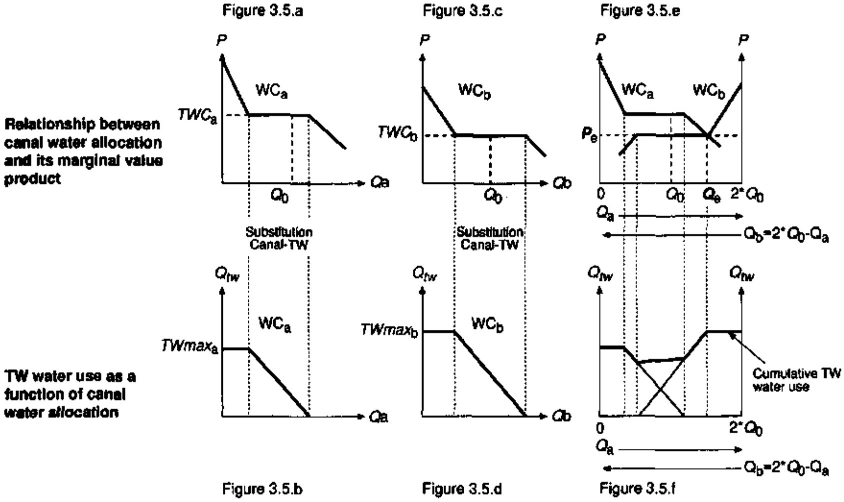

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Technical constraints on reallocation of surface water

Figure 3.6 illustrates how specific physical constraints would limit the development of canal water markets. Figure 3.6 presents the Marginal Value Product of canal water for *two distributaries*, Distributary A and Distributary B, as a function of the canal water allocation to Distributary A. Similarly to Figure 3.5.e, the allocation to Distributary B is obtained by deducting the allocation to Distributary B from the total allocation to the two distributaries, and is read from the right to the left along the x-axis. For simplification purposes, the figure uses the example of two distributaries that have the same initial canal water allocation Q_0, and that do not have any tubewell water use in their command area. The physical infrastructure limits the canal water allocation to Distributary A from a minimum allocation Q_1 to a maximum allocation Q_2. It is assumed that Distributary B does not face any physical constraint.

Figure 3.6. Impact of physical constraints in canal water allocation to Distributary A on canal water reallocation between Distributary A and Distributary B. Q_0 = initial allocation to Distributary A and Distributary B; Q_1 and Q_2 = minimum and maximum possible allocations to Distributary A; Q_e = equilibrium allocation to Distributary A with no physical constraint; P_e = equilibrium price with no physical constraint; MVP = Marginal Value Product of canal water.

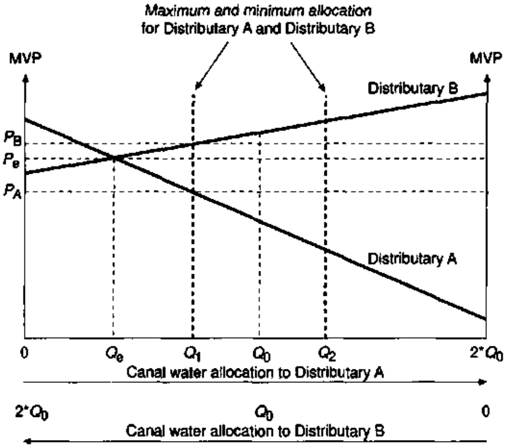


Figure 3.6 shows that the equilibrium points (Q_e, P_e) for Distributary A and (2*Q_0-Q_e, P_e) for Distributary B cannot be reached because of the constraints in allocation to Distributary A. Instead, Distributary A will use Q_1, thus more than the quantity Q_e that would be obtained in a unconstrained market. As a result, the quantity (Q_0-Q_1) will be transacted on the market between the two distributaries instead of the quantity (Q_0-Q_e). With this figure, it is not possible to specify the final equilibrium price that would be established for this transaction. The equilibrium price will be lower than P_B and higher than P_A, the two prices obtained at the intersection between the Marginal Value Product curves of each distributary and the vertical line of the minimum allocation to Distributary A, and will depend on the relative "bargaining power" of the two distributaries

Summary

In summary for this section, two important elements that have been discussed in the context of irrigation sector policies in Chapter 1 are re-emphasized. Firstly, as the case study investigates water markets, more emphasis is given to economic issues and the demand of irrigation water. Secondly, although the economic issues and the demand for water have a central role, it remains necessary to investigate supply-related issues to incorporate the existing situation and hydraulic reality into the analysis.

So far, research issues related to individual processes only have been examined. The following section concentrates on the operationalization of the integrated approach that combines these processes. In this context, different simulation models are developed and linked for the analysis of the functioning and impact of existing and potential water markets.

3.5 Operationalization of the integrated approach

3.5.1 Development of simulation and optimization models

Simulation and optimization models have been developed for the analysis of the decisional and biophysical processes selected for the present study. Models are developed to understand processes, to identify constraints that influence the output of these processes, and to estimate the impact of selected interventions on this output. Table 3.2 summarizes the main features of these models.

The development of the farm and watercourse stochastic linear programming models is the main focus of Chapter 5 of this thesis. Other models presented in Table 3.2 have been developed by Kuper (1997) for the analysis of the relationship between irrigation system management and salinity/sodicity, and by van Waijjen (1996) for the analysis of the net recharge to the aquifer. Appendix 1 summarizes information on the development of these models, namely the SWAP93 model, the empirical sodicity equation and the water-balance model. Appendix 2 briefly describes the main features of the operation and maintenance of the canal network, and presents the hydrodynamic SIC model that has been calibrated and validated for selected canals, and the water-balance model. For more insight into these physical processes and the application of these models in the context of the Pakistan, see Kuper (1997) and van Waijjen (1996).

The different simulation and optimization models presented in Table 3.2 have been used individually to analyze selected biophysical and decisional processes. They are also linked for investigating the functioning and impact of existing and potential water markets. Issues related to linking models and assessing the impact of interventions on irrigation system performance for large irrigation systems are discussed below.

3.5.2 Time and spatial scale issues

The different biophysical and decisional processes that are considered and analyzed take place at different spatial scales of the irrigation system. The interaction between water, soil and the plant

Table 3.2. Models used for the analysis of the functioning and impact of existing and potential water markets in Pakistan.

		Process	Name of model/software	Type of model	Spatial unit of analysis	Software/model developed by	Source
Potential water markets	Existing water markets	Impact of canal water supply on agricultural production	Stochastic Linear Programming farm model (Micro-LP software)	Economic optimization, linear programming model	Farm	IIMI	Present study (Chapter 5)
		Canal & tubewell water allocation/distribution within the watercourse command area	Stochastic Linear Programming watercourse model (Micro-LP software)	Economic optimization, linear programming model	Watercourse	IIMI	Present study (Chapter 5)
		Impact of water supply on salinity	SWAP93	Hydro-dynamic solute-transport model	Field	Wageningen Agricultural University	Smets (1996), Kuper (1997), van Dam et al. (1997)
		Impact of water supply on sodicity	Sodicity equation (spreadsheet)	Statistical model	Field, watercourse	IIMI	Kuper (1997)
		Water allocation and distribution at main canal	SIC version 2.1	Hydro-dynamic hydraulic model	Main canal	Cemagref	Malaterre (1997), Kuper (1997)
		Water allocation and distribution at distributary	SIC version 2.1	Hydro-dynamic hydraulic model	Secondary canal	Cemagref	Malaterre (1997), Kuper (1997)
		Water-balance	Water-balance model (spreadsheet)	Mass-balance model	Watercourse & secondary canal	IIMI	Perry (1995), Waijjen (1996)

takes place within the root zone at the field scale, while the allocation of canal water is considered within the tertiary unit command area or within the farm boundaries. The basic spatial unit considered for decisions related to the relative importance of crops in the cropping pattern is the farm. And the allocation of canal water between different distributaries takes place at the irrigation system level.

In theory, one may identify the smallest spatial unit, equivalent to the *Representative Elementary Area* used in hydrology (Woods et al., 1995), for which all variables and parameters are homogeneous for the processes considered. Then, simulation models can be applied to such units. In practice, however, as a result of spatial distribution of the main parameters that influence processes and the absence of systematic spatial structure of these parameters, a very high number of units would be identified leading to cumbersome processing of information and a very long time for model simulation. Thus, for very practical reasons, sensitivity analysis of key parameters is required to identify the most important ones for which spatial variability is to be considered, which can help in identifying an intermediary spatial scale for the purpose of integration.

The investigation of water markets makes the farm the central element and the unit of analysis where decisions are taken regarding (re-)allocation of irrigation water and participation in water markets. Based on farmers' production strategy and constraints, a decision is taken whether to purchase or sell irrigation water. In turn, this decision will be translated into changes in agricultural production and in the physical environment. And decisions of individual farmers aggregated at the scale of the tertiary or secondary unit will lead to changes in operation of the irrigation system.

Although the farm is selected as the basic decisional unit for the analysis of water markets, the farm is not accurately positioned within the irrigation system because of related high information requirements. However, the interdependency between farmers resulting from their position along the irrigation network is considered, and the appurtenance of a farm to a given watercourse command area is recorded. This implies that the characteristics of the physical environment cannot be specified for individual farms. Only average variables describing the physical environment can be defined for all of the farms belonging to the same watercourse command area.

As farms often cultivate land in several watercourse command areas, the analysis of existing water markets within the watercourse command area may incorporate farmers' decisions only partially. Also, problems in the development of economic models may arise, as water constraints are usually estimated for a tertiary unit, or for the area cultivated by a farmer within this command area and served by a given warabandi turn, and not for a farm.

Different time steps are associated with the processes considered. Farmer's decisions regarding re-allocation of canal water and cropping pattern are taken every year, while scheduling and application of irrigation water are weekly or monthly-based decisions. At the same time, in order to compensate for the variability in canal water supply and the unpredictable rainfall, short-term decisions in the order of magnitude of an hour are taken by farmers while effectively irrigating their fields. The analysis of the biophysical processes within the root-zone often uses much shorter time steps to estimate changes in the soil salinity profiles as a result of irrigation practices. On the other hand, salinization and sodification processes are slow processes that may take 5 to 10 years to develop and significantly affect the soil and crop production.

Since farmers' planning decisions are seen as central to the analysis of the potential for water market development in irrigation systems, the year with two separate crop seasons has been selected as the planning period. And the month has been selected as the basic time unit for allocation decisions within this planning period. The month represents approximately the time interval that separates two successive irrigation events for a given crop. It is seen as a more adequate time period than the year or the season to represent irrigation water constraints.

3.5.3 Spatial heterogeneity

Directly related to the decisions on spatial scale is the spatial heterogeneity of parameters and input variables listed in Table 3.1. As water markets may take place between different parts of the irrigation system, investigation of the spatial variability in key parameters that are expected to influence water market development and their impact is required. Spatial heterogeneity may be considered for:

- The *socio-economic characteristics of a farm population;*
- The *access to input and output markets,* as it will influence crop choices and level of intensification;
- *Irrigation water supply* constraints, whether canal water supplies or access to groundwater resources; and,
- The characteristics of the *physical environment,* such as groundwater quality, groundwater table depth, and soils, that will influence the impact of irrigation water on salinity, sodicity and net recharge to the aquifer.

The analysis of the spatial heterogeneity is a common difficulty in the analysis of complex systems as it is not possible to analyze separately each unit or representative elementary area mentioned above, or in the case study considered herein, all the farms of the irrigation system investigated. Expert knowledge is used to better understand the structure (if any) of the spatial heterogeneity. Classification techniques and typologies are developed to tackle the heterogeneity issue and identify *types, classes or patterns* that summarize the heterogeneity of the different variables considered for the whole area. And aggregation techniques are used to reduce the number of units considered and prioritize among variables and parameters.

It is important to stress that spatial heterogeneity is required for water market to develop, as differences in marginal value product of water between users is a prerequisite for reallocation of canal water. Variability in socio-economic characteristics and access to output markets will directly affect the marginal value product of farmers and is expected to influence the potential for water market development within the irrigation system. Also, the spatial variability in physical parameters such as groundwater quality, soils and groundwater table depth will affect the impact that water markets would have on salinity and sodicity.

The spatial heterogeneity of parameters and variables can be separated into a general trend or gradient for the irrigation system as a whole, and a short-distance spatial variability. The second type of variability will be of importance for the analysis of existing water markets within the tertiary unit command area, while larger-scale general trend will be considered for the analysis of the potential for water market development at higher scales of the irrigation system.

3.5.4 Linking simulation models to assess the impact of water market scenarios

As mentioned above, the models developed for the analysis of individual processes are linked for assessing the impact of water market scenarios on the agricultural production and on the environment at different scales and hydraulic units of the irrigation system. A modular approach has been selected where models remain independent one from another and can still be used independently. This is referred to as a *transparent modeling approach* by Shaw (1996) that allows users to trace inputs and outputs throughout the chain of processes, and is preferred to a black box approach. Elements considered while developing links between models and operationalizing the integrated approach include the following.

- The *coherence* between the different models developed in terms of the level of complexity, and the adequacy of the output of some models that is used as input for other models.

- The need to adapt some models that have been developed at a small scale for use at a larger scale. *Upscaling* is a major issue for parameters and processes that are non-linear in relation with other parameters, not only for hydrology (Bloschl and Sivapalan, 1995) but also for social sciences. More generally, scaling will be required when the modeling scale is much larger or much smaller than the observation scale. Upscaling has been performed for the SWAP93 model, initially calibrated and validated at the field scale, then used at the watercourse scale. Also, a similar approach has been used for the empirical equation linking soil sodicity with groundwater quality and soil parameters (see Appendix 1 and Kuper (1997)).

- The need *to limit the overall computational time* required for applying the integrated approach to the analysis of one scenario. Simplification may be required in the models themselves. Also, a limited number of spatial units representing the spatial heterogeneity in the irrigation system may be selected for application of the models.

- The *availability of information for a large-scale irrigation system* that constrains the potential use of the models. Accurate information may be available at specific scales, but not at the scale at which models were initially developed. Also, the lack of information on important parameters may lead to a simplification of the models used, or the application of interpolation/extrapolation techniques to estimate the missing information. The sodicity equation developed by Kuper (1997), for example, remains very simple, but can be easily applied to other areas as input requirements are limited. In fact, the balance between model complexity, scale of interest, and information availability is an issue central to the development of the integrated approach.

Linking models requires the development of a database that considers parameters along with input and output variables, at different spatial scales. Specific computational procedures may be required to transform the output of a given model into an appropriate input for another model. Thus, the operationalization of the integrated approach requires an integrated spatial database that can be adequately developed within the structure of a Geographic Information System (GIS).

3.6 Development of a performance matrix for evaluating water market scenarios

The final issue discussed in this chapter relates to the comparison between different water market scenarios and the evaluation of their impact on irrigation system performance. Although the discussions above have highlighted the different dimensions and variables that are to be considered while analyzing water markets, a simple and objective way of establishing a hierarchy between water market scenarios may be a requirement of potential users of results obtained from the application of the integrated approach.

Literature on performance assessment is rather prolific and proposes a large number of indicators that can be used to assess the impact of water markets on irrigation system performance. Examples of such studies include Snellen and Murray-Rust (1994), Molden and Gate (1994) and Bos et al. (1994). Elements that favor a large number of performance indicators to evaluate water market scenarios include:

- The need to evaluate the impact of water market scenarios on indicators that express the *complexity of irrigation systems* and stress bottlenecks and constraints that affect irrigation system performance;
- The investigation of dimensions related to *water, agricultural production and environment* in the assessment of the potential development and impact of water markets; and,
- The need to develop a *platform for discussion between actors*. Different actors may have different objectives (Svendsen and Small, 1990; Winpenny, 1994) that are to be considered. One actor may also have several simultaneous objectives. Such objectives include economic efficiency, irrigation efficiency, equity, sustainability (Winpenny, 1994). Other aspects considered while evaluating scenarios include political and social acceptability, administrative feasibility or technical feasibility.

From a more practical point of view, however, the number of performance indicators may soon be too large and lead to a cumbersome and impossible comparison between various interventions. A limited number of performance indicators are required to facilitate the comparison between scenarios (van Beek, 1995). An extreme option would be the selection of a single indicator, or the combination of different indicators into a single aggregated performance indicator. Multi-criteria evaluation methods are examples of techniques that have been developed and applied to rank scenarios or interventions in the water and irrigation sector (see for example the Electre method). These techniques rely on the identification of specific weights to be assigned to different indicator/criteria and on specific computational techniques to transform a series of values for various performance indicators into a single aggregated value.

The option favored in this study is the development of a performance matrix that presents the impact of water market scenarios in a table format for a limited number of performance indicators related to irrigation water supply, agricultural production, physical environment and equity. This limited number of indicators is preferred to the application of multi-criteria evaluation methods for three reasons. Firstly, it is believed that the identification of specific weights for different objectives as required in these methods is a difficult task. Such approaches pretend objectivity and uniformity while the attribution of weights remains highly subjective (Becker, 1996). Secondly, the aggregation of indicators is often not meaningful and the results obtained through such methods are more obscure for potential users of these results. Thus, they do not provide an effective platform where each actor can relate results and information to its own objectives. Thirdly, to keep separate performance indicators is of primary importance for investigating trade-offs between objectives. For example, economic efficiency and equity, or economic efficiency and environmental sustainability, are objectives that are often opposed without understanding the trade-off (if any) between these objectives.

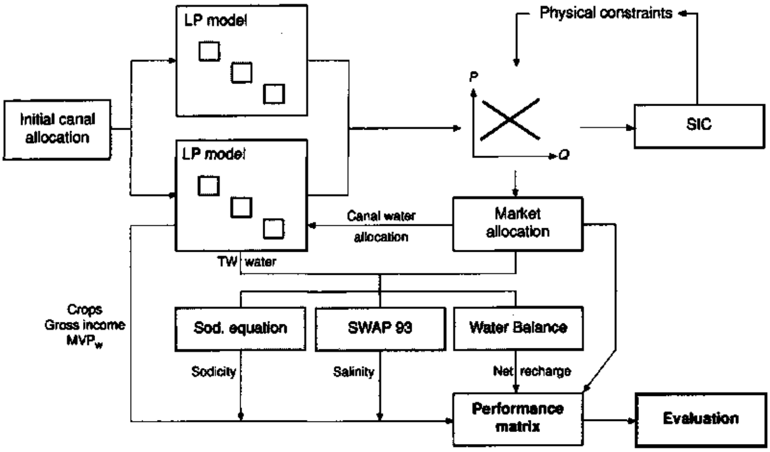
For each water market scenario, indicators are computed and analyzed at the level of the farm group within a tertiary unit command area. These indicators are then aggregated at higher spatial scales. Watercourse-based performance indicators can also be analyzed spatially using the GIS, used here as a data management and visualization tool and not as a modeling framework (Shaw, 1996). This enables the identification of areas that may potentially suffer from water market development. As a result, selected area-targeted measures may be proposed that would accompany the implementation of water markets and offset at least partially their (localized) negative impact.

3.7 Summary: operationalizing the integrated approach for the analysis of water markets in Pakistan

An integrated approach that aims at assessing the impact of interventions in the irrigation sector on irrigation system performance was presented, and operationalized for the analysis of the potential for water market development in the irrigation sector in Pakistan. Building on the output of disciplinary efforts, the integrated approach includes the development of links between different simulation and optimization models, and between these models and a spatial database developed in the context of a Geographic Information System. Figure 3.7 presents the use of, and links between, optimization and simulation models for the analysis of the functioning and impact of water markets in Pakistan.

Following the flow of information, the starting point in Figure 3.7 is the initial canal water allocation to different tertiary and/or secondary units. Relationships between quantity of surface water allocated and marginal value product of water are obtained for these units, using the stochastic linear programming models. The market allocation is them obtained by confronting these relationships developed for different units. The technical feasibility of the market allocation is checked with the SIC hydraulic model. Using the market allocation as input in the stochastic linear programming models, the overall farm gross income, cropping pattern and tubewell water use is obtained. Canal water and tubewell water are then input into the SWAP93, sodicity equation and water-balance models, to obtain salinity and sodicity levels and the net recharge to the aquifer that result from the market allocation.

Figure 3.7. Using optimization and simulation models for the analysis of the potential for water market development in Pakistan.



Interestingly, the order of use of the models presented in Figure 3.7 is at variance with the sequence presented in Figure 5.2 in Kuper (1997). In his study, Kuper (1997) uses the models to analyze *supply-based* interventions that modify farmer's water constraints that allows him to mitigate salinity and sodicity. As a result, farmers modify cropping pattern and tubewell water use, which in turn impacts on salinity and sodicity. The analysis of water markets is just the opposite, which starts from farmers and their *water demand*. Farmers' demand is then aggregated at various scales of the irrigation system and put as an operational target for the management of the canal system.

The following chapter presents the main features of the Chishtian Sub-division, the irrigation system that has been selected for the analysis of water markets and the operationalization of the integrated approach. Then, Chapter 5 summarizes the results of the farming system analysis, and presents the economic models developed at the farm and watercourse levels. As specified above, the processes related to the flow of surface water from the main canals into the secondary canals, along with the link between irrigation water, salinity and sodicity, are studied in detail by Kuper (1997). These elements of the integrated approach are then combined in Chapter 6 and Chapter 7 for the analysis of existing and potential water markets in the Chishtian Sub-division, respectively.

Chapter 4

Description of the Chishtian Sub-division, South-Punjab, Pakistan

This chapter presents the main features of the Chishtian Sub-division of the Fordwah/Eastern Sadiqia irrigation system that has been selected for the analysis of water markets in Pakistan. The Chishtian Sub-division is described in terms of its hydraulic network, physical environment and farming systems. The final section of the chapter summarizes the different samples selected at various scales, along with information collected for the present study and the development of simulation and optimization models used to assess the technical feasibility and environmental impact of water markets.

4.1 Irrigation system and hydraulic network

Located in the South-Punjab, Pakistan, the Fordwah/Eastern Sadiqia irrigation system irrigates a total Culturable Command Area (CCA) of 593,000 ha. It is delimited by the Indian border on the East, the Cholistan Desert on the South and the Sutlej River along the Northwest (Map 4.1). Two main canals, namely the Eastern Sadiqia Canal and the Fordwah Canal that off-take from the left side of the Sutlej River, provide surface water supplies to the irrigated cropland. These canals were constructed as part of the Sutlej Valley Project initiated in 1926 and incorporated already existing irrigation facilities, such as inundation canals off-taking from the Sutlej River and Persian wells.

The Fordwah Canal is rather short and is divided after less than 15 km from the headworks into the MacLeod Ganj Branch Canal and the Fordwah Branch Canal. The Chishtian Sub-division is the last and largest management unit along the Fordwah Branch. Although the hand-over point from the upstream sub-division is at km 61, or RD 199[1], of the Fordwah Branch Canal, the Chishtian Sub-division starts at RD 245 and commands a culturable area of 67,000 ha. The canal network includes 14 distributaries that serve 503 tertiary units, and 19 tertiary units that directly off-take from the Fordwah Branch Canal. Table 4.1 presents the main features of these distributaries ordered according to the location of their off-takes from the head to the tail of the Fordwah Branch Canal. The layout of the hydraulic network is presented in Kuper (1997).

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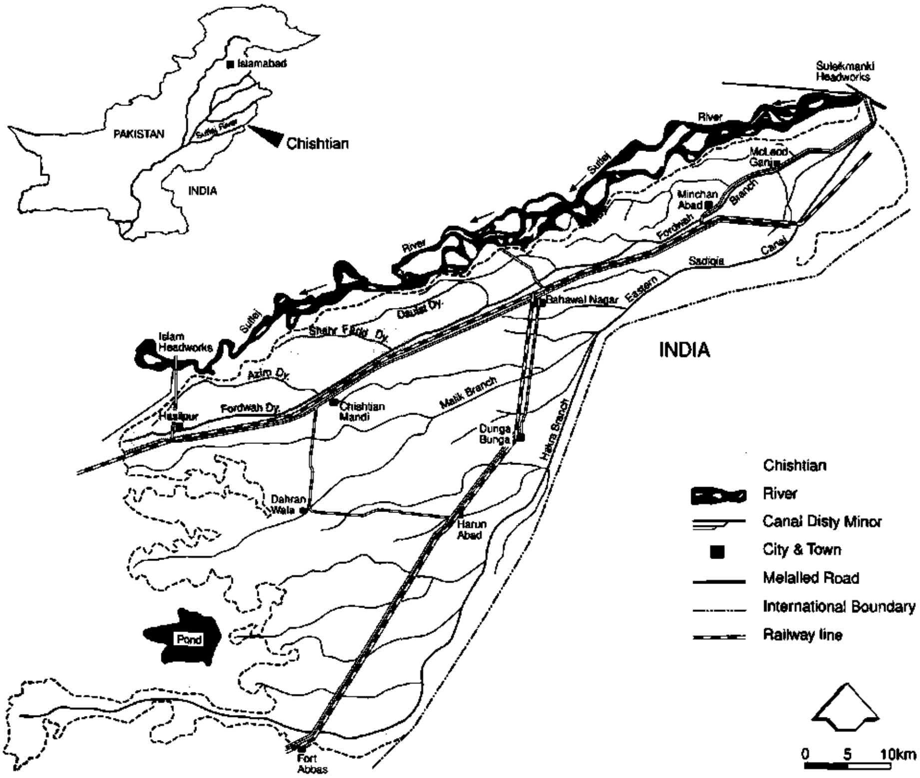
[1] The Reduced Distance (RD) expresses the distance from the head of a canal in 1000 feet. Thus, RD 199 is equivalent to a distance of 199,000 feet from the head of the Fordwah Branch Canal.

Map 4.1. Location of the Chishtian Sub-division of the Fordwah/Eastern Sadiqia irrigation system in Pakistan.



A particularity of the Fordwah Branch Canal is that it is a non-perennial canal that receives canal water supplies during the *kharif* (summer) season only. However, five of the distributaries of the Chishtian Sub-division are perennial and receive canal water supplies the year round, because of a feeder canal that off-takes directly from the Eastern Sadiqia Canal and is connected to the Fordwah Branch Canal at RD 125. The water allocation to distributaries ranges from 0.25 $l.s^{-1}.ha^{-1}$ for perennial distributaries to 0.49 $l.s^{-1}.ha^{-1}$ for non-perennial distributaries. While design irrigation intensities have been set at 80% (32% in kharif and 48% in *rabi* (winter)) for perennial distributaries, and 70% (35% in kharif and 35% in rabi) for non-perennial distributaries.

The sub-division is managed by one Sub-Divisional Officer (SDO) of the Punjab Irrigation & Power Department (PIPD), being assisted for technical matters by 5 Sub-engineers. Other staff includes revenue personnel for the assessment of water charges, gauge readers that operate control structures along the main canal, and a large number of workers (*bildars*) for the maintenance of the irrigation system.

Table 4.1. Main features of distributaries in the Chishtian Sub-division – The status column distinguishes between Perennial (P) and Non-Perennial (NP) canals. The CCA of the distributaries includes the CCA of the respective minors, while the area commanded by direct outlets has been included in the total CCA of the Sub-division.

Distributary	Status	No of minors	No. of outlets	Design discharge ($m^3.s^{-1}$)	CCA (ha)
3-L	NP	0	6	0.51	1,200
Mohar	NP	1	15	1.08	1,780
Daulat	NP	2	108	5.92	13,230
Phogan	NP	0	9	0.5	890
4-L	NP	0	7	0.4	830
Khemgarh	NP	0	9	0.68	2,040
Jagir	P	0	9	0.79	1,900
Shahar Farid	NP	1	74	4.33	10,070
Masood	P	0	16	1.0	3,280
Soda	NP	0	33	2.18	4,090
5-L	P	0	3	0.11	360
Fordwah	P	1	87	4.47	14,840
Mehmud	P	0	7	0.23	812
Azim	NP	3	98	6.91	12,330
Chishtian Sub-division	-	8	522	36.3	67,654

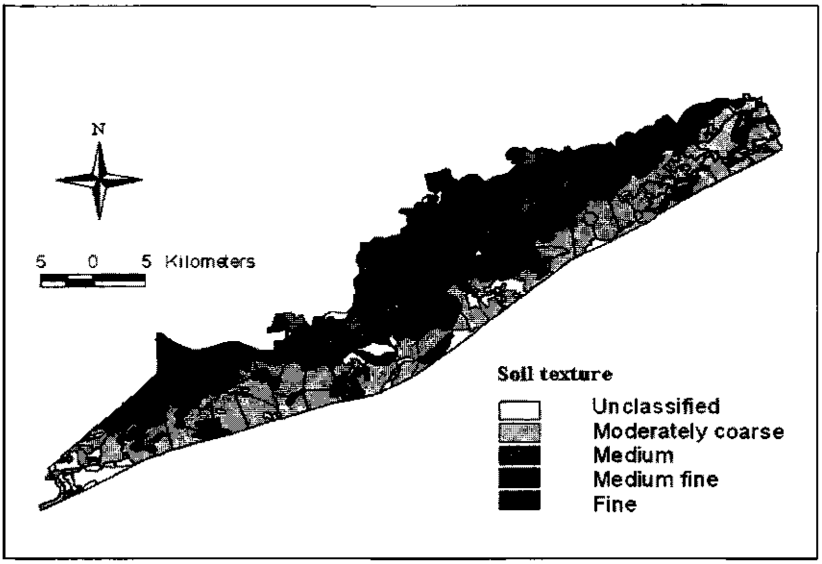
4.2 Physical environment

The climate of the Chishtian Sub-division is semi-arid continental, characterized by a very high potential evaporation rate of more than 2,400 $mm.yr^{-1}$, and by low and highly erratic rainfall with an average annual rainfall rate of 200 $mm.yr^{-1}$ mainly concentrated during the monsoon period from July to September. Thus, without irrigation, little can be grown in the area. The main soils in the Sub-division have developed in recent and sub-recent river terraces and are underlain by thick sediments. The origin of the soils induces a clear spatial structure of the main soils parallel to the Sutlej River. The main physiographic units of the Chishtian Sub-division are presented in Table 4.2 and Map 4.2. A more detailed analysis of the different soil types is included in Kuper (1997).

Table 4.2. Physiographic units in the Chishtian Sub-division (source: Soil Survey of Pakistan, 1996).

Physiographic unit	Location	Soil texture
Basins	Lowest part of the flood plains	Fine and moderately fine texture
Level plains	Level parts of the flood plains	Moderately coarse to moderately fine texture
Levees	Low ridges parallel to an ancient river course	Moderately coarse texture
Sand bars	Formed by deposition of sand on the inner side of a meandering river	Coarse texture

Map 4.2. Physiographic units in the Chishtian Sub-division (Source: Soil Survey of Pakistan, 1997).



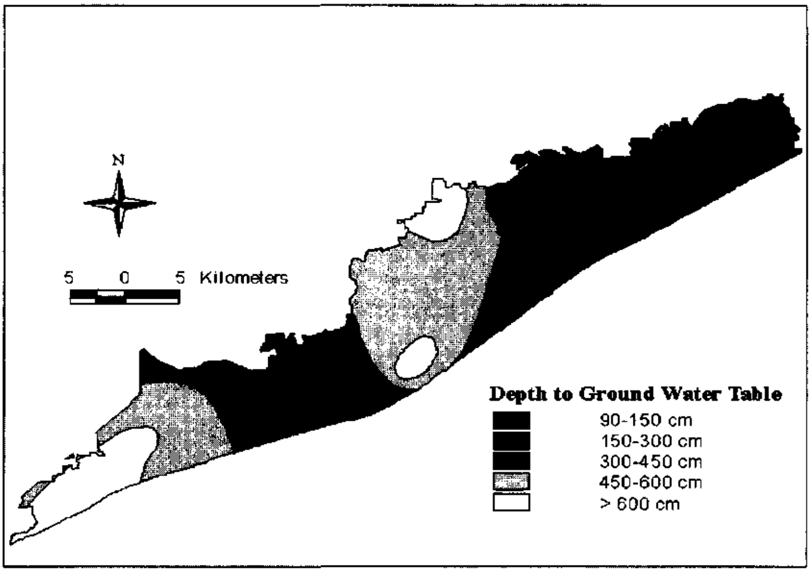
Salinity and sodicity affect part of the soils in the Chishtian Sub-division. A joint survey undertaken in 1996 by the Directorate of Land Reclamation of the PIPD and IIMI has shown that 20% of the commanded area is affected by salinity. Large patches of uncultivated areas of generic salinity are located in the central parts of the Sub-division and have been identified through satellite imagery (Tabet et al., 1997). Salinity in cultivated fields is also present, although the area affected remain modest at around 10% of the CCA.

The comparison between salinity surveys that have been undertaken in the past shows a *gradual decrease in saline and highly saline areas* in the Chishtian Sub-division (Kuper, 1997). This decrease is directly related to reclamation of large areas by farmers, as illustrated by increasing cropping intensities in the area, from 70-80% as per design to more than 140% today. More recently, however, concerns have arisen regarding *increasing sodicity problems* in areas irrigated with a high proportion of poor quality groundwater (Soil Survey of Pakistan, 1996). This sodification process leads to surface crusts and degradation of the soils that may become irreversible.

This problem stresses the importance of groundwater quality in an area where conjunctive use of surface and groundwater is the rule rather than the exception (see below). Using the results obtained from the analysis of groundwater pumped by approximately 500 tubewells, the average Electrical Conductivity (*EC*) is equal to 1.1 $dS.m^{-1}$, the average Sodium Adsorption Ratio (*SAR*) is equal to 3.8 $mmol.l^{-1}$, and the Residual Sodium Carbonates (*RSC*) is equal to 0.4 $meq.l^{-1}$. Overall, there is a decreasing trend in tubewell water quality from the Sutlej River to the Cholistan Desert. However, the spatial variability of the tubewell water quality parameters *EC*, *SAR* and *RSC* remains very high, even within the command area of a tertiary unit (Kuper, 1997).

Salinization through capillary rise affects only a limited area of the Chishtian Sub-division, as the groundwater table is generally deeper than 2 m below the soil surface. Areas along the Fordwah Branch Canal and in the Northwest portion of the Chishtian Sub-division contain a shallower aquifer (see Map 4.3). However, these areas represent less than 10% of the total CCA.

Map 4.3. Groundwater table depths in the Chishtian Sub-division in October 1993 (information obtained from the SCARP Monitoring Organization, Water and Power Development Authority).



4.3 Farming systems and socio-economic features of the Chishtian Sub-division

Although the command area of the Chishtian Sub-division is part of the cotton-wheat agro-ecological zone of Pakistan, the dominance of the cotton crop during the kharif season is limited. The main crops cultivated during the kharif season are cotton, rice and sugarcane, with 40%, 28% and 9% of the CCA, respectively. During the rabi season, sugarcane is also present, but wheat occupies the bulk of the area with around 65% of the CCA. Fodder crops are cultivated during the two seasons, and vegetables, orchards and oil seeds are also present. Overall, the cropping intensity, equal to (cropped area/culturable area)*100, is equal to 91% for the kharif season, and 64% for the rabi season (Mohtadullah and Manzar, 1997).

Farms in the area have an average land holding of 7.4 ha, out of which 6.7 ha is culturable. A third of the area is rented-in, mainly by landowners who want to maximize farm income and amortize their investments in tubewells and tractors. Less than 10% of the total farm population is composed of pure tenants, a surprisingly low number in this partly feudal society. However, this low number of tenants is in accordance with the general trend that shows a significant decrease in the importance of tenants in the rural economy of Pakistan since the Independence (Nazir and Chaudhry, 1988).

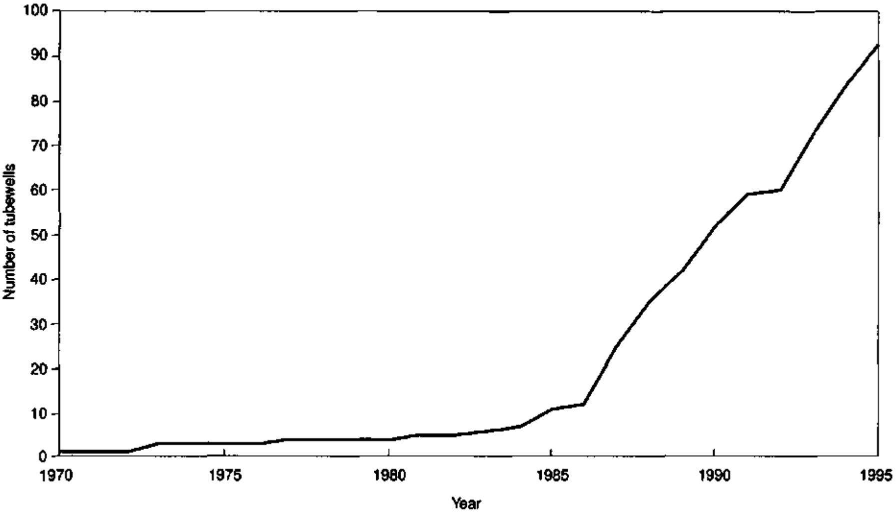
Labor used on the farm is mainly family labour, especially on small subsistence farms. Only landlords having large landholdings hire permanent labour. For specific activities, such as harvesting and threshing of wheat, harvesting of cotton, weeding of cotton fields or transplanting of rice, farmers hire temporary labour. Thirty percent of the farmers are tractor owners, but nearly all farmers use tractors for land preparation activities.

Most of the farmers in the Chishtian area have strong, although not always direct links with input and output markets. Fertilizers and pesticides are widely used by all farmers, especially by farmers specialized in cotton cultivation. Most of the rice and cotton produce is sold on the market. Sugarcane is sold to the local sugar-mill or directly transformed on the farm into raw sugar (*gur*) that is then directly sold on the market. For wheat, however, the dependency on agricultural commodity markets is lower. Wheat is mainly produced for auto-consumption but significant surpluses are usually obtained: 50% of the farmers sell on average 53% of their wheat production. The main markets for agricultural commodities in the area are Chishtian, Hasilpur and Bahawalnagar. The Chishtian market is the most important cotton market, while the Bahawalnagar market at the head of the Chishtian Sub-division is relatively more specialized in the marketing of rice output (Tahir, 1997). Wheat is important in all markets and is purchased at a procurement price by government-related procurement companies.

As a result of inadequate canal water supplies, farmers have invested heavily in private tubewells in the Chishtian Sub-division to tap groundwater resources. Totally, around 4,450 private tubewells have been installed in the area, equivalent to a tubewell density of 6.4 tubewells per 100 ha of CCA. These tubewells have an average discharge of 25-30 $l.s^{-1}$, with an electric or diesel engine permanently installed on the tubewell site in the field, or the possibility exists to use a tractor or transportable engine in the case of Power-Take-Off (PTO) tubewells. On the average, investment costs of electric tubewells are the highest as compared to diesel and PTO tubewells, but their operation and maintenance costs are the lowest. Thus, electric tubewells represent the preferred option for large farmers with no credit constraint and high tubewell water needs.

Tubewells have mainly been installed in the area since 1980-1985. Figure 4.1 illustrates the drastic increase in the number of private tubewells in the command areas of the 8 sample tertiary units that have been selected for the detailed analysis of existing water markets (see below). Private tubewells may be owned by a single farmer (40% of the total) or by joint tubewell owners (60% of the total). The most common arrangement for joint tubewell owners involves two brothers or other family members. Overall, around 45% of the farmers in the Chishtian Sub-division own a tubewell whether jointly or solely. However, as will be described in detail in Chapter 6, most of the non-tubewell owners rely also on groundwater resources for their irrigation through the purchase of tubewell water.

Figure 4.1. Private tubewell development in the command area (total: 1,204 ha) of the eight sample tertiary units of the Chishtian Sub-division over the period 1970 to 1995.



Although average farm characteristics and agricultural production provide a general picture of farming systems within the Chishtian Sub-division, it hides one of the most important features of its *farmer population, i.e. its variability and diversity*. Basic statistics for selected variables are presented in Table 4.3 to illustrate this diversity in farming systems. These statistics are computed using information pertaining to the Kharif 1994 and Rabi 1994-95 seasons, collected through a farm survey for 560 farmers distributed throughout the Chishtian Sub-division.

Table 4.3. Heterogeneity of the farm population in the Chishtian Sub-division: basic statistics for selected agricultural production variables for the Kharif 1994 and Rabi 1994-95 seasons. The 0 value in the minimum column for wheat and cotton yields corresponds to crop failure.

Variable	Average	Standard deviation	Minimum	Maximum
Area (ha)				
Owned	5.7	14.3	0.0	142.6
Operated	7.4	16.5	0.1	197.5
Cropping intensity (%)				
Kharif	91	15	20	100
Rabi	64	20	35	100
Crop yield (kg.ha^{-1})				
Cotton	765	565	0	3955
Wheat	2090	855	0	6425
Input use (kg.ha^{-1})				
Cotton	370	130	65	865
Wheat	360	105	60	800

This heterogeneity in farming systems can be illustrated at different scales or irrigation units of the Chishtian Sub-division. Using the same farm survey information, Table 4.4 compares the average farm area, the importance of land rented-in, the tubewell density, and the relative importance of different crops in the cropping pattern, for the 14 distributary command areas of the Chishtian Sub-division.

Table 4.4. Selected farming system and agricultural production variables estimated for the command areas of the 14 distributaries of the Chishtian Sub-division for the Kharif 1994 and Rabi 1994-95 seasons.

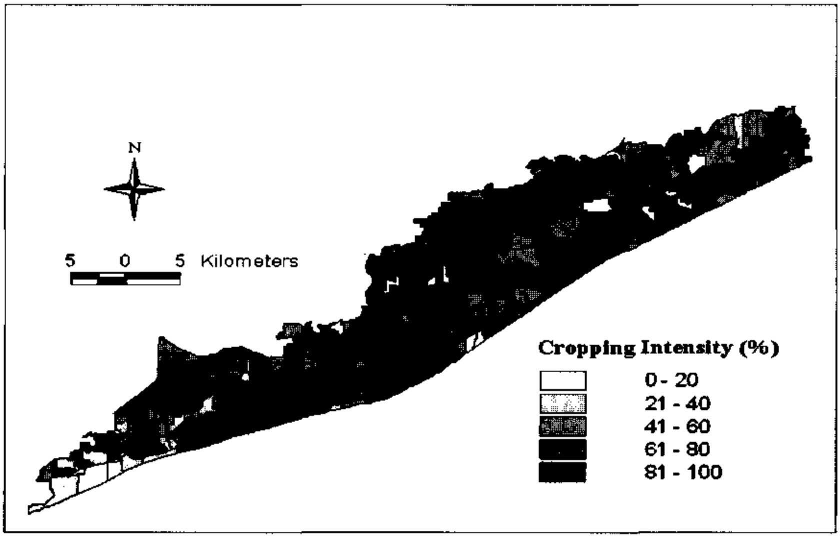
Distributary	Farm size (ha)	Area rented-in (%)	Family labor (unit.ha^{-1})	Tubewell density (No. per 100 ha)	Wheat area (%)	Cotton area (%)	Rice area (%)	Sugarcane area (%)
3-L	4.3	26	0.32	8.2	59	12	42	4
Mohar	8.7	25	0.27	5.5	35	4	62	3
Daulat	6.1	20	0.40	8.0	60	61	11	4
Phogan	7.3	3	0.50	4.0	38	12	49	1
4-L	16.7	16	0.57	3.5	73	31	49	1
Khemgarh	16.4	11	0.40	4.6	50	21	60	3
Jagir	3.7	24	0.46	3.5	62	31	37	5
Shahar Farid	10.1	29	0.24	7.9	42	48	8	18
Masood	9.7	29	0.17	4.2	45	29	7	34
Soda	5.5	30	0.28	11.1	58	31	15	6
5-L	4.6	42	0.37	8.0	68	51	2	5
Fordwah	5.9	37	0.24	9.2	59	54	5	12
Mehmud	4.1	26	0.37	2.8	44	26	13	29
Azim	8.6	24	0.16	9.4	45	46	13	8

Distributary-wise differences in the variables describing farming systems and agricultural production are partly related to the spatial variability in the physical environment presented in Maps 4.2 to 4.4. For example, the high percentage of area under rice in the upper reach of the Chishtian Sub-division is directly related to high groundwater table and good access to canal water supplies. However, socio-economic factors are also to be considered in explaining this spatial diversity. Such factors include:

- *Access to output markets.* The relative importance of sugarcane in the Shahar Farid, Masood, Fordwah and Mehmud distributaries is explained by the presence of a sugar mill close to the town of Chishtian. Also, higher areas are grown under fodder and vegetables close to the cities of Hasilpur, Chishtian and Bahawalnagar.
- *Origin and cultural background of the farm population.* In the Chishtian Sub-division, a distinction is made between *locals* (i.e. social groups that were living in the area before the development of the existing irrigation network) and *settlers* (i.e. social groups that came to the area in the context of the Sutlej Valley Project or at the time of the Independence in 1947). Locals are a heterogeneous population of large landlord and small tenants-sharecroppers cultivating large areas along the Sutlej River, while settlers are a more homogenous population of small to medium size owners-cum-tenants.

The command areas of distributaries, also, are not homogeneous units in terms of socio-economic characteristics of the farm population. An example of such heterogeneity is illustrated in Map 4.5 that presents the Kharif 1994 cropping intensity computed for all the tertiary units of the Chishtian Sub-division. The cropping intensity information has been obtained through the use of satellite imagery and application of supervised classification techniques (Jamieson, 1995; Ahmad et al., 1996). The lack of a clear spatial trend for this variable, as compared with the trends illustrated in Map 4.2 to Map 4.4 for physical variables, stresses the complexity of causes that explain differences in cropping intensity between tertiary units of the irrigation system, and the importance of socio-economic factors in understanding these differences.

Map 4.5. Kharif 1994 cropping intensity for tertiary unit command areas in the Chishtian Sub-division. This information is obtained through a supervised classification of a SPOT satellite image of October 1994.



Finally, watercourse command areas are also heterogeneous units. They contain farms with diverse agricultural production strategies and constraints. Also, as illustrated in more detail by Kuper (1997), they are heterogeneous with respect to soil types, tubewell water quality and groundwater table depth.

4.4 Sample selection and collection of information

Although the research efforts to operationalize the integrated approach will eventually be undertaken for the Chishtian Sub-division as a whole, the analysis presented in the following chapters of the present thesis concentrates on sub-areas of the Sub-division only. *The objective is to* *illustrate the main issues related to existing and potential water markets in the Chishtian Sub-division and Pakistan.* The analysis of existing water markets is undertaken in eight sample tertiary units. And the potential for water market development is investigated between these tertiary units and between the Fordwah Distributary and the Azim Distributary, the two very tail and largest distributaries of the Chishtian Sub-division.

The biophysical and decisional processes that have been selected were investigated separately using different samples and information. In some cases, activities were undertaken simultaneously for different processes, because it facilitated the organization and implementation of field and office activities. Simulation and optimization models were calibrated and validated for small areas representative of different environments. And information was collected for larger areas to investigate the spatial variability in key parameters, and for use of the simulation models for these larger areas.

The analysis of existing water markets and the development of farm and watercourse economic models is based on a sample of eight tertiary units of the Fordwah and Azim distributaries. The sample watercourses were initially selected to represent a variety of canal water supply, physical environment and socio-economic conditions. Referring to differences in the social and cultural conditions discussed in the last section, the Azim command area is mainly occupied by *locals*, while *settlers* cultivate the Fordwah command area. Selected features of the sample tertiary units are summarized in Table 4.5. For simplicity of notation in the following chapters of this thesis, the four watercourses located along the Fordwah distributary will be named FD14, FD 46, FD 62 and FD 130, and the four watercourses off-taking from the Azim distributary AZ 20, AZ 43 and AZ 63 and AZ 111.

Table 4.5. Main features of the eight sample watercourses of the Fordwah and Azim distributaries of the Chishtian Sub-division. The watercourse number refers to the location of the watercourse along the distributary expressed in RD, and to the side of the distributary to which the watercourse off-takes (*R* for Right and *L* for Left).

Distributary	Watercourse number	CCA (ha)	Number of farmers per watercourse	No. of tubewells (per 100 ha)	Average EC of tubewell water (dS.m^{-1})	Portion of watercourse lined
Fordwah	14 R	198	57	7.6	1.93	Yes
	46 R	180	41	4.0	0.82	No
	62 R	133	41	8.3	1.04	No
	130 R	268	49	5.2	1.21	No
Azim	20 L	119	22	3.4	0.77	No
	43 L	66	25	10.6	0.79	No
	63 L	121	20	5.0	0.76	No
	111 L	119	23	6.7	1.02	No

The eight watercourses cover approximately 5% of the total command area of the two distributaries. All farmers of these tertiary units have been monitored for their irrigation water supply, and have been interviewed through a farm survey that investigated issues related to farm characteristics, farming practices, agricultural production and participation in water markets. For the analysis of processes, such as the link between water and agricultural production (field and farm levels) and the link between water and salinity and/or sodicity, sub-samples of farms and fields were selected within the sample command areas.

Table 4.6 summarizes samples and information collected for the different research components integrated in this thesis. The resulting database is the primary outcome of the efforts undertaken jointly for the analysis of the link between irrigation management and salinity and sodicity presented in Kuper (1997), and the analysis of existing and potential water markets in Pakistan presented in this study. The data collection methods, the periodicity of data collection and the time period investigated are specified for each component of the database. Whenever required, specific elements related to sampling and data collection methods will be further described in sections of the following chapters.

4.5 Summary

Chapter 4 presents the main characteristics of the Chishtian Sub-division, the irrigation system that has been selected for the analysis of water markets in Pakistan. The important heterogeneity in physical and socio-economic parameters that is expected to influence the functioning and impact of existing and potential water markets is stressed.

A sample of eight watercourses was selected along the Fordwah and Azim distributaries for the analysis of existing water markets within tertiary units, and the development of simulation and optimization models. The functioning and impact of water markets at higher scales will be investigated between these eight sample watercourses, and between the Fordwah and Azim distributaries. The information and samples used for the different research components integrated in this thesis are summarized.

Table 4.6. Data collection and sampling plan for the analysis of water markets in the Chishtian Sub-division. Information has been collected as part of research activities under IIMI Dutch project *Managing Irrigation Systems for Environmentally Sustainable Agriculture in Pakistan* and under the IIMI-Cemagref collaborative research program funded by the Government of France (Kh = Kharif; Rb = Rabi; WC = watercourse).

Research issue	Activity	Sample	Information collected	Period considered	Collection method	Periodicity of collection
Existing water markets	. Functioning of water markets	. All farms in 8 WC	. Canal and tubewell water transactions	. Kh 92 & Rb 92/93; Kh 94 & Rb 94/95	. Farm survey, interviews	. Once, daily
	. Impact of water transactions on canal water supply	. All farms in 8 WC	. Canal water transactions, WC head discharge	. Kh 94 & Rb 94/95	. Interviews, measurements	. Daily
	. Participation in water markets	. All farmers in 8 WC	. Farm characteristics and participation in water markets	. Kh 92 & Rb 92/93	. Formal farm survey	. Once
	. Case study of intensive canal water markets	. 3 WC in Soda and Daulat distributaries	. Organization and functioning	. Period 90/96	. Informal Interviews of key informants	. Once
Linking water supply and agricultural production	. water-yield relationship	. 60 fields in 8 WC	. Irrigation, inputs, yields	. Kh 94 & Rb 94-95	. Interviews	. Twice a week
	. farm economic models	. 15 farms in 8 WC	. Access to resources, farm characteristics, agricultural production	. Kh 92 & Rb 92/93	. Interviews	. Once
	. WC economic models	. 8 WC	. canal water supply, cropping pattern	. Kh 92 & Rb 92/93	. Measurements, interviews	. Daily, once
Impact of irrigation water on the environment	. Developing the SWAP93 model	. 4 fields in 8WC	. soil characteristics, pressure, salinity, irrigation	. Kh 94 to Kh 95	. Measurements, interviews	. Once, thrice a week
	. Up-scaling SWAP93 to the WC level	. 600 fields in 8WC	. soil analysis	. Kh 94 to Kh 95	. Measurements	. Beg and end of season
	. Water-sodicity relationship	. 600 fields in 8WC	. soil analysis, irrigation water supply at farm	. Kh 94 to Kh 95	. Measurements	. Beg and end of season, daily
	. Water-balance at WC	. 8 WC	. canal & tubewell water use, seepage and conveyance losses	. Kh 94 and Rb 94/95	. Measurements, interviews	. Daily, daily, one campaign
Technical feasibility of water markets	. SIC at main canal	. Fordwah Branch	. topography, flows	. Rb 94-95	. Survey, measurements	. Once
	. SIC at distributary	. Fordwah & Masood distributary	. topography, flows	. Rb 93-94 & Kh 95	. Survey, measurements	. Once per distributary
	. Volume-balance at distributary	. Azim distributary	. flows	. Kh 95	. Measurements	. Once
Investigating diversity in the Chishtian Sub-division	. Typology of farms	. All farms in 8WC	. Farm characteristics	. Kh 92 & Rb 92/93	. Formal farm survey	. Once
	. Analyzing variability in physical parameters	. All WC in Azim & Fordwah	. Groundwater table depth, tubewell water quality, soils	. Kh 93 & Rb 93/94, Rb 95/96	. Maps digitized, measurements	. Once
	. WC classification	. All WC in Azim & Fordwah	. socio-economic characteristics of WC	. Kh 96	. Informal interviews with key informants	. Once

Chapter 5

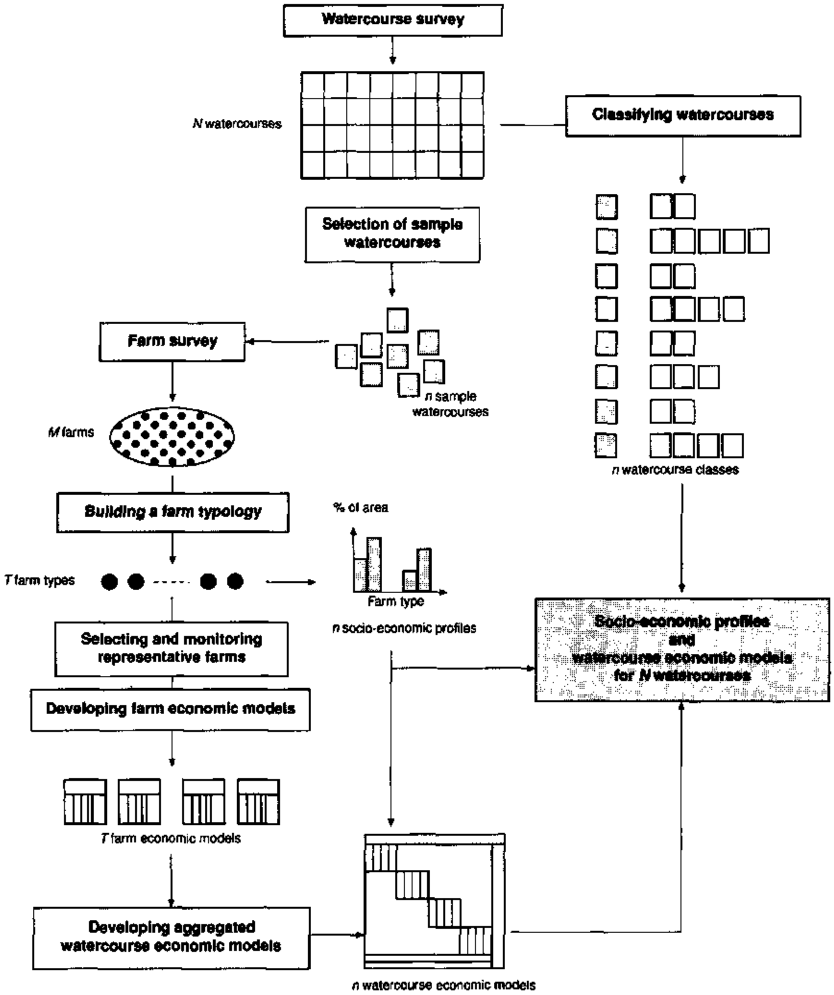
Development of farm and watercourse stochastic linear programming models

5.1 Methodology

The main objective of this chapter is to present the methodology developed to build farm and watercourse stochastic linear programming models to analyze the functioning and impact of existing water markets within the watercourse command area, and assess the potential for water market development at higher scales of the irrigation system. Figure 5.1 summarizes the different steps of this methodology that deals with the *collection of information*, the *analysis of the diversity* of farming systems within and between tertiary units, a detailed analysis of decisions taken by farmers regarding their crop portfolio and groundwater use, and the *development of the micro-economic models*. The different steps include:

- A *watercourse survey*, to collect aggregated characteristics of all the watercourses in the area considered;
- The *selection of sample watercourses* for a detailed investigation of biophysical and decisional processes, and the analysis of the diversity of farms;
- A *farm survey* to collect information on farm characteristics, farming and irrigation practices, and constraints on agricultural production for all farms of the sample watercourses;
- *Building a farm typology*: based on the information collected through the farm survey, homogeneous types or groups of farms with respect to farm characteristics, constraints and production strategies, are identified. The percentage of area under each farm type is then computed for each sample watercourse and presented in a figure format with the different farm types along the x-axis and the relative importance of each type in terms of area occupied along the y-axis. The figure of computed percentages is defined as the *socio-economic profile* of the watercourse;
- *Developing farm economic models*: representative farms are selected for each farm type. Irrigation and farming practices, along with agricultural output, are monitored for two cropping seasons to estimate basic parameters required to build micro-economic models for each farm group;

Figure 5.1. Methodological steps to develop farm and watercourse micro-economic models for the analysis of existing and potential water markets in the Chishtian Sub-division.



- *Developing aggregated watercourse economic models*: using aggregated farm group models and the socio-economic profile of each sample watercourse, watercourse economic models are developed. These models incorporate links between group models, and specify watercourse-level constraints that are faced jointly by farmers of a given watercourse command area. These models are used for the analysis of the functioning and impact of water markets within and between different tertiary units; and,

- *Classifying watercourses*: using the watercourse survey information, watercourses are classified into a limited number of classes based on their resemblance with the sample watercourses. The socio-economic profile and economic model of each sample watercourse is then allocated to all watercourses of its class. Using the total command area of each watercourse, watercourse economic models for all watercourses are built and used for the analysis of water markets between secondary units of the irrigation system.

In the following sections, the methodological steps related to the analysis of diversity and the development of micro-economic models are described. More specifically, the diversity of farming systems within the command area of a limited number of watercourses is first investigated through the development of a farm typology (Section 5.2). Then, theoretical issues related to the development of micro-economic models are presented (Section 5.3), before describing their application to the development of farm group models for the eight sample watercourses of the Fordwah and Azim distributaries (Section 5.4), and the calibration and validation of these models (Section 5.5.). Finally, the analysis of the diversity of watercourses for the Fordwah and Azim distributaries is presented (Section 5.6). The end-product of this analysis is a classification of watercourses that, combined with the economic models developed for the eight sample watercourses, leads to the development of economic models for all watercourses off-taking from the Fordwah and Azim distributaries.

5.2 Analyzing the diversity of farming systems and building the farm typology

General issues related to the development of farm typology

In social sciences, because objects are highly singular, it is not possible to reach a high level of generality without using a classification or typology (Perrot and Landais, 1993a). Classifying groups of observations or individuals that have common characteristics is by essence part of the scientific approach that makes different objects comparable, but leaves their particularities intact.

The main objective of a farm typology is to identify homogeneous groups and provide a basis for extrapolation of research results or recommendations. Broadly speaking, typologies can be applied for research purposes, for development purposes, or a combination of both. For researchers, the typology provides a frame for the analysis of farming systems, and a possibility to extrapolate research results obtained for a limited number of representative individuals to larger areas and populations. In the context of development interventions, the typology provides a good picture of the local diversity required to guide development interventions. It also supports the identification of reference farming practices by working with a few farmers, and the dissemination of improved practices more adapted to the heterogeneity of a larger farm population (Perrot and Landais, 1993a). Although diversity is often seen as an obstacle to modernization, its importance is increasingly recognized as it improves the adaptation capability of a given area to a large range of interventions.

Different methods have been proposed for developing a farm typology. Broadly speaking, one may distinguish two approaches that stress the differences between research and development. The first method is based on an *a-priori* selection of variables that describe farming systems. Information on these variables is collected through a farm survey and statistical techniques are applied to some of these variables to build a typology. The second method is based on a more dynamic and participatory process. Interviews of key informants are undertaken to identify variables and farm strategies that are seen as relevant to a typology (Perrot and Landais, 1993b). Farm level information is then collected and statistical analysis is performed to allocate each farm to these pre-identified strategies. The results obtained are then discussed with key informants for the identification of new strategies and data analysis in an iterative manner.

The second method is seen as more transparent as constant interactions take place with various actors (Perrot and Landais, 1993b). The involvement of actors in the development of the typology leads to a better appropriation of typology results and facilitates their use in extension and development interventions. However, a large number and diversity of key informants is required. Also, as the method is resolutely targeted towards intervention, it may create inappropriate expectations if applied in a purely research context. Also, differences between the two methods in terms of the typology results may be rather similar if the *a-priori* variable selection involves local expert knowledge, analysis of secondary information, and discussions with farmers.

An important issue in the development of a farm typology is the selection of variables that will be used to differentiate farms and classify them into homogeneous groups. A diversity of information can be used, such as farm structure, technical practices, agricultural output, future farmer's projects and plans. Often, however, structural variables only are selected for the development of a farm typology as these variables are expected to fully explain production choices and agricultural output of a farm (Boussard, 1987). It is important to stress that the selection of variables remains subjective and linked to the final use of the typology results. A typology developed on structural variables and static characteristics, or so-called *extracted typology* (Perrot and Landais, 1993a), will have a limited use for development interventions as variables related to the farm history, spatial location and future plans in terms of investments, or potential successor, have been omitted. Moreover, results of an extracted typology will be less robust as they will be sample dependent.

Another issue relates to the number of classes obtained from the classification procedure. This number remains arbitrary and is to be specified. The final number of types represents a compromise between diversity, precision level, time for model computation, and development of typology. Eventually, one has to choose between minimizing intra-group variability and limiting the number of groups identified. The number of groups should not be too small as differences between groups become too obvious and the typology does not provide any extra information or element for analysis and understanding. At the same time, the number of groups should not be too large as it becomes difficult to use typology results. Also, each group would rapidly be represented by samples that are too small. Although 6 to 20 groups is seen as acceptable, preference is given to typologies of 8 to 15 groups, independently of the size of the population analyzed (Perrot and Landais, 1993a).

Selection of variables to build the farm typology for the eight sample watercourses

The development of a farm typology in the present study was undertaken for two objectives:

- The farm is a complex object defined by a high number of elements and complex interactions between these elements. Thus, the typology helps to better understand farming systems in terms of the interrelationships between characteristics, constraints and production strategies; and,

- The typology helps to reduce the number of individuals that need to be analyzed in details, and facilitates the extrapolation of results from these individuals to their corresponding farm group. Based on the typology results, representative farms are selected for each group and monitored for two seasons. The information collected is used to build economic models that will be applied to each farm group as a whole.

The absence of clear development objective in the present research, along with the limited availability of key informants and experts on farming systems in the study area, has led to selecting the first typology method described above with an *a-priori* selection of farm variables for which information is to be collected. Analysis of farm level information collected in previous farm surveys, discussions with field staff having significant experience in dealing with irrigated agriculture and farmers in the area, and informal discussions with farmers, led to the identification and selection of variables required to describe farming systems in the area. Farm level information was collected in the eight sample watercourses selected along the Azim and Fordwah distributaries through a formal farm survey undertaken in September 1993. All the farmers of the eight sample watercourses (total of 278) were interviewed using a formal questionnaire that investigates farm characteristics, farming and irrigation practices, constraints on agricultural production, and participation in water markets.

A typology based on variables describing fixed farm production factors has been undertaken. The main assumption behind this choice is that crop choices and agricultural practices can be deducted from a good description of farm assets, farmer's attitudes towards risk, and physical environment (Boussard, 1987). As economic models will be developed for representative farms and then used for the group with aggregated farm resources, it is important that farms of a same group have the same strategy and risk aversion (Palacio et al., 1995). Also, fixed production factors such as labor, land, and (surface) water are to be homogeneous or proportional between farms of a same group to limit aggregation bias while building economic models for farm groups (Day, 1963).

As a result, variables describing farm agricultural output, such as crop yields or cropping pattern, could have been ignored in the development of the farm typology. In practice, however, a limited number of output variables were considered while building the typology. Cotton and crop yields were used as aggregated proxy for soil fertility. And the diversity of crops was selected to provide an insight into risk-aversion. Thus, the variables that have been used for the development of the farm typology are (Rinaudo, 1994):

- *Farm characteristics*: owned area, land tenure status, family labor, tractor and oxen ownership, and tubewell ownership;

- *Physical environment*: importance of salinity, with cotton and wheat yields used as a proxy for soil and irrigation water quality;
- *Access to water resources*: tubewell ownership, and adequacy indicator for canal water supply at the farm level; and,
- *Risk aversion*: number of crops in the cropping pattern used as an indicator of risk aversion.

As it is difficult to obtain information on canal water supplies through farmer's interviews, the adequacy indicator for canal water supply at the farm level was obtained through an independent data collection effort. Direct measurements of daily water levels for the period May 1992 to April 1993 were used to compute daily watercourse head discharges, using a calibration formula developed for each outlet. These discharges were averaged for the Kharif 1992 season, and divided by the respective design discharge of each outlet to obtain a seasonal Delivery Performance Ratio (DPR), a dimensionless indicator of *canal water supply adequacy* comparing actual supplies to design at the head of each watercourse (Kuper, 1997). This adequacy indicator was then transformed into a farm level adequacy indicator taking into account the distance from the watercourse head to the farm and seepage losses long the watercourse.

Classification method and results

To classify farms into farm groups or types, a cluster analysis method was selected and applied using the Cluster module of the SOLO statistical software (SOLO, 1988). This module uses the K-Means algorithm developed by Hartigan and Wong that divides N observations (farms) with P dimensions (or variables) into K groups (or clusters). The user specifies first the number of clusters (K). Using standardized variables, individual farms are sorted according to their distance to the overall mean (gravity center) of the population. For cluster C with C= 1 to C=K, the $[1 + (C\text{-}1) * N/K]$th farm is chosen as the initial center of the cluster. Then, the algorithm allocates each farm to its closest center, minimizing the square distance between the farm and the cluster center.

As the cluster module of the SOLO software cannot classify observations with missing dimensions, farms with missing variables are eliminated from the cluster analysis. Then, these farms are allocated to the different clusters by discriminant analysis, using the Discriminant module of the SOLO software (SOLO, 1988). Using the information available for each farm, this module estimates the probability that a farm belongs to any of the clusters or groups identified, and allocates each farm with missing variables to the cluster for which the highest probability is obtained.

Totally, nine groups have been obtained through cluster analysis. A second classification was performed based on agricultural production variables to assess the variability of these variables within the nine groups already identified. Two groups presented a large variability in crop yields and area under sugarcane. Farmers located at the head of the Azim and Fordwah distributaries recorded larger areas under sugarcane because of their proximity to the sugar-mill. And farmers located at the tail of the Fordwah Distributary recorded higher cotton and wheat yields as a result of lighter soils in this area.

Farm typology and production strategies

The farm strategies that have been identified through cluster analysis are described below. Group numbers are given to each farm group for simplicity of notation in Table 5.1 that presents selected characteristics of the nine farm groups identified. Production strategies are differentiated by the access to, and integration into, input and output markets, the level of intensification and the level of crop diversification expressed by the importance of crops other than wheat and cotton in the cropping pattern.

- Farms with auto-consumption strategy (Group 1)

The main objective of these farms is to produce wheat for auto-consumption. Limited areas are also grown under cotton mainly to generate limited cash to purchase inputs on the market. Limited assets, important cash flow and credit constraints, and limited access to input and output markets characterize these farms. With 20% of the operated area in the kharif season, fodder has an important position in the cropping pattern. This stresses the importance of livestock as a production activity but also as saving means. As a result of credit constraints, saline fields are not reclaimed and often left uncultivated. Overall, yearly cropping intensity remains low (average 122%). Also, wheat and cotton yields are low and result from salinity problems and low input use. The group is rather heterogeneous regarding canal water supplies. If canal water supplies are too low, part of the family may find job opportunities outside the farm and agriculture becomes a secondary activity.

- Market-oriented farms with cotton specialization
  - *Very small owner-cultivators* with average operated area of 1.5 ha (Group 2). These farms are very often the result of farm fragmentation due to inheritance. However, the joint management of the family resources greatly limits constraints that would have been expected with small landholding. A large number of farmers, for example, are *joint tubewell owners*. Joint tubewell ownership and a *very good canal water supply* allows these farms to maximize the agricultural output per unit area and the total output for the farm. High level of intensification, as illustrated by *cropping intensity of 178%, and very high cotton and wheat yields*, is obtained.
  - *Pure tenants with sharecropping* (Group 3) or *fixed rent arrangements* (Group 4). Although pure tenants along the Fordwah Distributary have smaller operated areas (4.5 ha) than pure tenants along the Azim Distributary (6 ha), their strategies are rather similar with a very high specialization in wheat and cotton production. As a result of perennial canal surface water supplies combined with better soil conditions, Fordwah tenants obtain higher yearly cropping intensities than Azim tenants, and also significantly higher cotton and wheat yields. Good access to groundwater resources is obtained as part of contracts with landowner-tubewell owners.

- Diversification in cropping pattern
  - Medium size farms with an average operated area and *good canal water supply* (Group 5). Farms from this group are rather similar to farms having auto-consumption strategies, with *limited access to input and output markets*. Because of their good canal water supply, however, they are able to cultivate 10% of the area under sugarcane. Yearly cropping intensities are medium (135%), as a result of the competition over surface water resources between sugarcane

and other crops. Also, the *credit constraints* faced by farmers from this group limit their tubewell water purchases.

- Medium size farms (5.9 ha of operated area) with *good canal water supply* and located *close to a sugar mill* (Group 6). As a result of reduced transportation costs from the farm to the sugar mill, 28% of the operated area is planted under sugarcane. Rice is also cultivated but only when the canal water supply is very high. Competition over water and inputs remains important and leads to reduced areas under cotton, wheat and fodder. Thus, the yearly cropping intensity is medium and equal to 138%, while cotton and wheat yields are medium to low.
- Medium size farms (4.4 ha of operated area) with *very low canal water supplies* and low credit constraints (Group 7). With operated areas close to the sample average, but a higher percentage of owned area, these farmers have *invested jointly in tubewells* (usually joint owners are brothers) and often tractors. Around 10% of the operated area is planted under sugarcane, for production of raw sugar (*gur*), to be sold directly on the local market. Rice and salinity tolerant fodder crops have been included in the crop rotation to mitigate *salinity problems* that affect a significant portion of the operated area. Although relatively high levels of inputs are used, cotton and wheat yields remain at a medium level as a result of the poor quality of the soils.
- *Large to very large commercial farms* (Group 8 & 9). With *very good access to formal credit*, large farms are able to invest in *tractors and single-owner tubewells.* The overall objective of these farms is the maximization of the total farm income. Large areas of land are rented-in and count for two-thirds of the total operated area. Also, permanent labor complements family labor. Control over water resources have led to the development of sugarcane cultivation, oilseeds in some cases, and rice when farmers have invested in cheaper electric tubewells. Although there are tubewell owners, the larger farmers of this group (Group 9) face some constraints in tubewell water availability. As a result, they cultivate a smaller portion of the area and record a yearly cropping intensity of 131%, versus more than 150% for farmers with smaller size farms (Group 7). The high level of inputs use leads to very high cotton and wheat yields, with 45 to 60% of the total wheat output being sold on the market.

Table 5.1. Main features of the 9 farm groups of the farm typology for the eight sample watercourse command area of the Fordwah and Azim distributaries. The value ½ in the *Tractor owner* and *Tubewell owner* rows means that both owners and non-owners of the tubewell or tractor may be found in the concerned farm group.

Variable	Gr. 1	Gr. 2	Gr. 3	Gr. 4	Gr. 5	Gr. 6	Gr. 7	Gr. 8	Gr. 9
Operated Area (ha) (=OA)	3.5	1.5	4.5	6	4.3	5.9	4.4	8.2	42.6
Area owned (% of OA)	77	88	30	27	47	31	75	69	50
Saline area (% of OA)	47	3	6	15	7	9	33	10	13
Tractor owner	No	No	No	No	No	No	½	Yes	Yes
Tubewell owner	No	½	No	No	No	No	Yes	Yes	Yes
Yearly cropping intensity (% of OA)	122	178	154	140	135	138	145	155	131
Sugarcane (% of OA)	4	7	6	7	10	28	10	12	11
Rice (% of OA)	0	0	2	0	0	11	8	0	4
Cotton yield (t.ha^{-1})	0.6	1.7	1.8	0.8	0.9	1.2	1.1	1.4	1.7
Wheat yield (t.ha^{-1})	1.4	2.7	2.7	1.6	1.4	1.3	1.7	2.1	2.0
Wheat sold (% of production)	15	25	40	30	20	10	30	45	60

Socio-economic profiles for the eight sample watercourses

Table 5.2 presents the relative importance of the farm groups in terms of area cultivated in each sample watercourse. The vector of percentages obtained for the nine groups for each watercourse is defined as the *socio-economic profile* of the watercourse.

Table 5.2. Relative importance of different farm groups for the eight sample watercourses of the Fordwah and Azim distributaries, expressed as a percentage of the total Culturable Command Area (CCA) of each watercourse.

Group	Fordwah Distributary				Azim Distributary				Total
	FD14	FD46	FD62	FD130	AZ20	AZ43	AZ63	AZ111	
1	18	0	0	0	1	0	0	0	3
2	2	3	3	6	0	4	0	0	2
3	12	10	9	60	3	0	0	0	11
4	0	20	0	0	9	26	19	8	10
5	33	56	44	9	0	0	4	0	18
6	3	3	0	6	65	4	1	0	7
7	0	0	0	3	0	16	7	28	7
8	32	8	37	11	0	20	0	0	13
9	0	0	7	5	21	30	69	64	29
Total	100	100	100	100	100	100	100	100	100

The values presented in Table 5.2 stress the socio-economic differences between the farm population in the Fordwah and Azim distributaries. Group 3, Group 5 & Group 8 are mainly "Fordwah" farm groups, while Group 4, Group 6, Group 7 and Group 9 are predominantly located in the Azim watercourses. On average, Fordwah watercourses host a more diverse farm population, while Azim watercourses are often polarized between two farm groups that occupy 85 to 90% of the watercourse command area. Also, Table 5.2 highlights the importance of considering farming systems at disaggregated scales such as the watercourse. Group 1, for example, occupies only 3% of the aggregated command area of the eight sample watercourses. However, this group occupies significant areas in FD 14, and thus is to be considered in the analysis of water markets and agricultural production in these watercourses. Moreover, Group 1 is composed of farms with small land-holdings and represents around 6% of the total farm population.

Summary

A farm typology is developed to analyze the main production strategies and farm constraints in the command area of the eight sample watercourses of the Fordwah and Azim distributaries. Nine farm groups have been identified. The socio-economic profile, that provides the percentage of the watercourse command area under each farm group that will be used to build the aggregated watercourse economic models, are developed for the eight sample watercourses. The following two sections present selected theoretical issues related to the development of stochastic linear programming farm models (Section 5.3), and their application to the case of the nine farm groups of the farm typology (Section 5.4).

5.3 Theoretical considerations on micro-economic linear programming models

5.3.1 General issues related to farm decisions and agricultural production

Farmers are central to the analysis of water markets and the link between water and agricultural production. For a given canal water supply, farmers specify their crop port-folio in terms of the types of crops and the area under each crop, decide on the quantity of tubewell water required to complement canal water; and allocate canal water and tubewell water to different crops. To model these decisions, five important assumptions are made:

- Farmers have a *rational behavior* and develop a specific strategy to meet their objectives under a given set of constraints. As a result, farming practices and farmer's decisions can be formalized into a set of rules that link farm production constraints, technical production coefficients, and farm objective(s);

- *Multiple farm objectives* is the norm rather than the exception as a result of the integration of farm activities into a broader household perspective (Ellis, 1989). Although profit maximization remains the principal objective, other objectives such as risk minimization, auto-consumption and income stability are considered in order to understand farm decisions and their outcome;

- *Planning decisions* are investigated in the micro-economic models that have been developed for the present research. These decisions are taken prior to the period considered, whether the season or the year, and are based on expectations of future events. These expectations are themselves based on the farmer's past experience, the past experience of neighboring farmers, and the farmer's (limited) knowledge of possible changes that may take place for the coming season or year, or any other time period considered for taking farm decisions;

- It is assumed that farmers are themselves in a situation of *equilibrium* that makes the past experience valid and applicable for the coming planning period. The analysis of farmers' decisions resulting from the development of water markets will also assume that farmers are in an equilibrium situation and have a similar knowledge about the availability of water resources, and the conditions of their socio-economic and physical environment; and,

- Agriculture is a risky business that suffers from variability in specific variables of the environment, whether physical (for example rainfall) or economic (for example changes in prices). Rational decisions taken by farmers consider this *variability* or *risk in planning decisions*. This does not alter the notion of anticipation that has been mentioned above. Farmers' decisions are then based on their knowledge about future states of nature and the probability of each of these states (Hazell and Norton, 1986; Boussard, 1980).

Linear Programming (LP), and more specifically *Stochastic Linear Programming* (SLP), has been selected as the modeling approach to develop micro-economic models to analyze existing and potential water markets in the Chishtian Sub-division. Quadratic relationships, such as the relationships between water and crop yield, or estimates of the variance of the income, are linearized. In fact, these linearisations are expected to provide results comparable to quadratic programming as demonstrated by Hazell and Norton (1986) in a particular case study.

5.3.2 Theoretical considerations on linear programming and risk

General structure of a linear program

Micro-economic modeling is based on the maximization of a utility function U given by the following equation.

$$U(X) = f(X_1,...,X_n) \text{ for } X = \{X_1,...,X_n\}, \text{ domain of possible activities} \qquad \textbf{(5.1)}$$

Activities considered by farmers at the planning stage include the relative importance of various crops in the cropping pattern, the sale and purchase of agricultural outputs, and the sale and purchase of inputs required to obtain a given level of agricultural production on the farm. The choice of farm activities is constrained by the fact that the activities selected need to be physically possible (i.e. total input use lower than input availability), and the need to consider specific farm strategies and constraints, such as the need to implement crop rotations to deal with soil salinity.

Further assumptions are required for building linear programming models. Activities are to be continuous variables, additive and proportional (i.e. to have a constant marginal value product of the activity with regards to the inputs considered). Under such assumptions, the utility function becomes linear for the activities considered (Hazell and Norton, 1986). Also, the constraints are assumed to be linear. Under such conditions, the linear program can be written in its matrix form as:

Objective

$$\mathit{Max}\ \mathbf{UX} \qquad \textbf{(5.2)}$$

Under the constraints

$$\begin{aligned} &\mathbf{AX} \le \mathbf{B} \\ &\mathbf{X} \ge \mathbf{0} \end{aligned} \qquad \textbf{(5.3)}$$

where (dimensions of the matrices and vectors are specified in brackets)
U = utility function (1,n);
X = matrix of activities (n,1);
A = matrix of technical coefficients (n,m) that relate the level of activities to constraints; and,
B = matrix of constraints (m,1).

Specific methods have been developed to solve this linear optimization problem and identify its optimal solution, if any. The most well known method is based on the algorithm of the simplex (for a clear description of the mechanism of this simplex method, see Hazell and Norton, 1986). The utility function and constraints being linear, the existence of a solution is ensured under specific conditions of closed domains. In all cases, however, a unique solution (if any) is ensured. The resolution of the optimization problem is more complex when risk is considered in the optimization problem, mainly as a result of the non-linearity of risk-related parameters and constraints. Solutions that have been developed to include risk into linear programming models are detailed below.

Risk in the objective function

Risk may be considered for parameters included in the objective function, in the matrix of technical coefficients or in the matrix of constraints. To include risk in the objective function means that the farmer maximizes his utility which outcome is stochastic once activities have been selected. Thus, a choice of activities based on an average situation will not be adapted (Bouzit et al., 1993). With the assumption that farmers maximize their expected utility, a widely used model is the *Mean-Variance* or E,V model (Hazell and Norton, 1986). For a utility function expressed as a function of the farm revenue, R, and defined by Equation (5.4),

$$U(R) = 1 - e^{-\beta R} \qquad \textbf{(5.4)}$$

the expected utility can be written as a combination of the mean revenue, $E(R)$, and the standard deviation of the revenue, $\sigma(R)$, if R is normally distributed such as:

$$E(U(R)) = E(R) - \frac{1}{2}\beta\sigma^2(R) \qquad \textbf{(5.5)}$$

Using similar assumptions and concepts closely related to the E,V model, Hazell and Norton (1986) proposed the *Mean-Standard Deviation* or E,σ model. This model, based on the work about the gain-confidence limit criteria proposed by Baumol (1963), has the following expected utility function if the revenue is normally distributed:

$$E(U(R)) = E(R) - \phi.\sigma(R) \qquad \textbf{(5.6)}$$

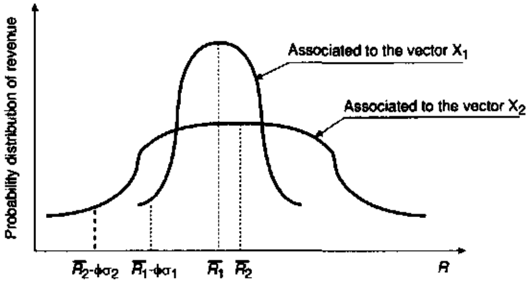
where ϕ is a risk-aversion coefficient for the farm considered.
The cumulative function Θ of the centered reduced normal distribution $p(x)$ is now introduced and defined as:

$$\Theta(b) = P(x \leq b) = \int_{-\infty}^{b} p(x).dx \;, \forall \text{b} \qquad \textbf{(5.7)}$$

Using this function, the probabilistic meaning of the risk aversion coefficient, ϕ, can be given: $E(R) - \phi.\sigma(R)$ is the value of the revenue R that has the probability $\Theta(-\phi)$ of being obtained. For example, for $\phi = 1.65$, the probability is equal to 0.95 or 95%, equivalent to the value obtained for a one-tail confidence test on the centered reduced normal distribution.

Figure 5.2 illustrates the choices made by a farmer between two vectors of activities $\mathbf{X}_1$ and $\mathbf{X}_2$, each one associated with a mean revenue $\overline{R}_i$ and a standard deviation of the revenue σ_i.

Figure 5.2. Probability distribution of revenue for two different vectors of activities $\mathbf{X}_1$ and $\mathbf{X}_2$.



Although the mean revenue $\overline{R}_1$ for the vector of activities $\mathbf{X}_1$ is lower than the mean revenue $\overline{R}_2$ for the vector of activities $\mathbf{X}_2$,the farmer will select $\mathbf{X}_1$ as it will provide the higher revenue that he can expect $(\overline{R}_1 - \phi\sigma_1 > \overline{R}_2 - \phi\sigma_2)$ with a given level of probability determined by his risk-aversion coefficient ϕ .

With a revenue that is a linear function of $\mathbf{X}$, the standard deviation term in the objective function is most often quadratic. Hazell (1971) proposed using the Mean Absolute Deviation (MAD) as an appropriate linear approximation of the variance or standard deviation term. This approximation is used when chronological series or cross-sectional information is available for the stochastic terms. For the mathematical demonstration of the approximation, see Hazell (1971) and Belouze (1996). Based on an empirical example, Hazell and Norton (1986) show that the linear approximation of the MAD for the variance provides optimization results similar to the use of a quadratic function.

Risk in the constraints and technical coefficients

For risk in the constraints and technical coefficients, the farmer specifies a minimum threshold for which the constraints are to be realized when taking his decisions. Based on Charnes and Cooper (1959), the program can be rewritten by including probabilistic terms into the constraint equations as presented below:

Objective

$$Max\ \mathbf{UX} \qquad \textbf{(5.8)}$$

Under the constraints

$$P(\tilde{\mathbf{A}}\,\mathbf{X} \leq \tilde{\mathbf{B}}) \geq \alpha \qquad \textbf{(5.9)}$$
$$\mathbf{X} \geq \mathbf{0}$$

where (dimensions of the matrices in brackets)

α = matrix of probability thresholds for the realization of constraints as specified by the farmer (1,m), the equality $\alpha_i = 1$ means that the i^{th} constraint is deterministic, and the "~" sign is used for matrices of stochastic parameters and coefficients.

The constraint specifies that the total requirements for the i^{th} resource should not exceed its supply more than α percent of the time (Hazell and Norton, 1986). As for the inclusion of risk in the objective function, the constraints are not linear. With the assumption that the stochastic terms are normally distributed, the same linear approximation of the MAD can be developed. This approximation will also have a risk aversion coefficient that will increase with the risk aversion of the farmer and his willingness to respect his constraints. The risk aversion coefficient will lead to a security margin for each constraint that the farmer selects when choosing his activities

5.3.3 General form of a stochastic linear programming model

Using the approximation of the MAD for the objective and constraint functions, the following general structure of the stochastic linear programming model is obtained.

$$Max\ \overline{\mathbf{U}}\mathbf{X} - \phi\hat{\sigma} \qquad (5.10)$$

Under the following constraints

- Inclusion of risk in the objective function

$$\sum_j ((U_{j_t} - \overline{U_j})X_j) + D_t^- \geq 0 \quad \forall t \in \{1..T\} \qquad (5.11)$$

$$\frac{2F}{T}\sum_{t=1}^{T} D_t^- = \hat{\sigma} \qquad (5.12)$$

$$D_t^- \geq 0 \qquad (5.13)$$

- Deterministic constraints

$$\mathbf{A}_1\mathbf{X} \leq \mathbf{B}_1 \qquad (5.14)$$

- Stochastic constraints

$$\mathbf{A}_2\mathbf{X} + \phi_2\sigma_2 \leq \overline{\mathbf{B}}_2 \qquad (5.15)$$

- Stochastic technical coefficients

$$\overline{\mathbf{A}}_3\mathbf{X} + \phi_3\hat{\sigma}_3 \leq 0 \qquad (5.16)$$

$$\sum_{j}((A_{3_t}-\overline{A}_3)X_j)+D^-_{3_t}\geq 0 \quad \forall t=1..T_3 \tag{5.17}$$

$$\frac{2F}{T_3}\sum_{t=1}^{T_3}D^-_{3_t}=\hat{\sigma}_3 \tag{5.18}$$

$$D^-_{3_t}\geq 0 \tag{5.19}$$

where

$\overline{\mathbf{U}}$ = mean utility vector of stochastic utility vector in the objective function $\widetilde{\mathbf{U}}$;

$\mathbf{X}$ = column vector of activities $\left\{X_1,\dots,X_n\right\}$;

ϕ = risk-aversion coefficient in the objective function;

$\hat{\sigma}$ = estimated standard deviation of utility equal to $\sqrt{\text{MAD}}$ at the optimum;

$F=\sqrt{\dfrac{T\pi}{2(T-1)}}$ a *Fisher coefficient* for the objective function with T being the number of observations of the stochastic utility vector $\widetilde{\mathbf{U}}$;

U_{j_t} = the t^{th} observation of the j^{th} component of vector $\widetilde{\mathbf{U}}$ and $\overline{U}_j$ the mean of this j^{th} component;

$\mathbf{A}_1$ = matrix of deterministic technical coefficients associated to deterministic constraint vector $\mathbf{B}_1$;

$\mathbf{A}_2$ = matrix of deterministic technical coefficients associated with stochastic constraint vector $\widetilde{\mathbf{B}}_2$ with mean $\overline{\mathbf{B}}_2$ and standard-deviation σ_2;

ϕ_2 = vector of risk aversion coefficients associated with stochastic constraint vector $\widetilde{\mathbf{B}}_2$ (with $\phi_{2_i}=\Theta^{-1}(\alpha_i)$ and α_i the probability threshold to meet constraint $\hat{\mathbf{B}}_{2_i}$);

$\widetilde{\mathbf{A}}_3$ = matrix of stochastic technical coefficients associated with deterministic vector constraint $\mathbf{B}_3$;

$\overline{\mathbf{A}}_3$ = matrix of means of matrix of stochastic technical coefficients $\widetilde{\mathbf{A}}_3$;

$\hat{\sigma}_3$ = matrix of estimated standard-deviations of matrix of stochastic technical coefficient $\widetilde{\mathbf{A}}_3$;

ϕ_3 = vector of risk aversion coefficients associated with stochastic matrix $\widetilde{\mathbf{A}}_3$ (related to probability threshold α_i and the Θ function as explained above);

$F_3=\sqrt{\dfrac{(T_3+k_3+1)(T_3+1)\pi}{2T_3(T_3-1-k_3)}}$ a *Fisher coefficient* with k_3 being the number of elements in the stochastic matrix $\widetilde{A}_3$ and T_3 the number of observations for each element; and,

$\mathbf{A}_{3_t}$ = the t^{th} matrix of observations of matrix of stochastic technical coefficients $\widetilde{A}_3$.

$D^-_t, D^-_{3_t}$ = Intermediary terms, equal to the differences between observation t and the mean of the chronological series available for these observations, for the stochastic components of the utility vector and for the technical coefficients, respectively.

5.4 Development of stochastic linear programming models for farms in the Chishtian Sub-division

Stochastic linear programming models have been developed for each of the nine farm groups identified by the farm typology and described in Section 5.2. As specified above, the models investigate planning decisions taken by farmers at the beginning of the year, or season, regarding the crop portfolio that will be grown on the farm, as well as the quantity of tubewell water required to complement canal water supplies. Emphasis is given to water related constraints in the models, as the models will be used to investigate the impact of changes in water related parameters, such as quantities and prices, on farmer's decisions.

Selecting activities to build the stochastic linear programming models

The main activities that are considered by the micro-economic models include:

- *Type of crops*. For the kharif season, farmers can choose between cotton, rice, sugarcane (annual crop) and fodder. While farmer's choices for the rabi season include wheat, sugarcane (annual crop) and fodder. Wheat is partly used on the farm for household consumption, but may be sold if there is surplus.

- *Farming and irrigation practices for wheat and cotton.* Based on expectations in canal water supply and access to tubewell water resources, farmers may plan to shift the sowing date and apply various quantities of irrigation water on crops. Both practices will have an impact on crop yields. For the date of sowing, choices are to be made between three possible dates for wheat and cotton. And farmers may choose between three different options of water stress for wheat and cotton, i.e. 100%, 80% and 60% of the crop water requirements.

- *Access to output markets*. Cotton, rice and sugarcane are solely sold on the market, while kharif fodder and rabi fodder are used on the farm for livestock. Wheat is mainly grown for home consumption. In case of a surplus in wheat production, however, wheat will be sold on the market.

- *Access to input markets*. Input uses are fixed for every crop activity considered and do not require specific input purchase activities. However, input use will indirectly influence farmers' decisions as they are accounted for in the gross margins included in the objective function (see below). The only input use that is left to farmers' decisions in the stochastic linear programming models is the monthly quantity of tubewell water used on the farm, whether from the farmer's own tubewell at given operation and maintenance costs, or purchased from other tubewell owners at a given price. For tubewell owners, the sale of tubewell water is also an activity to be considered that may compete with tubewell water use on the farm.

Deterministic terms of the objective function

The stochastic linear programming model maximizes the gross income at the farm for crop related activities. The gross income is defined as the difference between the total gross output of production and total variable costs. The objective function is defined as presented below:

$$\text{Max} \quad \begin{array}{l} \left[\sum_{i \in I} (gm_i X_i) + p_{w_s} W_s + p_{TW_s} \sum_t TW_{s_t} \right] \\ - \left[\sum_{j \in J} (tvc_j X_j) + p_{w_p} W_p + p_{TW_p} \sum_t TW_{p_{tt}} + p_{TW} \sum_t TW_t \right] \end{array} \qquad \textbf{(5.20)}$$

where

I = Ensemble of cash crops that will be sold on the market with a gross margin gm_i (Rs.ha^{-1});

X_i = area (ha) under cash crops;

W_s = quantity (kg) of wheat sold in the market at price P_{w_s} (Rs.kg^{-1});

TW_{s_t} = quantity (m^3) of tubewell water sold per month ($t \in \{Jan, Feb, ..., Dec\}$) at price p_{TW_s} (Rs.m^{-3}). This activity is not considered while building the individual or group models but is integrated in each tubewell owner model in the watercourse-based economic models;

J = ensemble of crops primarily used on the farm, and cultivated using various inputs that amount for total variable costs per unit area tvc_j (Rs.ha^{-1});

X_j = area (ha) under crops primarily used on the farm;

W_p = quantity (kg) of wheat purchased on the market at a price p_{w_p} (Rs.kg^{-1});

TW_{p_t} = quantity (m^3) of tubewell water purchased per month ($t \in \{Jan, Feb, ..., Dec\}$) at a price p_{TW_p} (Rs.m^{-3}); and,

TW_t = quantity (m^3) of tubewell water used per month ($t \in \{Jan, Feb, ..., Dec\}$)on the farm and pumped from own tubewell at a price p_{TW} (Rs.m^{-3}).

The gross margin of a crop that is used in the objective function is obtained by multiplying the crop yield by the price of the product, and subtracting all variable costs related to input use and farming practices. As specified above, the only variable costs that are not included in the computation of the crop gross margin are tubewell operation or purchase costs, as they are specified as separate activities in the objective function.

In practice, farm models will either include TW_{s_t} and TW_t if the farm group considered is composed or tubewell owners, or TW_{p_t} if the group is composed of non-tubewell owners relying on tubewell water purchases. This is a simplification of the reality, as illustrated by farmers with large land holdings that are often tubewell owners and tubewell water purchasers. Also, farmers sometimes purchase tubewell water at different prices from two or more tubewell owners. This possibility has not been included in the objective function of the models.

Deterministic elements of constraints

The activities selected by the farm models cannot take any value as they have to satisfy the various constraints faced by farmers. These constraints are described below.

- Land constraints

The first land constraint specifies that the total area cultivated is lower than the total operated area of the farm, and this for any period of the year. No difference is made between area operated and area rented-in for farmers that combine both types of tenure. Investigation of land markets in the Chishtian Sub-division has shown that farmer's operated area in the medium term can be considered as a fixed constraint. The sale and purchase of land is very rare, and the lease of new areas is possible but limited. The following inequality is included in the models:

$$\sum_{k\in K} X_k \leq A_{op} \qquad \textbf{(5.21)}$$

where

$\{X_k\}_{k\in K}$ = area (ha) under crops grown during the period k considered; and,

A_{op} = total operated area (ha) of the farm.

The periods k considered include the kharif season, the rabi season, the month of November, the month of December and the month of May. The last three periods have been included to take into account the possible competition between cotton and wheat crops during the inter-season. For example, farmers often extend cotton harvest to obtain higher cotton yield, thus delaying wheat sowing as a result of competition over land. This has eventually a negative impact on wheat yields.

As the objective function considers only the total variable costs of rabi and kharif fodder crops, a minimum area under fodder is required for both seasons. Thus, the following equation is included in the model for both the kharif and rabi fodder crops:

$$\sum_{i} F_{i_k} \geq Fod_{\min_k} \qquad \textbf{(5.22)}$$

where

F_{i_k} = area (ha) under a given type of fodder during the season k (rabi, kharif); and,

$Fod_{\min_i}$ = minimum area (ha) required under fodder for the season k (rabi, kharif).

- Water constraint

Obviously, quantities of water required to grow the chosen cropping pattern are to be lower than quantities of water available on the farm. Water availability depends on canal water supplies and access to tubewell water, whether their own tubewell water or purchased tubewell water. The analysis of irrigation practices and farmers' decisions has shown that seasonal values of supply of, and demand for, irrigation water are not specific enough to identify water constraints and bottlenecks that will affect farmer's decisions and agricultural production (Pintus, 1995; Meerbach, 1996). As farmers irrigate their crops roughly once a month, the month is selected as the temporal unit to specify water constraints. The following monthly inequalities are then included into the farm models:

$$\sum_{i}(iwr_{i_t} X_i) - TW_t - TW_{p_t} \leq cws_t \quad \forall t \in \{Jan,Feb,...,Dec\} \qquad \textbf{(5.23)}$$

where

X_i = area (ha) of crops selected in the cropping pattern;

iwr_{i_t} = irrigation water requirements ($m^3.ha^{-1}$) for crop i and month t, $t \in \{Jan,Feb,...,Dec\}$; and,

cws_t = canal water supply (m3) available at farm for month t, $t \in \{Jan,Feb,...,Dec\}$.

Although farmers may allocate preferentially canal water of good quality to some crops and plots, this decision is not integrated into the present farm stochastic linear programming model. Canal water supply and tubewell water use are computed at the farm level and aggregated for each crop, without distinguishing the relative importance of each source of water for different crops.

In some watercourses, a specific constraint has been added that limits tubewell water use during the sowing period of wheat. This translates into the farmers' strategy for limiting the use of tubewell water of poor quality, as it affects negatively the germination process and thus crop yields. This constraint specifies a maximum value for the ratio between tubewell water use and total water use on the farm. Also, monthly tubewell water use constraints have been defined for some farm groups and watercourses.

- Labor constraint

A rapid appraisal was conducted in the Chishtian Sub-division to investigate the functioning of the labor market and the possibility of a labor shortage during periods with peak labor requirements. Farmers, however, did not identify labor shortage as a major constraint. Thus, it is assumed that labor is not a constraint for the farms considered under the existing situation. However, a counting variable was included in the models to compute yearly labor requirements at the farm, which offers the possibility for monitoring the impact of interventions and changes in model parameters on labor use.

- Multiple farm objectives

Although the maximization of the farm gross income is an important objective for farmers in the studied area, it is not the only one. Other objectives that are specified in the farm models include the need to obtain a minimum gross income each year to be able to pay or reimburse for household expenditures and fixed production costs, or producing wheat for auto-consumption to be able to feed members of the family from the farm's own production. Also, the minimization of risk is an important objective that has been included in the model that is further detailed below.

The minimum gross income inequality is specified as follow:

$$\left[\sum_{i\in I}(gm_i X_i) + p_{w_s} W_s + p_{TW_s}\sum_t TW_{s_t}\right] - \left[\sum_{j\in J}(tvc_j X_j) + p_{w_p} W_p + p_{TW_p}\sum_t TW_{p_{tt}} + p_{TW}\sum_t TW_t\right] \geq R_{\min} \quad \textbf{(5.24)}$$

where

$R_{\min}$ = minimum gross income (Rs) for the farm; and,

Other variables are defined as for Equation 5.20.

The minimum quantity of wheat required for household needs is taken into account with the following inequality.

$$\sum_j X_j Y_j + W_p - W_s \geq W_{req} \quad \textbf{(5.25)}$$

where

X_j = area (ha) under wheat *j* defined by specific sowing date and irrigation application;

Y_j = wheat yield (kg.ha^{-1}) for wheat *j*; and,

W_{req} = total yearly wheat requirements (kg) for the farm household.

Finally, as specified in the general form of the linear programming model, all activities that are considered in farm decisions are to be positive. Thus, the following inequalities complement the constraint inequalities presented above:

$$X_i \geq 0 \quad \forall i \in \{X_1 \ldots X_n\} \quad \textbf{(5.26)}$$

where

X_i = quantity of activity *i* selected by the model, $\forall i \in \{X_1 \ldots X_n\}$ ensemble of all possible activities.

Taking into account risk in farm models

Risk that is included in the stochastic linear programming models developed for farmers in the Chishtian Sub-division relates to the variability in monthly canal water supplies received at the farm gate, the variability in wheat yields, and the variability in cotton gross margins. These different components of risk are discussed below and formalized for integration into the stochastic linear programming models.

- Variability in canal water supply

As highlighted by several studies, canal water supplies received by farmers in the Chishtian Subdivision and the eight sample watercourses of the Fordwah and Azim distributaries are highly variable within the month (Kuper and Kijne, 1992; Hart, 1996; Kuper, 1997). With four canal water turns on average per months, farmers may receive high or low canal water supplies according to the watercourse head discharge at the time of their canal water turn. Thus, it is assumed that farmers consider the variability in canal water supply to select their cropping pattern. And the importance given to this variability in the planning process is expected to be influenced by farmers' risk-aversion and control over groundwater resources. The formalization of the monthly water constraints to account for the variability in canal water supplies is given below.

$$\sum_{i}(iwr_{i,t}.X_i) - TW_t \leq cws_t - \phi_{cws_t}.\sigma_{cws_t} \quad \forall t \in \{Jan, Feb, ..., Dec\} \qquad \textbf{(5.27)}$$

where

σ_{cws_t} = standard deviation of canal water supply (m^3) for month t, $\forall t \in \{Jan, Feb, ...Dec\}$;

ϕ_{cws_t} $(= \Theta^{-1}(\alpha_{cws_t}))$ = risk aversion coefficient related to canal water supply for month t, $\forall t \in \{Jan, Feb, ...Dec\}$; and,

Other variables are defined as for Equation 5.23.

- Variability in wheat yields

The variability in wheat yields, as a result of variable climatic conditions and pest attacks, will directly affect the quantity of wheat available for auto-consumption. Thus, modification are required for the wheat yield terms in the left side of Equation 5.25. As explained in Section 5.3, this inclusion of risk involves simplifications in the quadratic terms of yield variances using the method MAD. Chronological series for *T* years are usually used for these simplifications. In the case of the farms investigated in the 8 sample watercourses, such time series were not available, and cross-sectional data is used to approximate the temporal variability of yields as proposed by Hazell and Norton (1986) and further developed in Rinaudo (1994). Following the formalization presented in Section 5.3.3, the MAD approximation that include yield variability in Equation 5.25 is presented below.

$$\sum_{j}\left(\overline{Y}_j X_j\right) + W_p - W_s - \phi_y \hat{\sigma}_y \geq W_{req} \qquad \textbf{(5.28)}$$

$$\frac{2F_y}{N}\sum_{n=1}^{N} D^-_{y_n} - \hat{\sigma}_y = 0 \qquad \textbf{(5.29)}$$

$$\sum_{j}\left(\left(Y_{j_n} - \overline{Y}_j\right)X_j\right) + D^-_{y_n} \geq 0 \quad \forall n = 1...N \qquad \textbf{(5.30)}$$

$$D^-_{y_n} \geq 0 \qquad \textbf{(5.31)}$$

where

X_j = area (ha) under wheat *j* defined by specific sowing date and irrigation application;

Y_j = wheat yield (kg.ha^{-1}) for wheat *j*;

$\phi_y \left(= \Theta^{-1}(\alpha_y)\right) =$ risk aversion coefficient associated with wheat yield;

$F_y = \sqrt{\frac{(N + k_y + 1)(N + 1)\pi}{2N(N - 1 - k_y)}}$ a *Fisher Coefficient* with k_y being the number of stochastic wheat yield terms in the constraint, and N the total number of observations in the sample;

$Y_{j_n} = n^{th}$ observation (kg) in the farm sample of the stochastic variable wheat yield $\tilde{Y}_j$; and,

$\bar{Y}_j =$ mean (kg) of the N observations in the farm sample of the stochastic variable wheat yield $\tilde{Y}_j$.

Unlike Hazell and Norton (1986) that consider different crops with various positive and negative correlations between yields and gross margins of these crops, only wheat with different sowing and irrigation practices is considered in Equations 5.28 to 5.31. As the main causes for yield variability are related to external factors such as unexpected high rains, and virus and pest attacks, two wheat crops differing only by their sowing date and quantity of irrigation applied will have deviations in yields entirely correlated with each other. From a farmer's perspective, if high (low) yields are expected under a given sowing date and irrigation application, then high (low) yields are expected for all wheat crops cultivated under different practices.

As a result, the overall standard deviation of wheat yields for the farm can be approximated with the weighted average of the standard deviations of wheat yields for different sowing dates and irrigation applications (Belouze 1996). A more simple linear combination of the standard deviations of wheat yield for each wheat activity is included in the model (Belouze 1996) and the MAD formulation is not required anymore in the program. This reduces significantly the size of the matrix of technical coefficients, as Equations 5.28 to 5.31 are replaced by Equations 5.32 and 5.33 only.

$$\sum_j \left(\bar{Y}_j X_j\right) + W_p - W_s - \phi_y \hat{\sigma}_y \geq W_{req} \qquad \textbf{(5.32)}$$

$$\sum_j \hat{\sigma}_j X_j = \hat{\sigma}_y \qquad \textbf{(5.33)}$$

where

$\hat{\sigma}_j =$ Standard deviation (kg.ha^{-1}) of wheat yield in the farm sample for wheat j defined by the specific sowing date and irrigation application.

Other variables have the same definition as used for Equations 5.28 to 5.31.

- Variability in cotton gross margins

Only the variability in cotton gross margins is included in the stochastic linear programming models. Variability in gross margins for other cash crops is not considered, as prices are controlled by government policies (rice and sugarcane via control on sugar price), as farmers are expected to closely match crop water requirements with supplies for crops with high water requirements and high total input costs (sugarcane).

The variability in cotton gross margins considered in the models and observed in the Chishtian Sub-division is mainly related to a variability in yields associated with the sensitivity of the crop to pest attacks, and a variability in cotton prices that are highly dependent on the relative balance between the supply and the demand for cotton. Similarly to what has been explained in the case of wheat, the fact that one crop only is considered significantly simplifies the integration of risk and variability in gross margins. The linearization of the MAD is replaced by a single linear equation, which is a combination of the standard deviations of cotton gross margins of the various cotton activities included in the models. Variability in cotton gross margins can have an effect on the minimum revenue constraint, or directly on the objective function constraint. Both formulations are provided below.

a. Gross margin variability in the minimum revenue constraint

$$\begin{aligned}&\left[\sum_{i\in I}(gm_i X_i)+p_{w_s}W_s+p_{TW_s}\sum_t TW_{s_t}\right]\\&-\left[\sum_{j\in J}(tvc_j X_j)+p_{w_p}W_p+p_{TW_p}\sum_t TW_{p_{tt}}+p_{TW}\sum_t TW_t\right]\geq R_{\min}\end{aligned} \tag{5.34}$$

$$\sum_i \hat{\sigma}_{gm_i}X_i=\hat{\sigma}_{gm} \tag{5.35}$$

where

$\hat{\sigma}_{gm_i}$ = standard deviation (Rs.ha^{-1}) for gross margin of cotton i with the specific sowing date and irrigation application and estimated from sample data;

$\hat{\sigma}_{gm}$ = aggregated standard deviation (Rs.ha^{-1}) on the farm for the cotton gross margin; and,

$\phi_{gm}\left(=\Theta^{-1}\left(\alpha_{gm}\right)\right)$= risk aversion coefficient for cotton gross margins in the minimum revenue constraint.

Other variables have the same definition as used for Equations 5.28 to 5.31.

b. Gross margin variability in the objective function

$$\text{Max}\quad\begin{aligned}&\left[\sum_{i\in I}(gm_i X_i)+p_{w_s}W_s+p_{TW_s}\sum_t TW_{s_t}\right]\\&-\left[\sum_{j\in J}(tvc_j X_j)+p_{w_p}W_p+p_{TW_p}\sum_t TW_{p_{tt}}+p_{TW}\sum_t TW_t\right]-\phi'_{gm}\hat{\sigma}_{gm}\end{aligned} \tag{5.36}$$

Under the following constraint

$$\sum_i \hat{\sigma}_{gm_i}X_i=\hat{\sigma}_{gm} \tag{5.37}$$

where

$\phi'_{gm}\left(=\Theta^{-1}\left(\alpha_{gm}\right)\right)=$ risk aversion coefficient for the cotton gross margins in the objective function.

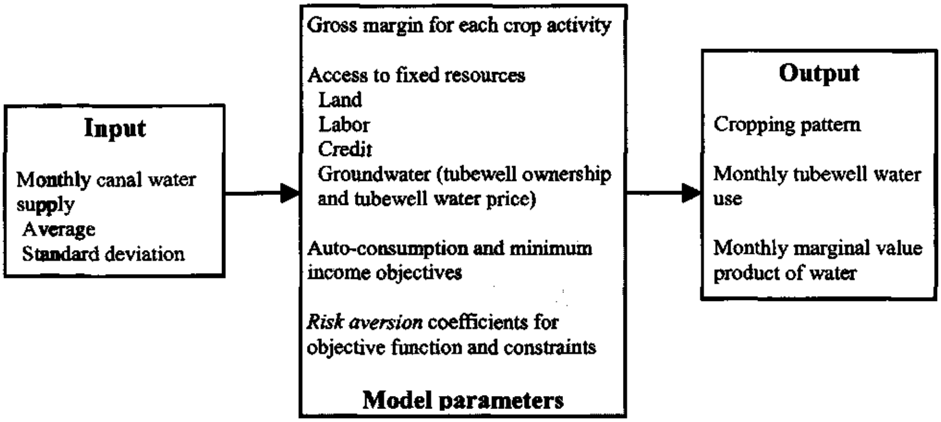
All other variables have the same definition as used for Equations 5.20 and 5.35.

For some farm groups, the variability in wheat yields will be included in the objective function, using a formalism equivalent to the one proposed for Equations 5.36 and 5.37 for the cotton crop.

Summary

Micro-economic models that maximize expected farm gross income under constraints related to land and water are developed. Other objectives, such as auto-consumption for wheat and minimum farm income, are also considered and integrated into the farm models as constraints to the objective function. Specific constraints account for risk related to the variability in cotton gross margins, wheat yields, and monthly canal water supplies. Figure 5.3 summarizes the structure of the stochastic linear programming models developed for each farm group in terms of their input, parameters, and output.

Figure 5.3. Schematic representation of the stochastic linear programming farm models developed for farmers from the eight sample watercourses of the Fordwah and Azim distributaries.



The main outputs of the stochastic linear programming models include the cropping pattern, the monthly tubewell water use, and the Marginal Value Product of water. This Marginal Value Product of water, defined in Section 2.1 as the marginal increase in farm gross income obtained by increasing the canal water allocation by one unit, represents the farmer's willingness to pay for extra canal water supplies. As emphasized in Chapter 3, this Marginal Value Product of water is an important variable for the analysis of the potential for canal water reallocation between farmers and units of the irrigation system.

The equations presented in the previous section form the basic stochastic linear programming model used for the nine farm groups being considered. Differences, however, are kept between models developed for each farm group to account for differences in farm strategies and constraints. Table 5.3 summarizes the choices made for building the models for the nine farm groups.

Table 5.3. Elements considered in building stochastic linear programming models for the nine farm groups identified through the farm typology.

Elements of the model	Choices made for different farm groups	Comments
Proposed activities	All crops included in all models Tubewell water sale and own use for Groups 2, 7, 8 and 9 Tubewell water purchase for Groups 1, 3, 4, 5 and 6	Group differences in final cropping pattern result from the optimization process.
Specific constraints	Saline areas with lower yields included in Groups 1 and 7	
Risk in the objective function	For Groups 1, 3, 4, 7, 8 and 9	Different risk aversion coefficients estimated through calibration
Risk in the matrix of technical coefficients		Different risk aversion coefficients estimated through calibration
Wheat auto-consumption	For Groups 1, 3, 5, 6	
Cotton gross margin	For Groups 1, 2, 6	
Risk in canal water supply	All farm groups	Different risk aversion coefficients estimated through calibration

The following section will present the results of the calibration and validation of the nine farm groups and eight sample watercourse stochastic linear programming models.

5.5 Calibration and validation of the farm and watercourse stochastic linear programming models

Building the farm group and watercourse stochastic linear programming models

Stochastic linear programming models are built for each farm group by aggregating farm resources for all farmers of each group. Appendix 3 presents the information that has been used to build these farm models.

The watercourse stochastic linear programming models are built by adding individual farm group models according to the relative importance of each farm group in the watercourse command area. Specific equations are added to account for commercial links between farm groups and balance tubewell sales with tubewell water purchases at the scale of the watercourse command area. Also, monthly constraints in terms of maximum tubewell water availability are set for each watercourse.

The main elements considered for estimating the maximum tubewell water availability constraint include:

- The total number of tubewells in the watercourse command area;
- Tubewell ownership and the relative importance of joint tubewell owners;
- Total canal water supplies. As tubewell water is often sold using the official canal watercourse, there is a competition between tubewell water sales and canal water use by other farmers. Thus, watercourses with very high canal water supplies would offer less opportunities for farmers to purchase tubewell water; and,
- The maximum number of operating hours, including time for breakdowns, reduced operation during nighttime, and load-shedding periods for electric tubewells.

The large number of elements that influence tubewell water availability makes an estimate of tubewell water constraints difficult. In practice, the elements described above have been considered for estimating a maximum tubewell water availability that has been refined through the calibration process. Tubewell water price is estimated for each watercourse command area, using price information collected through the farm survey for tubewell water purchases. The variability in tubewell water prices within the watercourse command area is neglected and only the average tubewell water prices are incorporated into the farm and watercourse models.

Main steps followed for calibration and validation of the farm and watercourse stochastic linear programming models

Farm and watercourse models are initially calibrated for four sample watercourses that together have some area under each of the nine farm groups being considered. The watercourses selected are FD 14, FD 130, AZ 20 and AZ 111. The calibration of these farm groups for the four sample watercourses is obtained by refining risk aversion parameters for the different groups, and modifying specific model parameters that are location specific, such as the gross margins of rice and sugarcane. For example, sugarcane gross margin is increased for farms located in the two head watercourses FD 14 and AZ 20 close to the sugar mill. Also, as mentioned above, tubewell water constraints are specified for each watercourse.

The risk aversion parameters specified through the calibration process for the nine farm group models are then used to build the remaining four watercourse models (i.e. FD 46, FD 62, AZ 43 and AZ 63) and to validate the farm group models under different conditions of canal water supplies, tubewell water availability and tubewell water prices. The calibration and validation of the farm group and watercourse stochastic linear programming models is based on the comparison between actual cropping pattern and cropping pattern estimated by the stochastic linear programming models. As the areas cultivated under kharif and rabi fodder are fixed in the farm models, the area under these crops is not considered in the calibration and validation process.

Calibration results

Results of the calibration in terms of area under each crop for each group in the four selected watercourses is presented in Appendix 3. The calibration accuracy of the farm group and watercourse models is computed and expressed in terms of the relative difference in area under each crop between the actual situation and model prediction. These calibration accuracies computed for the watercourses are presented in Table 5.4.

Table 5.4. Relative difference (%) between actual and estimated cropping intensity and cropping pattern for four watercourses of the Fordwah and Azim distributaries used for the calibration of the farm stochastic linear programming models.

Watercourse	Kharif cropping intensity	Rabi cropping intensity	Area under sugarcane	Area under rice	Area under cotton	Area under wheat
FD 14	+5%	+8%	+16%	-	+5%	+8%
FD 130	-2%	+19%	+18%	-	-2%	+21%
AZ 20	-2%	+0.1%	+1%	-3%	-3%	-0.1%
AZ 111	+1%	-5%	+4%	+1%	+2%	+17%

The calibration results show a very good fit between actual and estimated values for the kharif cropping intensity and the area under cotton. For the other variables investigated, the accuracy results are also good, except for the Watercourse FD 130 that over-estimates the area under sugarcane and the area under wheat, and thus the rabi cropping intensity. The various risk-aversion coefficients estimated during the calibration process are presented in Table 22 for the nine farm groups defined in Section 5.2 (for the definition and meaning of the risk aversion coefficient, refer to Sections 5.3 and 5.4).

Table 5.5. Risk aversion coefficients for the nine farm groups of the farm typology: results from calibration of the stochastic linear programming models. High absolute values of the risk aversion coefficients express high degrees of risk aversion.

Risk aversion related to	Grp 1	Grp 2	Grp 3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
Variability in cotton gross margin in the objective function	-0.1	-0.5	-1.35	-0.5	-0.35	-0.85	-1.1	-0.7	-0.5
Variability in wheat yield in the objective function	-0.4	-0.5	-	-0.85	-	-0.85	-0.5	-0.85	-0.5
Variability in wheat yield in the minimum wheat requirement constraint	-	-	-0.4	-	-1.4	-	-	-	-
Variability in canal water supply	0.5	0	0.5	0.5	0.5	0.5	0	0	0

Risk aversion coefficients related to canal water supply variability are equal to 0 for tubewell owners and 0.5 for non-tubewell owners. On an average, and as expected, the risk aversion coefficients related to the cotton gross margin and wheat yield variability are lower for large farms and tubewell owners. The unexpected very low absolute value of the risk aversion factors for Group 1 is explained by the high level of remittances received from family members working outside the farm in Pakistan or in the Gulf States. Far farmers of Group 1, farming has become a secondary activity mainly targeted towards their own household needs.

Validation of the farm stochastic linear programming models

As explained above, the four remaining watercourses of AZ 43, AZ 63, FD 46 and FD 130 are used to validate the farm stochastic linear programming models. Using the risk aversion parameters obtained through calibration and presented in Table 5.5, farm group models are built according to the socio-economic profile for each of the four watercourses. Canal water supply variables and tubewell water availability constraints are specified for each watercourse, along with tubewell water prices. Specific modifications are made in sugarcane and rice gross margins to take into account local variability and differences, such as soil type and proximity to the sugar mill.

The models are then run for the four watercourses. The accuracy of the model output in terms of the area under each crop and seasonal cropping intensities is summarized in Table 5.6. A more detailed output of the simulations for the validation process is presented per crop per farm and per watercourse in Appendix 3.

Table 5.6. Relative difference (%) between actual and estimated cropping intensity and cropping pattern for four watercourses of the Fordwah and Azim distributaries used for the validation of the farm stochastic linear programming models.

Watercourse	Kharif cropping intensity	Rabi cropping intensity	Area under sugarcane	Area under rice	Area Under cotton	Area under wheat
FD 46	-2.2%	+8.0%	+54%	-	-8%	+5%
FD 62	-8.5%	+1.7%	+50%	-	-14%	-1%
AZ 43	-16.4%	-13.7%	-27%	-	-10%	-3%
AZ 63	+7.5%	+8.2%	+54%	-	+5%	+6%

Similarly to the calibration step, significant differences are found between the actual area under sugarcane and model estimates. However, the estimates of the models for the area under cotton and wheat and the two seasonal cropping intensities are rather good, with an accuracy level within 10%.

As part of the validation procedure, more attention was given to the ability of the watercourse models to predict total tubewell water use. As tubewell information collected through monitoring for the year 1992-93 was not available, tubewell operation information for the Kharif 1994 and Rabi 1994-95 seasons was compared with model predictions in total tubewell water use. Several issues arise when comparing model predictions and tubewell operation information:

- The farm operated areas used in the models are not the same as the command areas for which actual tubewell water use is collected. The stochastic linear programming models consider also the area cultivated by farmers *outside* the command area of the watercourse considered.
- Total tubewell water use predicted by the model includes an effective increase in the quantity for irrigation (similar to what is obtained through tubewell monitoring data), and volumes that are planned to compensate for the variability in canal water supply.

- Capillary rise has not been considered in the watercourse models, while it is an important element of the water balance for some watercourses, more particularly FD 14 and AZ 20 (van Waijjen, 1996). Thus, stochastic linear programming models are likely to predict higher tubewell water use to account for the missing capillary rise component of the water balance.

Table 5.7 presents the results of the comparison between the 1994-95 data and the prediction of the stochastic linear programming models for the 1992-93 season. Information obtained after each computational step is included in this table for better understanding of each step. Overall, the difference between actual tubewell pumping aggregated for the eight watercourses and tubewell pumping predicted by the watercourse models is equal to +18%, showing that the predictions of the models in terms of tubewell pumping are realistic as compared with the actual situation. As illustrated by Table 5.7, however, the prediction are rather good for five watercourses out of eight, but are not in accordance with monitoring data for FD 46, FD 130, and AZ 20.

The overestimation of tubewell pumping would stress that farmers apply in reality lower quantities of irrigation water per unit area than model predictions. Although cotton and wheat activities with different irrigation requirements are proposed in the models, the farm models mostly select the highest levels of irrigation requirements. Further investigation of the relationship between crop yield and quantities of irrigation water applied would be required to refine this element in the stochastic linear programming models.

Table 5.7. Comparison between actual yearly tubewell water use in 1994-95 and model predictions based on the 1992-93 situation. Values are expressed in $10^3 m^3$.

Variable	Fordwah				Azim			
	FD 14	FD 46	FD 62	FD 130	AZ 20	AZ 43	AZ 63	AZ 111
A. Actual yearly tubewell water use (1994-95)	423	168	277	1,171	121	168	429	1,229
B. Model predictions for total yearly tubewell water use	2,460	739	772	1,363	600	858	1,726	1,909
C. Model prediction for tubewell water to increase quantity	1,057	665	695	1,336	534	395	1,105	1,661
D. Model prediction modified to account for differences in areas	801	704	494	1,849	518	183	368	837
E. Model prediction modified to account for capillary rise	449	415	346	1,849	259	183	368	837
Relative difference between actual and predicted tubewell water use ((E-A)/A)	+6%	+147%	+25%	+58%	+113%	+9%	-14%	-32%

For FD 130, the higher cropping intensity predicted by the model directly explains the higher tubewell pumping predicted by the model. For FD 46, the difference pertains to a higher predicted area under sugarcane as compared with the actual situation. Finally, the higher tubewell water pumping estimated by the model for the Watercourse AZ 20 may be related to an underestimation of canal water supplies. This watercourse is located at the head of the Azim Distributary and may benefit from temporary illegal canal water supplies that have not been accounted for in the input of the stochastic linear programming models. For all watercourses, however, it is important to stress that two different years are compared, and that out-of-command areas for which canal water supplies are unknown have been included in the stochastic linear programming models. Both elements are likely to explain part of the observed inaccuracies in tubewell water use.

Summary

Stochastic linear programming models have been developed, calibrated and validated for 9 farm groups and 8 sample watercourses. The overall accuracy of the farm and watercourse models is rather good in terms of cropping intensity and cropping pattern, as the area under a given crop for a given farm group in a given watercourse are estimated within an average accuracy of 10%. The area under sugarcane, however, is not well predicted for some of the farm and watercourse models and often over-estimated. The absence of specific labor constraints in the farm models that may arise in practice during the sugarcane-harvesting period may explain the differences between the actual and predicted area under sugarcane. Although appropriate information on tubewell water pumping is not available for the period considered, preliminary validation of tubewell pumping predicted by the watercourse models is performed. It shows that tubewell-pumping predictions are rather appropriate for five watercourses out of eight.

5.6 Classifying Fordwah and Azim watercourses to identify their socio-economic profiles and watercourse models

The analysis and model development presented so far has concentrated on the eight sample watercourses selected along the Azim and Fordwah distributaries. To investigate eight watercourse command areas may be sufficient for the analysis of existing water markets within a watercourse command area. However, the analysis of the potential for water transactions between watercourses and between distributaries requires an investigation of a larger number of watercourses and the development of economic models for each watercourse of the distributaries considered.

The simplest option would consist of building a distributary level model by aggregating available sample watercourse economic models and linking these models with well-defined distributary related constraints. However, this approach assumes that the watercourse population can be divided into classes of equal weight represented by the initial sample watercourses. At the opposite, the most complex option would consist of collecting information for all farmers of the distributary command area, identifying the relative importance of each farm type in each watercourse, and developing distinct socio-economic profiles for each watercourse of the distributary. Neither one of the two options are seen as appropriate, and therefore, an intermediate option is selected and presented below.

The approach is based on the analysis of watercourse-scale information, instead of farm level information as previously used. Using this watercourse-scale information available for all watercourses of the Fordwah and Azim distributaries, watercourses are compared with the sample watercourses for which socio-economic profiles and watercourse economic models have been built, and classified based on their resemblance to the sample watercourses. Then, it is assumed that each watercourse of a given class has a socio-economic profile (and associated watercourse stochastic linear programming model) similar to the sample watercourse that has defined the class. The assumption may be rather strong, as it assumes a perfect two-way relationship between watercourse-scale information and the relative importance of each farm type within the watercourse command area. In other terms, two different socio-economic profiles cannot have the same aggregated watercourse-scale information.

For such classification of watercourses, the method is based on clustering techniques using:

- *Thematic information* collected or computed for each watercourse, related to the physical environment and the socio-economic characteristics of farm populations in each watercourse command area.
- *Spatially defined variables* related to distance from specific points such as market places or cities located within the area considered, and to the proximity between elements or watercourses to be classified (here watercourses).

This inclusion of spatially defined variables allows for the integration of spatial trends into the classification process that exists within the area but have not been captured by thematic variables selected for classification. At the same time, it provides a typology output that produces a more structured spatial localization of the different watercourse classes and that can be better used as a basis of intervention and policy implementation. A classification without the inclusion of these variables usually leads to a mosaic map with too many small zones for which it is difficult to specify interventions that have a sense from the implementation point of view. On the other hand, the use of administrative or hydraulic boundaries provides larger zones for interventions but has little chance to provide areas homogeneous with regards to the thematic variables considered. This eventually limits the impact of the proposed interventions (Rio, 1997).

The application of the classification methodology developed by Rio (1997) has been presented by Bouzit et al. (1997) for all of the watercourses in the Chishtian Sub-division. The following paragraphs summarize the methodology and the results of its application to the watercourses of the Fordwah and Azim distributaries (total of 160 watercourses) that will be analyzed for testing scenarios in Chapter 7.

The clustering method under contiguity and spatial constraint has been implemented using the MatLab software and is similar to the iterative principle of the *Nuées Dynamiques* developed by Diday (1971). The clustering algorithm is based on two functions that are used consecutively after an initial selection of N nuclei or initial class centers (Rio, 1997). The first function allocates each element of the population to its closest center, while the second function computes the gravity center and average profile of the class after allocation of its elements.

The two functions are used in an iterative manner to meet optimality criteria, such as the minimization of the distances to the nuclei of each class, equivalent to the maximization of the distances between classes. The gravity centers obtained after iteration *n* is used as the new nuclei for iteration *n+1*. The distance selected in the proposed classification is the quadratic distance, but other distances such as the absolute value or the Minkoswki distance may also be used for this affectation process (Rio, 1997). As shown by Diday (1972), this iterative procedure converges and leads to the minimization of the criteria. However, the minimum obtained is a local minimum as it depends on the selection of the initial nuclei or centers. Repeating the classification procedure several times, with different initial nuclei, limits this problem and identifies stable or strong forms of classification existing within the population considered.

In the case of the Azim and Fordwah distributaries, a single iteration is implemented to classify each watercourse into one of the eight sample watercourse classes, and compute the average profile of each class. The main variables that are used for the classification procedure are related to:

- *Socio-economic characteristics of the farm population*: number of cultivators, tenancy of these cultivators, level of mechanization (tractors, tubewells), and importance of landlords with large landholdings;
- *Physical environment* (including hydraulic infrastructure): groundwater quality, soil type, and length of watercourse; and,
- *Agricultural production*: area under the main crops, along with the importance of barren and fallow land.

The application of the methodology leads to the following classification of the 160 watercourses of the Fordwah and Azim distributaries as presented in Table 5.8. The results presented in Table 5.8 lead to several conclusions. Firstly, watercourses have been allocated to each of the eight sample watercourses. Large differences exist, however, in the relative importance of the classes, ranging from 3% to more than 47% of the total number of watercourses for the classes FD 46 and FD 62, respectively. Totally, the two largest classes (FD 62 and AZ 63) represent 62% of the watercourse population.

Table 5.8. Classification of the Azim and Fordwah watercourses using the eight sample watercourses as initial class nuclei.

Distributary	Sample watercourse (class)	Number of watercourses allocated to the class of each sample watercourse		
		From the total population (Azim + Fordwah)	From the Fordwah Distributary	From the Azim Distributary
Fordwah	FD 14	16	14	2
	FD 46	5	3	2
	FD 62	66	43	23
	FD 130	12	12	-
Azim	AZ 20	7	1	6
	AZ 43	8	-	8
	AZ 63	37	12	25
	AZ 111	9	1	8
	Total	160	86	74

Secondly, most of the watercourses from the Fordwah Distributary command area have been allocated to the four sample watercourses of the same distributary. And the same rule holds for the Azim distributary watercourses that have been preferentially classified with the four sample watercourses of the Azim Distributary. The results of the classification are confirmed by discussions with farmers, irrigation department staff, or IIMI field staff that clearly mention the significant differences between the two distributaries in terms of physical environment and farm population.

To validate the results of the classification, stochastic linear programming models were built for all watercourses of the Fordwah Distributary using the results of the watercourse typology and the socio-economic profile of the eight sample watercourses. Using monthly canal water supplies estimated by the SIC model for the Kharif 1994 and Rabi 1994-95 seasons, the stochastic linear programming models were run. Estimated cropping intensities for the rabi season were compared with values of cropping intensities obtained from the processing of satellite imagery information (Jamieson, 1995; Asif et al., 1996) integrated into a Geographic Information System. Overall, the error between cropping intensities predicted by the stochastic linear programming models and obtained through the use of satellite imagery range from 5% to 35%, with an average value of 25%.

The average error obtained for the rabi cropping intensities was not as good as the error obtained by using a preliminary version of the linear programming models that did not adequately account for tubewell water availability constraints and canal water supply variability (See Kuper (1997)). In fact, although the models presented in this section show better calibration and validation results for the eight sample watercourses considered, their use for a larger number of watercourses requires extra information on tubewell water availability that may not be available and that is also difficult to estimate. Thus, although the simpler models are less well calibrated and validated, their low information requirement make them more robust for use in new watercourses.

5.6 Summary

A farm typology is developed based on information collected through a farm survey for all farmers in the command area of the eight sample watercourses of the Fordwah and Azim distributaries. And nine farm groups are identified. Farm group and watercourse stochastic linear programming models have been calibrated and validated for the nine farm groups and the eight watercourses. Overall, the accuracy of model predictions is good, with validation results showing an accuracy within 10% for seasonal cropping intensities and for the area under cotton and wheat. Model predictions in terms of area under sugarcane, however, are overestimated for some of the watercourses considered. The validation of the models has also investigated the difference between model prediction and the actual situation in terms of tubewell water use. Overall, the predictions appear consistent with reality for most of the watercourses.

For each watercourse command area of the Fordwah and Azim distributaries, the relative importance of each farm type or socio-economic profile is obtained, based on the appurtenance of the watercourse to a specific watercourse class. The combination of the stochastic linear programming models developed for the eight sample watercourses of the Fordwah and Azim distributaries, and of the watercourse typology that allocates each watercourse of these two distributary to one of the eight sample watercourse classes, leads to the building of a *stochastic linear programming model for each watercourse in the command areas of the Fordwah and Azim distributaries*.

The watercourse stochastic linear programming models for the eight sample watercourses will be used to analyze the functioning of existing water markets within the watercourse command area (Chapter 6). Along with the stochastic linear programming models developed for all of the watercourses in the Fordwah and Azim distributaries, they will be applied to the analysis of the potential for water markets development between watercourses and distributaries (Chapter 7).

Chapter 6

Current water markets in the Chishtian Sub-division: functioning, organization and impact on agricultural production

Water markets in Pakistan have been described in various papers and reports. In general, analyses of canal water markets are sparse, rather descriptive or outdated (Lowdermilk et al., 1975; Renfro and Sparling, 1986; WAPDA, 1990; Strosser and Kuper, 1994; Bandaragoda and Rehman, 1995). Tubewell water markets are mentioned in a large number of project reports that deal with groundwater management (see, for example, World Bank, 1996b), but specific research studies remain rare. Examples of recent studies include Strosser and Meinzen-Dick (1994), Strosser and Kuper (1994) and Meinzen-Dick (1996). An important aspect stressed by these studies is the variability in the functioning of existing water markets in terms of type and intensity of water transactions. Factors that explain this variability include the physical environment such as climate and soils, access to water resources, socio-economic attributes of individual water users or economic development of the area considered.

This chapter presents a detailed analysis of existing water markets in eight sample watercourse command areas of the Chishtian Sub-division, looking at both *surface water markets* and *groundwater markets*. The analysis investigates the functioning of these markets, their impact on agricultural production and productivity, and their impact on the physical environment. The analysis presented is based on detailed information obtained through regular monitoring of canal and tubewell water use at the farm level for the Kharif 1994 and Rabi 1994-95 seasons. This is complemented by information collected through a farm survey undertaken in 1993 and covering the Kharif 1992 and Rabi 1992-93 season.

6.1 Functioning of water markets in eight sample watercourses of the Chishtian Sub-division

6.1.1 Description of existing water markets

Types of water transactions

Water markets in Pakistan involve both surface and groundwater resources. Although forbidden by the Canal and Drainage Act of 1873, canal water transactions are frequently performed in large-scale irrigation systems in Pakistan (WAPDA, 1990). The main types of water transactions taking place within the command areas of the eight sample watercourses include (based on Rinaudo et al., 1997b):

- *Exchange of partial canal water turns.* These transactions are mainly aimed at reducing the short-term variability of canal water supplies, and/or adjusting the canal water supply for more efficient field application. Exchange of partial canal water turns allows farmers to finish irrigating their fields while their own canal water turn is going to stop. Partial water turns are also exchanged to account for changes in the location where farmers start using their water turn along the watercourse. In such cases, the time required to fill the watercourse with water (*Nikkal*), or to drain water from the watercourse (*Khal Barai*), is compensated by a change in time duration, usually 5 min for every 67 m change in location along the watercourse. Exchange of partial turns to finish irrigation may be given back, usually the following week, but location-for-time exchange does not require time compensation.

- *Exchange of full canal water turns.* The exchange of full water turns takes place when farmers need higher quantities of good quality irrigation water at once. This is mainly the case at the beginning of the season for pre-sowing and sowing irrigation of wheat (Pintus, 1995) and cotton (Meerbach, 1996). Such a practice has also been found in other irrigation systems in Pakistan for crops such as maize (Beeker, 1993). Periods with rapid changes in watercourse head discharges are also prone to the exchange of full water turns. Farmers that would normally have their turns may not be in a position to use them, as canal water does not reach their farm yet, or the watercourse head discharge is too low to efficiently use surface water supplies. Full canal water turns are then given to farmers located upstream along the watercourse. Finally, during periods with low demand for irrigation water, such as the harvesting time of wheat (April-May), some farmers may not require canal water. They give their turns to other farmers that are growing inter-seasonal fodder crops or that need extra good quality canal water to leach salts from saline fields.

- *Sale and purchase of canal water turns.* This type of water transaction is rare and is significant in two watercourses only, FD 46 and FD 130. Canal water sales take place when tail farmers receive little or no canal water as a result of watercourse head discharge being too low and high conveyance losses along the watercourse. Water turns then are sold to upstream farmers, whether for a season as is the case for two farmers in FD 130, or more often temporarily. In the case of seasonal sales, the agreed warabandi schedule is modified accordingly to take the transaction into account. In some cases, farmers purchase good quality canal water to mitigate salinity problems on their plots.

- *Sale and purchase of tubewell water.* The main objective of tubewell water purchases is to increase the quantity of irrigation water available on the farm. In some cases, tubewell water purchases play the role of an insurance to compensate for canal water supply variability. Plots that cannot be reached by canal water, or that are too far from a farmer's own tubewell, and mechanical failure of that tubewell, are other reasons explaining farmers' participation in tubewell water purchases. Tubewell owners sell tubewell water as they have a surplus of water (one-third of the tubewell owners), to make profits from sales (20% of the tubewell owners), to

Table 6.1. Canal and tubewell water transactions in the command area of the eight sample watercourses of the Fordwah and Azim distributaries for the Kharif 1994 and Rabi 1994-95 seasons. Watercourse AZ 111did not receive any canal water during the two seasons considered.

Object of transaction	Period	Variable	Fordwah				Azim			
			FD14	FD46	FD62	FD130	AZ20	AZ43	AZ63	AZ111
Canal Water	Kharif	No. of transaction per canal water turn in the warabandi schedule	7.2	8.5	2.8	3.6	10.8	8.8	3.0	-
		Time transacted as percentage of total hours in a season	28	33	11	14	41	34	11	-
	Rabi	No. of transaction per canal water turn in the warabandi schedule	5	6.3	2.8	3.3	3.1	2.1	0.1	-
		Time transacted as percentage of total hours in a season	19	24	11	13	12	8	0.5	-
Tubewell water	Year	Total hours sold	2800	230	285	5610	475	120	550	260
		Hours sold per unit area	14.3	1.3	5.9	20.9	4.0	1.8	4.5	2.2
	Kharif	% of tubewell water sold	60	7	20	59	41	6	15	1
	Rabi	% of tubewell water sold	59	19	40	60	45	11	18	3

Overall, both canal and tubewell water transactions are more developed in the Fordwah watercourses as compared with the Azim watercourses. Also, the percentage of total tubewell water use transacted is higher than the percentage of total canal water use transacted for both seasons. Further analysis of the factors that explain differences between watercourses will be presented in the sections below.

Based on an average tubewell discharge of 28 l.s^{-1}, total yearly tubewell water sales for the eight watercourses are estimated at 1.2 10^6m^3, equivalent to a water depth over the total command area of nearly 100 mm. Using information on total canal water supplies presented in van Waijjen (1996), the total volumes of canal water involved in canal water transactions are estimated at roughly 20% of the total canal water supplies for the Kharif 1994 season, which is equivalent to a water depth of 70 mm. And 10% of the total canal water supplies, equivalent to a water depth of less than 20 mm, are the estimates for the Rabi 1994-95 season. Overall, this would mean that around 20% of the total irrigation water supplies in the eight sample watercourses are transacted among water users.

The exchange of partial canal water turns has the same importance in terms of hours transacted as the exchange of full canal water turns. Differences, however, are recorded between watercourses. Farmers from AZ 43, FD 14 and FD 130 exchange more full water turns, while farmers from AZ 20, AZ 63 and FD 62 exchange a larger number of partial turns. For FD 46, both types of exchange have a similar importance. Overall, location-for-time exchanges represent 5% (rabi) to 10% (kharif) of the total number of exchanges, but are more important in the Fordwah watercourses than in the

Azim watercourses. The shorter average duration of canal water turns, along with the need to ensure good canal water supplies for the sowing and pre-sowing irrigation as a result of poorer groundwater quality, may explain the higher importance of exchanging full canal water turns in FD 14 and FD 130.

While in Table 6.1 the importance of tubewell water transactions, in terms of hours per unit area, is similar to the information presented in Rinaudo et al. (1997b), Table 6.1 shows a much more active canal water market than discussed in Rinaudo et al. (1997b) based on farmer's interview data. The importance of short-term exchanges of partial canal water turns that would be neglected during interviews with farmers probably explains this difference. The restriction imposed on canal water transactions by the Canal and Drainage Act may also result in under-reporting of transactions.

Temporal variability in water transactions

A significant temporal variability in the importance of water transactions can be expected as a result of changes in canal water supply, crop water requirements and relative water scarcity. As highlighted in Table 6.1, farmers participate more in canal water transactions during the kharif season than during the rabi season, showing a greater need to adapt irrigation water supplies to crop requirements. Within a season, however, farmers respond more to short-term changes in canal water supply than to changes in crop water requirements and relative canal water scarcity. Figure 6.1 illustrates the temporal variability in the percentage of farmers lending canal water turns during the Kharif 1994 season for the four sample watercourses of the Fordwah Distributary. Figure 6.1 stresses the absence of a clear intra-seasonal trend for canal water transactions. As mentioned above, the exchange of full canal water turns only are more often practiced at the beginning of the season at a time when farmers need higher quantities of good quality canal water for the pre-sowing and sowing irrigation for the wheat and cotton crops.

The analysis of tubewell water transactions shows a clearer temporal trend within seasons. Although the aggregated number of hours sold in the eight watercourses are not very different between the rabi season (5,150 hr) and the kharif season (5,540 hr), trends exist for monthly tubewell water sales expressed in the number of hours sold per month. In fact, sales closely follow crop water requirements. However, as tubewell water use by tubewell owners follows a similar trend, the percentage of tubewell water sales out of the total tubewell water use does not vary greatly from month-to-month. Figures 6.2 and 6.3 present the monthly quantities of tubewell water used by tubewell owners and sold to other farmers, along with the relative importance of tubewell water sales for FD 62 and FD 130 watercourses for the period April 1994 to March 1995.

Figure 6.1. Week-wise percentage of farmers lending canal water turns for four sample watercourses of the Fordwah Distributary during the Kharif 1994 season.

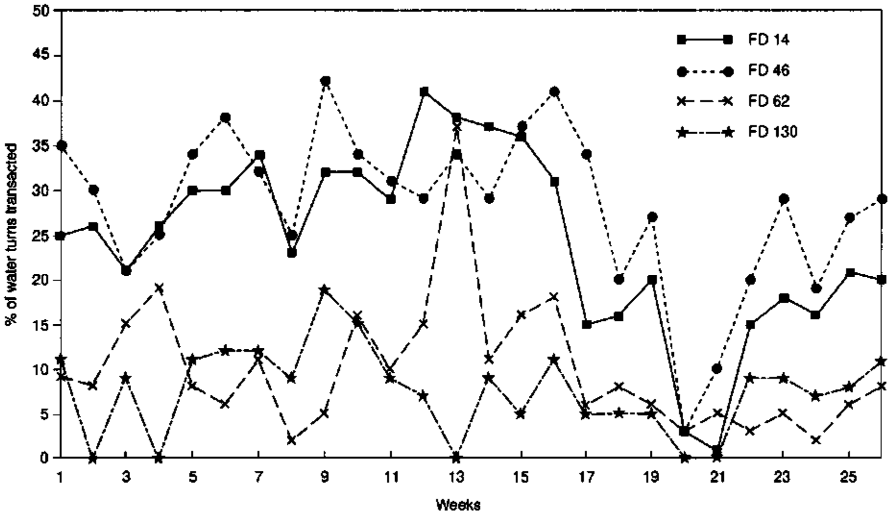


Figure 6.2. Monthly tubewell water use by tubewell owners and tubewell water sales for the FD 62 watercourse during the period April 1994 to March 1995.

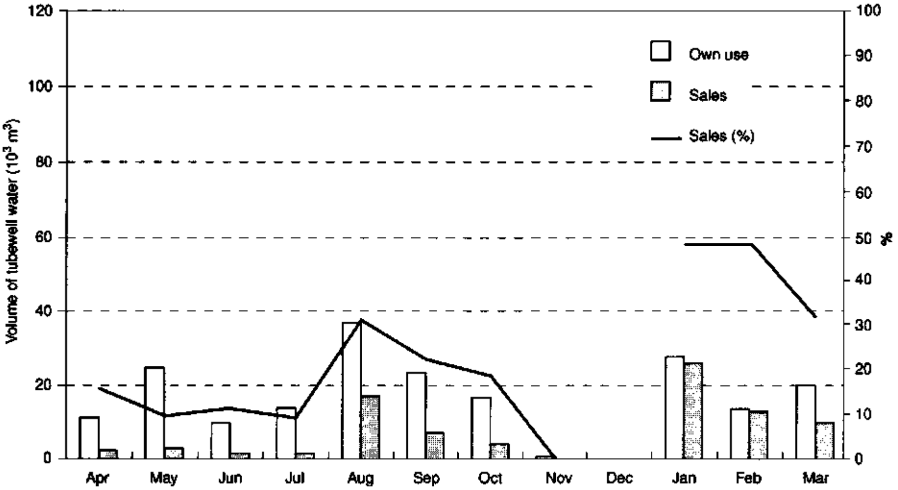
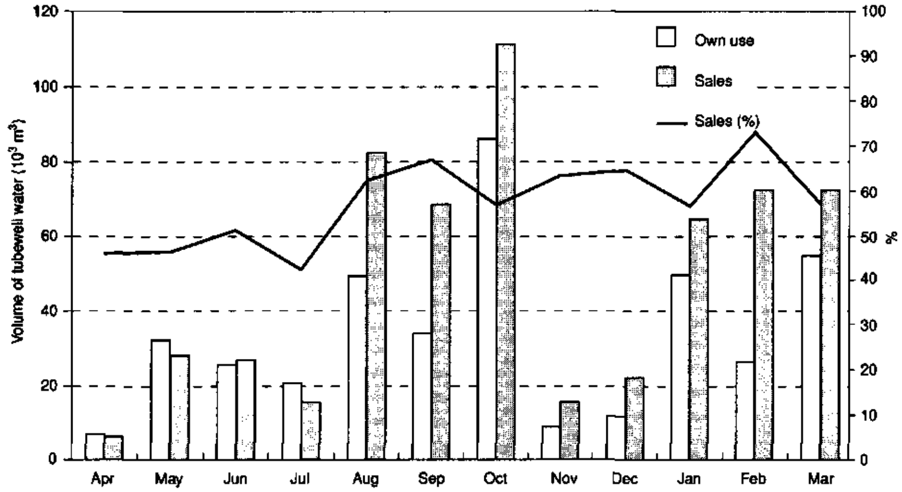


Figure 6.3. Monthly tubewell water use by tubewell owners and tubewell water sales for the FD 130 watercourse during the period April 1994 to March 1995.



6.1.2 Who participate in water transactions?

The variability in the importance of water transactions is high between watercourse command areas, as stressed in Table 6.1. Also the heterogeneity of participation in water markets for farmers of the same watercourse command area is high. In this section, the factors that may explain the variability in water market functioning are investigated, looking both at the characteristics of the physical environment, and individual water users that are involved in water transactions.

Participation in canal water markets

A simple regression analysis was performed to identify factors that explain differences in the average number of transactions per warabandi turn presented in Table 6.1 for the Kharif 1994 and Rabi 1994-95 seasons and for the eight sample watercourses of the Fordwah and Azim distributaries. The variables used in the analysis include:

- The size of the watercourse command area;
- The average cropping intensity to express pressure on water resources;
- The average farm size as smaller farms are expected to be more actively involved into canal water transactions;
- The seasonal canal water supply per unit area;
- The variability of canal water supplies expressed by the seasonal coefficient of variation of watercourse head daily discharges, or by the number of dry days (zero discharge) during the season considered; and,
- The tubewell density used as a proxy for the potential access to groundwater resources.

The analysis showed that the cropping intensity and the average seasonal canal water supply per unit area positively influence the level of water transactions within the watercourse command area. Watercourses with high canal water supply variability, high average farm size, and high tubewell densities record a lower intensity of water market activity (Debernardi, 1996). The fact that farmers prefer to use their own canal water turn, as they do not know what to expect the next week, may be the explanation behind the negative impact of canal water supply variability on water transactions. The most influential factor, however, remains the average canal water supply per unit area of the watercourse.

Using weekly information on water turns taken by farmers, specific transaction matrices were developed to identify the *importance of location in explaining the development of canal water transactions*. Transaction matrices represent a simple way to capture the spatial dimension of water distribution along the watercourse. These matrices are obtained by putting warabandi codes in a proper order along the x-axis and along the y-axis. Thus, for a warabandi schedule of *n* turns, a *nxn* matrix is developed to store and represent transactions between water users (identified by their warabandi code). A given value *x* at the intersection between row *i* and column *j* means that canal water transactions have taken place *x* times from farmer *i* to farmer *j*.

Matrices developed for the eight watercourses for the Kharif 1994 and Rabi 1994-95 seasons stress that canal water transactions are mostly localized and taking place between neighboring water users. In some cases, water transactions involve farmers that have several other farmers between their respective canal water turns. The matrices also show that the larger number of transactions take place between farmers that already have developed specific water allocation and distribution arrangements. Such arrangements include rotations between canal water turns to share losses related to the advancement of canal water in the watercourse, or merged water turns that are taken by two or three farmers week-after-week. Figure 6.4 illustrates the localization of water transactions for the AZ 20 watercourse using information pertaining to the Kharif 1994 season.

Using the information stored in the matrices, further analysis was undertaken to identify other factors that may explain participation in canal water transactions and possible links between participants. For AZ 43 and FD 14, Murgai and Winters (1997) analyzed factors that influence the probability of entering into canal water transactions between two farm households. The analysis emphasized that farmers who are from the same family, who cultivate plots belonging to the same landowner family, who have consecutive water turns in the warabandi schedule, and who cultivate plots that are physically close in the watercourse command area, have significantly higher chances to participate in canal water transactions. Although the analysis of farm survey information had stressed that small farmers are more active participants in canal water transactions (see below), the duration of canal water turn did not explain farmers' participation into canal water markets. The fact that two watercourses only were analyzed could explain the lack of significance of the water turn duration variable.

Figure 6.4. Canal water transactions in the Watercourse AZ 20 for the Kharif 1994 season. Values in the cells of the matrix represent the number of canal water transactions that have taken place from farmer row ID to farmer column ID of this cell. Boxes in the matrix highlight existing water turn arrangements between farmers, such as rotations or merger of turns.

Watercourse head → Watercourse tail

Watercourse head ↓ Watercourse tail

Farm ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Total
1		7	6																										13
2	4		8																										12
3		10		1																									11
4		6	2																										8
5				9		3			2																				14
6					3		2	1																					6
7					1	4		4																					9
8						3	2		3	1																			9
9						1		1		3																			5
10									5		3																	1	9
11									4	1		2		1		1													9
12										1	7					1													9
13												2		3															5
14													6		2														8
15				3						1				1		2									1				8
16				1						1					9								2						13
17																		2					1						3
18																	1												1
19																1	2	1		2	1								7
20																	1	1			2	2	1						7
21																				6									6
22																				5	5								10
23																			1										1
24												1							1				12		5	1			20
25															1									3		1			5
26																								3	14				17
27																								1		1			2
28				2								1				18							1	2			10		4
Total	4	23	16	16	4	11	4	6	14	8	10	6	6	5	12	37	4	4	2	13	8	2	17	9	20	3	10	1	275

Participation in canal water markets was also analyzed in the context of farm production strategies and constraints. Small intensive farms are the main participants in canal water transactions, whether exchange or purchase of canal water turns. Large commercialized farms, however, show a very limited involvement. The longer canal water turns and the control over groundwater extraction of farmers having large landholdings may provide enough flexibility in itself, and hence transactions with partial canal water turns may not be required anymore.

Tenants also show a low participation in canal water transactions. This low involvement may be related to their high participation in tubewell water markets in the context of their share tenancy contracts. Also, the fact that tenants do not own the water turn that is linked to land ownership may explain their reluctance to participate in canal water transactions. Overall, however, canal water transactions are better explained by location variables, topographical variables, and by the characteristics of watercourse head canal water supplies, than by farm production strategies and constraints.

Participation in tubewell water markets

The variability in tubewell water transactions has been analyzed first from the seller's point of view, using daily tubewell operation data collected for all tubewells of the eight sample watercourse command areas of the Fordwah and Azim distributaries. To illustrate the variability in tubewell owner's participation in groundwater markets, Figure 6.5 and Figure 6.6 show the frequency distributions of the total amount of hours sold for the period May 1994 to April 1995, and the frequency distribution of the relative importance of tubewell water sales as a percentage of total tubewell operation for the same period. Overall, 20% of the tubewell owners have not participated in groundwater markets. Around 25% of the tubewell owners sell more than half of the groundwater extracted by their tubewell, but a bit less than 5% sell more than 300 hours (roughly equivalent to 30,000 m^3) for the year considered.

Matrices similar to the ones developed for the analysis of canal water transactions showed that tubewell water transactions are less localized than canal water transactions. Farmers have reported distances of more than 1,300 m between tubewell owners and tubewell water sellers (Strosser and Kuper, 1994).

Using tubewell monitoring information, regression analysis was also performed to identify factors that explain the volumes pumped by individual tubewells and sold on the market. The variables selected for the analysis include watercourse-related variables that describe the overall water demand and economic pressure over water resources in the watercourse command area considered. Also, tubewell–related variables that describe tubewell and tubewell owner characteristics are incorporated in the analysis. The results of the analysis are presented in Table 6.2.

Figure 6.5. Frequency distribution of tubewells located in the eight sample watercourses of the Fordwah and Azim distributaries, for *total groundwater sales in hours.*

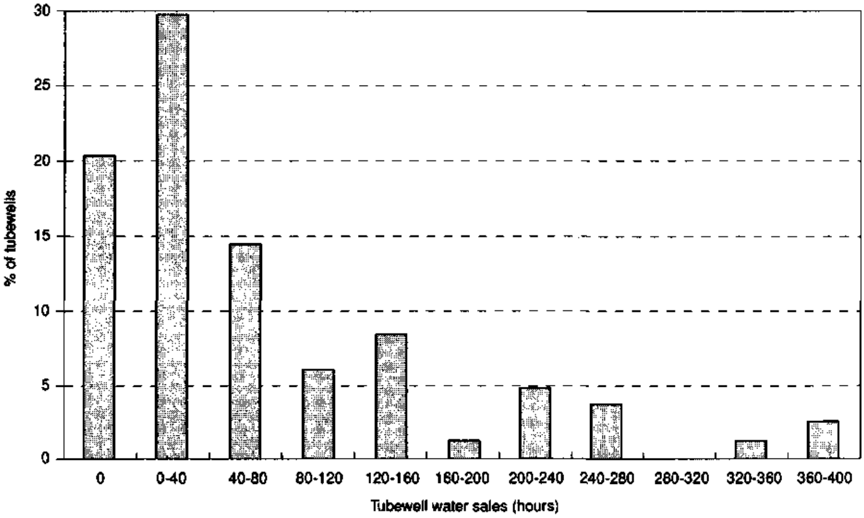


Figure 6.6. Frequency distribution of tubewells located in the eight sample watercourses of the Fordwah and Azim distributaries, in *percentage of total groundwater use.*

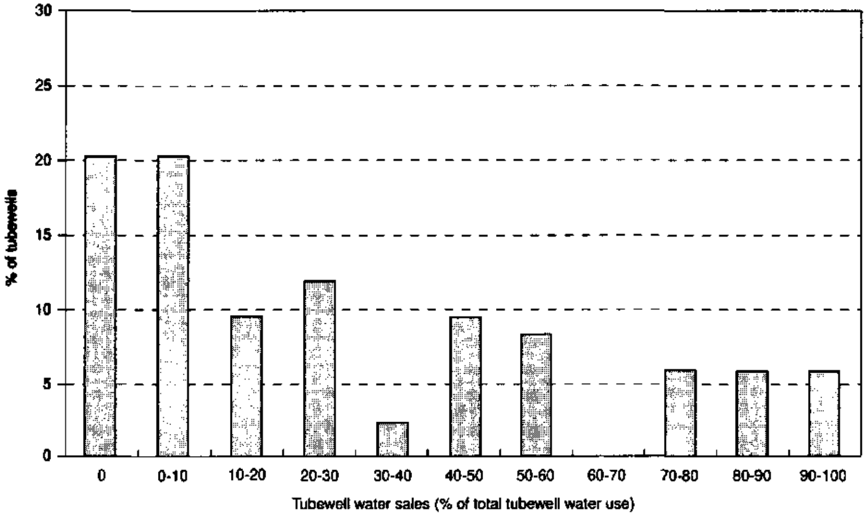


Table 6.2. Factors influencing the volumes of tubewell water sold on the market: tubewell level analysis for 81 tubewells located in the eight sample watercourses of the Fordwah and Azim distributaries for the Kharif 1994 and Rabi 1994-95 seasons.

TW holding = land holding size (ha) of tubewell owners (including all tubewell shareholders in the case of multiple tubewell ownership)
Power source = dummy variable with value 1 for electric tubewells, and 0 otherwise
TW density = average number of tubewells per 100 ha in the watercourse
TW cultivator = average number of cultivators per tubewell
Perennial = dummy variable with value 1 for perennial canal and value 0 for non-perennial canal
Dry days Rabi = number of days with no canal water supply during the Rabi season
Sugarcane = percentage of the watercourse command area under sugarcane
Rice = percentage of the watercourse command area under rice

Independent variable	Total volume of tubewell water sold during the Kharif 1994 season (m^3)			Total volume of tubewell water sold during the Rabi 1994-95 season (m^3)		
	Estimate	Standard error of estimate	Significance level	Estimate	Standard error of estimate	Significance level
Constant	46115	9144	0.01	18477	9909	0.10
TW holding	225	103	0.05	377	105	0.01
Power source	22494	4758	0.01	13454	4409	0.01
TW density	-1141	542	0.05	-1087	616	0.10
TW cultivator	-9005	2142	0.01	-7943	2339	0.01
Perennial	-	-	-	12857	4802	0.01
Dry days Rabi	-253	42	0.01	-	-	-
Sugarcane	275	135	0.05	478	158	0.01
Rice	-	-	-	-1472	513	0.01
General statistics	F-Ratio		10.6	F-Ratio		9.4
	Adjusted R^2		0.42	Adjusted R^2		0.43
	Durbin-Watson statistics		2.03	Durbin-Watson statistics		1.63

Table 6.2 confirms the importance of the tubewell power source already emphasized in the literature (Malik and Strosser, 1994; Strosser and Kuper, 1994; Meinzen-Dick, 1996) in explaining the quantities of tubewell water sold on the market. Electric tubewells with lower operation and maintenance costs and often flat rate electricity pricing, are the main sellers of groundwater, selling on average 22,494 m^3 more than Power-Take-Off (PTO) and diesel tubewells during the kharif season, and 13,454 m^3 more during the rabi season.

Differences in tubewell water sales between the Azim (non-perennial) and Fordwah (perennial) watercourses are significant only for the Rabi season, with tubewells located in the Fordwah watercourses selling 12,857 m^3 more than tubewells located in the Azim Distributary. In fact, as a result of the higher water shortage, most of the farmers in the Azim area are tubewell owners, whether jointly or solely, and the level of tubewell water sales is significantly lower than in the Fordwah area. The negative sign before the TW cultivator variable and the high significance of this variable confirms this hypothesis.

While the positive sign before the *Sugarcane* variable was expected, the negative sign before the *Rice* variable was not. This negative sign may express the competition between using tubewell water on the farm for agricultural production and selling tubewell water to other water users. With higher areas under rice, tubewell owners will need to control tightly their irrigation water supply, and will offer lower quantities of groundwater for sale during the peak demand period.

Farm survey data were further analyzed to identify the linkage between tubewell water transactions and the agricultural production strategy of farmers. The analysis showed that the main tubewell water purchasers, in terms of total volumes purchased, are market-oriented farmers specialized in cotton production, and also large farms with a diversified cropping pattern. However, these farms buy little in terms of number of hours per unit area. With an average of 35 $hr.ha^{-1}.yr^{-1}$, tenants record the highest intensity per unit area. Small intensive farms also participate actively in tubewell water purchases, even if they are already very active in canal water transactions and are often tubewell shareholders. Farms that are less market oriented purchase less tubewell water. Cash-flow and short-term credit constraints may limit their participation in tubewell water markets.

The main sellers of tubewell water are large commercialized farms. They sell 80% of the total volumes transacted on the market. Tubewell shareholders sell, on average, less hours, i.e. 27 hr per owner per year, than single tubewell owners that sell around 100 hr per owner per year. However, this result was not confirmed by the analysis of tubewell monitoring data: the number of shareholders for each tubewell is not related to tubewell water sales in this data set.

Social relationships may also explain specific tubewell water transactions. Rigourd (1996) showed the importance of direct family relationships and tenant-landlord relationships in explaining specific tubewell water transactions among water users. However, a high variability was observed among watercourses, with tubewell water transactions involving family members varying from 2% of total tubewell water transactions for FD 46 to 45% of total tubewell water transactions for AZ 63. Similarly, tenant-landlord relationships are involved in only 2% of the transactions for FD 62, to 25% of the transactions for AZ 20. In fact, the variability of the situations and the limited information available make any clear conclusion hazardous regarding the importance of social relationships in explaining existing tubewell water transactions.

6.1.3 Contracts and water prices

Water transactions within the watercourse command areas remain informal transactions between water users. The more formalized level of transaction is found when tenure relationships are superimposed on seller-purchaser relationships. In that case, tubewell water sales by the tubewell owner to the tenant may be specified before hand and are part of the tenure contract. Most of the transactions involve two farmers only, sometimes three to four farmers when the exchange of canal water turns modifies also the irrigation timing of farmers that are not directly involved in the transaction.

Monitoring data show that each tubewell owner participating in tubewell water markets has an average of 7 purchasers. A few tubewell owners, however, have access to a larger network of tubewell water purchasers. Active tubewell water sellers may sell water to 20-30 farmers. From the purchaser side, the majority of farmers purchase tubewell water from one tubewell owner only.

Prices are usually fixed by the tubewell owner, and are strongly influenced by the tubewell operation and maintenance costs. Factors that influence hourly prices of tubewell water include (see Malik and Strosser, 1994; Strosser and Kuper, 1994):

- The source of power of the tubewell, with lower prices for water obtained from electric tubewells that have lower operation and maintenance costs;
- The quality of pumped groundwater that has a negative (although limited) impact on prices;
- The tubewell discharge that determines the quantity of water pumped per hour of operation; and,
- Also, tubewell water prices paid at the end of the season are usually higher, to take into account the short-term credit provided by the tubewell owner.

Most of the tubewell water is paid for with cash in the command areas of the eight sample watercourses. In the case of Power-Take-Off tubewells, different types of arrangements may exist that are proposed to different purchasers. These arrangements range from a situation where the purchaser comes with his own tractor and does not pay anything to the bore and pump owner, to a situation where the tractor is provided by the tubewell owner and a per hour price is paid by the tubewell water purchaser.

Tubewell water prices are highly variable within very short distances, ranging from 8 $Rs.hr^{-1}$ to 80 $Rs.hr^{-1}$ in the command areas of the eight sample watercourses investigated. With a 1997 exchange rate of US$ 0.025 for one Pakistani rupee, and an average tubewell discharge of 28 $l.s^{-1}$, this is equivalent to a range from US$ 0.002 per m^3 to US$ 0.02 per m^3. Table 6.3 illustrates this spatial variability with basic statistics for tubewell water prices, using information collected through regular monitoring of tubewell water sales in the command areas of the eight sample watercourses.

Table 6.3. Basic statistics for tubewell water sale prices within the command area of the eight sample watercourse of the Fordwah and Azim distributaries. Information collected through weekly monitoring of tubewell water transactions during the period April 1994 to May 1995.

Distributary	Watercourse	Average TW sale price Rs.hr^{-1}	Minimum price Rs.hr^{-1}	Maximum price Rs.hr^{-1}	Standard deviation Rs.hr^{-1}	Coefficient of variation
Fordwah	FD 14	33	8	40	8	0.24
	FD 46	45	15	60	17	0.38
	FD 62	46	20	80	16	0.35
	FD 130	35	20	50	12	0.34
Azim	AZ 20	38	15	60	23	0.61
	AZ 43	31	18	45	12	0.39
	AZ 63	28	13	40	11	0.39
	AZ 111	38	20	50	9	0.24

The analysis of variance performed to compare prices between the 8 sample watercourses showed that prices are statistically different at the 95% significance level, with a value of the F-ratio equal to 2.04. The reasons explaining this difference have not been further identified. Looking at canal water supplies, it is interesting to note that the coefficient of variation of tubewell water prices is lower for watercourses with poor canal water supply (FD 14 and FD 130 along the Fordwah Distributary, AZ 111 along the Azim Distributary). Under such conditions, tubewell water markets are very active as in FD 14 and FD 130, or most of the farmers have invested in private tubewells as in AZ 111. The higher pressure on water resources may explain the reduced variability in tubewell water prices within the command area of these tertiary units.

The monitoring data also confirmed the absence of temporal variability in tubewell water prices within a season. More surprisingly, and unlike information reported in previous studies (Strosser and Kuper, 1994; Rinaudo et al., 1997b), these data show significant differences in tubewell water prices paid by different purchasers for a given tubewell. Out of a sample of 47 tubewells participating in tubewell water markets, 12 tubewell owners (25%) had constant prices for all of their purchasers. Other tubewell owners had been charging variable prices, with the extreme example of tubewell prices ranging from 23 Rs.hr^{-1}to 80 Rs.hr^{-1} for one tubewell owner.

Part of the observed variability could be explained by the diversity of payment arrangements for Power-Take-Off tubewells described above. Other factors that explain this purchaser-related price variability include:

- Tenure relationships with tenants paying lower prices than other purchasers;
- Social relationships, with family members being charged with lower prices; however, this is far from being a common practice, and some farmers even prefer not to sell to family members as they are not sure of being paid; and,
- Interlinked markets, with transactions between farmers involving other inputs, credit, labor, etc. Thus, participation of purchasers into specific farm activities of the tubewell owner, or use of the purchaser's tractor may explain different tubewell water prices by the tubewell owner, or short-term credit provided by the tubewell owner to the purchaser.

On average for the eight watercourses considered, hourly canal water prices are similar to hourly tubewell water prices. However, canal water prices are few. Also, it is not possible to estimate canal water prices per unit of water with accuracy, because of the high variability of watercourse head discharges. More information on canal water prices is presented in Box 6.2 that describes examples of intensive canal water markets.

6.1.4 Looking at examples of intensive canal water markets in the Chishtian Sub-division

Although the description of water markets presented in the previous sections represents the "average" situation for command areas with conjunctive use of surface and groundwater in irrigation systems in Pakistan (Renfro and Sparling, 1986; WAPDA, 1990), local conditions may modify the relative importance of the different types of water transactions. Of particular interest are watercourse command areas where intensive canal water markets, in terms of sale and purchase of canal water turns, have developed.

As little is known about these intensive canal water markets, a specific field activity was undertaken to investigate their functioning and organization in a limited number of watercourses. Three sample watercourses of the Daulat and Azim distributaries of the Chishtian Sub-division were selected for a set of limited field activities. The information collected during this exercise is summarized and presented in Box 6.2.

Rapid appraisal of larger areas close to these watercourses, as well as in other irrigation systems of the Punjab, have shown that these intensive canal water markets are often found in areas with high seepage losses, access to groundwater resources of good quality, and cheap pumping costs for groundwater (electric tubewells and aquifer close to the surface). As stressed by the comparison between the three sample watercourses of the Daulat and Azim distributaries, the variability and reliability of canal water supplies at the watercourse head directly influence the functioning of these intensive canal water markets.

Box 6.2. Intensive water markets in the command area of three watercourses in the Chishtian Sub-division.

Intensive canal water markets are illustrated below, using the example of three watercourses selected along the Daulat and Azim distributaries of the Chishtian Sub-division.

Daulat Watercourse 45810-R

Two sellers and a large number of potential purchasers characterize canal water markets in the Daulat Watercourse 45810-R. The plots of the two sellers are too high for canal water to reach. Both are tubewell owners and use tubewell water only on their farm. Usually, potential purchasers contact the sellers in June before sowing the cotton and rice crops. A meeting between all potential purchasers and each seller is organized to divide the full water turn between purchasers, and also to agree on the final price for canal water. Sellers prefer to sell canal water to friends or relatives and favor up-front cash payment. As both sellers are part of a *kaccha* warabandi, no adjustment in the warabandi is required as a result of the transaction. Transaction prices are around 400 Rs for an hour of water turns for the full season (26 weeks); thus, around 15 Rs.hr^{-1} for each hour. In 1994, prices were lower as a result of good rain and lower demand. Purchasers may pay different prices according to their social status. The revenue from canal water sales is sufficient to cover the operation and maintenance costs of the seller's tubewell. For purchasers, prices paid are still cheaper than operating diesel tubewells. In 1996, as a result of too unreliable canal water supplies at the beginning of kharif season, no purchaser was interested in buying the available canal water turns. As a result, to ensure that none would use their turns, the two (potential) sellers closed the watercourse outlet every time their turn would take place.

Daulat Watercourse 99440-L

Canal water transactions started to develop 10 years ago in the Daulat Watercourse 99440-L. As a result of the degradation in canal water supply reliability, however, these markets have further developed during the last three years. All farmers of the watercourse command area are involved in canal water transactions. But only landowners can sell canal water. Sellers are located in the middle and tail reaches of the watercourse and cannot use efficiently the little canal water supply that arrives at their farm as a result of high conveyance losses and high watercourse head discharge variability. Purchasers are located at the head of the watercourse command area. A few farmers do not participate in canal water transactions, as a result of their social status and honor (*Izzat*). Negotiations between potential sellers and purchasers start at the beginning of June before sowing cotton and transplanting rice. A price for the season is established by initial transactions and is usually valid for the whole watercourse command area. However, variability in price has been reported by purchasers, night water turns for example being slightly cheaper than day water turns. Prices reported by farmers for the last three years are around 100 Rs per hour of water turn for the full season, or around 4 Rs.hr^{-1}. Water may be paid up-front or at the end of the season. A three-fold gradual decrease in hourly prices has been reported during the last three years and results from the decreasing reliability of canal water supplies. Individual canal water turns are also sold during periods of scarcity, for prices at around 30-35 Rs.hr^{-1}, which is ten times more than seasonal prices. In case of several potential purchasers, canal water is sold to the highest bidder. Revenue from canal water sales are not sufficient to cover tubewell operation and maintenance costs. Changes in the warabandi schedule as a result of canal water transactions are not required as all users/purchasers are close to each other at the head of the watercourse command area.

Azim Watercourse 88130-L

Intensive canal water markets are functioning in the Azim Watercourse 88130-L for the last 20 years. All farmers of the watercourse are participating in canal water markets, with an equal proportion of sellers and purchasers. Some farmers participate as seller and purchaser, selling canal water to close neighbors and purchasing canal water from tail-enders. The main reason explaining canal water sales is the highly unreliable canal water supply and high conveyance losses along the watercourse. Tail-enders, that are electric tubewell owners with flat rate electricity price, sell their canal water turns to head-enders. Sale of individual water turns is the practice as canal water supply is too unreliable. Prices range from 10 to 30 Rs.h^{-1} mostly paid in cash at the time of the transaction. Although prices are fixed at the beginning of the water turn, they may be modified during the water turn transacted as a result of decreasing canal water levels and supply. In fact, the price of water is directly related to the water level in the distributary. If the canal water supply remains good during the kharif season, the intensity of canal water transactions increase with the passage of time. The warabandi schedule is not modified as a result of canal water transactions. Farmers reported cases of coalitions between head-reach farmers for not purchasing canal water turns from tail–reach farmers. At the time of tail-reach water turns, head-reach farmers would use canal water without notifying the tail-end farmers that own the turns. Thus, some policing is required from tail-enders regarding use of canal water during their turns.

6.1.5 Summary

Table 6.4 summarizes the type and functioning of existing water transactions in watercourse command areas based on the analysis of water markets in eight sample watercourses.

Table 6.4. Existing water trading activities in watercourse command areas (source: Rinaudo et al., 1997).

Type of transaction	Intensity	Rational for participation in water transaction	Type of payment (if any)	Characteristics of participants
Exchange of partial water turn	High	. To finish irrigation of given field (technical efficiency) . To compensate for variability in canal water supply . Change in location	No cash payment. Partial turns borrowed often not given back	Between neighbors, family members
Exchange of full water turn	Medium	. Higher water requirements during sowing period . Periods with limited demand (water used on fodder, to leach salts) . Sudden decrease/increase in canal water supply	No cash payment. Turn borrowed not necessarily given back	Between neighbors, depends on who has the turn and who can use it for exchange during periods of limited demand of high variability
Sale/purchase of canal water	Low	<u>Seller</u> . topography/high land . low canal water supply at watercourse head . canal water supply at farm too unreliable <u>Purchaser</u> . need of good quality canal water to leach salts	Usually cash payment, rare cases of water-for labor or water-for-tractor payments	From tail-enders to head-enders, some cases of seasonal sales of canal water turns that lead to modification of warabandi schedule
Sale/purchase of tubewell water	Very high	<u>Seller</u> . to build social capital . to maximize production as part of sharecropping arrangements . to amortize tubewell investments . to make profits from sale <u>Purchaser</u> . to increase quantities available for cultivation . to mitigate variability in canal water supply (insurance)	Mostly cash payment, transaction counted for in some sharecropping arrangements, preferential price given to tenants	Single owners selling larger volumes than joint tubewell owners, usually transactions between neighbors or within short distance, but longer distances also found
Exchange of canal water for tubewell water	Rare	. reducing overall losses <u>Giving canal water</u> . too low discharge at farm <u>Giving tubewell water</u> . good quality canal water required	No cash payment involved	Canal water given by tail-ender to head-ender, with head-ender having tubewell located close to tail-ender

Referring to the literature on water markets presented in Chapter 2, existing water markets in Pakistan can be more accurately defined.

- With canal water turns playing the role of *de facto* water rights, the sale and purchase of water turns can be considered as *water lease agreements* between farmers (Gould, 1989).

- No groundwater right is defined and tubewell ownership provides (unlimited) access to groundwater resources. In this context, tubewell water sale can be considered as *lease of extraction equipment or tubewell.*
- Most of canal water transactions do not involve any price. These transactions will be defined as *water trading* (Reidinger, 1994).

6.2 Impact of water transactions on irrigation water supply

The direct impact of farmers' participation in water markets is a modification in their irrigation water supply, in terms of quantity as well as in terms of quality (as will be discussed in Section 6.5). Several quantity-related aspects of water supply performance may be modified as a result of groundwater and surface water transactions, which include:

- The *volumes* of irrigation water received on the farm, whether for the whole year or for the season;
- The *timing* of irrigation water supplies, where water transactions may improve the balance between demand and supply of irrigation water for specific time periods;
- The *reliability and temporal variability* of irrigation water supplies; under conditions of very high variability and unreliability of canal water supplies that exist in the watercourses monitored, water markets may provide a localized way to mitigate this variability and unreliability (smoothing effect); and,
- The *equity* in water distribution within the watercourse command area; this issue is of primary importance in the context of Pakistan, and has often been raised by opponents to water market development. Higher flexibility in water allocation and distribution is often associated with increasing inequity, powerful landlords becoming also *water lords*.

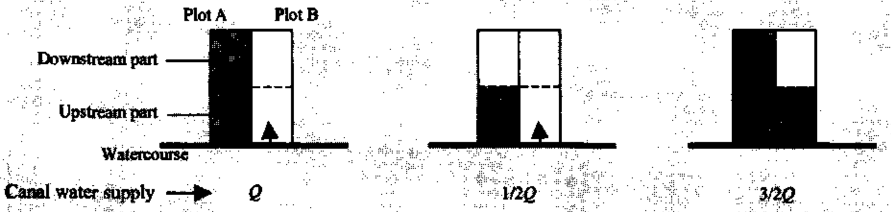
These aspects are discussed below, looking separately at canal water transactions and tubewell water transactions for the purpose of clarity. As it is difficult to estimate the impact of water transactions on irrigation water supply, the following sections combine simple examples that illustrate water supply performance issues, complemented whenever possible with the water supply and water transactions data collected for the eight sample watercourses that were discussed in section 6.1.

Impact of canal water transactions on canal water supply at the farm

The main objective for exchanging canal water turns is to mitigate the variability in canal water supplies and more closely fit the available canal water supplies to farm and crop water requirements. As explained in Section 6.1, the exchange of partial canal water turns primarily allows farmers to finish the irrigation of a given field and compensate for discharge variability at the watercourse head. As a result, improvements in irrigation application efficiency are expected for all participants, along with better yields for the downstream ends of their fields and for the farm as a whole. Although no data are directly available to estimate the overall impact of the exchange of partial canal water turns, this aspect is investigated through a simple simulation with the CropWat software (FAO, 1991) presented in Box 6.3. In practice, it is clear that the variability in canal water supplies is less predictable than the one used in this example. Also, less than half of a plot will be irrigated with $1/2Q$, and more than 3/2 plots will be irrigated with $3/2Q$, making the estimate of the expected impacts not as straightforward

Box 6.3. **Using the CropWat software to estimate the impact of short-term canal water transactions.**

A simple simulation is performed to estimate the importance of exchanging partial canal water turns on irrigation application efficiency and crop yields. A farmer with two plots A and B of equal size, that can be irrigated from separate field *nakkas* (see schematic diagram below), has a water turn that allows him to irrigate one plot A (or B) per week with an average canal water supply Q that is sufficient to satisfy the crop water requirements during one water turn. The actual canal water supply, however, is highly variable: it is assumed that the farmer receives $3/2Q$ half the time, and $1/2Q$ half the time. When the farmer receives $1/2Q$, he can irrigate the upstream half of any of the plots A or B, leaving the downstream half non-irrigated. When the farmer receives $3/2Q$, he can irrigate fully plot A and he has enough water to irrigate the upstream half of the plot B (or vice versa).



As a result, the two downstream parts of plots A and B will only receive the required amount of irrigation water every other warabandi turn. While the two upstream parts of these plots located close to the field nakka will be irrigated every week and receive 50% more water than their requirements. This will negatively impact on the irrigation application efficiency of the upstream portions, and on the yield of the downstream portion. Taking the example of a cotton crop, losses in cotton yields for the downstream parts of the plots are estimated by CropWat at 24% of a maximum yield obtained with appropriate irrigation, thus a total loss of 12% in the cotton production for the farm. With the possibility to exchange partial water turns every week, the farmer would give $1/2Q$ to another farmer when his supply is $3/2Q$, and get $1/2Q$ from another farmer when his supply is $1/2Q$. As a result, his irrigation application efficiency would improve and his average cotton yield would increase by 12% for the farm.

In practice, farmers do not rely only on the exchange of canal water turns to mitigate the variability in canal water supplies. To decrease the size of plots is a widely used option that improves irrigation application efficiency. By keeping plots of different sizes, farmers increase their potential to deal effectively with canal water supply variability, and reduce the duration of time to be transacted to finish irrigating a plot. This may explain the short-time duration involved in the exchange of partial canal water turns in the eight watercourses investigated, often around 15-20 min only. In the simple example given above, to split the farm into 4 plots of equal size allows the farmer to use variable canal water supplies efficiently. Also, the purchase of tubewell water to complement low canal water supplies is an option that improves irrigation application efficiency. Finally, as canal water supplies to neighboring farmers are correlated, only a portion of the overall variability in surface water supplies can be mitigated by such transactions.

The exchange of full canal water turns at the beginning of the season directly impacts on the timeliness of canal water supplies. With such exchanges, farmers are able to undertake pre-sowing irrigation and preparation of the land in an appropriate and more efficient manner. Because farmers do not rely (or rely less) on tubewell water for pre-sowing and the first irrigation, this results also in a positive impact on the quality of irrigation water and thus on seed germination.

The sale of canal water turns from downstream to upstream users leads to an overall gain in quantities of canal water available to the crops, as the total watercourse conveyance losses that would have been lost to bring canal water to downstream users are saved. In the eight watercourses analyzed in section 6.1, total conveyance losses from the watercourse head to the field have been estimated at 25-30% (Barral, 1994; van Waijjen, 1996), out of which half takes place along the main watercourse. Thus, 12.5-15% of the canal water supply related to the turn transacted is saved as a result of purchases from downstream to upstream water users. For the watercourse as a whole, this transaction is equivalent to saving or "creation" of canal water.

Overall, however, conveyance losses are reduced and lost to the aquifer and to potential tubewell water users. Thus, at the higher scale of the irrigation system, such water savings are more likely to be financial ones, and not real water savings. A similar situation occurs when rapid changes in the watercourse head discharge take place. Transactions that take place as a result of these changes allow upstream farmers to use canal water that would be lost anyway to tail farmers.

To acquire extra canal water turns does not only modify the total quantity of surface water received by the purchaser, but is also expected to improve the reliability of volumes of canal water received during the period considered. A watercourse with seven farmers, each one having a turn of duration, h, of one day, is used as example to illustrate this issue. The daily canal water discharge to the watercourse, q, follows a probability distribution with mean $\bar{q}$ and standard deviation $\sigma(q)$, and coefficient of variation $CV(q)$ defined as:

$$CV(q) = \frac{\sigma(q)}{\bar{q}} \tag{6.1}$$

For every farmer, the volume v received during his canal water turn for any given week is directly related to the probability distribution of q. The mean $\bar{v}$ and standard deviation $\sigma(v)$ are given by the Equation 6.2 and Equation 6.3. From these equations, it is clear that the coefficient of variation of v, $CV(v)$, is also equal to $CV(q)$.

$$\bar{v} = h\bar{q} \tag{6.2}$$

$$\sigma(v) = h\sigma(q) \tag{6.3}$$

If a farmer purchases the full turn of one of his fellow farmers, the duration of his turn will be $2*h$. With the assumption that the discharge received during two turns of a given week are statistically independent, the volume received after purchase, v_p, has the mean $\bar{v}_p$ and standard deviation $\sigma(v_p)$ given by the following equations:

$$\bar{v}_p = 2h\bar{q} \tag{6.4}$$

$$\sigma(v_p) = 2^{\frac{1}{2}} h\sigma(q) \tag{6.5}$$

As a result, the coefficient of variation of the volume after purchase, $CV(v_p)$, is equal to:

$$CV(v_p) = \frac{2^{\frac{1}{2}} h\sigma(q)}{2h\overline{q}} = \frac{CV(q)}{2^{\frac{1}{2}}} \qquad \textbf{(6.6)}$$

Thus, the variability in volume received after purchase is lower than the variability in volume received before purchase. In reality, however, the reduction in variability of volume received may be valid for some of the purchases only. Discharges and volumes received during canal water turns of neighboring farmers will be correlated and covariance terms are to be included in the calculations presented above. In such situations, to purchase canal water turns from neighboring farmers would reduce less drastically the variability of volume received.

Using the information collected through regular monitoring of canal water turns and watercourse head discharges, an attempt is made to analyze equity in canal water distribution, as well as the marginal impact of water turn transactions on equity. Two situations are compared:

- The actual situation with farmers participating in canal water transactions; and,
- A scenario where farmers would not participate in canal water transactions (i.e. following the agreed warabandi schedule specified for the watercourse).

A simple hydraulic model that estimates the volumes of canal water received at the farm based on the watercourse head discharge, the duration of the canal water turn, and conveyance losses along the watercourse, was used to compute both estimates of canal water depth received by farmers *with* and *without* canal water transactions (Barral, 1994).

Table 6.5 presents the coefficients of variation of seasonal canal water depths received by all farmers of a given watercourse, used here as the equity indicator. These coefficients of variation have been computed for the eight sample watercourses of the Fordwah and Azim distributaries and for the Kharif 1994 season, using detailed information on canal water turns effectively taken by farmers for the 26 weeks of the season similar to the information presented in Box 6.1 for the AZ 43 watercourse. Table 6.5 also includes the coefficient of variation of farmers' time allocation per unit area, and the seasonal temporal coefficient of variation of daily discharges at the head of the watercourse for the season considered.

The last row of Table 6.5 emphasizes the high inequity in actual seasonal canal water supplies within the watercourse command areas, with coefficients of variation of seasonal canal water depths ranging from 0.25 (FD 62) to 0.77 (FD 14). However, a minimal portion only of the inequity in seasonal canal water depths is related to canal water transactions. This is highlighted by the comparison between Row 3 and Row 4 that shows similar values for the coefficient of variation of seasonal canal water depths under agreed allocation and under actual distribution (i.e. taking canal water transaction into account). For three watercourses, namely FD 46, FD 62 and AZ 20, canal water transactions even led to a slight improvement in the coefficient of variation of seasonal canal water depth, thus, equity in seasonal canal water supplies was improved within the watercourse command area.

Table 6.5 Analysis of the impact of canal water transactions on the coefficient of variation of seasonal canal water supplies within the watercourse command areas. Canal water depths are estimated for all farmers of the eight sample watercourses of the Fordwah and Azim distributaries for the Kharif 1994 season, based on daily monitoring information and using a simple volume-balance model developed by Barral (1994). AZ 111 watercourse did not receive any canal water during the season considered.

Variable	Fordwah Distributary				Azim Distributary			
	FD14	FD46	FD62	FD130	AZ20	AZ43	AZ63	AZ111
Spatial coefficient of variation of time allocation per unit area	0.20	0.16	0.16	0.27	0.64	0.23	0.27	-
Temporal coefficient of variation of watercourse head discharge	0.73	0.49	0.38	1.0	0.74	0.90	0.94	-
Coefficient of variation of seasonal water depths for *agreed allocation*	0.70	0.45	0.28	0.32	0.54	0.33	0.42	-
Coefficient of variation of seasonal water depths for *actual distribution*	0.77	0.32	0.25	0.33	0.47	0.47	0.61	-

In fact, most of the inequity in seasonal canal water depths between farms is linked to the inequity in allocation of water turns (Row 1), and to the high temporal variability in watercourse head discharges (Row 2). The fact that farmers may or may not receive canal water during their turns according to the supply situation at higher levels of the irrigation system, is the major cause behind the observed seasonal canal water supply inequity. Further analysis of the actual seasonal canal water depths shows that small farmers with short water turns face a more variable seasonal water depth than large farmers with longer water turns. Similar to what has been explained above for changes in the variability of volume received resulting from the purchase of canal water turns, large farmers face a more reliable canal water supply as a direct result of their longer canal water turn.

Impact of tubewell water transactions on irrigation water supply at the farm

Easier than canal water transactions is the estimation of the impact of tubewell water transactions on volumes of irrigation water received by farmers. Yearly quantities of tubewell water pumped in the sample watercourses, along with the relative importance of tubewell water sales and tubewell water use by tubewell owners, is presented in Table 6.6 for the eight sample watercourses. The quantities presented in this table are computed by multiplying the number of hours of tubewell operation or tubewell water sale for each tubewell, obtained through regular monitoring of all tubewells of the eight sample watercourse command areas, by the measured discharge of the tubewell considered.

Table 6.6. Tubewell water use and transactions (10^3m^3) in the eight sample watercourses of the Fordwah and Azim distributaries for the period May 1994 to April 1995.

Variable	Fordwah				Azim			
	FD14	FD46	FD62	FD130	AZ20	AZ43	AZ63	AZ111
Tubewell water use	423	168	277	1,073	121	168	429	1,229
Tubewell water sales	254	22	81	642	54	15	71	24
(% of tubewell water use)	(60%)	(13%)	(29%)	(60%)	(44%)	(9%)	(17%)	(2%)

Tubewell water transactions play a dual role. Firstly, the purchase of tubewell water increases the overall quantity of irrigation available at the farm. This has allowed non-tubewell owners to increase their cropping intensity, although those are usually still lower than cropping intensities of tubewell owners. This may stress the lower quality of irrigation services provided by tubewell owners to tubewell water purchasers, as compared to the service obtained by tubewell owners themselves (Meinzen-Dick, 1996). Secondly, tubewell purchases play the role of an insurance to compensate partly or fully for the variability in canal water supply that reaches the farm.

To distinguish between the relative importance of these two roles is not possible with the tubewell water purchase information summarized in Table 6.6. The stochastic linear programming models developed in Chapter 5, however, provide the means to distinguish between tubewell water required to complement the average monthly canal water supply to obtain the full crop water requirements, and tubewell water counted for in planning decisions to compensate for canal water supply variability.

Table 6.7 illustrates the relative importance of each aspect estimated by the stochastic linear programming models for the eight sample watercourses. No direct comparison can be made between tubewell water use values presented in Table 6.7 as predicted by the stochastic linear programming models, and tubewell water use presented in Table 6.6 based on information obtained through monitoring for the period May 1994 to April 1995. The difference between actual values and predicted values has been investigated in Section 5.4 on the calibration and validation of the watercourse stochastic linear programming models. The dual role of tubewell water, differences in the areas considered, and the fact that capillary rise have not been considered in the stochastic linear programming models, are the main reasons explaining the observed differences.

The quantities of tubewell water required to increase irrigation water supplies are obtained by subtracting average canal water supplies, used as input into the stochastic linear programming models, from the total irrigation supplies required for the cropping pattern obtained through the optimization process. These tubewell water quantities are then subtracted from the total tubewell water use predicted by the models to obtain the quantities of tubewell water required to mitigate variability in canal water supplies.

Table 6.7. Yearly tubewell pumping (10^6m^3), tubewell water sales (10^6m^3), and relative importance of tubewell water to increase irrigation water availability or mitigate canal water supply variability, as predicted by the stochastic linear programming models for the eight sample watercourses of the Fordwah and Azim distributaries.

Distributary	Watercourse	Tubewell pumping	Tubewell water sales	Percentage of tubewell water to increase irrigation water supplies	Percentage of tubewell water to mitigate canal water supply variability
Fordwah	FD14	2.45	1.68	43	57
	FD46	0.74	0.64	90	10
	FD62	0.77	0.32	90	10
	FD130	1.36	0.98	98	2
Azim	AZ 20	0.60	0.32	89	11
	AZ43	0.86	0.32	46	54
	AZ63	1.73	0.73	64	36
	AZ111	1.91	0.20	87	13

The relative importance of tubewell water for reducing variability of the overall irrigation water supply at the farm (insurance) is higher in the watercourses with medium canal water supplies and relatively high variability such as FD 14, AZ 43 and AZ 63. In watercourses with poor canal water supplies, such as AZ 111, and to a lesser extent FD 130, and in watercourses with very high canal water supplies such as FD 46 and FD 62, tubewells are mainly used to increase the overall quantity of irrigation water for crop production.

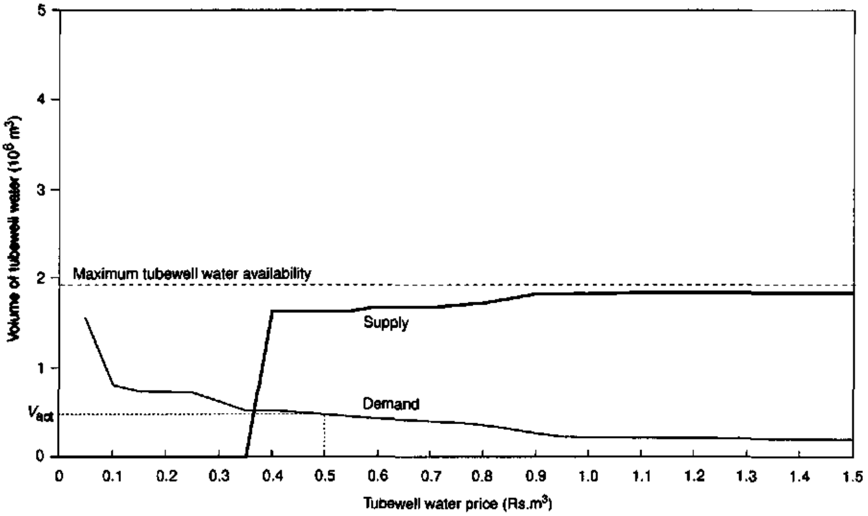
6.3 Use of stochastic linear programming and physical models to investigate the functioning and impact of existing water markets

The main objective of this section is to summarize results obtained by investigating water market issues by means of the optimization and simulation models introduced in Chapter 3 and further presented in Chapter 5. Issues related to the efficiency of existing water markets, the impact of water markets on agricultural production, farm income, and the impact on the physical environment are discussed below.

6.3.1 Analyzing supply and demand curves for tubewell water

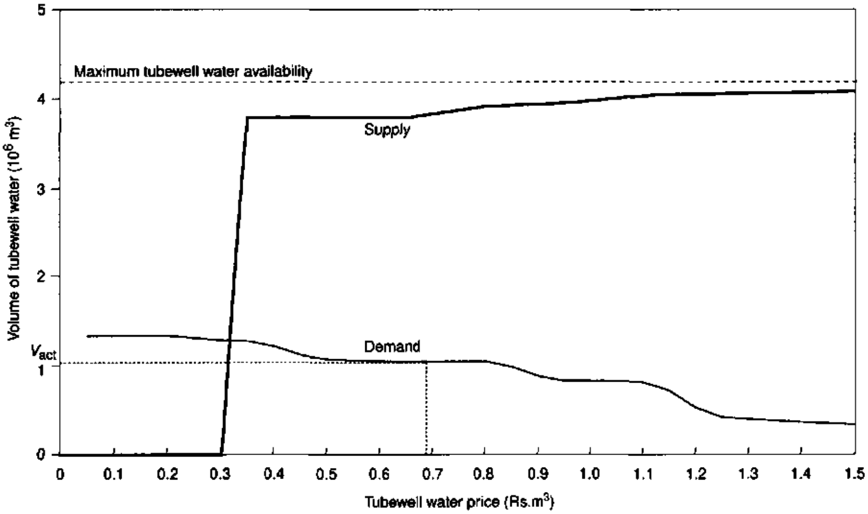
Using the stochastic linear programming models, supply and demand curves for tubewell water are obtained for each farm group and aggregated for the eight sample watercourses. To obtain these curves that link the quantity of tubewell water purchased or sold and its price, the stochastic linear programming models for each watercourse are run for different tubewell water (sale/purchase) prices. For *potential tubewell water purchasers*, the models are run *without* an upper boundary on monthly tubewell water quantities. For *potential tubewell water sellers* (tubewell owners), an estimate of the monthly quantity of tubewell water available for the watercourse is used as an upper limit for tubewell water use (owner use plus sales). Monthly quantities of tubewell water used/sold by each group and obtained through the optimization procedure are then aggregated into yearly quantities. Figure 6.7 and Figure 6.8 present tubewell water supply and demand curves obtained for two sample watercourses, AZ 20 and FD 130. In this context, two issues are now discussed: *allocative efficiency* of tubewell water markets and market perfection, and then the *monopoly power* of tubewell water sellers.

Figure 6.7. Aggregated supply and demand curves for tubewell water on the *AZ 20* watercourse, obtained by means of the stochastic linear programming models run for different tubewell water prices. The dotted line indicates the volumes of tubewell water currently used within the watercourse command area.



Both figures emphasize that tubewell water purchases at the present price are lower than the equilibrium quantities at the intersection between the supply and demand curves. The constraints faced by purchasers to access groundwater resources are in fact higher than those faced by tubewell water sellers themselves, and the tubewell water market does not allocate groundwater resources efficiently. Tubewell water sellers still favor own-farm tubewell water use, and transfer tubewell water shortages to purchasers. Although such shortages take place for very short periods of time, their impact on the planning decisions of potential tubewell water purchasers is significant. The difference in quality of irrigation services received by tubewell owners and tubewell water purchasers has been stressed by Meinzen-Dick (1996). The analysis of tubewell data collected through regular monitoring for the eight sample watercourses also shows that punctual shocks in canal water supply (such as the closure of the distributary for a couple of weeks) are mainly transferred to tubewell water purchasers. They have to wait for tubewell owners to satisfy their own needs before having access to tubewell water.

Figure 6.8. Aggregated supply and demand curves for tubewell water on the *FD 130* watercourse, obtained by simulations with the stochastic linear programming models for different tubewell water prices. The dotted line indicates the volumes of tubewell water currently used within the watercourse command area.



Although constraints on tubewell water purchases have been expressed in terms of quantity and lower quality of irrigation services received in the economic modes, price related issues may also explain that the quantity of tubewell water purchased is lower than the estimated equilibrium quantity. So far, tubewell water prices have been expressed solely in monetary terms, and are computed by dividing the hourly tubewell water price by the total quantity of water pumped during a hour. However, tubewell water transactions may also involve non-monetary elements that distort tubewell water prices reported by sellers and purchasers. As a result, a tubewell water purchaser would face a real price (value) for tubewell water higher than its cash market price.

For example, the supply of labor by the tubewell water purchaser to the seller may be required during periods of high labor demand such as sowing and harvesting of crops. Often, also, tenant-landlord relationships are superimposed on purchaser-seller relationships, hence tubewell water transactions have to be considered in the context of complex inter-linked input and output markets (Ellis, 1989). In some cases, tubewell water transactions involve social elements and the building of *social capital* by tubewell owners, similarly to what has been reported in the cases of intensive water markets in Box 6.2.

Transaction costs faced by tubewell water purchasers that are not accounted for in tubewell water prices may also limit the participation of tubewell water purchasers in tubewell water transactions. This would be mostly the case for non-active participants that rely on tubewell water purchases under exceptional situations and for which transaction costs per transaction or per unit of tubewell water purchased are relatively high. Further analysis of the relationship between actual purchases and tubewell water prices would be required to confirm that non-active participants in tubewell water markets have a higher Marginal Value Product of water than active participants.

The second element of discussion is the possible *monopoly* position of tubewell water sellers. A monopoly position of sellers also influences allocative efficiency and market perfection, but is treated here separately as it is a controversial element in discussions on markets in general and water markets in particular. Under current conditions of localized tubewell water markets, most of the tubewell owners are in a monopoly position. Tubewell seller's price strategy will depend on the price elasticity of the demand (i.e. the relative change in quantity purchased divided by the relative change in price) he is facing.

Based on information used to develop Figure 6.5 and Figure 6.6, arc price elasticities of demand for tubewell water have been computed. These range from close to zero values (see flat portions of the FD 130 demand curve) to around 0.85-0.9, or even higher values for tubewell prices lower than 0.1 $Rs.m^{-3}$ for the Watercourse AZ 20. It is important to note that the curves obtained through simulations with the stochastic linear programming models are not as smooth as what the economic theory would expect, as a result of shifts in farm choices for the different farm groups at different levels of tubewell water prices.

Overall, the price elasticity of demand estimated is rather low for the two watercourses considered. Thus, a monopolist setting of the tubewell water price would favor a high price and low volume strategy to maximize profit (Richard, 1996). In practice, however, and although water sellers may be interested to set up a high price for tubewell water, a high tubewell water price strategy was not found in the sample watercourses: on average, and although a large variability in tubewell water prices is observed, tubewell water prices remain close to the tubewell operation and maintenance costs (Strosser and Kuper, 1994). Several factors may explain this situation:

- Social pressure within the watercourse command area and the village may keep tubewell prices low or within a reasonable range.
- Water sellers may still ask extra services (e.g. labor) in the context of other input markets as discussed above. As a result, they would be able to maximize their profit and still comply with local social requirements.
- The variability of price elasticity reported in the sample watercourses among farm groups may also explain the low price policies opted for by tubewell water sellers. Any tubewell owner faces farmers with different price elasticities of demand that would require separate price policies. However, the possibility of differentiating between tubewell water purchasers may be limited as a result of the social context. Also, to establish the appropriate price policy for each potential seller may be too costly and difficult in terms of acquiring information on each potential purchaser.
- A competition between tubewells still exists, and may become an increasing element of tubewell water markets in the sample areas as illustrated by the increasing number of tubewells and tubewell owners presented in Chapter 4. Tubewells with lower operation and maintenance costs and competition between sellers would then limit the potential for high price policies.
- Finally, most of the tubewell water purchasers are themselves in situations of monopsone. This would counter-balance the monopoly power of tubewell water sellers and explain the current level of tubewell water prices.

6.3.2 Estimating the impact of water market scenarios on agricultural production using the stochastic linear programming watercourse models

The main objective of the following paragraphs is the comparison between different scenarios of tubewell and canal water markets taking place within the watercourse command area. The main objectives are to assess the impact of existing tubewell water markets on agricultural production and farm gross income, as well as assess the potential for developing enhanced tubewell and water markets within the command areas of watercourses.

Four scenarios have been selected for the analysis of the impact of water markets. These scenarios investigate the impact of existing tubewell water markets, and also discuss potential development of both tubewell water and canal water markets within the tertiary unit command area. The four scenarios are described below. Short abbreviations for these scenarios are provided in brackets.

- *Actual situation* (Actual) with existing tubewell water use and purchases constrained by farm group;
- *Absence of tubewell water markets* (NoTWWM), where the access to tubewell water is denied to all non-tubewell owners that rely on canal water supplies only;
- *Enhanced tubewell water markets* (TWWM+), where constraints on tubewell water use and purchases for specific groups are removed and replaced by watercourse level constraints on tubewell water use. Also, tubewell water sales are included as specific activities for tubewell owners that compete with owner-use of tubewell water for agricultural production.
- *Enhanced canal water markets* (CWM+), where monthly canal water constraints for each group are removed and replaced by monthly watercourse level constraints. This leads to separate reallocations of canal water between farm groups for each month, according to differences in the Marginal Value Product of canal water. This is also expected to influence tubewell water transactions.

Comparing the impact of water market scenarios on agricultural production

Table 6.8 summarizes the output of the simulations for the four scenarios, aggregated for the eight watercourses of the Fordwah and Azim distributaries. Several lessons can be drawn based on the results presented in Table 6.8.

- Firstly, the comparison between the actual situation (Actual) and the no tubewell water market scenario (NoTWWM) stresses the importance of existing tubewell water markets in increasing agricultural production and farm gross income. Overall, existing tubewell water markets increase the yearly cropping intensity by 56% (from 107% to 163%) and farm gross income by 67% (from Rs 10.7 million to Rs 17.8 million).

- Secondly, and although significant changes in the cropping pattern takes place, the overall impact of enhanced tubewell water market (TWWM+) on farm gross income remains limited. The increase in farm gross income as compared with the actual situation is around 6% only.

- Thirdly, the overall impact of enhanced canal water markets (CWM+) remains also limited. The increase in the aggregated farm gross income resulting from enhanced canal water markets is estimated at 4% of the actual farm gross income.

- Fourthly, enhanced canal water markets (CWM+) have a positive impact on the volumes of tubewell water use and the volume of tubewell water sales. However, the relative importance of tubewell water sales with comparison to total tubewell water use is not significantly modified (from 50% in the actual situation to 47% in the CWM+ scenario).

Table 6.8. Impact of four water market scenarios, i.e. actual situation (Actual), no tubewell water markets (NoTWWM), enhanced tubewell water markets (TWWM+) and enhanced canal water markets (CWM+) on irrigation water supply, agricultural production and gross income. (Aggregated results obtained by means of the stochastic linear programming models for the eight sample watercourses of the Fordwah and Azim distributaries)

Variable		Unit	Water market scenarios			
			Actual	NoTWWM	TWWM+	CWM+
Water	Canal water supply	10^6m^3	11.3	11.3	11.3	11.3
	Tubewell pumping	10^6m^3	10.4	5.3	13.0	11.3
	Tubewell water sales	Percentage of total pumping	50%	0%	55%	47%
Agricultural production	Yearly cropping intensity	Percentage of CCA	163%	107%	166%	168%
	Area under sugarcane	Ha	162.6	88.1	146.1	163.3
	Area under rice	Ha	69.9	52.9	115.74	106.6
	Area under cotton	Ha	918.5	591.9	968	953.3
	Area under wheat	Ha	1029.5	617	976.5	1020.9
Economic output	Total gross income	10^6Rs.	17.8	10.7	18.9	18.5
		Percentage of actual scenario	100%	60%	106%	104%

The four scenarios, however, do not record similar impacts on the eight watercourses considered because of differences in tubewell water constraints, and relative importance of different farm groups. Differences in relative terms between watercourses with regards to total farm gross income and tubewell water use are illustrated in Figure 6.9 and Figure 6.10.

Figure 6.9. Relative changes in *farm gross income* for no tubewell water market (NoTWWM), enhanced tubewell water market (TWWM+) and enhanced canal water market (CWM+) scenarios as compared to the gross income estimated for the actual situation. (Results are the output of the stochastic linear programming models for the eight sample watercourses of the Fordwah and Azim distributaries)

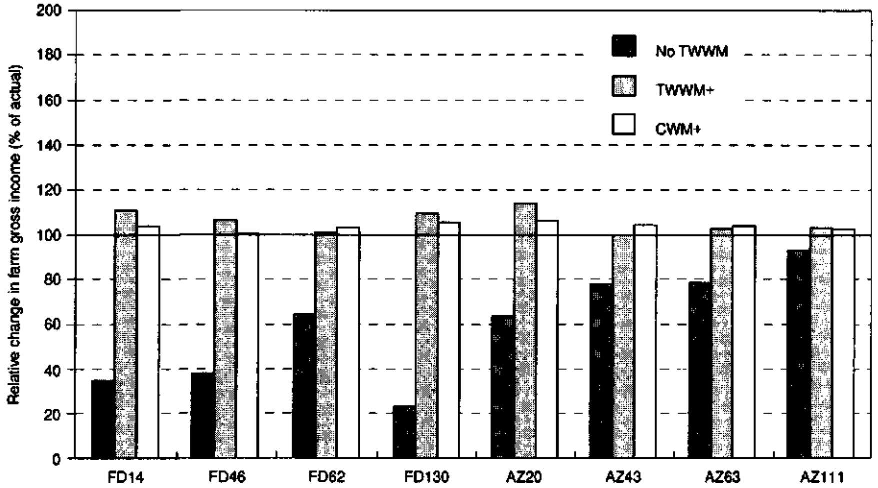
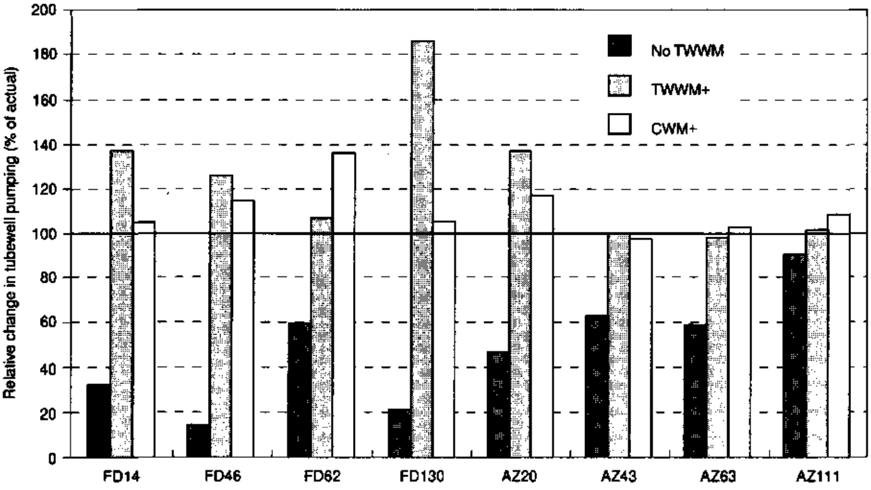


Figure 6.10. Relative changes in *yearly tubewell pumping* for no tubewell water market (NoTWWM), enhanced tubewell water market (TWWM+) and enhanced canal water market (CWM+) scenarios as compared to the yearly tubewell pumping estimated for the actual situation. (Results are the output of the stochastic linear programming models for the eight sample watercourses of the Fordwah and Azim distributaries)



The two figures re-emphasize the large difference between the non-tubewell water market scenario and the three other scenarios. However, this difference varies from watercourse to watercourse, and is lower for AZ43, AZ63 an AZ 111 watercourses where a large number of farmers are tubewell owners. The highest increase in farm gross income for both enhanced water market scenarios is recorded for the AZ 20 watercourse, that benefits from relatively high return from sugarcane cultivation as a result of the proximity to the sugar mill.

Although the change in total gross income remains modest, changes in total tubewell water use are very significant for FD 130 for the TWWM+ scenario as compared to other watercourses. However, this is mainly the result of a reallocation of tubewell water among tubewell owners themselves. Because group-wise tubewell quantity constraints have been removed and replaced by watercourse-wise constraints in the models, large tubewell owners that were already fully using the capacity of their own tubewells are able to access tubewell water from other owners in the TWWM+ scenario.

An important assumption used to develop the stochastic linear programming models has been to consider an average price for tubewell water for all tubewells of a given watercourse command area. Although this may be the best alternative for the analysis of water markets between tertiary units, secondary units and primary units, it does not reflect the heterogeneity of tubewell water prices existing within the watercourse command area that has been stressed in Table 6.3. In fact, the heterogeneity of tubewell water prices is expected to offer a higher opportunity for reallocation of canal water, with canal water being sold from tubewell owners with low operation and maintenance costs to tubewell owners with higher operation and maintenance costs.

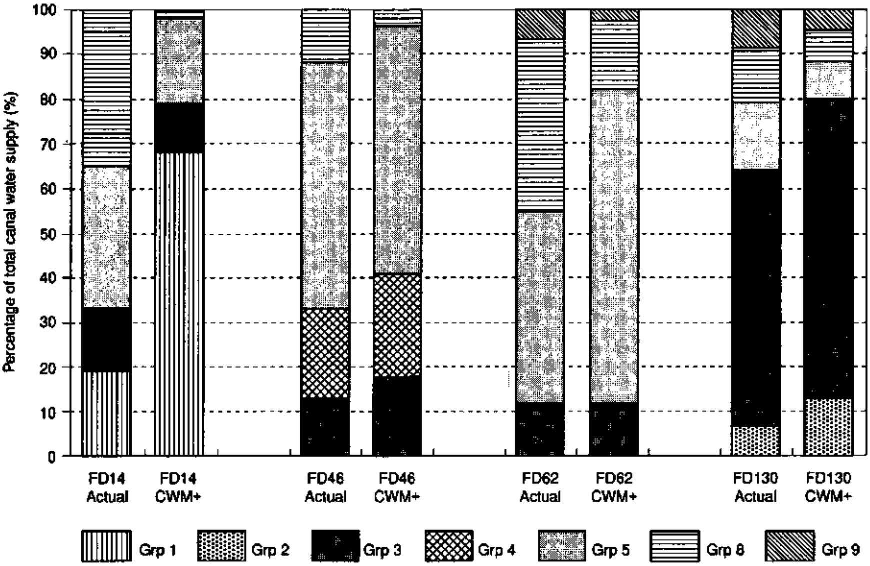
The impact of the heterogeneity of tubewell water prices was tested for the AZ 63 and AZ 111 watercourses, where two distinct groups of tubewell owners are present. Stochastic linear programming models were developed for both watercourses with different prices for tubewell owner groups. A tubewell water price of 20 $Rs.hr^{-1}$ was used for the first group, while a tubewell water price of 50 $Rs.hr^{-1}$ was used for the second group. The enhanced canal water market scenario (CWM+) was run with this modified model. For the AZ 63 watercourse, the relative increase in total gross income due to enhanced canal water markets was estimated at +7.5% for the situation with heterogeneous tubewell water prices, as compared to an increase of only +5.5% estimated with homogeneous tubewell water prices. For the AZ 111 watercourse, the difference was more significant, as the benefits from canal water reallocation with heterogeneous tubewell water prices were estimated at 10%, or three times more than the 3.5% increase recorded for the homogeneous tubewell water price condition.

There is a need to stress that although the stochastic linear programming models have been calibrated and validated under different canal water supply, tubewell water constraints and tubewell water price conditions, the constraints of the models may be at variance with constraints effectively faced by farmers. Thus, the limited difference between the actual situation and the two enhanced water market scenarios may have its source in the definition of the model itself. For all results presented, in fact, it is important to recall the canal water supplies and price conditions for which the model has been calibrated and validated. Thus, the results of simulations outside a given range of canal water supplies should be used cautiously.

Further analysis of the potential for reallocation of canal water within the watercourse command area

The scenario of enhanced canal water markets (CWM+) is selected to illustrate the heterogeneity of situations that exist within watercourse command areas, as well as in time. Using the output of the simulations of the stochastic linear programming models, the allocation to each farm group is computed for the different watercourses for the actual situation as well as for the enhanced canal water market situation. Figure 6.11 presents the relative allocation in percent of the total watercourse allocation for selected watercourses. Farmers whose relative allocation is reduced from the actual situation (Actual) to the enhanced canal water market scenario (CWM+) are canal water sellers, while an increase in the relative canal water allocation characterizes canal water purchasers. The farm group numbers that are used in Figure 6.11 refer to the farm groups presented in Section 5.2 and Table 5.1.

Figure 6.11. Yearly canal water allocation to farm groups (in % of total canal water allocation) for the actual situation (Actual) and for the enhanced canal water market scenario (CWM+). (Results of simulations with the watercourse stochastic linear programming models for the four sample watercourses of the Fordwah Distributary)



Overall, canal water transactions involve on average 20% of the total canal water supply for the eight watercourses considered. This varies from 50% of the total canal water supply for the FD 14 watercourse to a bit less than 3% of the total canal water supply for the AZ 111 watercourse, a watercourse located at the tail of the Azim Distributary and with limited canal water supplies. Within watercourse command areas, large differences exist between farm groups as illustrated by Figure 6.11. It is interesting to note, however, that there is no general group-wise trend in terms of farmer's potential role as seller or purchaser of canal water. The group's propensity to sell or purchase canal water is, in fact, directly related to the characteristics of the irrigation water supply for the watercourse considered, and also to the relative importance of the other farm groups within the watercourse command area.

The participation in canal water transactions of farms of Group 5, characterized by a limited crop diversification and the production of wheat for auto-consumption, illustrates this aspect. These farms are canal water sellers in FD 14 and FD 130, do not participate in canal water markets in AZ 63 and also FD 46, and are an important canal water purchaser in FD 62. Thus, further development of canal water markets within the watercourse command area would not lead specifically to increasing inequity among farm groups in terms of access to surface water resources and of overall economic returns.

The variability in the intensity of canal water transactions for the enhanced canal water market scenario exists also between months, with most of the reallocation taking place in August and September when the pressure on water resources is at its highest.

6.3.3 Impact of water markets on the environment using the water balance model, the SWAP93 model and the sodicity equation

The impact of water markets on the physical environment is investigated for the different water market scenarios discussed in the previous section, using the simulation models that have been presented in Chapter 3 and Appendix 2.

The water balance model, calibrated by van Waijjen (1996) for the Kharif 1994 and Rabi 1995 season for the eight sample watercourses of the Fordwah and Azim distributaries, is used to estimate the impact of these scenarios on the recharge to the aquifer and groundwater table depth. Canal water supplies computed for the sample watercourses, the cropping pattern obtained from simulation with the stochastic linear programming models, and crop irrigation applications obtained from the analysis of information collected for the period 1994-95, are input into the water balance model. The model includes also capillary rise, an element of the water balance that was neglected for the computation of irrigation water requirements included in the stochastic linear programming models.

As discussed in Section 5.4, to neglect capillary rise in the stochastic linear programming models eventually leads to higher predictions of tubewell pumping. From a water balance point of view, however, this does not influence estimates of the net recharge, defined as the difference between positive (percolation and conveyance losses) and negative (capillary rise and tubewell pumping) additions to the aquifer. Table 6.9 summarizes the impact of the four scenarios defined in Section 6.3.2, i.e. actual situation (Actual), no tubewell water markets (NoTWWM), enhanced tubewell water markets (TWWM+) and enhanced canal water markets (CWM+), on the yearly net recharge to the aquifer expressed in mm.

Table 6.9. Yearly net recharge (mm) estimated for four water market scenarios, i.e. actual situation (Actual), no tubewell water markets (NoTWWM), enhanced tubewell water markets (TWWM+) and enhanced canal water markets (CWM+), using the water balance model for the eight sample watercourses.

Scenario	Fordwah				Azim				Average
	FD14	FD46	FD62	FD130	AZ20	AZ43	AZ63	AZ111	
Actual	-380	233	189	-70	253	42	-165	-394	-37
NoTWWM	-26	510	313	227	438	227	-8	-355	166
TWWM+	-401	217	148	-96	214	42	-140	-382	-50
CWM+	-378	247	95	-63	219	38	-176	-433	-56

Overall, Table 6.9 stresses the important impact of existing tubewell water market on the net recharge, from a positive net recharge of 166 mm without tubewell water markets to a negative (although modest) net recharge of –37 mm in the actual situation. Thus, tubewell water sales have an important impact on the lowering of the groundwater table. Although computed values of net recharge are rather similar for the actual situation and the two enhanced water market scenarios, the lower average net recharge computed for the TWWM+ and CWM+ scenarios (from –37 mm to –50 mm and –56 mm, respectively) stresses a slightly higher pressure on water resources. As the last five years have recorded a significant drop in the groundwater table depth for some of the watercourse command areas (van Waijjen, 1996), this extra pressure on water resources may increase the mining of the aquifer that is already taking place. It is important to note, however, that the difference in net recharge between the actual situation and the two enhanced water market scenarios TWWM+ and CWM+ is less significant than what could have been predicted by looking only at the estimated increase in tubewell water use for these two scenarios.

Complementary to the analysis of recharge to the aquifer is the analysis of the long-term impact of water markets on soil salinity and sodicity. The difference between the actual situation and the same water market scenarios is computed using the simulation output of the SWAP93 model as calibrated and validated by Kuper (1997), as well as the output of the empirical equation linking soil texture and irrigation water quality. These differences are presented in Table 6.10 in percentage of the actual situation.

The drastic difference between the actual situation and the no tubewell water market scenario (NoTWWM), that has already been illustrated for the net recharge in Table 6.9, is also valid for soil salinity and to a lesser extent soil sodicity. However, the impact is now negative, stressing the impact of purchases of tubewell water of poor quality on these two parameters. The difference between the NoTWWM scenario and the actual situation is very small for watercourses that have:

- A large percentage of tubewell owners in their population such as AZ 63, AZ 111 and to a lesser extent AZ 43;
- A high capillary rise and poor groundwater quality such as FD 14;
- A high percentage of fine textured soils and significant capillary rise such as FD 62.

Table 6.10. Long-term changes in salinity and sodicity for the four water market scenarios, i.e. actual situation (Actual), no tubewell water markets (NoTWWM), enhanced tubewell water markets (TWWM+) and enhanced canal water markets (CWM+), as a percentage of the actual situation. (Estimates are obtained using the output of simulations of both the SWAP93 model and the empirical sodicity equation developed by Kuper (1997))

Variable	Scenario	Fordwah				Azim				Average
		FD14	FD46	FD62	FD130	AZ20	AZ43	AZ63	AZ111	
Total salt content in the soil profile	Actual	100	100	100	100	100	100	100	100	100
	NoTWWM	97	26	68	44	22	77	98	97	66
	TWWM+	89	100	116	70	86	100	82	97	93
	CWM+	98	95	70	80	90	100	95	97	91
Sodicity expressed in SAR	Actual	100	100	100	100	100	100	100	100	100
	NoTWWM	79	90	83	50	96	98	97	99	87
	TWWM+	103	101	102	108	102	100	100	100	102
	CWM+	100	101	109	103	102	100	100	101	102

The results for salinity are rather favorable for the two enhanced water markets scenarios, and more particularly for the CWM+ scenario. Thus, enhanced canal water markets would reduce the long-term salinity in the watercourses considered. The sodicity results, however, are less favorable for the two enhanced water market scenarios, although the average difference between sodicity estimated under these scenarios and the actual situation remains modest at +2%. Two locations, however, would require special attention: for the FD 130 watercourse, the average sodicity level would increase by 8% under the enhanced tubewell water market scenario, as a result of the increase in the use of tubewell water of poor quality; and a similar increase in the average sodicity level would be recorded for FD 62 under the enhanced canal water market scenario as a result of its finer soil texture and the importance of capillary rise in the water and salt balance of this watercourse.

6.4 Summary and discussion

This chapter stresses the importance of surface and groundwater markets in eight sample watercourse command areas of the Chishtian Sub-division. The types of water transactions observed in these sample areas are similar to what has been described in other areas of Pakistan. However, the use of more accurate and detailed information on canal water use stresses a higher intensity of canal water transactions as compared with what had been reported so far in other studies.

The analysis of existing water markets within the watercourse command areas shows the importance of short-term exchanges of canal water turns to mitigate the variability of canal water supplies, as well as tubewell water purchases to increase the availability of irrigation water and reduce the variability of total irrigation water supplies. Mainly informal and localized, existing water markets increase significantly the flexibility of irrigation water supplies. Under specific conditions of high canal water supply reliability, high watercourse conveyance losses, good groundwater quality and low tubewell operation and maintenance costs, intensive canal water markets also develop. In fact, farmers show that they are able to adapt to changes in canal water supply and access to tubewell water resources.

The impact of existing tubewell water markets on agricultural production is significant, estimated at 40% of the actual farm gross income for the eight watercourses of the Fordwah and Azim distributaries. As expected, the impact is more significant in watercourse command areas with a low percentage of tubewell owners. The impact of existing short-term canal water transactions on agricultural production, however, remains difficult to evaluate with the models developed for the present study. Surprisingly, the analysis of the potential impact of enhanced tubewell and canal water markets within the watercourse command areas show a limited impact on agricultural production. Several issues may explain this limited impact.

- For the two scenarios of enhanced water markets, the reallocation of canal water and tubewell water between farm groups is made independently for each month. A separate monthly constraint in tubewell water availability or canal water supplies is kept in the models. However, the comparison between the marginal value product of irrigation water, an output of the stochastic linear programming models, shows a higher potential for reallocation of canal water (or tubewell water constraint) between months for given farm groups than between farm groups. Thus, the reallocation of water supplies between farm groups for each month separately is likely to yield limited impact on agricultural production. This issue, seen as an important element of the discussion on the potential for water market development in irrigation systems in Pakistan, is further discussed in the last section of Chapter 7.

- The limited difference between the existing situation and enhanced water market scenarios would support the statement that existing water management within the watercourse command area functions rather efficiently and is close to its local optimum.

- With the significant increase in cropping intensity recorded for the last 20 years, and the relatively small difference in financial returns from different crops, the potential for increased cropping intensity and drastic changes in the cropping pattern may be limited. This would imply that increased agricultural production is to be mainly found in increases in crop yields and productivity per unit area, an element that may not specified be enough in the stochastic linear programming models developed for the present study.

The analysis of the impact of existing canal water transactions on equity of water supply, along with the estimated reallocation of canal water among farm groups, does not support the often-expressed fear that water markets (may) increase inequity in access to water resources. The analysis undertaken in the present study considers only the economic aspects of water allocation. The addition of political and social dimensions and power relationships between water users may significantly modify the analysis of inequity in water allocation. But such political and social dimensions are always present whatever management option (market or no market) is selected. Further analysis on the relationship between existing water markets and equity, however, would be required.

The significant impact of tubewell water markets on the physical environment is quantified, and found to be highly significant. At the opposite, enhanced canal water and tubewell water transactions within watercourse command areas do not pose a real threat to the sustainability of irrigation systems. However, the analysis stresses the diversity of situations between watercourses, based on the groundwater table depth, groundwater quality, and the relative importance of tubewell water and canal water.

Chapter 7

Scenarios for potential canal water market development in the Chishtian Sub-division

This chapter discusses the potential for water market development above the inlet of the tertiary unit. Current policy discussions taking place in Pakistan are first summarized. Then, selected technical and institutional issues related to water market development are discussed. The impact of selected water market scenarios between watercourses and between distributaries is estimated, looking at both the agricultural production and farm gross income, as well as the physical environment. The final section summarizes and discusses the main results obtained in this research on the potential for water market development in the irrigation sector in Pakistan, using results of both the analysis of existing water markets (Chapter 6) and potential water markets (present chapter).

7.1 Background

Discussion about the potential for water market development in Pakistan started in 1992-93 with the publication of the first draft of a controversial World Bank report (World Bank, 1994). The report stated that irrigation water had too long been treated as a public good, allowing deficiencies of the system to grow and to remain unsolved. The lack of a mercantile relationship between water suppliers and users, combined with the lack of management autonomy of the line agencies, were seen as the main factors explaining the breakdown in administrative discipline, the poor performance of the irrigation sector, and the low productivity of irrigated agriculture in Pakistan (World Bank, 1994).

The report advocated drastic changes in irrigation sector policies if Pakistan was to tackle the coming challenge of increasing population and consequent food requirements. It listed four possible options to improve financial and physical sustainability, and increase water use efficiency:

- *Direct intervention by the legislative body to restore discipline via exhortation and coercion*;
- *Revival of the existing agency via internal reorganization and realignment of staff and responsibilities*;
- *Restructure the agency to form a public authority with real autonomy, a hard budget constraint, and a mandate of self-sustainability*; and,
- *Privatization of the public utility by selling government held equity to private shareholders*.

The first option was seen as unfeasible, because of its political repercussions. The second one, although possible, had already failed in past projects and was not expected to lead to major improvements in irrigation system performance. Also, the impact of both options on water use efficiency was not clear as no new incentive was provided to improve water use efficiency. The fourth option was seen as suitable to address issues related to efficiency, productivity and self-sustainability, but too abrupt and politically not acceptable.

The third option was seen as appropriate and further promoted through high level meetings with decision-makers. It includes major institutional changes such as the autonomy of public agencies, a greater role of the private sector and the development and institutionalization of market mechanisms for efficient allocation of irrigation water at different scales of the irrigation system. As a result of these high level meetings and of a large number of discussions with actors involved in the irrigation sector, the Government of Pakistan decided to create autonomous Provincial Irrigation and Drainage Authorities (PIDAs) for the development and management of the irrigation and drainage sector in each Province, along with Area Water Boards (AWBs) that would manage main canal command areas. An ordinance for the creation of this new institutional setup was presented before the Provincial Assemblies of each Province and promulgated by these assemblies in July 1997.

So far, however, most of the policy debate has focused on the modifications of the existing organizational and institutional setup. Relatively little attention has been given to the responsibilities of each actor and the tasks to be performed to effectively improve the performance of the irrigation system. Also, no further proposal has been made on the development and implementation of water markets with the existing infrastructure and a new institutional set-up. Although it is clear that water markets envisaged will differ from the existing localized and short-term water markets described in Chapter 6, what is meant by water market development in the irrigation sector in Pakistan remains everybody's opinion and lacks proper analysis of the existing system and of its particularities.

7.2 Defining potential water market scenarios

Scenarios for water market development can be classified according to the spatial scale at which the transaction take place, the object transacted (whether volumes of water or water rights), and the source of irrigation water considered (surface water, groundwater or both). Here, the choice has been made to investigate the potential for *surface water markets* only. The assumption is that tubewell water markets would still continue to exist as in the present situation, but remain localized and limited to the command area of a given watercourse. The following paragraphs discuss different options for canal water market scenarios, looking first at the spatial scale at which reallocation of canal water may take place, then investigating possible ways of defining rights for surface water.

Looking at different spatial scales

The spatial scale at which the reallocation of irrigation water is expected to take place is seen as a central element to the discussion on the potential for water market development. The scale at which water markets yield the highest increase in agricultural production and productivity would likely become the target of interventions promoting water market development. The spatial scale has several implications for the following issues:

- The need to confront supply of, and demand for, irrigation water. This means information sharing between potential sellers and purchasers, agreement on a common market price, payment of purchases;
- The possibility to technically, physically or operationally reallocating canal water at that scale;
- The information requirements to monitor canal water supplies and transactions; and,
- The need to develop a mechanism that transfers the output of the market reallocation from the marketplace to the operator/manager of the canal network. This means translating the information produced on the market into specific operational targets. The operator/manager would then take appropriate and timely decisions at the appropriate scale being considered, as well as at higher scales of the irrigation system.

As presented in Figure 3.5 in Chapter 3, water markets can be envisaged between individual farms from the same or different tertiary units, between tertiary units from the same or different secondary units and between secondary units. Two main scenarios are selected for detailed analysis of their technical feasibility and impact:

- Canal water markets *between tertiary units off-taking from the same distributary*; water transactions may be envisaged between individual watercourses, or between groups of watercourses that off-take from a common reach of a secondary canal. Transactions between reaches may require reduced changes in the physical infrastructure and canal operation, but are expected to yield lower productivity gains.

- Canal water markets *between distributaries* off-taking from the same main canal or branch canal.

Both scenarios are considered independently in order to identify their marginal impact on performance indicators related to water supply, the physical environment, and agricultural production. Also, current limitations in modeling and optimization capabilities of the software used for the present study do not allow an easy simultaneous reallocation of canal water between tertiary units and between secondary units for the high number of tertiary units considered (160!).

Transactions between individual farms of the same tertiary unit have already been analyzed in Chapter 6. As a result of operational difficulties and expected high transaction costs, transactions between individual farmers located on different watercourses, and between watercourses off taking from different distributaries, are not considered. As the system under consideration is the sub-division, water markets within the sub-division only are considered. The potential for water market development between sub-divisions and canal command areas is fully recognized, but is out of the scope of the present study. It can be better tackled with the use of optimization models developed at higher scales of the irrigation system, such as the Indus Basin Model, an optimization model that has been developed in the 1980s for planning purposes that considers the canal command area as the basic unit of analysis.

Defining the object of the transaction and water rights

For each scale where reallocation of canal water is envisaged, several options exist in terms of the definition of the object of the transaction. These include:
- A volume of canal water transacted punctually as needs arise;
- A volume of water transacted at the beginning of the season, that may be either linked or not to a given time period; and,
- A water right transferred for a temporary but long enough period, or transferred permanently to another water user.

The literature on water markets has stressed the importance of water rights as a basic requirement for water market development (Rosegrant and Binswanger, 1994). This does not necessarily imply formal ownership rights: in fact, water users rarely have property rights over water resources, and a long-term lease agreement with the State who remains the sole water owner is the most common situation. However, a clear definition of the entitlement of each user is required, not only in terms of quantities or probabilities to receive these quantities, but also in terms of its location and time of use. As stressed above, formalized surface water rights do not exist in Pakistan, although the term *de facto* water right has been used to define canal water turns within the watercourse command area (Bandaragoda and Rehman, 1995). Elements integrated into the design of the irrigation system are important to defined *de facto* water rights or existing user's entitlements.

The definition of existing user's entitlements or *de facto* water rights, along with the means to enforce these entitlements, varies according to the scale investigated. In theory, the basic entitlement in surface flows for irrigated areas in Pakistan is defined by the *water duty* in cubic feet per second (or cusec) per 1000 acres (i.e. the flow of water an area is supposed to receive throughout the season). Water duties defined for watercourse command areas are aggregated and seepage losses added to obtain water duties and design discharges at higher scales of the irrigation system. Different elements that are directly related to the water duty include:
- The *design or authorized discharge* and related target gate opening/water levels defined at the head of the main canal or secondary canals. Enforcement of the design or authorized discharge requires strict control over the distributary head gates by staff from the provincial irrigation departments operating these gates.
- The *dimensions of the watercourse outlet*, that specifies the *division factor* or percentage of the flow that enters into the watercourse command area and the (design) discharge at the head of the tertiary unit when the distributary is run at its Full Supply Level. The enforcement of the water entitlement is obtained through the physical structure and dimensions of the outlet.
- The *time allocation per unit area* within the command area of the tertiary unit. The time allocation is aggregated for each landowner into a *water turn* that represents a weekly time duration during which the landowner is entitled to use the entire surface water supply entering into the watercourse. At this level, enforcement is mainly related to social control and mutual agreement among water users.

In practice, these elements are at variance with the official rules and design values. Changes in target discharges at the head of the distributaries (Kuper, 1997), modification of outlet dimensions (Kuper, 1997; Rinaudo et al., 1997a) and variability in time allocation per unit area for farmers located along a given watercourse (Bandaragoda and Rehman, 1995) are part of the current management of the irrigation system. Part of this variability results from physical and technical constraints, localized objectives of gauge readers, and interference of water users into the management of the irrigation system. However, the same basic elements discussed above are still used to define actual entitlements.

Also, the large variability in the inflow to the study area, and in discharges supplied to distributaries and watercourses, means that entitlements have a probability dimension highly variable among locations and scales. Gauge readers, for example, favor specific distributaries against others (Litrico, 1996). And the variability of the distributary head flows is not shared equally between all watercourses along a given distributary. The water turn remains the only portion of the entitlement that is not variable. Minor changes are incorporated into the agreed warabandi schedule from season-to-season, and farmers actively exchange part of their water turns, but the entitlement or *de facto* water right remains intact.

As specified in Chapter 2, several alternatives exist for the definition of water rights, such as volumetric water rights, time based water rights, share of the flow water right, or portion of a water storage. The definition of the right may depend on the characteristics of the water resources, but is strongly influenced by the infrastructure required to allocate or reallocate these rights among users.

At the head of secondary canals, surface water rights can be defined in terms of a volume of water. This volume can be disaggregated into a duration of use and a flow rate (similar to the actual target discharge). With the high inflow variability at the head of the system, a probability distribution has to be attached with this volume. Practically, the volume may be divided into sub-volumes with various levels of certainty: 70% of the volume defined by the water right with 100% certainty, then 15% of the right with 75% certainty, and the remaining 15% of the right with 50% certainty. This is, in fact, very close to the way the irrigation system is currently operated with rotations implemented between distributaries with specific preference orders (equivalent to probabilities of receiving the target discharge).

At the head of the watercourse, surface water rights can be defined as a share of the flow supplied to the distributary. Using the principle of proportionality as the basic concept, a reduction in distributary head discharge would be equally shared between all outlets. The distributary head volume, combined with the share of the flow at the head of the watercourse, is in fact equivalent to a watercourse head volume with a given probability distribution directly related to the probability of distribution of the distributary head discharge.

Finally, the surface water right at the farm can be defined as a time allocation per unit area similar to the existing canal water turn. One may wonder the complexity of some of the definitions of water rights, the way water users may understand these rights, and then take specific decisions accordingly. The practice, however, has shown that farmers have a very good understanding of some of the elements that influence their water supply (See Hoeberichts, 1995), although they may not have all of the information required to add certainty to this understanding. Existing water users' interference in the management of the system at the head of the distributary and at the watercourse heads, shows that farmers are able to estimate gains from changes in distributary target discharges or share of the flow for watercourses. Also, farmers are able to attach an economic value to these changes (Rinaudo et al., 1997a).

Two important comments can be made regarding the definition of the water rights at different scales of the irrigation system. Firstly, the definition of volumetric surface water rights at a certain level of the irrigation system is the combination of three elements: time, flow rate, and probability. To transfer a portion of the water right may be implemented for any of the three elements. Taking the example of the distributaries, reallocation may be undertaken by modifying the distributary target discharges, by modifying the duration of time a distributary receives its target discharge, or by modifying the probability of receiving the target discharge. This last option is similar to shifting distributaries from one preference order to the other one in the current rotational programs undertaken by the Irrigation Department to share canal water shortage between distributaries in the Chishtian Sub-division.

Secondly, as a result of the existing infrastructure and its supply-driven design, water rights defined as volumes are constrained by a pre-defined given temporal distribution of supplies within the year or season. Although the water right equivalent to a volume of canal water can be defined at the head of a watercourse, the reallocation of this right to another watercourse, implemented through a change in the outlet dimensions, means that this temporal distribution is kept. As will be demonstrated below, this is an important constraint to current reallocation among units of the irrigation system of canal water rights as defined above.

Institutional and organizational issues related to the development of water markets

With the implementation of water markets, new activities are required to manage the irrigation system. Apart from the existing tasks that are currently performed for the operation and maintenance of the irrigation system, new tasks would include:

- To collect information on supply and demand and aggregate this information at the scale at which the market operates;
- To confront supply of and demand for irrigation water, to identify market price and quantities for reallocation;
- To assess the technical feasibility of reallocation, and identify externalities and third party effects;
- To implement the reallocation of canal water: to modify target for canal operation, to change gate opening, to modify the size of outlets, to prepare scheduling plan accordingly to new targets, etc;
- To monitor water flows/share of the flow at various points along the irrigation system;
- To enforce the reallocation of canal water and resolve conflicts that may arise regarding water rights and reallocation (third -party effects and compensations);
- To transfer the proceeds of sales from purchasers to sellers.

The implementation of a water market may require significant changes in the institutional setup and tasks performed by the different actors involved in irrigation management. To implement water markets requires a move from purely supply-driven irrigation system to something that is more demand-driven under specific physical and supply constraints. Issues of importance that are to be considered relate to the role of different actors in the management of the irrigation system and the development of water transactions, and the interface between actors for water, information and financial flows. Actors that may participate in water markets include existing actors such as individual farmers, groups of farmers and the operating agency that manages the canal network. New actors may include market committees to organize the transactions and put potential purchasers and sellers in contact, or a legal body for resolution of conflict, monitoring of canal water reallocation, and control of third-party effects.

The selected institutional setup will depend on the scale where reallocations are envisaged, and the need to formalize the transactions. Options that can be considered for the organization of water markets range from *centralized,* with an organization playing the role of intermediary between potential participants, to *decentralized* in which potential sellers and purchasers are in direct contact. In the case of centralized organization, transactions may be organized as auctions where each participant bids for a share of the quantities put on sale, or separate negotiations between water right owners and the intermediary organization.

The main focus for the analysis of potential water market development described in the following sections is on the *reallocation of canal water rights defined as a total volume of surface water temporally distributed between months* of the year and taken at a specific location of the irrigation system. As mentioned above, this definition of a water right means that the allocations to the different months of the year are interdependent. Technical issues related to reallocation of these surface water rights between watercourses of the same distributary, and between distributaries, are developed in Section 7.3, using the example of the Fordwah, Azim and Masood distributaries of the Chishtian Sub-division.

7.3 Technical issues related to the development of water markets in the Chishtian Sub-division

The reallocation of canal water rights between distributaries may influence simultaneously the three elements of the water right: the time duration, the target discharge and the probability distribution of the discharges. Changes in the time duration and probability distribution of discharges would require operational changes and new rotational schedules that incorporate the reallocation output. And no specific constraint related to the existing physical system is expected. Field observations have shown that the Fordwah Branch Canal could handle a large range of discharges, with inflows at the head of the Fordwah Branch Canal varying from 7-8 to 33 $m^3.s^{-1}$, thus allowing enough flexibility to reallocate surface water along the Fordwah Branch.

Changes in distributary target discharges, however, may be more problematic. It is clear that the presence of gates at the head of most of the distributaries in the Chishtian Sub-division provides flexibility and modification in distributary target discharges are possible. For un-gated small distributaries, it may not be possible to individually modify target discharges. But it is technically possible to do so through the combined use of cross-regulator gates and gates of close-by distributaries. The most serious constraint in reallocation between distributaries, however, would lie in the upper and lower limits that are imposed on distributary head discharges.

The basis for the official rules that limit discharges to distributaries between 70% and 110% of the design (authorized) discharge, are: safety reasons to reduce risk of a breach along the banks that may occur at high discharges; sediment deposition (siltation); and, water distribution problems along the distributary at low discharges (Habib and Kuper, 1996). Differences, however, exist between the 70-110% range specified by official rules and the actual range of discharges that can be supplied to a given distributary. Field observations for the Kharif 1994 season show that maximum discharges significantly higher than 110% of the authorized discharge are supplied to most of the distributaries of the Chishtian Sub-division as presented in Table 7.1. Of interest is the case of the Azim Distributary with a maximum discharge of only 100% of its authorized discharge. This results from a prudent operation by gauge readers because of the poor physical conditions of the banks of the Azim Distributary.

Table 7.1. Maximum discharge to the 14 distributaries of the Chishtian Sub-division, as measured during the Kharif 1994 season.

Distributary	Maximum observed discharge	
	$m^3.s^{-1}$	Percent of authorized discharge
Daulat	6.7	113
Mohar	1.3	120
3-L	0.55	108
Phogan	1.1	220
Khem Garh	1.1	162
4-L	0.75	188
Jagir	1.7	218
Shahar Farid	6.1	141
Masood	1.45	149
Soda	2.5	118
5-L	0.4	355
Fordwah	6.0	134
Mehmud	6.9	217
Azim	0.5	100

The values of the maximum discharges presented in Table 7.1, however, are to be used cautiously as it may not be possible to safely sustain such high discharges for long periods of time. To better understand the possible range of discharges that can be supplied to a distributary, simulations with the SIC model for the Fordwah and Masood distributaries were undertaken. The results of these simulations are summarized in Table 7.2.

In the actual situation, discharges that can be safely supplied to the Fordwah Distributary range from 83% to 115%, thus rather close to the official values. However, a targeted maintenance that would strengthen the banks of the distributary from RD24 to RD 114 by 10-15 cm would increase the maximum discharge to 140% of the authorized discharge. For the Masood Distributary, the actual range of possible discharges is wider, with a lower minimum discharge as compared to the Fordwah Distributary. To strengthen the distributary banks by 10-15 cm from the head to RD 36 (almost the tail) would also increase the maximum discharge to 140 percent of the authorized discharge. In fact, the length of the distributary is expected to be a major element influencing the range of discharges that can be supplied to a distributary, and thus the potential for reallocation among distributaries. With more significant problems of water distribution along the distributary, the minimum discharge is expected to be higher for distributaries with a higher number of outlets than for fewer outlets, which may represent the major constraint on reallocation of canal water between distributaries.

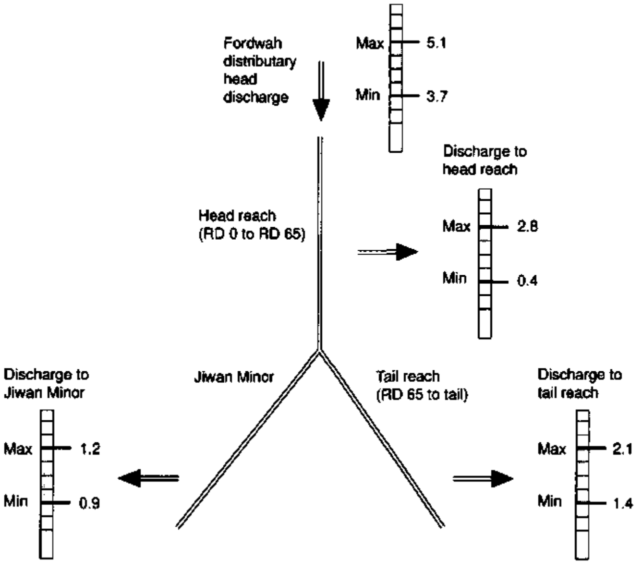
Table 7.2. Maximum and minimum discharges for the Fordwah and Masood distributaries for the actual situation and after-strengthening of banks, based on field estimations and simulations with the SIC model developed by Kuper (1997). The minimum discharge is not modified after strengthening of banks, thus minimum discharge values have not been duplicated for the after-strengthening situation.

Variable		Fordwah Distributary		Masood Distributary	
		$m^3.s^{-1}$	Percent of authorized discharge	$m^3.s^{-1}$	Percent of authorized discharge
Maximum discharge	Actual situation	5.2	115	1.2	120
	After strengthening of banks	6.2	140	1.4	140
Minimum discharge	Actual situation	3.7	83	0.5	50

As already mentioned above, specific operational schedules can be established to reduce limitations fixed by the infrastructure. Rotational schedules that modify the time factor can be established with distributaries run at, or close to, 100% of the authorized discharge for part of the time. For example, a distributary that would be receiving its design discharge one week per month would, in fact, receive 25% of its allocation. However, complex rotational schedules may rapidly be required to allocate and distribute canal water as defined by the market. This would require improved skills for irrigation managers and significantly upgrading the information system supporting the management of the irrigation system. This may also eventually lead to a higher variability and unreliability of canal water supplies, with negative effects that may off-set (part of) the benefits expected from the reallocation of canal water.

Along distributaries, physical constraints on canal water reallocation are more pronounced as compared to reallocation between secondary canals. The capacity of the channel to carry water is an important element to be considered. Also, minimum discharges are required at specific points to ensure appropriate distribution of canal water below these points. Using the SIC model for the Fordwah Distributary, limits in transfers between three selected reaches of the Fordwah Distributary, namely from the head to RD 65, from RD 65 to the tail, and the Jiwan Minor, were analyzed. Maximum and minimum discharges at selected points were estimated and are presented in Figure 7.1.

Figure 7.1. Minimum (Min) and maximum (Max) discharges ($m^3.s^{-1}$) at three reaches of the Fordwah Distributary, obtained with the SIC model developed by Kuper (1997).



For a given discharge at the head of Fordwah Distributary, the main limitations in transfer between the three different units would come from the maximum and minimum discharges that can be dealt with at various locations. A minimum of 2.3 $m^3.s^{-1}$ is to be allocated to the Jiwan Minor and the tail reach of the distributary combined. And the total discharge at these points cannot go above 3.3 $m^3.s^{-1}$. This leaves 1 $m^3.s^{-1}$, or about a third of the actual discharge at these points that can be reallocated without meeting difficulties with distribution and free board below RD 65 and along the Jiwan minor.

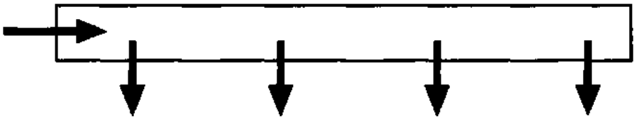
With a minimum discharge at the head of the Fordwah Distributary, and a maximum discharge at RD 65 and Jiwan Minor combined, there would be 0.4 $m^3.s^{-1}$ left for the head reach of the distributary. While a maximum discharge at the head of the Fordwah Distributary and a minimum discharge at RD 65 and the head of Jiwan Minor, a maximum of 2.8 $m^3.s^{-1}$ could be allocated to the head reach. Thus, the range of discharges that could be allocated to the head reach is very large, much larger than what can be handled by the Jiwan Minor and the tail reach combined. In fact, more limitations on reallocation of surface water between reaches would come from tail reach constraints.

Reallocation of canal water between watercourses can be envisaged in two different ways. Firstly, dimensions of outlets may be modified accordingly. Such a change requires masonry work, and cannot be undertaken too often. Thus, changes in outlet dimensions could be envisaged for reallocation of water rights that would take place every 2-3 years, and would not allow an independent monthly reallocation of canal water. Secondly, gates may be installed at the head of each watercourse command area. Modification in the gate opening would change the target discharge of each outlet and make possible reallocation of water on a monthly or even shorter-term basis. However, to make possible the purchase and sale of canal water, outlet dimensions need to be enlarged. Also, modifications of outlet gates need to be coordinated. Experience in the Lower Swat Canal irrigation system in the North-West Frontier Province of Pakistan highlighted the difficulties faced in operating watercourse head gates (Bandaragoda, 1994). In fact, the enforcement of the gate opening is an important issue that require specific institutional arrangements.

An important issue relates to the direct *externalities* that may occur as a result of reallocation of surface water between two reaches of a distributary or two outlets. The sale of a water right from a tail outlet to a head outlet will reduce discharges flowing in the distributary downstream of the head outlet purchaser. As a result, reductions in the water level are expected downstream of the outlet purchaser, leading to a reduction in the discharge received by downstream outlets (*negative externalities*). At the opposite, the sale of a surface water right from a head outlet to a tail outlet will increase the discharge flowing in the distributary downstream of the seller outlet. This in turn will increase water levels and lead to higher discharges for outlets located between the seller and the purchaser (*positive externalities*). In both cases, modifications in the outlet dimensions or gate settings of all (most of) the outlets located between the seller and the purchaser may be required to adjust for changes in water levels. The shorter the distance between sellers and purchasers, and the more upstream the transaction, then the need to modify other outlets will be less.

Figure 7.3 illustrates the issue of direct externalities related to the impact of reallocating water rights between watercourses. A simple example of a distributary with an initial allocation of 4 $m^3.s^{-1}$ is chosen and divided into four watercourses with equal allocations. The *division factor* of each outlet, defined as the percentage of water flowing at the point where a watercourse off-takes from the distributary that is diverted into this watercourse, is specified in the upper portion of the figure for each outlet. The four watercourses are assumed to be proportional, i.e. a change by x percent in the distributary flow rate leads to a change by x percent in the flow rate of individual outlets. The mathematical definition of the division factor is given in Kuper (1997).

Figure 7.3. Direct externalities linked to canal water transfers along distributaries.



Initial discharge	1 $m^3.s^{-1}$	1 $m^3.s^{-1}$	1 $m^3.s^{-1}$	1 $m^3.s^{-1}$
Transfer from D to A	2 $m^3.s^{-1}$	0.66 $m^3.s^{-1}$	1.33 $m^3.s^{-1}$	0 $m^3.s^{-1}$
Transfer from A to D	0 $m^3.s^{-1}$	1.33 $m^3.s^{-1}$	1.33 $m^3.s^{-1}$	1.33 $m^3.s^{-1}$

Using these division factors, discharges to each outlet are computed for two reallocation scenarios:

- A transfer of canal water from the tail outlet D to the head outlet A;
- A transfer of canal water from the head outlet A to the tail outlet D.

Both transfers are undertaken by modifying accordingly the division factor of the outlets A and D directly involved in the transactions, but keeping the division factor of the two other outlets B and C constant. In practice, this means modifying the size of the outlets A and D, while keeping the size of outlets B and C constant.

As specified in Figure 7.3, a transfer from D to A reduces the allocation to B and increases the allocation to C. And the transfer from A to D increases the allocation to both B and C, limiting the allocation received by D to less than the allocation sold by A. To keep the allocation of B and C constant and equal to 1 $m^3.s^{-1}$, changes in the division factors (equivalent to changes in outlet dimensions) are required: from 1/3 to ½ for outlet B in the case of a transfer from D to A, and from 1/3 to ¼ for outlet B and from ½ to 1/3 for outlet C in the case of the transfer from A to D.

The analysis of direct externalities related to the reallocation of canal water among watercourses along a distributary was further investigated using the SIC model developed for the Fordwah distributary (Kuper 1997). Two scenarios for reallocating canal water within the Fordwah Distributary command area, similar to the two simplified reallocation scenarios presented in Figure 7.3, were investigated. The first scenario is a reallocation of canal water from the first reach to the third and fourth reaches, and the second scenario is a reallocation of canal water from the third reach to the first reach. Table 7.4 summarizes the results of the two scenarios.

Table 7.4. Impact of canal water reallocation within the Fordwah Distributary command area, as simulated with the SIC model developed by Kuper (1997).

Reach	Actual simulation	Transfer from A to C and D			Transfer from C to A and D		
	Q_{head}	$Q_{expected}$	$Q_{obtained}$	Difference (%)	$Q_{expected}$	$Q_{obtained}$	Difference (%)
A: Head-RD33	0.56	0	0	-	0.85	0.85	-
B: RD33-RD65	1.04	1.04	1.12	+7.6%	1.04	1.0	-3.8%
Jiwan minor	1.0	1.0	1.0	-	1.0	0.95	-4.9%
C: RD65-RD102	0.91	1.28	1.28	-	0	0	-
D: RD102-Tail	0.73	0.92	0.84	-8.7%-	1.35	1.44	+6.7%

Results presented in Table 7.4 re-emphasize the results presented in Figure 7.2 and shows the impact of reallocating canal water supply on supplies to watercourses that are not involved in the transaction. The relative difference in discharges of outlets that do not participate in the transaction range from –8.7% to + 7.6%, and is more pronounced for the tail reach D for both transfer scenarios. However, as a result of the sub-proportionality of most of the watercourse outlets, the direct externalities related to surface water reallocation between the first and third reaches were lower than expected as stressed by the simple example of Figure 7.1.

There is a need to emphasize that direct externalities are not a problem for transfers between distributaries, as there is enough flexibility within the main system with gates at the head of the distributaries and cross regulators. With the existing control structures, the strong head-to-tail dependency that exists between watercourses along the distributaries does not hold at the main system level, and distributaries can be more independently operated. However, the reallocation of canal water between distributaries may impact on the variability of distributary supplies located downstream of a seller distributary if the reallocation is made to downstream distributaries, or distributaries located upstream of the seller distributary if the reallocation is made to upstream distributaries. Unlike the situation within watercourse command areas, where users increase the probability of receiving a volume of canal water by purchasing canal water turns, no improvement in variability results from a transfer of volumes between distributaries, apart if the probability (e.g. preference order) itself is the object of the transaction.

The potential impact of water market development on agricultural production and on the physical environment is now discussed in more detail in the following sections for two examples:

- The reallocation of canal water rights, defined by a pre-defined monthly canal water allocation between watercourses along a given distributary, using the eight sample watercourses of the Fordwah and Azim distributaries (Section 7.4); and,
- The reallocation of canal water rights similarly defined between the command areas of the Azim and Fordwah distributaries (Section 7.5).

7.4 Analyzing the potential for canal water market development between sample watercourses of the Fordwah and Azim distributaries

The present section investigates the potential for canal water reallocation between the four watercourses of the Fordwah Distributary, and the four watercourses of the Azim Distributary. The analysis focuses on the transfer of water rights for a full year, and not on the independent reallocation of volumes of canal water for the different months. As specified above, and for the purpose of the analysis, canal water rights are defined as a total volume allocated to a given unit with a well-defined temporal distribution of this volume within the year. Thus, *a modification in the allocation to this unit by x percent, equivalent to a change in watercourse outlet dimensions or in distributary target discharges, leads to a similar x percent change for the twelve monthly canal water allocations.*

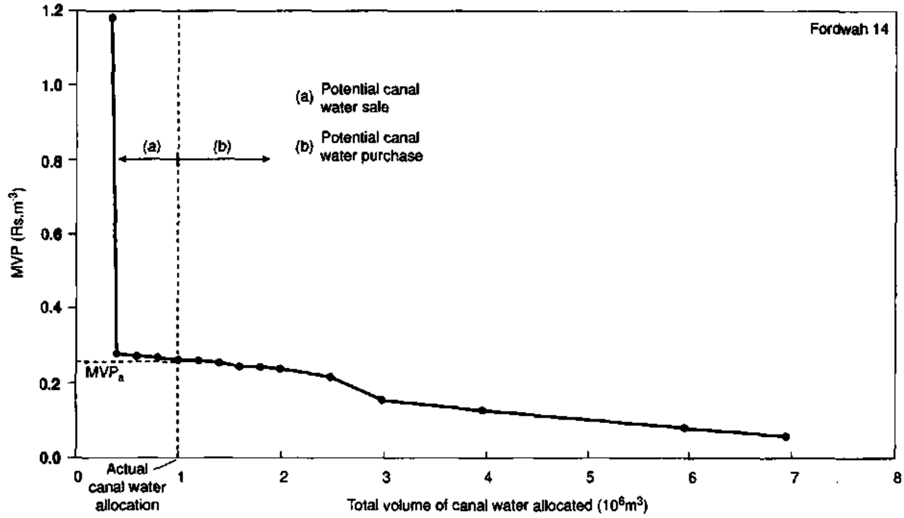
Establishing the relationship between quantity and Marginal Value Product of water for sample watercourses using the stochastic linear programming models

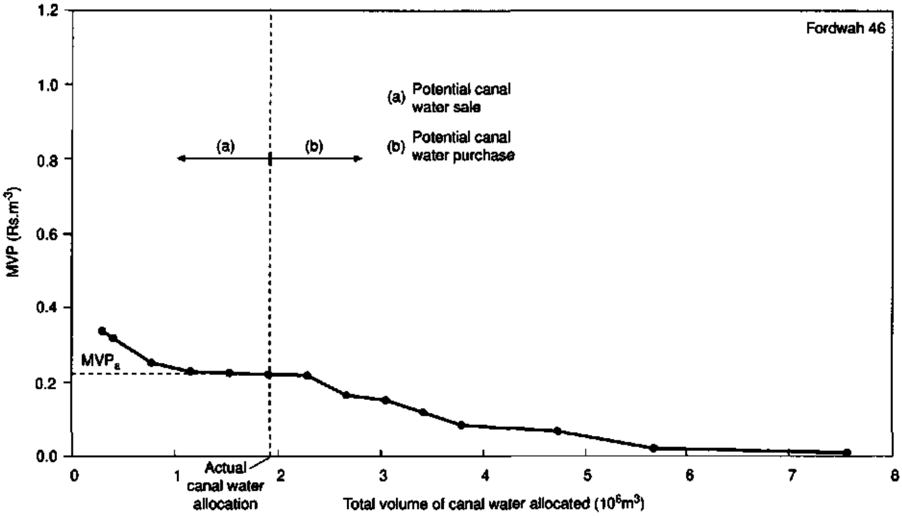
The stochastic linear programming models are used to estimate the relationship between the quantity of canal water allocated to a watercourse and its Marginal Value Product (MVP). As explained in Chapter 3, the relationship between the canal water allocated and its Marginal Value Product is the basis for identifying the potential for reallocating canal water between different units.

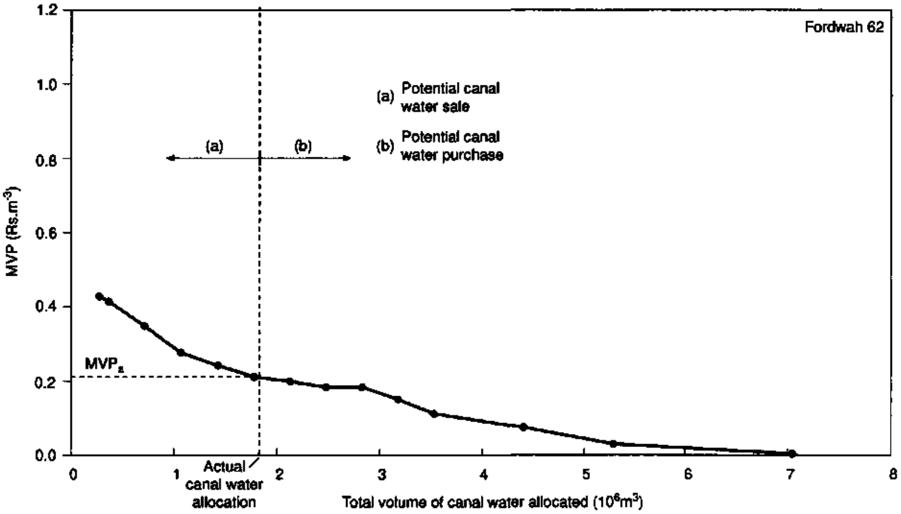
Different levels of canal water supplies, with a similar temporal distribution between months, are selected as input, and the models are run with these different canal water supplies. The monthly marginal value product of canal water obtained from these simulations are then aggregated into a single weighted average marginal value product, using the canal water supplies for each month as weights. This average marginal value product is then used for developing the curves that relate yearly canal water allocation and marginal value product. Figure 7.3.a to Figure 7.3.h present the curves obtained for the eight sample watercourses of the Fordwah and Azim distributaries.

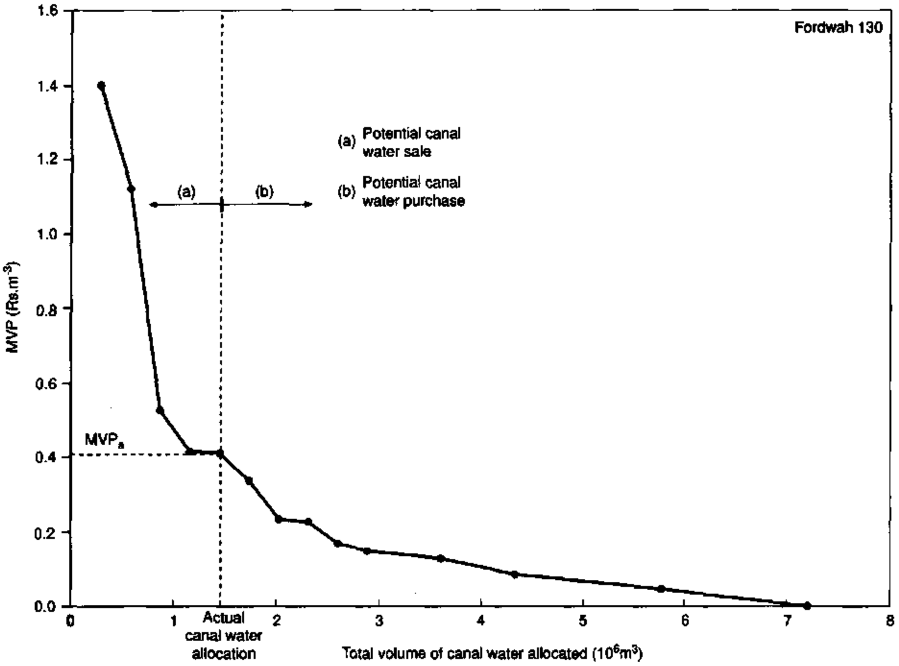
A few comments on the curves are required before going further into the analysis of the potential for canal water reallocation. It is important to note that the curves are not as smooth and convex as would be expected by economic theory. This results from the way that the models have been constructed, with several farm groups taking decisions independently from each other. Also, with 12 monthly water supply constraints being modified simultaneously, it is difficult and rather cumbersome to develop the curves in the required step-wise approach (i.e. selecting a level of canal water supply, running the stochastic linear programming model, identifying the range of canal water supplies around this level that records constant marginal value products, and then select a canal water supply out of this range for the next model run). As a result, the simulations have been undertaken for different canal water supplies defined before hand, and this may explain some irregularities in the observed shape of the curves.

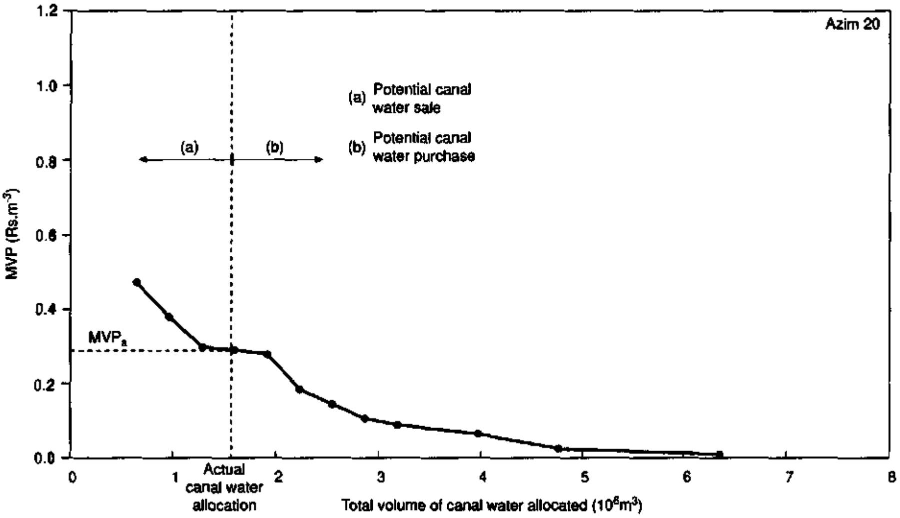
Figure 7.3. Relationship between yearly allocation of canal water and its Marginal Value Product (MVP) for the eight sample watercourses of the Fordwah and Azim distributaries, obtained through simulations with the stochastic linear programming models. (The dotted lines in each figure represent the actual canal water allocation of each watercourse)

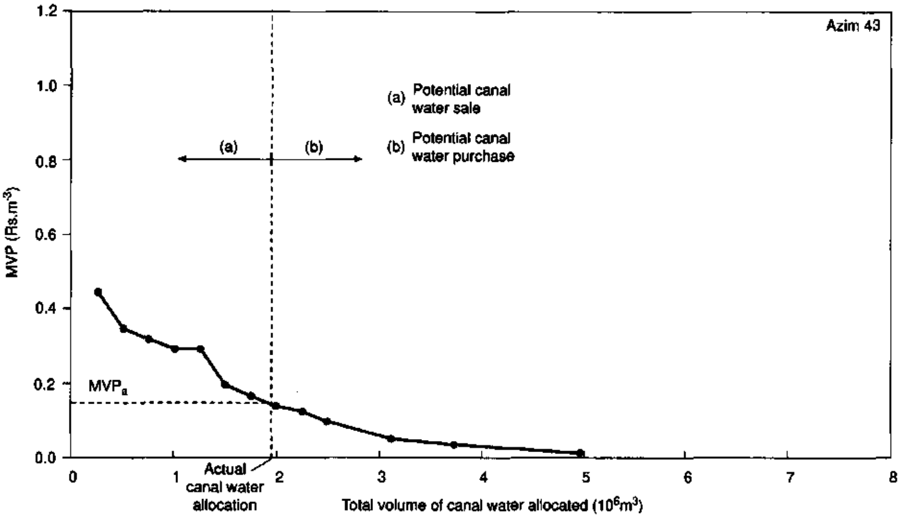


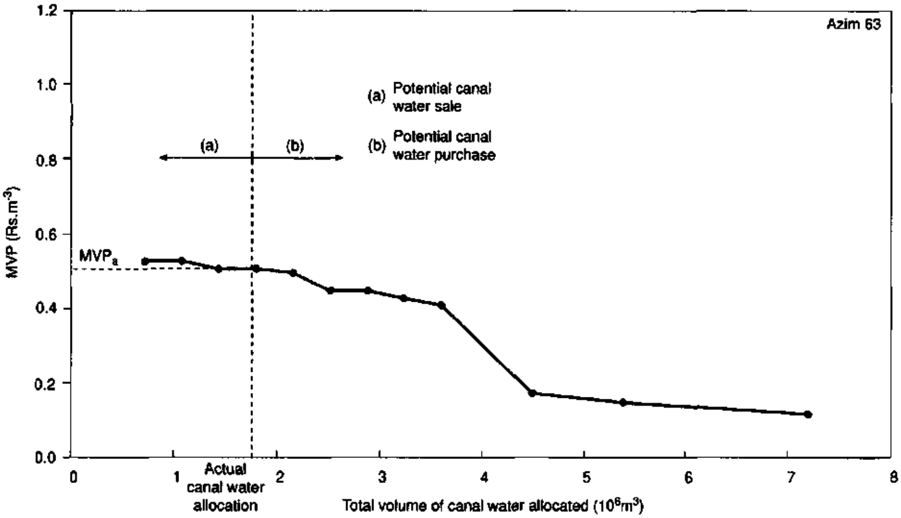

Fordwah 46
(a) Potential canal water sale
(b) Potential canal water purchase
(a)
(b)
MVP$_a$
Actual canal water allocation
MVP (Rs.m^{-3})
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
Total volume of canal water allocated (10^{6}m^3)

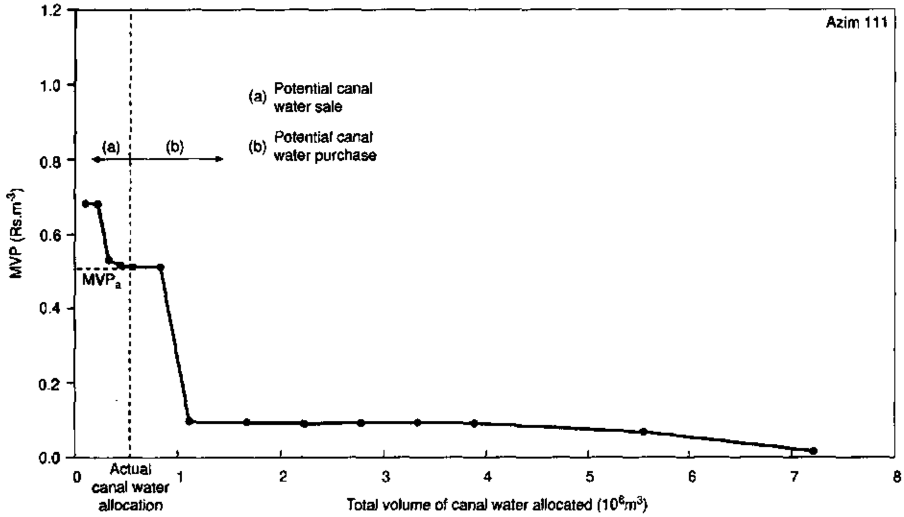

Fordwah 62
(a) Potential canal water sale
(b) Potential canal water purchase
(a)
(b)
MVP$_a$
Actual canal water allocation
MVP (Rs.m^{-3})
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
Total volume of canal water allocated (10^{6}m^3)


Fordwah 130
(a) Potential canal water sale
(b) Potential canal water purchase
(a)
(b)
MVP$_a$
MVP (Rs.m^{-3})
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
Actual canal water allocation
2
3
4
5
6
7
8
Total volume of canal water allocated (10^{6}m^3)


Azim 20
(a) Potential canal water sale
(b) Potential canal water purchase
(a)
(b)
MVP$_a$
MVP (Rs.m^{-3})
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
Actual canal water allocation
2
3
4
5
6
7
8
Total volume of canal water allocated (10^{6}m^3)


Azim 43
(a) Potential canal water sale
(b) Potential canal water purchase
(a)
(b)
MVP (Rs.m-3)
MVPa
Actual canal water allocation
Total volume of canal water allocated (10^6m^3)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8


Azim 63
(a) Potential canal water sale
(b) Potential canal water purchase
(a)
(b)
MVP (Rs.m-3)
MVPa
Actual canal water allocation
Total volume of canal water allocated (10^6m^3)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8



Some of the conclusions that can be drawn from the analysis of these eight graphs in Figure 7.3 are presented below.

- The allocation of canal water is rather elastic with regard to changes in marginal value product or (shadow) price. Average elasticities of allocation with regard to prices of more than 1 are found in a wide range of volumes for most of the watercourses. Elasticies lower than 1 are found for AZ20 and FD 130, and for AZ 111 for low volumes. However, elasticities for these watercourses remain in the order of 0.8-0.9.
- The highest price elasticity of demand is found for Watercourse AZ 63, a watercourse with a relatively low canal water supply per unit area, and an important constraint on tubewell water availability.
- For AZ 20, AZ 63, FD 14 and FD 130, volumes lower than 40% of the existing canal water supplies are not sufficient to satisfy farmers' constraints in terms of minimum area under fodder and wheat for auto-consumption. Too low volumes of canal water lead to infeasible solutions with the stochastic economic models for these watercourses.

Reallocation of canal water between sample watercourses: Potential for, and impact on agricultural production

The differences between the Marginal Value Products (MVP) of canal water computed for the different watercourses at their present allocation and obtained from the curves presented in Figure 7.3 are presented in Table 7.5, along with the monthly availability constraints on tubewell water use and the average tubewell water price. It highlights the potential for reallocation of canal water for both distributary from watercourses with low marginal value products to watercourses with high marginal value products. For the Fordwah Distributary, for example, reallocation of canal water from FD 14, FD46 or FD 62 to FD 130 is expected to improve water use efficiency. Similarly, reallocation of canal water from AZ 20 or AZ 43 to AZ 63 or AZ 111 would also improve water use efficiency and agricultural productivity.

Table 7.5. Actual yearly canal water supplies and Marginal Value Product (MVP) of canal water estimated with the stochastic linear programming models for the eight sample watercourses of the Fordwah and Azim distributaries.

Distributary and watercourse		Tubewell water		Canal water	
		Monthly constraint on quantity ($10^6 m^3$)	Tubewell water price ($Rs.m^{-3}$)	Actual yearly supply ($10^6 m^3$)	MVP of canal water ($Rs.m^{-3}$)
Fordwah	FD 14	0.5	0.31	0.988	0.25
	FD 46	0.17	0.35	1.892	0.23
	FD 62	0.16	0.31	1.761	0.21
	FD 130	0.35	0.31	1.443	0.42
Azim	AZ 20	0.16	0.37	1.588	0.29
	AZ43	0.2	0.42	1.237	0.29
	AZ63	0.375	0.35	1.804	0.45
	AZ111	0.285	0.2	0.556	0.52

Table 7.5 stresses also that canal water reallocation may not necessarily take place from watercourses with the lowest tubewell water prices to watercourses with the highest tubewell water prices, an assumption that was discussed in Chapter 3. Although it is clear that tubewell water prices influence the actual marginal value product of irrigation water, the relative shortage in access to surface and groundwater resources is also to be considered, which will influence the overall marginal value product of irrigation water. For example, although Watercourse AZ 111 records a very low tubewell water price, the estimated Marginal Value Product of water is very high for this watercourse, as a result of quantity constraints on groundwater pumping.

To estimate the quantities of canal water that would be reallocated through market mechanisms between watercourses located along given distributaries, the relationships between quantity and MVP obtained for different watercourses are represented in the same figure (i.e. Figure 7.4 for watercourses of the Fordwah Distributary, and Figure 7.5 for watercourses of the Azim Distributary). The intersection between the horizontal line of actual aggregated supplies and the cumulative demand curves for the watercourses of each distributary provides the market equilibrium price at which canal water would be transacted. The intersection between the vertical line at equilibrium price and the different cumulative curves (for three watercourses, two watercourses and one watercourse, respectively) provides also the relative volumes allocated to each individual watercourse.

Figure 7.4. Cumulative yearly canal water allocation for the Fordwah watercourses as a function of the MVP of canal water, obtained from simulations with the stochastic linear programming models. (The intersection between the horizontal dotted line of the actual canal water allocation and the cumulative curve specifies the market equilibrium price. The allocation to each watercourse is given by the intersection between the vertical dotted line at this price and the cumulative curves)

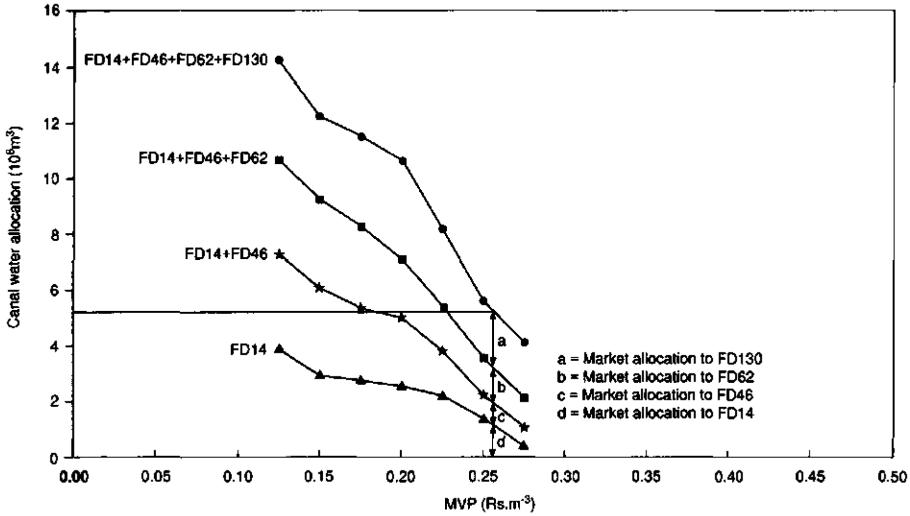
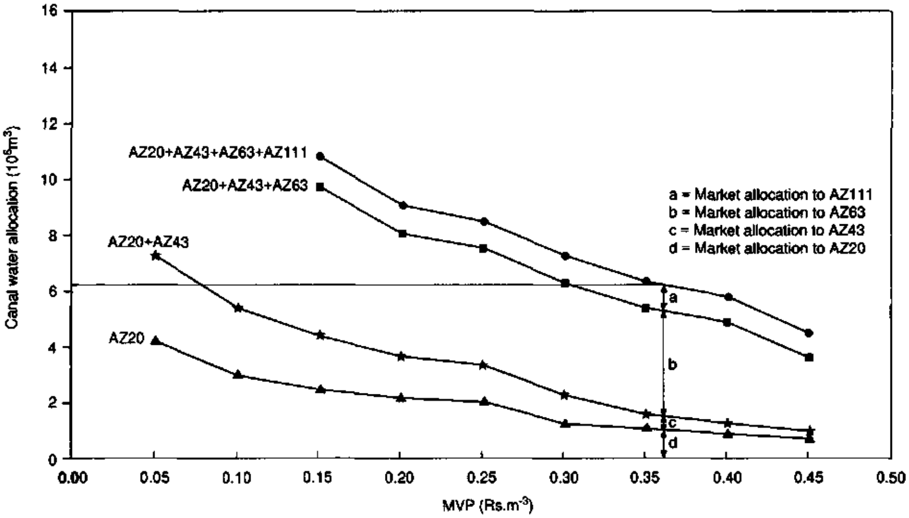


Figure 7.5. Cumulative yearly canal water allocation for Azim watercourses as a function of the MVP of canal water, obtained from simulations with the stochastic linear programming models. (The intersection between the horizontal dotted line of the actual canal water allocation and the cumulative curve specifies the market equilibrium price. The allocation to each watercourse is given by the intersection between the vertical dotted line at this price and the cumulative curves)



The results in terms of volumes of canal water allocated through market mechanisms and market prices for canal water obtained from a graphical analysis of Figure 7.4 and Figure 7.5 are summarized in Table 7.6.

Table 7.6. Volumes allocated through the distributary-level market mechanism and associated market price. Results from simulations of stochastic linear programming models for the 8 sample watercourses of the Azim and Fordwah distributaries..

Distributary & watercourse		Volume allocated in actual situation (10^6m^3)	Volume allocated through market mechanism		Market equilibrium price ($Rs.m^{-3}$)
			10^6m^3	Percentage of actual volume	
Fordwah	FD 14	0.988	1.550	156	0.245
	FD 46	1.892	1.067	56%	
	FD 62	1.761	1.467	83	
	FD 130	1.443	2.0	139	
Azim	AZ 20	1.588	0.864	54	0.42
	AZ 43	1.237	0.432	35	
	AZ 63	1.804	3.024	168	
	AZ 111	0.556	0.864	155	

As anticipated with the values of Marginal Value Products presented in Table 7.6, FD 14, FD 130, AZ 63 and AZ 111 are purchaser watercourses, while FD 46, FD 62, AZ 20 and AZ 43 are seller watercourses. The total volume purchased or sold by each watercourse, however, could not have been predicted by these values only. For example, canal water purchases are higher for the AZ 63 watercourse as compared to the AZ 111 watercourse, although the latter has the highest marginal value product of canal water in the actual situation.

Overall, the reallocation through market mechanisms involves 1.12 10^6m^3 or 18 percent of the total canal water supplies in the Fordwah Distributary, and 1.53 10^6m^3 or 29 percent of the total canal water supplies in the Azim Distributary. The market price for canal water is estimated at 0.245 $Rs.m^{-3}$ for the Fordwah Distributary, and 0.42 $Rs.m^{-3}$ for the Azim Distributary. The impact of such transactions on farm gross income (excluding proceeds from sales and costs of purchases) and agricultural production is summarized in Table 7.7 for each watercourse command area.

The reallocation of canal water between watercourses has a greater influence on the cropping pattern than on the cropping intensity. The reallocation of canal water leads to a slight decrease in the expected cropping intensity, from 164% to 161% of the Culturable Command Area (CCA). This maybe-unexpected result is explained by the increase in the area under sugarcane, by 10% for the Azim watercourses and by 70% for the Fordwah watercourses.

Table 7.7. Impact of distributary-wise canal water markets on agricultural production and farm gross income: comparison of results of simulations using the stochastic linear programming models for the eight sample watercourses of the Fordwah and Azim distributaries for the actual situation (ACT) and the canal water market situation (MKT). (Proceeds and costs related to reallocation of canal water have not been counted for in the total gross income)

Distributary & watercourse		Expected gross Income (million Rs)		Yearly cropping intensity (% of CCA)		Wheat area (ha)		Cotton area (ha)		Sugarcane area (ha)	
		ACT	MKT	ACT	MKT	ACT	MKT	ACT	MKT	ACT	MKT
Fordwah	FD14	1.31	1.47	171	165	163	115	151	103	36	75
	FD46	0.97	0.80	179	168	124	119	90	78	15	19
	FD62	1.20	1.12	144	141	115	111	88	84	12	12
	FD130	1.95	2.13	175	179	146	142	125	130	5	8
Azim	AZ20	1.13	0.93	187	173	81	83	35	34	23	21
	AZ43	1.26	1.04	157	158	56	71	64	73	40	28
	AZ63	2.72	3.30	140	146	184	142	236	272	20	34
	AZ111	2.02	2.19	155	160	161	153	128	134	12	21

Overall, the aggregated gross farm income for the four watercourses of the Fordwah Distributary increases by 1.5% as a result of the development of canal water markets between watercourses, while the increase in gross farm income for the four watercourses along the Azim Distributary has been estimated at 4.6%. The gains from such transactions as compared with the volumes transacted appear rather low. These results will be discussed in Section 7.6, along with results obtained from the analysis of potential for canal water reallocation between the Fordwah and Azim distributaries.

Impact of canal water reallocation between watercourses on the physical environment

The impact of water markets on the physical environment is investigated for water markets between watercourse command areas similarly to what has been presented in Chapter 6 for the analysis of the impact of existing water markets on the physical environment. The water balance model developed by van Waijjen (1996) was used to estimate the impact of canal water reallocation between watercourses on the net recharge to the aquifer. The SWAP93 model and the empirical sodicity equation (Kuper, 1997) were used to estimate the impact on salinity and sodicity. Table 7.8 presents the results obtained from simulations with these different models.

Overall, the reallocation of canal water resources between watercourses is expected to significantly increase the pressure on groundwater resources, with an average yearly net recharge of –116 mm, as compared to the actual situation presented in Chapter 6 of –31 mm. This problem will be particularly acute for the Azim watercourses, with an average yearly net recharge of –190 mm, as compared to a value of –41 mm for the Fordwah watercourses.

Table 7.8. Yearly net recharge (mm), salinity (percentage of actual situation) and sodicity (percentage of actual situation) resulting from market reallocation of canal water between watercourses of the Fordwah and Azim distributaries. (Results obtained using the water balance model (van Waijjen, 1996), the SWAP model (Kuper, 1997) and an empirical equation for sodicity (Kuper, 1997))

Variable	Fordwah				Azim				Average
	FD14	FD46	FD62	FD130	AZ20	AZ43	AZ63	AZ111	
Net recharge (mm)	-212	-125	81	92	-71	-422	69	-339	-116
Salinity (% of actual situation)	92	132	121	80	134	157	76	92	110
Sodicity (% of actual situation)	89	113	107	86	107	104	96	96	100

The impact of canal water reallocation between watercourses is negative in terms of salinity. Salinity levels would increase on average by 10% for the eight watercourses considered. The increase in salinity would be particularly significant for the Watercourse AZ 43 that is expected to sell two-thirds of its canal water allocation through market mechanisms. Sodicity, however, shows more stability on average, with however a significant degradation of the existing sodicity levels for the Watercourse FD 46. While gains and losses related to the reallocation of canal water can be balanced between the different watercourse command areas in the case of sodicity, this is not the case for the yearly net recharge and salinity.

7.5 Analyzing the potential for canal water market development between the Fordwah and Azim distributaries

The present section investigates the potential for canal water reallocation between the Fordwah Distributary and Azim Distributary. To express constraints arising from the physical infrastructure, the reallocation of canal water between watercourses is not permitted under this scenario. Thus, reallocation of canal water to distributaries influences the allocation to all watercourses along the distributary in a similar manner according to the relative proportionality of the watercourse outlets.

Similarly to what has been presented in Section 7.4, the relationship between the quantity of canal water supplied to the distributary and the marginal value product of canal water was established using the watercourse stochastic linear programming models of each watercourse. As presented in Chapter 5, a stochastic linear programming model was set for each watercourse, according to its appurtenance to a watercourse class. However, it is also required to use the hydraulic models for the distributary to establish the relationship between a change in canal water supply at the head of the distributary and changes in canal water supply at the head of any watercourse along the distributary.

Figure 7.6 summarizes the different steps followed to compute the Marginal Value Product (MVP) of canal water for a given canal water allocation and develop the relationship between these two variables for the Fordwah Distributary. As explained in Chapter 3 and Appendix 2, a simpler volume-balance model is used for the Azim Distributary to estimate the relationship between canal water supply at the distributary head and canal water supply for any given watercourse along this distributary. The relationship between canal water allocation and Marginal Value Product (MVP) obtained for the Fordwah and Azim distributaries is presented in Figure 7.7, along with the cumulative curve for both distributaries. As the Fordwah Distributary is perennial and the Azim Distributary is non-perennial, the reallocation of surface water is limited to transfers during the kharif season. Thus, the rabi supplies of both distributaries are kept constant, and only the kharif supply is modified for building the relationship between surface water allocation and Marginal Value Product of water.

Figure 7.6. Flow of information and use of the hydraulic SIC model and stochastic linear programming models to develop the relationship between yearly canal water allocation and its Marginal Value Product (MVP) for the Fordwah Distributary.

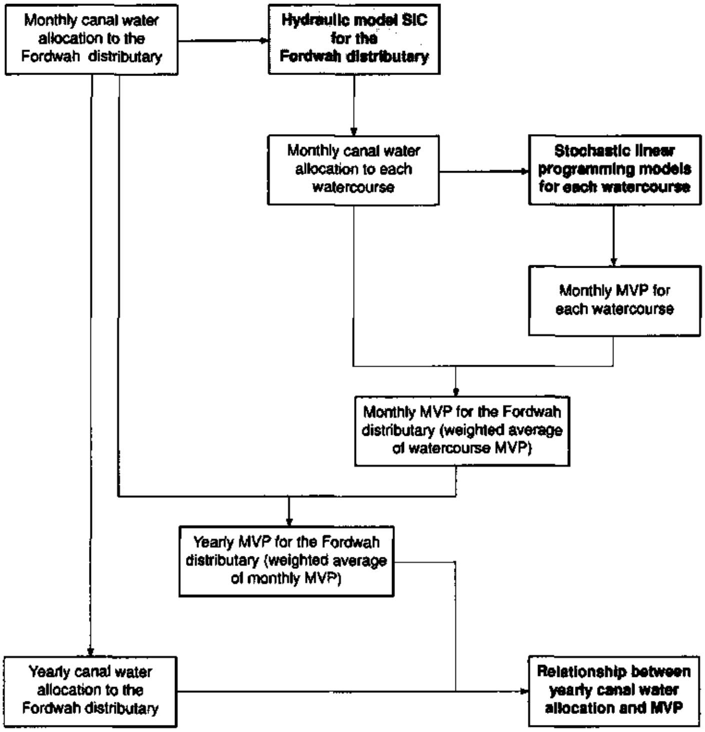
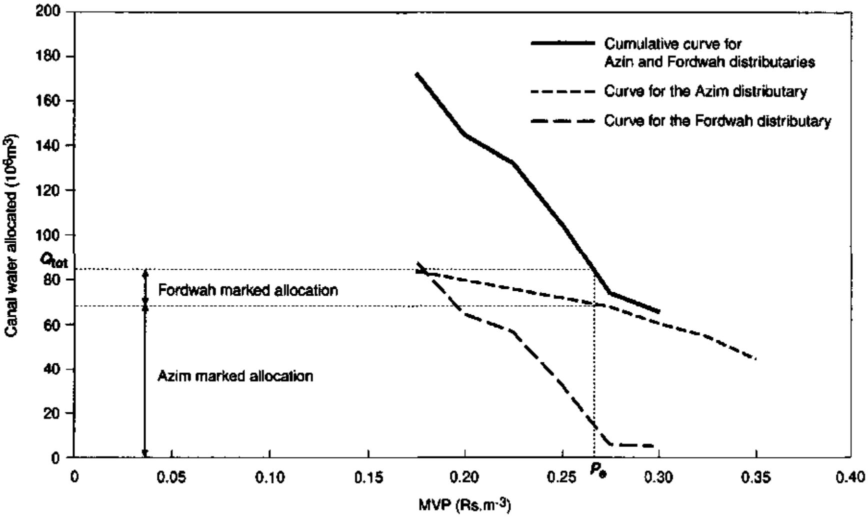


Figure 7.7. Relationship between Marginal Value Product (MVP) of canal water and canal water allocation for the Fordwah and Azim distributaries. (The intersection between the cumulative curve and the horizontal dotted line of the actual canal water allocation aggregated for both distributaries gives the equilibrium market price. The vertical dotted line at this price specifies the market allocation to each distributary)



Based on Figure 7.7, the quantities of canal water reallocated through market mechanisms have been estimated, along with their expected impact on farm gross income aggregated for both distributaries. The comparison between the actual situation and the market allocation is summarized in Table 7.9.

Table 7.9. Development of surface water markets between the Fordwah and Azim distributaries: initial allocation, market allocation, MVPs and aggregated impact of reallocation on farm gross income, estimated through the combined use of hydraulic models for secondary canals and watercourse stochastic linear programming models.

Variable		Actual situation	Market allocation
Yearly canal water allocation (10^6m^3)	Fordwah	40.3	72.9
	Azim	44.6	72.9
MVP of yearly canal water allocation (Rs.m^{-3})	Fordwah	0.355	0.265
	Azim	0.245	
Aggregated gross farm income (10^6Rs)		143	146

As a result of differences in the Marginal Value Product of canal water in the present situation, large quantities of canal water are reallocated from the Fordwah Distributary to the Azim

Distributary through market mechanisms at an equilibrium price of 0.246 Rs.m^{-3}. The overall impact of this reallocation on the farm gross income aggregated for the two distributaries remains limited, from 143 million Rs to 146 million Rs, equivalent to a 2% increase.

The total reallocation of canal water from the Fordwah Distributary to the Azim Distributary would reduce the allocation to the Fordwah Distributary to around 30% of its actual allocation. As illustrated by the discussion on the technical feasibility of water market development presented in Section 7.3, to reduce the authorized discharge of the Fordwah Distributary proportionally is impossible because of the serious problems in distribution that would arise along the distributary. Thus, a rotational schedule would have to be established between the two distributaries. At the same time, the poor physical conditions of the banks of the Azim Distributary would require a heavy maintenance effort for this distributary to handle much higher canal water allocation safely. This would induce high investment costs that are likely to be significantly higher than the estimated reallocation benefits.

Finally, the reallocation of canal water from the Fordwah to the Azim distributary is accompanied by a drastic increase in tubewell pumping in the Fordwah Distributary watercourses. Although the impact on the physical environment has not been assessed for the 80 watercourses of the Fordwah Distributary, the poorer groundwater quality in this distributary is expected to lead to serious salinity problems.

7.6 Summary and discussion: what future for water market development in irrigation systems in Pakistan?

The present chapter deals with the potential for reallocation of canal water through market mechanisms between watercourses along the same distributary and between distributaries. The development of relationships between the quantity of canal water allocated and its Marginal Value Product has shown that there is potential for reallocation of canal water between watercourses and between distributaries. However, the overall impact of the reallocation on farm income remains limited. The following paragraphs investigate the reasons behind this limited impact.

Looking at activities and constraints included in the stochastic linear programming

The first issue at stake relates to the economic models that have been developed and used to assess the potential for water market development and build the relationships between quantity allocated, marginal value product of water and farm gross income.

Firstly, the limited calculated impact may be related to the small differences between the activities proposed by the models for different farm groups. In fact, the financial returns of crops grown in the area remain within a limited range of low and close values. Thus, the activities included in farm groups and watercourse models are rather similar, explaining part of the high-volume low-impact situation. Examples in the literature (e.g. Howitt, 1995; Bauer, 1997) stress the highest impacts are obtained from irrigation systems that combine crops with very high economic returns (such as orchards) and crops with low economic return. Thus, different groups of farms, or geographic zones, would offer a high potential for reallocation and high impact on economic indicators.

Secondly, although the variability of canal water supplies is considered in the models, the reallocation between irrigation units has not considered changes in this variability. Very practically, this means that the reallocation of canal water from the Fordwah Distributary to the Azim Distributary that has been tested by the models, is equivalent to the reallocation of a given volume of canal accompanied by a change in the variability of these supplies, i.e. from the Fordwah variability to the Azim variability. As the variability of supplies is higher in the Azim Distributary, and because the variability constraint has been linearized and is equivalent to a reduction in the average canal water supply, the reallocation from the Fordwah to the Azim Distributary is equivalent to a loss in canal water supplies that is used by neither of the two distributaries. Using simulations undertaken with the watercourse models, to include the reduction in variability that would take place for the Azim Distributary as a result of the reallocation of Fordwah Distributary water, the changes in variability would lead to an extra increase in farm gross income of roughly 2%, thus an overall increase in farm gross income resulting from the reallocation of canal water of around 4% instead of only 2%.

The third point relates to the importance of tubewell water. In the present conjunctive use environment, a change in canal water supply is balanced by a change in tubewell water use for most of the watercourses. Thus, the main impact of the reallocation of canal water is a change in the tubewell water use by the different participants in the market, and an overall financial gain related to differences in tubewell water prices between areas. However, when the availability of tubewell water is also constrained, such as for the Watercourse AZ 63, the potential for increased farm gross income as a result of reallocation of canal water is significantly higher.

Temporal constraints in canal water allocation

The fact that water rights have been described with a pre-defined distribution of volumes allocated over the year, similar to the existing distribution of canal water supplies, is seen as a major impediment on reallocation, and explains partly the low impact on farm gross income that is obtained. The relationship between volume allocated and Marginal Value Product of canal water relates to a defined monthly distribution of canal water. To purchase a given volume of canal water may imply purchasing canal water also for months for which such supplies are not required. Thus, the definition of water rights that incorporates the distribution over the year for volumes imposes a clear rigidity and constraint on farmers' participation in water right markets. Such water rights do not provide water users with the same flexibility as the one obtained from a water right defined solely by a total yearly volume with no pre-defined definition of monthly allocations.

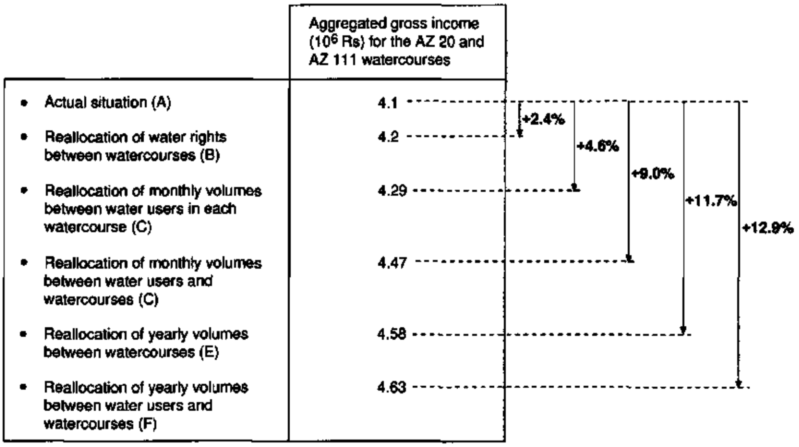
To support this observation, complementary simulations were undertaken to investigate the potential for reallocation of canal water between the AZ 20 and AZ 111 watercourses that would illustrate the constraints imposed on canal water reallocation by the definition of temporally distributed water rights. The simulations compare:

- The reallocation of *canal water rights with well defined temporal distribution* of volumes as investigated so far (B);
- An *independent reallocation of monthly volumes of canal water between watercourses* (C);

- An *independent reallocation of monthly volumes of canal water* both *between farm groups* within a given watercourse, *and between watercourses* (D);
- A reallocation of *yearly volumes between watercourses*, each farm group having a given share that cannot be reallocated through market mechanisms (E);
- A reallocation of *yearly volumes*, both *between watercourses and between farm groups* within the watercourse command area (F).

The impact of such scenarios on aggregated farm gross income for the two watercourses is summarized in Figure 7.8

Figure 7.8. Impact of various canal water market scenarios on total gross income for the AZ 20 and AZ 111 watercourses. (Results of simulations with the stochastic linear programming models)



	Aggregated gross income (10^6 Rs) for the AZ 20 and AZ 111 watercourses
• Actual situation (A)	4.1
• Reallocation of water rights between watercourses (B)	4.2
• Reallocation of monthly volumes between water users in each watercourse (C)	4.29
• Reallocation of monthly volumes between water users and watercourses (C)	4.47
• Reallocation of yearly volumes between watercourses (E)	4.58
• Reallocation of yearly volumes between water users and watercourses (F)	4.63

Figure 7.8 shows that the reallocation of water rights between watercourses (B) would in fact yield much lower benefits than the monthly reallocation of volumes of canal water between watercourses, the combination between monthly reallocation between farm groups and between watercourses, and the two scenarios (E and F) with yearly volumes. Overall, the gains obtained from a reallocation between watercourses of the rights with a pre-determined temporal distribution are equal to +4.6% of the actual farm gross income, versus +12.9% for the scenario with yearly volumes allocated to each watercourse.

To further investigate the potential for reallocation of canal water supplies between months, Table 7.10 presents basic statistics stressing the variability in monthly Marginal Value Product of canal water.

Table 7.10. Actual yearly Marginal Value Product (Yearly), maximum monthly Marginal Value Product (Maximum) and minimum monthly Marginal Value Product (Minimum) as estimated by the stochastic linear programming models for the eight sample watercourses of the Fordwah and Azim distributaries.

Distributary & watercourse		Marginal Value Product (Rs.m^{-3})		
		Yearly	Maximum	Minimum
Fordwah	FD 14	0.25	0.34 (Sep)	0.18 (Dec)
	FD 46	0.23	0.6 (Sep)	0 (May)
	FD 62	0.21	2.0 (Jan)	0 (Nov, Dec)
	FD 130	0.42	1.47 (Mar)	0 (May, Dec)
Azim	AZ 20	0.29	1.8 (Feb)	0 (Dec)
	AZ 43	0.29	0.36 (Jan)	0 (Nov, Dec)
	AZ 63	0.45	1.91 (Apr)	0.05 (May)
	AZ 130	0.52	3.9 (Sep)	0.18 (Dec)

The Marginal Value Products presented in Table 7.10 are used to illustrate the impact of changes in canal water supplies on farm gross income for different situations:

- If an extra cubic meter of canal water is allocated to each watercourse for the month with the highest MVP, then the total increase in farm gross income would be 12 Rs for eight cubic meters, or 1.66 Rs.m^{-3}.
- If an extra unit were allocated to each watercourse with the existing temporal distribution of canal water between months, the expected increase in farm gross income would be 2.7 Rs, or 0.33 Rs.m^{-3}. This is 5 times less than what is obtained with the same volume targeted to the months with the highest constraints and MVP.
- With the existing temporal distribution of canal water between months, the reallocation of one unit of canal water among watercourses would yield an extra 0.21 Rs for the Fordwah watercourses and 0.23 Rs for the Azim watercourses (obtained by subtracting the lowest monthly MVP from the highest monthly MVP);
- With no monthly constraint on canal water supplies, the reallocation of one unit of canal water among watercourses would yield an extra 2 Rs for the Fordwah watercourses and 1.8 Rs for the Azim watercourses, thus nearly 10 times more than the reallocation with constraints on the temporal distribution.

The issue of temporal variability is further emphasized by comparing the output of the stochastic linear programming models for a monthly allocation of canal water (actual situation), and for a yearly allocation of canal water. Table 7.11 shows that an overall increase in the farm gross income by 12.6% would occur without any increase in the total quantity of canal water, but with an increasing temporal flexibility in canal water supplies.

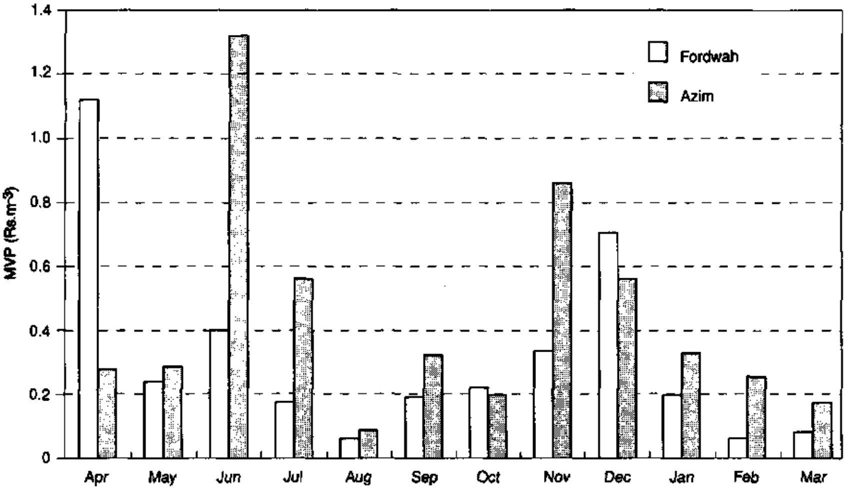
As expected, higher gains are obtained for the Azim Distributary watercourses that are non-perennial and that record a temporally distorted canal water supply distribution. Also, the highest impact is obtained for Watercourse AZ 63 that is the most constrained watercourse in terms of tubewell water availability.

Table 7.11. Impact of temporal reallocation of canal water supplies on farm gross income. (Results of simulation with the stochastic linear programming models for the eight sample watercourses of the Fordwah and Azim distributaries)

Distributary & watercourse		Farm gross income		
		Actual situation (10^6Rs)	Temporal reallocation (10^6Rs)	Difference in percentage
Fordwah	FD 14	2.46	2.50	+1.6%
	FD 46	1.50	1.65	+10%
	FD 62	1.78	1.87	+5.1%
	FD 130	2.43	2.54	+4.5%
Azim	AZ 20	1.53	1.61	+5.2%
	AZ 43	1.78	1.93	+8.4%
	AZ 63	3.82	5.15	+34.8%
	AZ 130	2.67	2.98	+11.6%
Total		17.97	20.23	+12.6%

To finalize the discussion on this issue, Figure 7.9 stresses that the high temporal differences in MVP is also valid at the distributary level. The range of monthly marginal value product of canal water estimated for the Azim and Fordwah distributaries is 0.05-1.1 $Rs.m^{-3}$ for the Fordwah Distributary, and 0.06-1.3 $Rs.m^{-3}$ for the Azim Distributary.

Figure 7.9. Monthly Marginal Value Product of canal water for the Fordwah and Azim distributaries, obtained through simulations with the hydraulic and stochastic linear programming models.



Interdependency between water users

Secondly, the *rigid physical infrastructure* places constraints on the potential for reallocation of canal water and limits transactions between secondary canals. In fact, with the present infrastructure, it is not possible to allocate different canal water supplies to individual watercourses along a given distributary. Thus, watercourses that would potentially participate actively in water markets, as they have high Marginal Value Product of canal water, are constrained by the participation of other watercourses located along the same distributary that have lower marginal value products of canal water. The variability in marginal value product of canal water, as estimated by the combination of the hydraulic model and stochastic linear programming models, is presented in Figure 7.10 and Figure 7.11 for the Fordwah and Azim distributaries.

The heterogeneity of the marginal value product between watercourses has three implications. Firstly, the reallocation of canal water to distributaries is likely to have limited impact, as watercourses with marginal value product lower than the average will see little change in their agricultural production and farm income. Secondly, if canal water is effectively transacted between distributaries without the possibility for watercourses to reallocate canal water among themselves, a mechanism of financial compensation would be required, so that watercourses with currently low marginal value product do not see their income decreasing as a result of canal water price being higher than their marginal value product. And, thirdly, higher gains would be expected from the combination of transfers between distributaries *and* between watercourses along each distributary.

Figure 7.10. Yearly Marginal Value Product of canal water for all watercourses of the Fordwah Distributary, as estimated by the combined use of the hydraulic models and the stochastic linear programming models applied to all the watercourses.

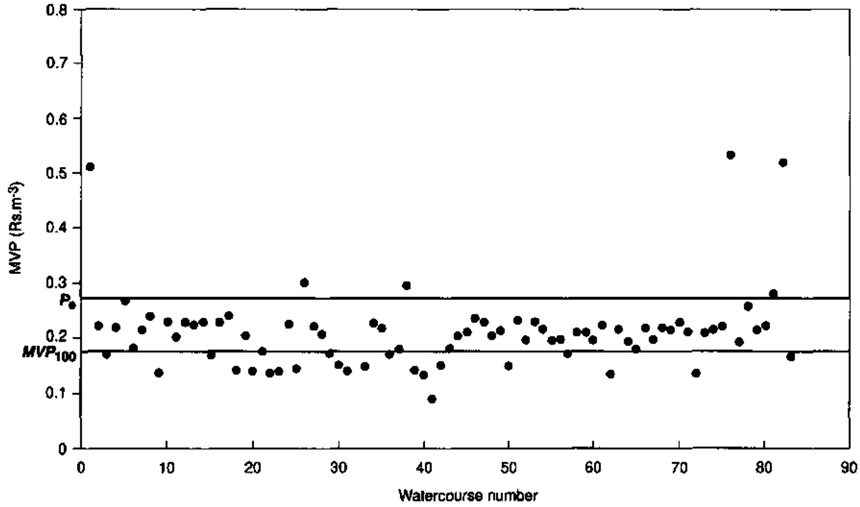
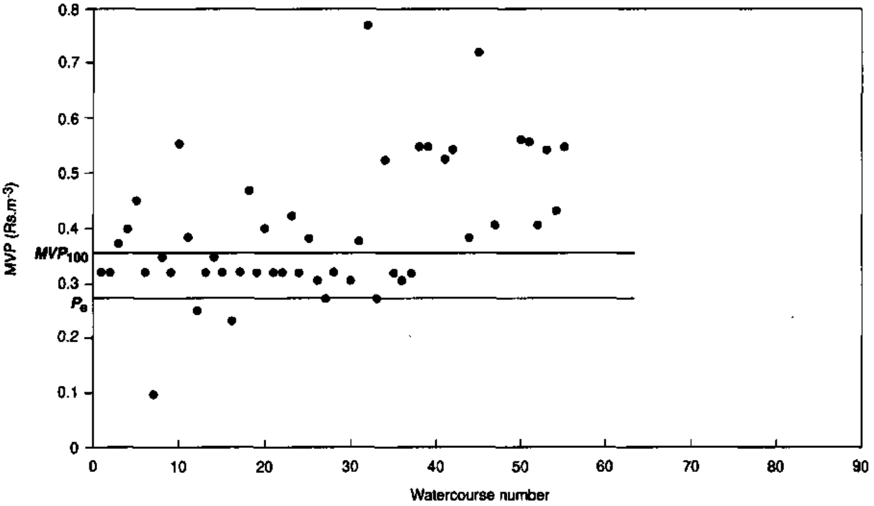


Figure 7.11. Yearly Marginal Value Product of canal water for all watercourses of Azim Distributary, as estimated by the combined use of the hydraulic models and the stochastic linear programming models applied to all the watercourses.



Summary

Table 7.12 summarizes the main results obtained so far in this research on the functioning and impact of existing and potential water markets in irrigation systems in Pakistan. Selected issues for further research are also proposed in the last column of Table 7.12.

An important result of the research has been to reemphasize the importance of the definition of water rights, and the need to match water right definition and infrastructure. A water right that incorporates a temporal distribution of canal water allocation constrains the potential impact for canal water reallocation. Higher impact would be obtained if the temporal constraints would be removed and water rights defined solely as a yearly volume of canal water. In a typical supply-based system, to accommodate these rights would require a higher flexibility in operation in order to respond to the varying use of canal water between months. A move towards a more demand-based system would be required to provide this flexibility. However, this would have important implications for the infrastructure and operation at higher levels of the irrigation system. For example, the integration of storage facilities within the irrigation system would be required for reallocating surface water supplies between time periods.

Table 7.12. Summary of research results and issues for further research.

	Functioning	Impact	Selected issues for further research
Existing water markets	. Importance of groundwater and surface water markets for increasing flexibility in water distribution . Socio-economic and physical factors influencing water transactions . Cases of intensive sales/purchases of surface water observed under specific water resources conditions	. High impact of tubewell water markets on agricultural production, farm gross income, and the environment . Existing allocation and distribution close to efficient allocation and distribution	. Spatial analysis of allocation/distribution of surface and groundwater resources within tertiary units (use of GIS and spatially-defined economic models) . Impact of short-term canal water transactions on agricultural production
Potential water markets	. Surface water rights defined as yearly volume and pre-defined monthly distribution . Limited physical constraints on reallocation, but initial rehabilitation may be required for reallocation between distributaries . Changes in institutional setup required	. High-volume low-impact transactions of surface water rights . Limited impact of reallocation between tertiary and secondary units because of interdependency between supplies for different time periods and to different users	. Incorporating water quality issues in economic models and analyzing how this modifies the analysis of the potential for water market development . Combining surface water reallocation between watercourses and distributaries . Potential for water market development under different water right definitions . Combining surface and groundwater rights for an efficient allocation of water resources

The importance of storage facilities in enhancing water market development is further supported by the literature. Active water markets within irrigation systems have been reported in irrigation systems with storage facilities that allow banking and transfer of specific volumes of water. For example, the Colorado-Big Thompson irrigation system (Michelsen, 1994); irrigation systems in Australia (Pigram et al., 1992); the Water Bank in California (Howitt, 1993); the more intensive cases of water markets in Chile (Hearne, 1995; Bauer, 1997).

As a conclusion, the following statement is then proposed as an issue for further research and testing: *there is potential for surface water market development in irrigation systems that contain some elements of demand-based operation, and for which the interdependency in allocation between users and irrigation units and between time periods is reduced to a limited level.*

Chapter 8

Integrated approach: lessons from implementation and perspectives

The methodology developed to analyze the functioning and impact of existing and potential water markets has its basis in the integration of different disciplines, (economics, hydraulics, soil sciences, agronomy) and the analyses of biophysical and decisional processes at different spatial scales of the irrigation system. As a result of its focus on large areas, an important element of the approach is the analysis of the spatial heterogeneity of key parameters and variables that influence the relationships between water, salinity and sodicity, and agricultural production.

The results obtained by the application of some elements of the integrated approach, both for the present case study and for the companion study by Kuper (1997), have already illustrated the potential use of the integrated approach. The main objective of the last chapter of this thesis is to build on these experiences and identify more generic lessons that can be learned from the development and application of the integrated approach in the Chishtian Sub-division.

This chapter discusses three elements related to the integrated approach. Firstly, its added value is assessed, based on its application to the analysis of existing and potential water markets. Secondly, based on constraints and weaknesses identified through the application of the integrated approach for the two case studies, directions for further improvement of the integrated approach are specified. Thirdly, and finally, the rationale for integrated approaches is re-emphasized, stressing the increasing needs of developing and applying such approaches in the field of water resources management.

8.1 Using the integrated approach for the analysis of water markets in Pakistan

Added value of the integrated approach for the analysis of existing and potential water markets

The development of the integrated approach has involved extra efforts that would not have been required for purely disciplinary studies. Such efforts are required to investigate the links between disciplines, to investigate different scales of the irrigation system simultaneously, to understand several (other) disciplines, and to collect information required to analyze the heterogeneity of a large number of parameters and apply the approach at a relatively large scale. The limited application of the integrated approach to the analysis of water markets, however, has already shown part of the added value resulting from this approach. Primarily, it provides simultaneously information on water supplies, agricultural production and farm income, salinity, sodicity and recharge to the aquifer at different spatial scales and for the whole command area of an irrigation system, a requirement for taking decisions on appropriate interventions in irrigation management and irrigation sector policies. More specific examples of the added value of the integrated approach are presented below.

A good description and understanding of irrigation water supplies has been obtained. With water being the main constraint on agricultural production, whose impact is further investigated through different scenarios, this is seen as an essential strength of the present analysis of water markets. More specifically, canal water supplies used as input into stochastic linear programming models are based on measurements of *actual* canal water supplies. This is seen as an appropriate option in situations where design values of canal water duties are not valid anymore, and that is much more robust and rich than the use of simple proxies such as source of irrigation and number of irrigations applied to crops. Still, the issue of farmer's perception about these supplies that will eventually explain farmers' decisions regarding crop choices remains to be investigated.

The analysis of the current management of the irrigation system, from the farm to the main canal, has provided a clear understanding of existing constraints and potential in the management of the irrigation system. The nature of water makes this part of the analysis essential to the water market study, as it specifies the existing limitations on water reallocation within the system investigated. This is seen as an essential element of the present research, required to bridge the gap between economic theory and a complex and diverse reality of current field situations. Also, it provides the appropriate information and understanding to the identification of possible improvements that takes the current system as a given (Gould 1989). For example, existing limits in maximum and minimum allocations (flow rate) to specific areas, limited direct externalities related to transfer of canal water between two watercourses, and constraints on water allocation imposed by the existence of a strong temporal and spatial dependency in water supplies, are important elements that are considered in the analysis of potential water markets.

The combination of the hydraulic simulation models and the stochastic linear programming models has been useful in developing an understanding about the variability in canal water supplies and its marginal value product for a large number of watercourses off-taking from the same distributary. It stresses the existing heterogeneity of these marginal value products along a distributary, a positive factor for the reallocation of canal water between watercourses, but that may limit the potential impact of canal water reallocation between distributaries. Although the combination of the hydraulic and economic models has only been used for the present case study and the companion study by Kuper (1997), it is expected to become a powerful tool to support discussions on the potential for improved canal operation and maintenance in Pakistan.

The combination of economic and environmental issues is probably an area that requires more refinement and investigation to better incorporate salinity and groundwater issues in farm decisions. However, the results obtained so far with the combination of economic models and biophysical models have already shown their strength in providing quantifiable criteria to analyse the trade-off between economic efficiency and environmental sustainabaility. Although no one would argue about the positive impact of an increase in canal water supply on soil salinity in areas with deep

groundwater tables, to estimate the overall impact of canal water *reallocation* on environmental factors remains everybody's guestimates without the support of tools similar to the ones that have been used in the present study.
The integrated model will be further used to investigate the robustness of the results obtained so far and their validity for a wider range of situations. Model parameters will be modified to represent different physical and socio-economic environments. The output of scenarios under different conditions, or sets of parameters, will be compared to assess the impact of farm population composition, access to groundwater resources, canal water supply, and crop portfolio on the potential for reallocation of canal water between separate units of the irrigation system. This is also seen as an important strength of the integrated approach. To test hypotheses before hand reduces the need to collect information in a large range of irrigation systems, and enables researchers to target areas for further analysis.

8.2 Future of the integrated approach developed in the Chishtian Sub-division

The integrated approach developed in the Chishtian Sub-division has not been used yet to its fullest extent. However, the application of part of the approach to the two case studies has emphasized limitations and weaknesses that may constrain its future use. Some of these limitations arise from the type of intervention analyzed in the two case studies that has influenced the choice of simulation and optimization models included in the integrated tool. For example, while the integrated model is appropriate to investigate planning decisions taken by farmers as a result of changes in their irrigation environment, it is not adapted to the analysis of short-term canal water transactions and their potential impact on agricultural production.

In its present configuration, however, the range of interventions that can be analyzed through the integrated tool is large enough. Thus, there is more potential to using the existing integrated model to assess the impact of other interventions rather than to add new models that would widen the range of possible interventions that can be tested. Of particular interest in this context is the comparison between supply-based and demand-based interventions, an important element discussed in the first chapter of this thesis. The identification of appropriate policies is likely to require a mix of demand-based and supply-based interventions, as highlighted by most of the discussions in Chapter 7 on the potential for water market development. The integrated approach provides an appropriate framework for investigating this issue.

There is still scope for improving the individual models that have been developed and then linked into the integrated tool. Due to the modularity of the tool, improvements in individual models can easily be incorporated. Improvements may refer to the simplification of models to improve the adequacy between models and information available to apply the model at a given scale. As stressed above, the balance between the complexity of the individual models and information requirements to use models at a larger scale is a complex issue. The process of developing the economic models illustrates this point. Simple stochastic linear programming models were initially developed without tubewell availability constraints. Their refinement led to the inclusion of such constraints and risk-aversion parameters related to the variability in canal water supplies. Although the more refined versions of the models have been calibrated and validated for the eight sample watercourses, their use for the 80 watercourses of the Fordwah Distributary showed a lower accuracy than the simpler models in predicting rabi cropping intensities. The lack of knowledge about local water management and groundwater conditions makes it difficult to estimate the tubewell availability constraints that are included in the refined models, which is required for proper use of these models when applied to other watercourses.

Improvements in the individual models can also mean a higher degree of complexity to incorporate processes, variables or links between processes that had been neglected so far. This applies, for example, to the economic models that consider a one-year planning frame. This planning frame may be too short with respect to environmental processes that are investigated simultaneously and are to be considered for longer time periods. Farmers, for example, implement specific crop rotations between rice and fodder to reclaim saline areas. Often, several years should be considered in economic models to adequately represent and investigate such decisions and analyze farmers' choices with a longer-term perspective.

This applies also to the work on the geo-chemistry, expected to have high payoffs as highlighted by the importance of sodicity and soil degradation in the Chishtian Sub-division in Kuper (1997). Condom (1996) and van Dam and Aslam (1997) have shown that it is possible to use state-of-the–art tools such as GYPSOL (Valles and Bourgeat, 1988) and UNSATCHEM (Simunek and Suarez, 1994) for soils in Pakistan to predict salinity and sodicity levels. However, these models have not been calibrated and validated yet. In both cases, however, the information requirements to use and apply the models at higher scales will be an important aspect that will influence the potential use for these models for analyzing large irrigated areas.

At present, the different models still function independently, and the exchange of information between models takes place manually. A user-friendly interface that facilitates the links between models is being developed. This would facilitate the analysis of a large number of scenarios, e.g. Monte-Carlo simulations, an important element to test the robustness of the integrated model itself. The modular aspect of the integrated tool, however, will be kept to allow users to monitor the flow and processing of information, and to use individual models independently whenever a specific process requires further investigation. Although the interface will facilitate the use of the integrated model, direct users of the integrated tool are likely to be researchers in the foreseeable future, because of the complexity of the tools integrated and the interpretation of results.

Although improvements in individual models are a part of improving the integrated approach, this may not be the priority, as it does not directly build on the integrated dimensions of the approach. More related to integration would be the incorporation of feedback loops in the integrated tool. An example of a feedback loop is the link between the output of the SWAP93 model in terms of salinity and transpiration, and decisions taken by farmers that are represented in the stochastic linear programming models. So far, the integration of groundwater quality and salinity issues into the stochastic linear programming models has been rather limited, and farmers' decisions regarding tubewell water use do not consider directly its potential negative impacts on salinity and sodicity.

The validation of the tool for the present conditions was carried out partially, but should be done more thoroughly. The verification of predictions for the future has not been done so far, and remains an issue for discussion (Konikow and Bredehoeft 1992). An important element in the validation of the integrated approach is to assess the usefulness of the information obtained for actors to take (better) decisions. In Chapter 3, the importance of interactions among actors was emphasized. Frequent interactions have taken place during the research, mainly with farmers, staff from line agencies, and researchers. Further interaction is required to discuss the results of the integrated approach and to evaluate the usefulness of the information provided. In this context, it is believed, for example, that the integration of the technical component into the analysis of water markets will be a strong element facilitating discussions with irrigation system managers on the potential for water market development in Pakistan.

8.3 General perspectives on integrated approach

An irrigation system is characterized by a high degree of interdependency between users, a large spatial heterogeneity of different physical and socio-economic parameters and variables, a temporal variability with risk and uncertainty in a large number of parameters related to the nature of agricultural production, and a large number of actors who all share a common system, but have different objectives that may be conflicting for the same water resources (Molle and Ruf, 1994). The arguments for pursuing an integrated approach are found both in the nature of an irrigation system as well as in the assertion that linking biophysical and human decision-making processes will lead to a broader recognition on the comparative advantages for a large range of interventions to improve irrigation system performance.

Recent concepts of managing common resources in river basins, catchment areas and irrigation systems, involving individuals, community groups and government agencies, strengthen the argument of further stimulating the concept of an integrated approach (e.g. Shaw, 1996). Decision-making needs to be tailored towards proposing optimal solutions for the management of these resources that are understood and accepted by all. This requires information in order to diagnose the effect of current practices on water resources, the environment and economics, and to assess the marginal impact of interventions on these resources. When comparing the effectiveness of various options, which do not necessarily target the same space and time scale, nor the same organizational level, an integration of knowledge and experiences from different disciplines is required. Thus, integration takes place sooner or later. The better solution is to consider integration in the early stages of research, and complement disciplinary work by an understanding of the complexity of the system investigated and the analysis of the links between processes.

In this context, important efforts will be required to develop appropriate databases that fulfill simultaneously the requirements of each discipline and the need for integration. These databases are likely to be complex, including a wide range of information collected for different time and spatial scales. Geographic Information Systems will provide an appropriate framework to develop the structure of these databases. The use of such information is likely to require new skills in geo-statistics to ensure the soundness of information processing undertaken by investigating different spatial and temporal scale simultaneously. In this context, techniques related to upscaling of information and/or models, classification, extrapolation and interpolation will become increasingly important. It is believed that the success in developing an integrated database will partly determine the success in developing and applying the integrated approach.

Chapter 9

Summary and conclusions

An integrated approach was developed to assess a priori the impact of policy and management interventions on irrigation water supply, salinity and sodicity, and agricultural production. This approach was operationalized in this study to assess the functioning and impact of existing and potential water markets in irrigation systems in Pakistan. In a parallel study, the approach was further tested for analyzing the effects of interventions in the management of the irrigation system on soil salinity, sodicity and crop transpiration. In Section 9.1, the findings of the present analysis of water markets in irrigation systems in Pakistan are summarized and concluded. The lessons from the application of the integrated approach to the two case studies have been combined and discussed in Section 9.2.

9.1 Potential for water market development in irrigation systems in Pakistan: do we have more answers?

The need for water markets to manage the irrigation sector

Increasing pressure on water and financial resources has led to recognizing the importance of economic dimensions for water resources, and the need to incorporate the economic value of water in the design of new policies for the irrigation sector. Supply-based interventions, such as large infrastructure projects, that have long been the favored intervention in the irrigation sector, are not appropriate nor possible anymore to tackle issues related to water use efficiency or financial and resource-base sustainability.

Recognizing the economic value of water, however, has not yet led to a major shift in the choice of economic instruments required to improve water use efficiency. Instead, the main focus of recent interventions has been on changes in the institutional framework to transfer part of the tasks and responsibilities to water users. Although the impact of such transfers are clear for the government budgetary deficit, their impact on water use efficiency and long-term sustainability has not been clearly demonstrated.

Water pricing is the option traditionally proposed for improving water use efficiency. More recently, increasing attention has been given to the potential for water markets to improve both the allocative efficiency of water resources and the efficiency of water use. Although the difference between the required theoretical conditions for water markets to function perfectly, and existing conditions in the irrigation sector, is considerable, water markets have been reported in diverse socio-economic and physical environments under a wide variety of arrangements, and likely represents a better alternative than the existing situation.

In Pakistan, as a result of the poor performance of the irrigation sector and the need to reduce the government's budget deficit, drastic changes in the irrigation sector have been proposed and are currently underway. The development of water markets is seen as an option that would improve water use efficiency and lead to an increase in agricultural production sufficient to match population growth and the related demand for food products.

This thesis aims at assessing the potential for, and impact of, water market development in irrigation systems in Pakistan. To do so, the study uses elements of an integrated approach developed jointly with Kuper (1997) to assess the potential impact of policy and management interventions on irrigation system performance. This integrated approach includes an analysis of the complexity of the irrigation system, the identification of physical and decisional processes that directly affect water supplies, salinity, sodicity, and agricultural production, and an analysis of the existing heterogeneity and spatial diversity of the main parameters and variables of these processes. The research concentrates on the Chishtian Sub-division, South-Punjab, and more specifically on eight sample tertiary units of the Azim and Fordwah distributaries. Located in the cotton-wheat agro-ecological zone of Pakistan, this irrigation system is characterized by a conjunctive use environment with extensive use of groundwater resources to complement surface water supplies.

Existing water markets within tertiary units of the irrigation system

There exist very active surface and groundwater markets in all the eight sample tertiary units, which were investigated. As a result of the detailed monitoring of irrigation water use, a better grasp was obtained on canal water transactions that are, in fact, more active than what has been reported in the literature. Canal water transactions are mainly short-term transactions that involve a part of farmers' water turns and compensate for the variability in watercourse head discharges. Groundwater transactions play a dual role: they increase the water quantities available on the farm, and compensate also for canal water supply variability.

The functioning of water markets is influenced by the characteristics of water resources in terms of quantity and quality and by farmers' constraints and agricultural production strategies. In cases of high unreliability in canal water supply, high conveyance losses, and cheap access to groundwater resources of good quality, farmers within tertiary units develop *intensive canal water markets* with the sale and purchase of water turns for a week or for the season.

The *impact of tubewell water markets* on farm gross income is significant and estimated at *40% of the actual gross income* aggregated for the eight sample watercourses. Tubewell water markets significantly decrease the net recharge to the aquifer, and increase the danger of soil salinity and sodicity. The impact of tubewell water markets on sodicity, however, is less pronounced than the impact on the net groundwater recharge and on salinity.

The impact of existing canal water markets on agricultural production is more difficult to estimate. Short-term flexibility is a very important element of such transactions. But the impact of canal water transactions on irrigation water supply within a season is difficult to capture with the approach and models developed in the present study, as it deals more with the timeliness of canal water supplies.

Potential for water market development

The potential for water market development is investigated at various spatial scales of the irrigation system: within tertiary units, between tertiary units, and between secondary units. For each scale, the analysis investigates the impact on agricultural production and on the physical environment, and discusses elements related to the operationalization and technical feasibility of the proposed water market scenarios. Water rights are defined as a volume with a pre-defined monthly distribution of canal water.

Within the watercourse command area, the marginal increase in farm gross income that would arise as a result of *enhanced canal water or tubewell water markets* is around *5-6%* for the eight sample watercourses aggregated. Thus, a combination of both enhanced tubewell and canal water markets is expected to yield sizeable increases in farm gross income. Also, no significant negative impact on environmental parameters is to be expected. Differences among tertiary units, however, remain important. As a result of an enhanced tubewell water market, for example, salinity would increase by nearly 8% as compared with the actual situation for the Watercourse FD 130. And a similar increase in the sodicity level is expected for the Watercourse FD 62 as a result of enhanced canal water markets.

As one moves to higher scales of the irrigation system, the expected increase in farm gross income, resulting from a reallocation of surface water supplies defined by a total yearly volume with a pre-defined monthly allocation, becomes less significant. An increase of 3-4% in farm gross income is predicted as a result of reallocating surface water supplies between watercourses along the Azim and Fordwah distributaries. Between distributaries, the total volumes of canal water reallocated through market mechanisms from the Fordwah distributary to the Azim distributary are high. However, this reallocation of yearly canal water supplies would yield an increase in farm gross income of only 2%.

The reallocation of canal water supplies between watercourses and between distributaries is expected to increase the pressure on groundwater resources, and may lead to further mining of the groundwater aquifer. The reallocation of canal water between watercourses would improve the average salinity and sodicity levels for the eight watercourses considered. The reallocation of canal water between distributaries, however, would yield an overall (although limited) increase in salinity and sodicity, especially for the FD 14 and FD 130 watercourses underlain by poor quality groundwater.

The existing conveyance infrastructure is not expected to be a major constraint on further water market development. Within the watercourse command area, operational problems are limited and watercourses with intensive canal water markets show that farmers have also the organizational capability to develop such markets. Between watercourses, the reallocation of canal water can take place by modifying the dimensions of the outlets. Modifications of supplies to watercourses which are not participating in the reallocation of canal water are expected. But the impact of such reallocation would remain limited as a result of the sub-proportionality properties of most of the outlets.

Between distributaries, maximum and minimum discharges may limit the reallocation of canal water. The problem, in fact, relies more with minimum discharges as it leads to problems of canal water distribution along distributaries. And the maximum discharge constraints can easily be removed or reduced by a limited strengthening of the distributary banks. The analysis of the potential for reallocation through market mechanisms between the Azim and Fordwah distributaries, shows that problems of water distribution along the distributary would arise with the expected reduction in allocation to the Fordwah Distributary. Also, problems would arise with the predicted increase in canal water allocation to the Azim Distributary because of its poor physical condition.

The definition of the object of transaction directly influences the potential development and the impact of surface water markets. The analysis shows that there is limited potential for reallocation of water rights defined with a pre-defined monthly allocation. In fact, this definition includes an interdependency between volumes allocated to each month and this rigidity limits the impact of reallocation. With water rights defined as a yearly volume, however, expected benefits are significantly higher. This is illustrated with two watercourses: with a pre-defined temporal allocation of canal water, the impact of the reallocation between the two watercourses is close to 5%, while the impact of the reallocation of a yearly volume (i.e. without the rigidity imposed by the pre-defined monthly allocation) between the same two watercourses is more than doubled and close to 13%. However, drastic changes in the infrastructure and the addition of storage capacity would be required to enable the reallocation of volumes between months and time periods.

Also, the scenario of reallocation investigated between the two distributaries did not allow for reallocation of canal water supplies between watercourses along the distributaries. Thus, the spatial interdependency between watercourses leads also to a reduced impact of reallocation between distributaries. To combine both markets between watercourses and between distributaries would probably yield a higher impact. However, this is to be tested with the available simulation and optimization models.

9.2 General application of the developed integrated approach to irrigation management

Using the integrated approach: outlook

The integrated approach has been tested for two case studies, yielding valuable insights into the functioning of an irrigation system, the effects of interventions in the system, as well as into the issues related to operationalizing an integrated approach. The most important follow up of the present studies relates to the utilization of the developed approach. In collaboration with the actors in the irrigation system that was studied, different scenarios should be formulated and simulated using the combined tool. This could form the basis of continued discussions between actors to improve the performance of the system during a more action-oriented phase. A successful implementation of the approach would strengthen the arguments of this study on the pertinence of an integrated approach, and could lead to the identification of other necessary refinements in the approach. Based on the present experiences, some further improvements in analyses and tools can be identified. Firstly, feedback loops between different processes, such as the impact of salinity on farmers' strategies, should be included in the approach. Secondly, the software environment could be improved to facilitate running multiple scenarios. In addition to this, improvements on the individual models or analyses should be considered. This pertains, for example, to the incorporation of a geo-chemical model or the inclusion of a larger range of household objectives and constraints in the modeling of farmers' decisions. The inclusion is relatively straightforward due to the modular set-up of the approach. The interface between different models and processes needs also attention. Finally, a more detailed analysis of the transfer of inaccuracies should be studied. In the present configuration, it was found that looped computations did not amplify errors in individual models. This phenomenon should be analyzed and tested for a larger range of scenarios. It should be emphasized, however, that all these improvements seem desirable, but that the first priority should be to use the combined tool in its present configuration, within the general context of the integrated approach.

The process

An integrated approach is a concept heralded by many researchers, but applied by few. This is probably related to difficulties in the implementation. Different disciplinary teams need to coordinate the research, and in doing so have to harmonize research objectives and methodologies. In addition, some of the choices that need to be made in the research will be constrained by other disciplines. This relates to very practical details like the choice of the study area, sampling frame, and the time frame. It may also be related to a choice between the relative certainty of a disciplinary outcome, as compared to the uncertainty in outcome of an integrated approach. However, the case studies discussed here have shown that disciplinary research and the development of an integrated approach can coexist.

Depth or breadth? In order to achieve a successful integration, this process should start as far upstream as possible in the flow of research. Combining and linking research results and tools will yield valuable lessons and cannot be left to the last minute when it is discovered that important relationships have not been studied. It is recommended to develop a simplified integrated model in the early stages of the research, on the basis of an integrated framework. This can be subsequently adjusted or replaced in the process, but it gives clear signals about the relationships that need to be studied, helps to identify the weak points of the approach, and gives indications about the variability of key parameters that are studied. However, an integrated approach will need to leave sufficient room for disciplinary teams to carry out their studies, as sufficient depth needs to be attained in the research. The value of the integrated approach depends on the rigor of the individual parts. The balance between disciplinary research and integration is a difficult equilibrium to find.

In implementing an integrated approach, there are many difficulties related to information. The information requirements are high, although carrying out sensitivity analyses can reduce them, and the information needs to be shared between groups of people, studying different processes at different spatial and temporal scales. In order to do this, common spatial and time steps need to be defined and databases need to be standardized.

Heterogeneity and variability

The spatial heterogeneity of physical parameters and temporal variability of different processes, as well as the diversity of farms are inherent in the analysis of irrigation systems. This is a disadvantage, because it implies that the spatial and temporal structure of information needs to be analyzed, requiring a more substantial data set, and advanced geo-statistical techniques to classify and extrapolate. For policy makers and irrigation managers, this poses also a serious problem as the effectiveness of global interventions is reduced.

However, heterogeneity/variability can also be seen as an important strength and opportunity. Strength because the system is better adapted to external shocks, and opportunity because the heterogeneity and variability offer possibilities for redistribution of resources. This was shown in both case studies. The present study showed that by making use of the seasonality of irrigation, a reallocation of water would lead to an increase in agricultural production. In the study by Kuper (1997), it was shown that due to the heterogeneity in groundwater quality and soil types, a redistribution of water can lead to a considerable decrease in the area affected by salinity and sodicity.

The challenge is thus in understanding and quantifying the existing heterogeneity/variability at different scales for defining policy and management interventions.

Interventions

The policy and management interventions that were proposed and analyzed in the present study and the parallel study of Kuper (1997) cover a wide range. While the former study analyzes policy level interventions, such as water pricing and the development of water markets, the latter focuses on irrigation system management interventions, i.e. changing the operational rules of the irrigation agency and modifying the characteristics of tertiary outlets. In practice, policy makers and irrigation managers have a choice in selecting a mix of different policy and/or management interventions. The complementarity of the interventions that were analyzed in both studies has not been investigated so far, and provides an interesting scope for further work. This is especially true, because a large number of variables, reflecting the complexity of an irrigation system, have been included in the tools that were developed in these studies. This means that a comparison is possible of the impact of different policy and management interventions on the agricultural production and on the sustainability of irrigated agriculture, i.e. salinity, sodicity and groundwater mining. Thus, a better combination of interventions can be proposed to the different actors.

Transferability

The application of the integrated approach to two different case studies showed that the developed approach allows an investigation of a wide range of policy and management interventions, and captures adequately the complexity of an irrigation system. This is due to the fact that a large number of physical and human decision-making processes were analyzed and modeled, allowing the modification of a wide range of variables. This makes the approach of interest also to policy makers and irrigation managers in other irrigation systems, dealing with similar or related issues. The transfer of the integrated approach should not be confined to the combined tool, but should be applied as part of an integrated concept, which includes phases of diagnosis, identification of relevant processes and parameters, and discussions with actors. These phases are important learning stages for understanding the physical and human relationships in a system. In doing so, the focus can remain on understanding the actual functioning of an irrigation system and preparing the future by assessing the effect of policy and management interventions, rather than attempting to make accurate predictions for the evolution of specific parameters.

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Appendix 1

Estimating the impact of changes in irrigation water supplies on salinity, sodicity and groundwater table depth

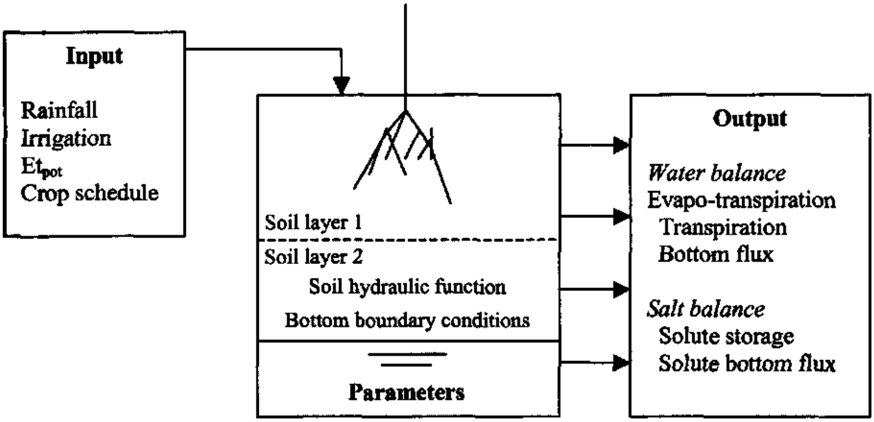
1. Investigating salinization with the solute-transport model SWAP93

The solute-transport model Soil-Water-Atmosphere-Plant, version 1993, or SWAP93 has been developed to simulate the vertical transport of water, heat and solute in variably saturated soils (van Dam et al. 1997). The model simulates processes at the field scale and during a full growing season of crops. It enables an investigation of the impact of different irrigation regimes on the water and salt balance within the root zone (Kuper 1997). The basic equations solved by the SWAP93 model include Richards' equation for the transient water movement in the soil matrix, a sink term for root water uptake, and a series of solute transport equations that describe mechanisms such as convection, diffusion and dispersion, non-linear adsorption and first-order decomposition (van Dam et al. 1997; Kuper 1997).

Information on rainfall, irrigation applications (quantity, quality, timing), daily meteorological conditions, crop (leaf area index, crop height and rooting depth), soil hydraulic functions and top and bottom boundary conditions are required to calibrate and run the SWAP93 model. The number of soil layers within the soil profile and the number of compartments within each soil layer are to be selected. Options offered for bottom boundary conditions include flux, groundwater table depth, flux as a function of groundwater height, free drainage and a lysimeter with free drainage. The output of the model of interest for the present thesis includes the water balance variables such as evaporation, transpiration, bottom flux, and salt balance variables such as solute bottom flux and solute storage for each compartment within the soil profile and each time step. Figure A1.1 summarizes the input, parameters and output of the SWAP93 model.

The SWAP93 model has been calibrated and validated for four fields representing the main soil types of the Chishtian Sub-division command area as presented in Smets et al. (1997). Information related to irrigation and farming practices, crop status and moisture content through the soil profile was collected for the four sample fields during three seasons (two cotton crops and one wheat crop) through interviews, crop measurements and tensiometer readings (Kuper 1997). The validation of the SWAP93 model is satisfactory for the water balance components, but slightly overestimates the solute leaching for coarse textured soils (Smets 1996; Kuper 1997). Testing different water supply scenarios with SWAP93 has shown that the quantity of irrigation water affects soil salinity and transpiration significantly more than its quality in terms of salt content. The results from simulation stress that salinity levels will be higher for medium textured soils than for coarse soils in the long-term (Kuper 1997).

Figure A1.1. Representation of the input and output of the soil-water flow-solute transport model SWAP93 (adapted from: Kuper 1997).



An important issue with the SWAP93 model relates to the possibility of using the model at higher spatial scales than the one for which the model has been calibrated and validated (e.g. the watercourse command area). Difficulties in up-scaling models in hydrology are recognized as a result of the complexity of the processes considered, the importance of different processes at different scales, the non-linearity of the phenomenon under study, and the spatial variability of the parameters used in the models (Bloschl and Sivapalan, 1995). Kuper (1997) used the SWAP93 model at the scale of the tertiary unit. The application at this scale showed satisfactory results as compared to more simple water and salt balance equations, or direct statistical relationships between water and salinity developed with information collected for 600 fields in the command areas of the eight sample watercourses. The model was performing better when using the relative importance of each soil type within the tertiary unit command area, as compared to using the predominant soil only. Thus, the different soil types will be considered when using the SWAP93 model at the scale of the tertiary unit.

2. Changes in sodicity

The complexity of the chemical processes that take place within the soil profiles have been discussed in Chapter 3 and are detailed in Condom (1996) and Kuper (1997). Computer models have been developed to simulate these processes but are still at the development stage. Thus, a simple statistical approach developed by Kuper (1997) is used in the present study to estimate the impact of changes in irrigation water supplies on soil sodicity.

Kuper (1997) compared equations linking the quality of irrigation water and sodium hazard developed by different authors under different conditions in the world (Bower et al., 1968; Jurinak and Suarez, 1990), and an empirical equation developed with information collected for 600 fields located in the command area of the eight sample watercourses. Results showed that the empirical equation developed for local conditions was performing better than other equations to estimate *SAR* at the field and watercourse scale. The equation is presented below.

$$SAR = 16.86 + 1.22\ SAR_{iw} - 0.17\ \%Sand \qquad \textbf{(A1.1)}$$

where SAR = Sodium Adsorption Ratio of the soil
SAR_{iw} = SAR of the irrigation water
$\%Sand$ = percentage of sand in the soil

The low R^2 of the regression (0.36) emphasizes the limitations of the relationships and the importance of variables others than the ones included in Equation A1.1 to explain the *SAR* of the soil. The equation stresses the importance of the soil texture in the sodification process, with coarse-textured soils being less affected than heavy and medium-textured soils.

3. Investigating the net recharge to the aquifer

To complement the analysis of the impact of water markets on the sustainability of irrigated agriculture, the balance between the recharge to the aquifer and extraction from the aquifer, or *net recharge,* is investigated. Using the results of the SWAP93 model, a simple water balance is developed for each watercourse and distributary command area investigated for the analysis. The main elements of the water balance for an irrigation scheme are described in Perry (1996) and van Waijjen (1996), and are simplified for the area considered as there is no drainage system.

The recharge to the aquifer is composed of various losses that take place while conveying surface water from the head of the system to the field, percolation losses at the field level, and infiltration related to non-effective rainfall and rainfall in non-cultivated areas. The extraction element is composed of the capillary rise and tubewell pumpages. With tubewell pumpages obtained from monitoring data or predicted by the watercourse linear programming models, and the bottom flux (i.e. the difference between percolation and capillary rise) predicted by the SWAP93 model, information for conveyance and seepage losses only is required to estimate the net recharge to the aquifer.

Values for seepage losses along the watercourse are taken from van Waijjen (1996). These values are adapted for each watercourse based on the soil texture in the watercourses considered and the presence of a lined portion in the watercourse. Values for conveyance losses along the Azim and Fordwah distributaries and the Fordwah Branch Canal are taken from Litrico (1995), Taheen et al. (1996) and Kuper (1997) and are considered constant. According to the scale at which the net recharge is estimated, total conveyance losses for the main canal and secondary canals are multiplied by the ratio of the area considered for the analysis of the net recharge divided by the total CCA of the Chishtian Sub-division.

4. Investigating the spatial variability in physical parameters

The previous sections have highlighted the importance of soil type, groundwater table depth and groundwater quality in the analysis of salinity, sodicity and net recharge to the aquifer. Thus, to investigate the spatial variability of these variables is required for adapting model parameters and using models for all watercourses of the Fordwah and Azim distributaries.

The variability in soil types is investigated using the map developed by the Soil Survey of Pakistan that identifies different soil series within the Chishtian Sub-division (Soil Survey of Pakistan, 1997; Kuper, 1997). Available in a digital format, soil information is simplified in two steps. Firstly, soil series are classified into four major soil types for which the SWAP93 model has been calibrated. Secondly, the relative importance of the four soil types in the command area of each watercourse is estimated by overlay in a Geographical Information System (GIS) of the soil map and the watercourse boundary map that has been prepared for the entire Chishtian Sub-division.

Tubewell water quality in terms of *EC*, *SAR* and *RSC*, has been collected through a large-scale tubewell survey and water analyses for around 500 tubewells in the Chishtian Sub-division. Water analysis information is used to compute average tubewell water quality indicators for each watercourse. The initial average quality information computed for each watercourse is modified through smoothing and interpolation using neighboring information (Schoenmakers, 1997) to compensate for the limited number of water quality samples for a given watercourse (average of two water samples) as compared with the high spatial heterogeneity of tubewell water quality. Although this procedure reduces the short-distance spatial variability, it emphasizes the general spatial trend existing within the irrigation system and of interest for the present research.

Watercourse level groundwater table depths are obtained by overlaying the watercourse coverage and the groundwater table coverage obtained by digitizing maps developed by the SCARP Monitoring Organization in the GIS. These maps display the areas under different water-table classes for different time periods. An average groundwater table depth is computed for each tertiary unit command area, according to the relative importance of each groundwater-table class within the command area.

5. Summary

To assess the impact of existing and potential water markets on the physical environment and sustainability of irrigated agriculture for the Azim and Fordwah distributaries, two complementary activities have been undertaken:

- Models have been developed to investigate the impact of changes in irrigation water supplies in terms of quantity, quality and timing on salinity, sodicity and net recharge to the aquifer; and,
- Using a GIS, a watercourse level database is built. This database includes information on soil types, groundwater table depths and tubewell water quality for use in the models for the 160 watercourses of the Azim and Fordwah distributaries.

The modeling activities are part of the study on the link between irrigation system management and salinity/sodicity undertaken in parallel with Kuper (1997). The analysis of the spatial diversity of physical parameters has been undertaken jointly in the context of the development of an integrated approach to assess the impact of interventions in the irrigation sector on the performance of irrigated agriculture in Pakistan.

Appendix 2

Analyzing current operation and maintenance of irrigation canals and assessing the technical feasibility of water market scenarios

The main objective of this appendix is to identify issues related to the operation and maintenance of main and secondary canals in the Chishtian Sub-division that are expected to influence the technical feasibility of water market scenarios and the potential for reallocation of surface water supplies within this irrigation system. This appendix summarizes the main characteristics of the current allocation and distribution of surface water supplies within the Chishtian Sub-division. This presents, also, the hydraulic models that have been developed to assess the impact of changes in operation and maintenance on water distribution for the main canal and for selected secondary canals.

1. Current constraints on canal water distribution in the Chishtian Sub-division

The Chishtian Sub-division is characterized by an overall situation of shortage when comparing actual canal water supplies to their design or authorized values. For the Kharif 1994 season, for example, the average discharge received by the sub-division was equal to 22 $m^3.s^{-1}$, significantly less than the authorized discharge of 36.3 $m^3.s^{-1}$. Also, the highest discharges received during the same period were lower than the authorized discharge and in the order of 30-32 $m^3.s^{-1}$ (Habib and Kuper 1996; Kuper 1997). The location of the Chishtian Sub-division at the very tail of the Fordwah irrigation system, along with the reduced capacity of the Fordwah Branch Canal and some of its distributaries, are the two reasons explaining the limited supplies received by the sub-division.

The shortage for the sub-division is further accompanied by a high variability of the inflow, transmitted and amplified from the head to the tail of the irrigation system. Thus, canal water supplies received by farmers are highly variable and unreliable. This, in turns, influences farmers decisions related to cropping pattern and tubewell water use, and is expected to negatively impact on agricultural production and farm income.

The analysis of existing canal water supplies to distributaries shows that the lower limit of 70% of the authorized discharge for distributary head discharges as specified in the Manual of Irrigation Practices is still valid (Habib and Kuper 1996). For distributary head discharges lower than 70% of the authorized discharge, it becomes difficult to distribute canal water to all tertiary units along the distributary, as the proportionality characteristics of outlets are not valid anymore. And this problem is particularly acute for the longest distributaries, such as the Azim and Fordwah distributaries.

Maximum discharges handled by distributaries are more variable. The official rule specifies that discharges to distributaries should not exceed 110-120% of their authorized discharge in order not to surpass their carrying capacity. However, this rule is not strictly followed. For example, during the Kharif 1994 season, the ratio of the maximum over authorized discharge is higher than 1.2 for 9 out of 14 secondary canals in the Chishtian Sub-division. Depending on their physical conditions and preferences given by local gauge readers from the Irrigation Department, such high discharges can take place for long time periods and cause long-term changes in the *de facto* allocation to some distributaries. For the Azim Distributary, high discharges are exceptional as a result of the poor physical conditions of this distributary. On the contrary, the Fordwah Distributary can cope with discharges higher than 120% of its authorized discharge.

Water shortage and variability in canal water supplies are not equally distributed between secondary canals in the Chishtian Sub-division (Habib and Kuper 1996). The difference is significant between the Fordwah and Azim distributaries, with the Fordwah Distributary receiving a less variable and more adequate canal water supply than the Azim Distributary. Part of the differences between the two distributaries is related to the preference given to the Fordwah Distributary by gauge readers. Also, and as discussed above, the banks of the Azim Distributary are in a very poor physical condition. To reduce the risk of breaches along the Azim Distributary to its minimum, discharges at the head of the distributary are kept significantly lower than its authorized discharge. In fact, since the abandonment of an escape that was off-taking from the tail of the Fordwah Branch Canal, the Azim Distributary is often operated as an escape to provide a higher buffer capacity for canal operation in the sub-division.

Along distributaries, large inequalities in canal water distribution are observed between watercourses. In the Chishtian Sub-division, 40% of the outlets are broken or over-sized (Tareen et al. 1996). Also, existing cross-sections of secondary canals are at variance from design cross-sections due to sediment deposition (siltation) and scouring. This eventually influences water levels along the distributary and discharges to tertiary units. The Azim Distributary presents a typical example of water supply inequity, as the very tail outlets of the distributary do not receive any canal water supply anymore. Farmers from these watercourses rely solely on groundwater resources for their agriculture.

2. Development of the hydro-dynamic simulation model SIC to investigate constraints in water allocation along the Fordwah Branch canal

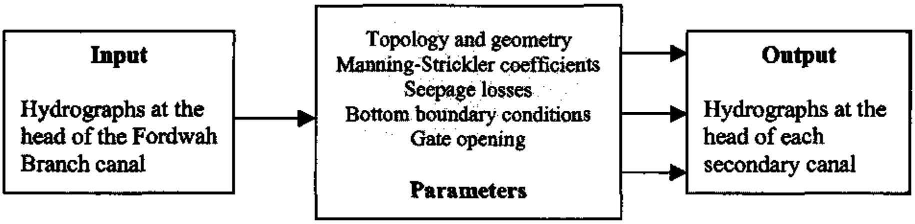
The hydraulic model SIC Version 2.1 developed by Cemagref is used to further specify constraints and limitations in (re-)allocation of canal water between secondary canal command areas. The SIC model is composed of three different units (Malaterre and Baume, 1997), namely:

- A topographical unit, to store the topological and geometrical information that describe the canal network;
- A steady-state hydraulic unit that performs steady-state computations of water surface profiles using the Manning-Strickler equation, based on boundary conditions such as inflow, gate openings for cross-regulators and off-takes, etc; and,

- An unsteady-state hydraulic unit, that performs unsteady-state computations of water surface profiles given the evolution of the boundary conditions as a function of time, based on the Saint-Venant equations discretized through the Preissman's scheme.

The SIC model has been calibrated and validated for the Fordwah Branch Canal with an error of less than 5% between predicted and measured distributary head discharges (Litrico, 1995; Kuper, 1997). The input of the SIC model is the inflow at RD 199 of the Fordwah Branch Canal. Based on the distributary gate openings, the model computes a water surface profile that can be used to estimate discharges at the head of each distributary. The output of the model includes hydrographs at different locations, water levels over time or over location, gate openings, and specific efficiency indicators proposed with the model (Malaterre and Baume, 1997). Figure A2.1 summarizes input, parameters and output of the SIC model developed for the Fordwah Branch Canal.

Figure A2.1. Schematic representation of the SIC model developed for the Fordwah Branch Canal.



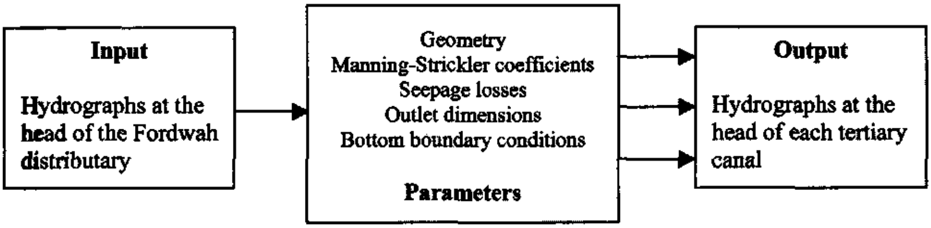
For the analysis of the physical constraints that may limit water market development, the steady-state unit only is used for simulations. Initial simulations with the SIC model have highlighted problems of freeboard along the Fordwah Branch Canal and the existence of weak bank sections at RD 245 and RD 353 close to the cross regulators, and also at RD 267, RD 298 and RD 363 far from cross-regulators. This results in a risk-averse operation by gauge readers that limit canal water supplies to the tail of the Fordwah Branch Canal, thus never operating both the Azim and Fordwah distributaries to full capacity so as to avoid overtopping at RD 350 of the Fordwah Branch Canal (Litrico, 1995). As a result, also, sedimentation has occurred and has reduced the canal capacity at the tail of the Fordwah Branch Canal.

3. Development of simulation models to investigate canal water allocation and distribution along secondary canals

A modeling approach similar to the one developed at the Fordwah Branch level is proposed to investigate constraints on, and potential for, reallocation of surface water between watercourses of a given distributary. The SIC model has been calibrated for the Fordwah Distributary and Masood Distributary with an accuracy of 5% for outlet discharges (Hart, 1996; Visser, 1996; Kuper, 1997). Figure A2.2 summarizes the input and output of the SIC model developed for the two distributaries.

The SIC model is an appropriate tool to investigate allocation and distribution of surface water to tertiary units, although some limitations exist for the use of the model with low distributary head discharges that requires extra computational procedures. As there is no control structure along the distributary, modifications in outlet dimensions is required for changes in allocation between watercourses. Kuper (1997) shows that a modification in the watercourse outlet width is the most appropriate way to remodel outlets and modify its allocation. However, to modify the dimension of a given outlet influences water levels in the distributary and discharges to downstream outlets, a phenomenon that can be investigated using the SIC model.

Figure A2.2. Schematic representation of the SIC model developed for the Fordwah distributary and Masood distributary.



The SIC model developed for the Fordwah Distributary is also used to develop the relationship between volumes of canal water allocated to distributaries and the Marginal Value Product of canal water. The SIC model provides the relationship between the distributary head discharge and the discharge to each watercourse that is input into the watercourse linear programming models to obtain the marginal value product of canal water for each watercourse. The marginal value product of canal water for the distributary is then obtained by computing the weighted average of the watercourse marginal value products.

For the Azim Distributary that has been selected along with the Fordwah Distributary to assess the potential for water market development between secondary canals, a similar relationship between canal water allocation and marginal value product of canal water is required. However, it is not possible to use the SIC model to obtain such a relationship as a result of the very poor physical conditions of the distributary. Thus, a simpler volume-balance approach has been developed to be able to investigate canal water distribution along the distributary as a result of changes in distributary head discharge. Using an initial set of measured discharge q_{0i} (in $m^3.s^{-1}$) at different points along the distributary for a given distributary head discharge Q_0 (in $m^3.s^{-1}$) (Tareen et al. 1996), the discharge q_i at each point is estimated for different distributary head discharges Q with the formula $q_i = q_{0i}.Q/Q_0$. As this relationship is established for points along the distributary and not for individual outlets, a discharge proportional to the watercourse command area is then estimated for each watercourse. The assumption is that each outlet has a sensitivity of 0.5 (Tareen et al. 1997), i.e. a change by 1% in the distributary head discharge leads to a change by 0.5% in the watercourse head discharge.

4. Summary

Several hydraulic models developed for the analysis of main system operation and distribution along secondary canals are used for the analysis of the technical feasibility of canal water markets between tertiary units and secondary units. The development of the SIC model for the Fordwah

Branch Canal, the Fordwah Distributary and the Masood Distributary, is part of the study by Kuper (1997) on the analysis of the potential for irrigation main system management to mitigate salinity and sodicity in Pakistan. While the volume-balance model for the Azim Distributary has been specifically developed for the integrated approach in the Chishtian Sub-division.

The main issues related to the technical feasibility of developing water markets that are tackled with these models are summarized below.

- The constraints in reallocation of canal water between distributaries at the main system level are assessed using the SIC model developed for the Fordwah Branch Canal;
- The constraints in reallocation of canal water between distributaries pertaining to the distributaries themselves are investigated using the SIC models for the Fordwah Distributary and Masood Distributary;
- The impact of reallocation of canal water supplies between watercourses or distributary reaches are analyzed using the SIC model for the Fordwah Distributary; and,
- The development of the relationships between distributary head supplies and marginal value product of canal water integrates the pattern of canal water distribution along distributaries. This pattern is obtained for the Fordwah Distributary using the SIC model, and for the Azim Distributary using a simplified volume-balance model.

Appendix 3

Building, calibrating and validating farm and watercourse stochastic linear programming models

This appendix presents the information used and computational procedures developed to estimate technical coefficients, constraints and parameters required to build the *stochastic linear programming models* for the nine *farm groups* and the eight sample *watercourses* of the Azim and Fordwah distributaries. This appendix also presents also in detail the calibration and validation of these models. To simplify the following descriptions, the stochastic linear programming models for farm groups are named *farm models*, while the stochastic linear programming models for the watercourses are named *watercourse models*.

The models maximize farm gross income under specific land and water constraints. Decisions related to crop production, only, are considered in the models, and other decisions related to livestock or household activities are neglected. The models also integrate risk aspects related to the variability of canal water supplies and wheat and cotton yields.

Several steps are followed to build these models. First, farm models are developed for each of the nine farm groups of the farm typology. Then, watercourse models are built for the eight sample watercourses of the Fordwah and Azim distributaries as combinations of the nine farm models. Farm and watercourse models are first calibrated for four watercourses. The validation of the farm models is then performed using the remaining four watercourses.

1 Building the farm group models

Parameters of the equations presented in Section 5.3 are estimated for each farm group by averaging or aggregating values for each farm. Computations are based on information collected in the 1993 Farm Survey pertaining to the Kharif 1992 and Rabi 1992-93 seasons.

1.1 Gross margins for cash crops

The farm models maximize the total farm gross income, computed as a combination of crop gross margins per unit area, sale and purchase of tubewell water, and sale of wheat produce. Crop gross margins are computed by multiplying the total agricultural output for a given crop by its price, and subtracting total variable costs related to input use (fertilizers, pesticides, farm yard manure) and farming practices (plowing, weeding, harvesting, etc.). As separate activities related to tubewell water use and tubewell water purchase are included in the models, related costs have not been included in the computation of crop gross margins.

The main cash crops considered are sugarcane, rice and cotton. For sugarcane, the average gross margin is computed for each farm group using farm survey information. For rice, the average gross margin for the group is used only for the groups that grow a significant area under rice, while the average gross margin for the whole farm sample (278 farmers) is used for other groups. For cotton, several activities are proposed to account for:

- Different levels of irrigation water application: 100%, 80% and 60% of the total irrigation water requirements as computed by the CropWat software (FAO, 1992);
- Different sowing dates: May 15 (early), June 1 (medium) and June 15 (late).

Table A3.1 summarizes average cotton production indicators for each group. Using results presented in Meerbach (1996) that relates sowing date and yield reduction, and yield reduction results obtained with simulation with the CropWat software, cotton yields are estimated for the different combinations of sowing dates and irrigation applications. These estimates are computed with the assumption that the actual cotton yields obtained from sample data and presented in Table A3.1 corresponds to a medium yield scenario (70% of maximum yield). Yields are then multiplied by the group average cotton price, and average total variable costs are subtracted to obtain group-wise cotton gross margins for each combination of sowing date and irrigation application. Final cotton gross margins, along with sugarcane and rice gross margins, are presented in Table A3.2.

Table A3.1. Parameters related to cotton production: yield, total variable costs and gross margin for each farm group obtained from farm survey data.

Parameter	**Grp 1**	**Grp 2**	**Grp 3**	**Grp 4**	**Grp 5**	**Grp 6**	**Grp 7**	**Grp 8**	**Grp 9**
Average cotton yield (kg.ha^{-1})	1016	1762	1791	1046	974	1292	1400	1379	1695
Standard deviation of cotton yield (kg.ha^{-1})	613	729	705	507	540	636	532	474	567
Coefficient of variation of cotton yield	0.6	0.41	0.39	0.48	0.55	0.49	0.38	0.34	0.33
Average cotton total variable costs (Rs.ha^{-1})	4620	5325	5072	5363	4686	4093	5036	5653	7107
Average cotton gross margin (Rs.ha^{-1})	5137	11973	13040	5371	4261	8136	8255	8202	10178
Standard deviation of cotton gross margin (Rs.ha^{-1})	5302	7059	6734	5847	5209	6619	5263	5575	6285
Coefficient of variation of cotton gross margin	1.03	0.59	0.52	1.09	1.22	0.81	0.64	0.68	0.62

Information presented in Table A3.1 and Table A3.2 is also used to estimate the standard deviation of cotton yields for different sowing dates and irrigation applications. This information is required to account for cotton yield variability in the farm models that may potentially have impact on decisions taken by risk-averse farmers. It is assumed that total variable costs are constant, that the coefficient of variation of cotton yield is the same for different sowing date/irrigation application combination, variation of cotton yield is the same for different sowing date/irrigation application combination, and that it is equal to the actual coefficients of variation presented in Table A3.1. Then, standard deviations of cotton gross margins are estimated for each sowing date/irrigation application combination. These standard deviations are presented in Table A3.3.

Table A3.2. Gross margin for, the main cash crops (Rs.ha^{-1}) for different sowing dates and irrigation applications and for each farm group, based on average cotton yield and total variable costs obtained from farm survey data, and estimated yield (in % of max yield) obtained using results from Meerbach (1996) and computations with the CropWat software.

Parameter	IWR (%)	Est. yield (% of max yield)	Grp 1	Grp 2	Grp 3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
Early cotton	100	100	8385	17698	19047	9002	7132	12203	12697	12917	15945
	75	82	6252	13923	15091	6646	5194	9531	9789	9872	12164
	60	70	4782	11321	12366	5023	3858	7689	7785	7773	9560
Medium cotton	100	85	7605	16317	17600	8140	6423	11226	11633	11803	14562
	75	72	6044	13554	14705	6416	5005	9270	9505	9575	11796
	60	55	3833	9640	10605	3974	2996	6500	6491	6418	7877
Late cotton	100	70	6824	14935	16153	7278	5714	10248	10569	10689	13179
	75	61	5263	12173	13258	5554	4296	8292	8441	8461	10413
	60	42	3313	8719	9640	3400	2523	5847	5781	5675	6955
Rice			8165	8165	8165	8165	8165	6123	6997	8165	15382
Sugarcane			8482	12077	11922	15661	8483	13738	3978	10394	8398

Table A3.3. Estimated standard deviations of cotton gross margin (Rs.ha^{-1}) for different sowing dates and irrigation applications and for each farm group, based on average cotton yields presented in Table A3.2 and coefficient of variations of cotton yields presented in Table A3.1 and obtained from farm survey data.

Parameter	IWR(%)	Grp 1	Grp 2	Grp 3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
Early wheat	100	5031	7256	7428	4321	3922	5980	4825	4392	5262
	75	3751	5708	5886	3190	2857	4670	3720	3356	4014
	60	2869	4642	4823	2411	2122	3768	2958	2643	3155
Medium wheat	100	4563	6690	6864	3907	3533	5501	4421	4013	4805
	75	3626	5557	5735	3080	2753	4542	3612	3255	3893
	60	2300	3953	4136	1908	1648	3185	2466	2182	2599
Late wheat	100	4095	6124	6299	3494	3143	5021	4016	3634	4349
	75	3158	4991	5171	2666	2363	4063	3208	2877	3436
	60	1988	3575	3760	1632	1388	2865	2197	1930	2295

1.2 Crops for auto-consumption

Total variable costs for wheat and fodder

The gross margin for wheat, kharif fodder and rabi fodder are not directly entered into the objective function of the economic models. Instead, total variable costs for these three crops are included in the objective function of the models. To account for the benefits obtained from wheat production, a separate ***wheat sale*** activity is specified, as it facilitates the inclusion of the minimum wheat requirement constraints in the farm models.

Total variable costs for kharif fodder and rabi fodder are included in the objective function, along with a minimum area under fodder specified as a constraint for the model. This choice results from the difficulty in estimating financial returns from fodder and its use for livestock, and the absence of sufficient and reliable information on fodder sales.

Average values of the total variable costs for wheat, kharif fodder and rabi fodder are estimated using the farm survey information which are presented in Table A3.4.

Table A3.4. Total Variable Costs (TVC) for wheat, kharif (Kh) fodder and rabi (Rb) fodder ($Rs.ha^{-1}$) for each farm group, based on farm survey data.

Parameter	**Grp 1**	**Grp 2**	**Grp 3**	**Grp 4**	**Grp 5**	**Grp 6**	**Grp 7**	**Grp 8**	**Grp 9**
TVC wheat	2450	3058	2845	2776	2744	2613	2506	3148	3131
TVC Kh fodder	1234	1874	1665	1741	1500	1217	1575	1676	2024
TVC Rb fodder	2434	2954	2735	2620	2310	2023	2434	2995	2427

Wheat yields and prices

Similar to what has been described for cotton yields and gross margins in section 1.1 of this appendix, average wheat yields and their standard deviations are computed for different combinations of irrigation application and sowing dates that are proposed as different activities in the farm models. The proposed activities account for:

- Different levels of irrigation water applications: 100%, 80% and 60% of irrigation requirements as computed by the CropWat software;
- Differences in the sowing dates: November 15 (early), December 15 (medium) and January 15 (late).

Using results obtained by Pintus (1995) that relate sowing date and wheat yield, and yield reduction obtained from simulation with the CropWat software, average yields are computed for each combination of irrigation application and sowing date, which are summarized in Table A3.6. The assumption made is that average wheat yields for each group presented in Table A3.5 represent a medium situation of approximately 70% of yield reduction.

Table A3.5. Average, standard deviation and coefficient of variation of wheat yields for each farm group, based on farm survey data.

Parameter	Grp 1	Grp 2	Grp 3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
Average wheat yield ($kg.ha^{-1}$)	1665	2735	2650	1587	1583	1423	1737	2062	2150
Standard deviation of wheat yield ($kg.ha^{-1}$)	803	964	603	604	588	716	660	673	801
Coefficient of variation of wheat yield	0.48	0.35	0.23	0.38	0.37	0.5	0.38	0.33	0.37

Table A3.6. Estimated wheat yield reductions and computed average wheat yields ($kg.ha^{-1}$) for different combinations of sowing dates and irrigation applications and for each farm group, based on average wheat yield obtained from farm survey data, and estimated yield (in % of max yield) obtained using results from Pintus (1995) and computations with the CropWat software.

Parameter	IWR (%)	Est. yield (% of max yield)	Grp 1	Grp 2	Grp 3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
Early wheat	100	100	2379	3907	3786	2267	2261	2033	2481	2946	3070
	75	82	1950	3204	3104	1859	1854	1667	2035	2415	2517
	60	70	1665	2735	2650	1587	1583	1423	1737	2062	2149
Medium wheat	100	85	2022	3321	3218	1927	1922	1728	2109	2504	2609
	75	72	1713	2813	2726	1632	1628	1464	1787	2121	2210
	60	55	1308	2149	2082	1247	1244	1118	1365	1620	1689
Late wheat	100	70	1665	2735	2650	1587	1583	1423	1737	2062	2149
	75	61	1451	2383	2309	1383	1379	1240	1514	1797	1873
	60	42	999	1641	1590	952	950	854	1042	1237	1289

The coefficient of variation of wheat yields presented in Table A3.5 and the average wheat yield values presented in Table A3.6 are used to estimate wheat yield standard deviations for each irrigation application/sowing date combination. These standard deviations are incorporated into the farm models to account for the potential impact of wheat yield variability on decisions taken by risk-averse farmers. *It is assumed* that all sowing date/irrigation application combinations record similar wheat yield variability (i.e. similar coefficients of variation) equal to the variability observed in the farm sample and presented in Table A3.5. Estimated standard deviations are presented in Table A3.7.

Table A3.7. Estimated standard deviations of wheat yield (kg.ha^{-1}) for different sowing dates and irrigation applications and for each farm group, based on wheat yields presented in Table A3.6 and standard deviations for wheat yields computed using farm survey data.

Parameter	IWR(%)	Grp 1	Grp 2	Grp 3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
Early wheat	100	1142	1368	833	862	837	996	918	943	1136
	75	936	1121	683	706	686	817	753	773	931
	60	799	957	583	603	586	697	643	660	795
Medium wheat	100	970	1162	708	732	711	847	780	801	966
	75	822	984	600	620	602	717	661	679	818
	60	628	752	458	474	460	548	505	518	625
Late wheat	100	799	957	583	603	586	697	643	660	795
	75	696	834	508	526	510	608	560	575	693
	60	480	574	350	362	351	418	386	396	477

Wheat sale prices used in the objective function are taken as constant among groups, and equal to 3.05 Rs.kg^{-1} (average for the farm sample). The analysis of prices did not highlight any difference in prices reported by farmers from different groups. Differences in prices were expected to account for different access to agricultural product markets, with large farmers obtaining higher wheat sale prices than small farmers who get fewer good deals with input suppliers and commission agents that deal with agricultural product marketing. However, the difference of power in relationships with input suppliers and commission agents is probably accounted for in input prices faced by the two categories of farmers and are taken into account in the calculations of the total variable costs.

1.3 Estimates of the minimum wheat requirement

Minimum wheat requirements for each farm are based on the total number of family members per group and total wheat requirements per family. Two approaches can be used to estimate minimum wheat requirements:

- To use a recognized figure for yearly wheat requirements, around 200 kg per family member for the year (Pintus, 1995), and estimate the total requirements for the farm or the farm group; and,
- To use actual wheat requirements computed by subtracting sales from total wheat production, then dividing this value by the total number of family members.

The first option is closer to wheat requirements for food consumption, while the second option integrates other needs (livestock, social network and payment for various small works in the village, permanent labor, temporary labor, etc.) and losses that may occur during the year for wheat stored on the farm. However, wheat sales are often under-estimated by farmers during interviews as they relate to cash and fiscal issues.

Information related to the quantities kept on farms and the number of family members was analyzed for the Group 3 and Group 5 for which minimum wheat requirement constraints are required. A value of 300 kg per family member per year was eventually chosen for the two groups.

1.4 Water related parameters

Irrigation water requirements

Irrigation requirements are computed using the CropWat software (FAO, 1992). The reference evapotranspiration ET_0 is estimated using average temperature, humidity, wind speed and sunshine information, following the Penman-Monteith approach. The information has been obtained from the Bahawalnagar Meteorological Station, located at the head of the Chishtian Sub-division, for the period May 1992 to April 1993. Rainfall has been collected on a daily basis for the same period by IIMI field staff using rain gauges located in four of the sample watercourses, namely AZ 63, AZ 111, FD 62 and FD 130. Watercourse level rainfall is averaged for the four watercourses for each month. ET_0 and rainfall information used as input for further CropWat software computations is summarized in Table A3.8. Effective rainfall is estimated using the US Bureau of Reclamation method proposed to users of the CropWat software.

Table A3.8. ET_0, rainfall and effective rainfall based on Bahawalnagar Meteorological Station data and IIMI rainfall data for four sample watercourses.

Month	**ET0** **Mm/day**	**Rainfall** **mm**	**Effective rainfall** **mm**
Jan	1.4	7.3	7.2
Feb	2.2	14.2	13.9
Mar	3.2	15.6	15.2
Apr	4.9	2.5	2.5
May	6.2	8.2	8.1
Jun	7.5	0.6	0.6
Jul	5.1	54.5	49.7
Aug	5.4	43.1	40.1
Sep	4.4	23.6	22.7
Oct	3.7	0	0
Nov	2.3	9.4	9.3
Dec	1.4	0	0
Total for the year	1452	179	169.3

Crop irrigation requirements are computed for the main crops and for the combinations of irrigation application/sowing date proposed for wheat and cotton that are presented in Table A3.9. An average soil for the Chishtian Sub-division is selected for the computations. For rice, sugarcane, kharif fodder and rabi fodder, it is assumed that farmers supply water according to irrigation water requirements as obtained from CropWat. This results from the importance of these crops for auto-consumption, from the high level of inputs applied to these crops, and from the need to ensure production as a result of contracts with the sugar mill.

Table A3.9. Monthly crop water requirements ($m^3.ha^{-1}$) computed using the CropWat software (FAO, 1992) and meteorological information presented in Table A3.8.

Month	IWR(%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Early cotton	100	0	0	0	0	359	981	837	1414	1294	1045	247	0
	75	0	0	0	0	276	755	645	1089	996	805	190	0
	60	0	0	0	0	215	589	502	848	776	627	148	0
Middle cotton	100	0	0	0	0	0	846	486	1272	1294	1172	512	0
	75	0	0	0	0	0	677	389	1018	1035	938	410	0
	60	0	0	0	0	0	465	267	700	712	645	282	0
Late cotton	100	0	0	0	0	0	394	239	953	1276	1197	527	0
	75	0	0	0	0	0	315	191	762	1021	958	422	0
	60	0	0	0	0	0	217	131	524	702	658	290	0
Rice		0	0	0	0	710	3400	1550	1723	1511	548	0	0
Sugarcane		0	83	396	1062	1706	2069	1002	1116	1030	1002	598	221
Kh. Fodder		0	0	0	0	0	986	789	1355	1074	231	0	0
Early wheat	100	424	658	535	0	0	0	0	0	0	0	122	252
	75	329	510	415	0	0	0	0	0	0	0	95	195
	60	254	395	321	0	0	0	0	0	0	0	73	151
Middle wheat	100	199	613	1018	939	0	0	0	0	0	0	0	99
	75	165	509	845	780	0	0	0	0	0	0	0	82
	60	119	368	611	563	0	0	0	0	0	0	0	59
Late wheat	100	75	311	1004	1514	343	0	0	0	0	0	0	0
	75	63	261	843	1272	288	0	0	0	0	0	0	0
	60	41	171	552	833	189	0	0	0	0	0	0	0
Rb. Fodder		336	488	750	360	0	0	0	0	0	753	703	476

Canal water supply

Estimates of canal water supplies have been obtained using information collected through regular monitoring of water flows at the head of each watercourse. Canal water levels upstream and downstream of each watercourse head have been collected daily for the eight sample watercourses for the period May 1992 to April 1993. This information is transformed into daily discharges using rating curves linking water levels and discharges, which were developed for each watercourse. Daily discharges are used to compute volumes of canal water supplied to each watercourse. The volume per unit area delivered to each watercourse and for each month is presented in Table A3.10.

Table A3.10. Average canal water supply at the head of the watercourse command area ($m^3.ha^{-1}$), based on daily water level information.

Parameter	Fordwah Distributary				Azim Distributary			
	FD 14	FD 46	FD 62	FD 130	AZ 20	AZ 43	AZ 63	AZ 111
Jan	0	0	0	0	0	0	0	0
Feb	319	891	734	562	178	0	0	0
Mar	362	1108	901	877	352	170	0	0
Apr	424	1165	888	1182	474	387	111	0
May	364	1208	990	1182	1591	1274	675	238
Jun	316	903	684	953	1630	646	687	308
Jul	271	973	791	950	1368	1047	594	360
Aug	305	1043	824	953	1220	942	558	461
Sep	335	929	793	891	1409	1055	566	195
Oct	410	1036	912	836	1931	1651	1150	597
Nov	369	1236	981	1045	865	713	322	127
Dec	345	1154	916	1057	828	768	319	70

Other information required to compute canal water supply delivered to the crops includes estimates of losses that take place from the watercourse head to the crop. Average conveyance efficiency from the head of the watercourse to the field, along with irrigation application efficiencies at the field level, have been estimated by Waijjen (1996) for the eight sample watercourses and are used in the present study. Their values are presented in Table A3.11.

Table A3.11. Conveyance and irrigation application efficiency for the eight sample watercourses in percent of the total inflow at the point considered (after Waijjen, 1996).

Watercourse	Seepage losses from the WC head to the field (%)	Irrigation application efficiency (%)
FD 14	65	75
FD 46	70	75
FD 62	70	75
FD 130	65	70
AZ 20	75	75
AZ 43	75	80
AZ 63	75	80
AZ 111	80	80

Canal water supplies at the head of the watercourse are transformed into canal water supplies for each group, based on the relative importance of each farm group in terms of operated area in each watercourse. As no clear difference in canal water allocation, in terms of hours per unit operated area, could be identified between farm groups, the official equitable allocation is used for estimating water turns allocated to each individual farmer and farm group.

Daily canal water flows are also used to estimate the variability in canal water flows as expressed by the monthly coefficient of variations of daily discharges to watercourses presented in Table A3.12.

Table A3.12. Average monthly coefficient of variation of daily canal water discharge at the head of the watercourse command area.

Parameter	Fordwah Distributary				Azim Distributary			
	FD 14	FD 46	FD 62	FD 130	AZ 20	AZ 43	AZ 63	AZ 111
Jan	0	0	0	0	0	0	0	0
Feb	0.78	0	0.54	0.88	1.65	0	0	0
Mar	0.58	0.3	0.25	0.49	1.29	2.3	0	0
Apr	0.22	0.29	0.17	0.21	1.2	1.43	2.3	0
May	0.06	0.27	0.03	0.17	0.3	0.35	0.66	1.33
Jun	0.42	0.45	0.4	0.54	0.32	0.56	0.52	0.77
Jul	0.88	0.39	0.34	0.59	0.45	0.47	0.72	1.14
Aug	0.55	0.35	0.38	0.66	0.52	0.66	0.8	0.95
Sep	0.59	0.54	0.47	0.55	0.46	0.52	0.67	1.2
Oct	0.44	0.37	0.16	0.52	0.08	0.13	0.19	0.7
Nov	0.07	0.03	0.03	0.14	0.68	0.73	0.92	1.38
Dec	0.4	0.27	0.24	0.37	0.74	0.79	1.03	2.1

Monthly coefficients of variation of *daily discharges*, however, are not the equivalent to coefficients of variation of monthly *volumes* received by farmers. On average, every farmer receives canal water four times a month during four different and successive warabandi schedules. The volume received at the end of the month is equal to $q_1*h + q_2*h + q_3*h + q_4*h$, with q_1, q_2, q_3 and q_4 being the canal water supply discharges ($l.s^{-1}$) during the four consecutive water turns, and h the duration of farmer's water turn (s). Three assumptions are made:

- The discharge is constant over the duration of the water turn (short-term variability neglected);
- The discharges q_1, q_2, q_3 and q_4 follow the same normal probability distribution q with average q_a, variance $\mathrm{Var}(q) = \mathrm{std}(q)^2$and coefficient of variation $\mathrm{CV}(q)$;
- The discharges q_1, q_2, q_3 and q_4 received for different weeks are independent from one another.

Under such conditions, the expected mean and variance of the volume received for the month is expressed as follows.

$$\text{Expected mean of the monthly volume} = 4 * h * q_a \qquad \textbf{(A3.1)}$$

$$\text{Variance of the monthly volume} = \mathrm{Var}\,(h*(q_1+q_2+q_3+q_4)) = \qquad \text{(A3.2)}$$
$$h^2*(\mathrm{Var}(q_1)+\mathrm{Var}(q_2)+\mathrm{Var}(q_3)+\mathrm{Var}(q_4)) = h^2*4*\mathrm{Var}(q)$$

Because of the independence between the variables q_i, the covariance terms between discharges are all equal to 0. Thus, the standard deviation and coefficient of variation of the monthly volume can be computed as follows:

$$\text{Standard deviation of monthly volume} = h*2*\mathrm{std}(q) \qquad \textbf{(A3.3)}$$

$$\text{Coefficient of variation of the monthly volume} = \tfrac{1}{2} * \mathrm{CV}(q) \qquad \textbf{(A3.4)}$$

Thus, the mean, standard deviation and coefficient of variation of daily discharges are used to estimate the mean, standard deviation and coefficient of variation of the monthly volume received by farmers. As farmers have on average four water turns per month, the coefficients of variation of the monthly volume will be equal to half of the coefficients of variation of the daily discharge presented in Table A3.11 for the whole watercourse command area.

Tubewell water prices

Tubewell water prices are computed for each watercourse and farm group based on tubewell water prices reported by farmers for tubewell transactions. As these prices are reported in rupees per hour of operation, an average discharge of 28.3 $l.s^{-1}$, based on discharge measurements for more than 100 tubewells located in the eight sample watercourse command areas, is used to compute average prices in $Rs.m^{-3}$. Table A3.13 presents tubewell water prices related to tubewell water purchases obtained through farm interviews.

Table A3.13. Tubewell water price ($Rs.m^{-3}$) faced by each farm group, based on farm survey data.

Parameter	**Grp 1**	**Grp 2**	**Grp 3**	**Grp 4**	**Grp 5**	**Grp 6**	**Grp 7**	**Grp 8**	**Grp 9**
TW purchase price ($Rs.m^{-3}$)	0.29	0.34	0.33	0.36	0.34	0.32	0.28	0.35	0.19

Conveyance and application efficiencies are also taken into account for tubewell water in the farm models, as it impacts on the tubewell water price per unit of water effectively received by the crop. As tubewell owners are expected to use tubewell water in fields closer to the tubewell than tubewell water purchasers, a conveyance efficiency of 0.9 is used for tubewell owners, while half of the conveyance efficiencies estimated for canal water are used for tubewell water purchasers. Irrigation application efficiencies used for canal water and presented in Table A3.11 are used for tubewell water.

1.5 Other farm constraints

Land

The total farm operated area is accounted for in the optimization and farm model constraints. It includes the area operated within the watercourse command area, as well as the area operated outside the watercourse command area. No difference is made between tenure types, i.e. area rented and area owned are treated similarly in the farm model. Two types of area, however, are considered based on salinity conditions to take into account different farming practices and crop choices made by farmers for saline fields: rice only will be grown in saline areas while all crops are considered in non-saline areas. A summary for each farm group is presented in Table A3.14.

Table A3.14. Operated area (ha) and importance of saline areas (in ha and % of operated area) for each farm group, based on farm survey data.

Parameter	Grp 1	Grp 2	Grp 3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
Total operated area (ha)	47	32	186	164	284	123	111	201	492
Area under saline conditions (ha)	18.0	1.1	12.2	23.3	23.9	13.4	32.0	16.1	44.6
% of operated area	38.3	3.4	6.6	14.2	8.4	10.9	28.8	8.0	9.1

Minimum area under fodder

As explained above, it is very difficult to estimate the financial return from fodder. Thus, the total variable costs of fodder have been included in the objective function and a minimum area under fodder is fixed for every farm group for the kharif season and for the rabi season. The minimum area under fodder for each season is set equal to the present fodder area computed from farm survey data for each season and is presented in Table A3.15.

Table A3.15. Importance of fodder (ha and % of operated area) for each farm group, based on farm survey data.

Crop	Grp 1	Grp 2	Grp 3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
Kharif fodder									
Ha	6	9	28	19	39	15	16	23	21
%	13	28	15	12	14	12	14	11	4
Rabi fodder									
ha	4	6	19	15	27	10	10	23	19
%	9	19	10	9	10	8	9	11	4

Labor

Labor requirements have been estimated for all groups for each crop, based on estimates presented in the Farm Management Handbook (1993). These requirements, aggregated by year and expressed in hours per ha, are summarized in Table A3.16.

Table A3.16. Labor requirements for the main crops ($hr.ha^{-1}$).

Farm activities	Total labor requirements ($hr.ha^{-1}$)
Rice	520
Sugarcane	1025
Cotton	440
Kharif fodder	700
Wheat	180
Rabi fodder	1300

Labor constraints are not directly taken into account in the optimization process. They are computed only for the cropping pattern selected at the optimum.

2 Calibration of the farm models

2.1 Initial calibration of the farm models

Farm group models are developed for each group by aggregating farm resources for all farmers of the group. Specific equations are added to the models to compute intermediary indicators, such as the total area cultivated, the percentage of area under each crop, seasonal and yearly cropping intensity, total tubewell water use, etc.

Calibration of the farm models is performed by adjusting risk aversion parameters, and by refining specific limitations such as minimum wheat requirements for which some estimates have been obtained. The main output variables of the models that are looked at are the area under the main crops. The initial calibration on the farm groups aimed at checking the feasibility of the actual situation and investigating the sensitivity of the optimization results to changes in the risk aversion coefficients related to variability in canal water supply, cotton gross margin and wheat yield. However, as there is no constraint on tubewell water use and tubewell water purchases for the farm models, it is not possible to finalize the calibration of the farm models, which are finalized during the calibration of watercourse models.

2.2 Input for calibration and validation of the watercourse-based SLP models

Watercourse models are initially built for four sample watercourses with area under the nine farm groups considered. These watercourses are FD 14, FD 130, AZ 20 and AZ 111. The four watercourse models and the nine farm models are then calibrated. Using the parameters defined during this calibration process for each farm model, watercourse models are then built for the remaining four watercourses (i.e. FD 46, FD 62, AZ 43 and AZ 63) and used to validate the group models that have been developed.

The information used for the calibration and validation of the watercourse and group models relates to canal water supply and cropping pattern. Canal water supply at the head of each watercourse command area, in terms of monthly volumes and monthly coefficient of variation of the daily discharges, is used to calibrate and validate the watercourse and farm models. Also, various conveyance and application losses are accounted for. This information has already been presented in Tables A3.10, A3.11, A3.12. As mentioned above, the same allocation in volume per unit area is made to each farm group.

At the level of the watercourse command area, links are established between tubewell sale and tubewell water purchase of the different groups. Also, monthly constraints in maximum tubewell water availability are set for each watercourse. The main elements that are to be considered for estimating the maximum tubewell water availability for each watercourse include:

- The total number of tubewells in the watercourse command area;
- Tubewell ownership and the relative importance of joint tubewell owners;

- Total canal water supplies. As tubewell water is often sold using the official canal watercourse, there is a competition between tubewell water sales and canal water use by other farmers. Thus watercourses with very high canal water supplies would offer less opportunities for farmers to purchase tubewell water;
- The maximum number of operating hours, including time for breakdowns, reduced operation during night time, and load-shedding periods for electric tubewells;

The large number of elements that influence the maximum quantities of tubewell water available for use and for sale makes an estimate of such quantities very difficult. In practice, the elements described above have been considered to estimate a maximum tubewell water availability that has been refined through the calibration process.

Tubewell water price is also estimated for each watercourse command area separately, using information collected through the farm survey for tubewell water purchases. The variability in tubewell water prices within the watercourse command area is neglected and average tubewell water prices only are incorporated into the farm models. Table A3.17 presents both the average tubewell water price used for calibration and validation of the farm and watercourse models, and the maximum monthly tubewell water availability expressed.

Table A3.17. Average tubewell water price (Rs.m^{-3}) and maximum monthly tubewell water availability (m^3) for the eight sample watercourses, based on farm survey data and the author's estimates.

Variable	FD 14	FD 46	FD 62	FD 130	AZ 20	AZ 43	AZ 63	AZ 111
TW water price (Rs.m^{-3})	0.30	0.34	0.40	0.31	0.37	0.42	0.34	0.21
Monthly maximum tubewell water availability (m^3)	500000	170000	160000	350000	160000	200000	375000	285000

2.3 Model output selected for calibration and validation of the farm and watercourse models

The calibration and validation of the farm group and watercourse SLP models is based on the comparison between actual crop choices and cropping pattern and model estimates for these variables. Table A3.18 summarizes crop information for each farm group in each sample watercourse command area. As the area under kharif and rabi fodder are fixed as a model parameter, the area under these crops is not considered in the calibration and validation process.

Table A3.18. Cropping pattern for farm groups in sample watercourses: area under sugarcane, rice, cotton and wheat (ha) obtained from the farm survey.

Group	Crop	FD 14	FD 46	FD 62	FD 130	AZ 20	AZ 43	AZ 63	AZ 111
Grp 1	Sugarcane	3.1	-	-	-	-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	27.8	-	-	-	-	-	-	-
	Wheat	32.8	-	-	-	-	-	-	-
Grp 2	Sugarcane	-	-	-	-	-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	-	-	-	8.4	-	-	-	-
	Wheat	-	-	-	9.0	-	-	-	-
Grp 3	Sugarcane	3.9	0.6	-	1.2	-	-	-	-
	Rice	-	0.4	-	-	-	-	-	-
	Cotton	21.4	15.1	14.6	80	-	-	-	-
	Wheat	22.7	15.1	18.6	69.2	-	-	-	-
Grp 4	Sugarcane	-	3.6	-	-	3.2	14.1	3.1	-
	Rice	-	-	-	-	1.4	-	-	-
	Cotton	-	18.7	-	-	4.8	32.8	52.2	12.8
	Wheat	-	18.5	-	-	9.1	24.4	44.0	16.8
Grp 5	Sugarcane	17.2	4.1	3.5	1	-	-	-	-
	Rice	-	-	0.8	-	-	-	-	-
	Cotton	44.2	60.1	43.5	10.3	-	-	15.6	-
	Wheat	25.6	71.0	47.3	12.4	-	-	16.3	-
Grp 6	Sugarcane	-	-	-	-	19.8	-	-	-
	Rice	-	-	-	-	11.7	-	-	-
	Cotton	-	-	-	-	30.9	-	-	-
	Wheat	-	-	-	-	42.2	-	-	-
Grp 7	Sugarcane	-	-	-	-	-	-	-	-
	Rice	-	-	-	-	-	-	0.1	11.2
	Cotton	-	-	-	-	-	-	20.0	24.9
	Wheat	-	-	-	-	-	-	21.2	39.4
Grp 8	Sugarcane	6.6	1.6	3.6	0.4	-	8.5	-	-
	Rice	-	-	0.2	-	-	-	-	-
	Cotton	51.2	13.5	38.2	18.4	-	10.5	-	-
	Wheat	56.5	13.0	46.5	18.6	-	14.0	-	-
Grp 9	Sugarcane	-	-	0.8	1.2	-	26.3	10.1	11.2
	Rice	-	-	-	-	-	-	-	10.2
	Cotton	-	-	5.7	10.1	30.4	16.2	129.1	88.6
	Wheat	-	-	4.6	10.5	30.0	9.3	92.3	80.7
Total per WC	Sugarcane	30.8	9.9	8.0	3.8	23.0	55.3	13.2	11.4
	Rice	-	0.4	1.0	-	13.2	-	0.1	21.5
	Cotton	144.1	107.6	101.9	127.3	66.1	70.9	223.2	126.4
	Wheat	150.6	117.7	116.9	119.8	81.3	58.1	173.9	136.9

2.4 Calibration results

The calibration of the farm groups in the four sample watercourses is obtained by refining risk aversion parameters for the different groups, and modifying specific model parameters that are location specific. Such parameters include the gross margin of rice and sugarcane, that are influenced by local soil conditions and the proximity of the sugar mill. For example, the sugarcane gross margin is increased for farms located in the two head watercourses of FD 14 and AZ 20 close to the sugar mill. Also specific tubewell water constraints are specified for each watercourse. The final output of the calibrated model under current canal water supplies is displayed in Table A3.19.

Table A3.19. Calibration of farm models in FD 14, FD 130, AZ 20 and AZ 111 command areas: estimated area (ha) under sugarcane, rice, cotton and wheat, and relative difference in percent between the actual situation and model prediction.

Group	**Crop**	**FD 14**		**FD 130**		**AZ 20**		**AZ 111**	
		ha	%	ha	%	ha	%	ha	%
Grp 1	Sugarcane	2.3	-25.8	-	-	-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	27.5	-1.1	-	-	-	-	-	-
	Wheat	38.9	+18.3	-	-	-	-	-	-
Grp 2	Sugarcane	-	-	-	-	-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	-	-	8.0	-4.8	-	-	-	-
	Wheat	-	-	9.0	+0	-	-	-	-
Grp 3	Sugarcane	2.5	-35.9	1.4	+14.2	-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	26.6	+24.3	76.6	-4.3%	-	-	-	-
	Wheat	28.6	+20.6	86.0	+19.5	-	-	-	-
Grp 4	Sugarcane	-	-	-	-	3.2	-0.6	-	-
	Rice	-	-	-	-	2.72	+94.0	-	-
	Cotton	-	-	-	-	5.5	-2.1	13.0	-6.3
	Wheat	-	-	-	-	11.4	+25.0	17.2	+2.4
Grp 5	Sugarcane	18.5	+7.6	1.1	+6.0	-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	43.6	-1.4	11.2	+8.8	-	-	-	-
	Wheat	45.1	+26.7	20.8	+68.0	-	-	-	-
Grp 6	Sugarcane	-	-	-	-	20.1	+1.5	-	-
	Rice	-	-	-	-	10.1	-13.7	-	-
	Cotton	-	-	-	-	30.2	-2.3	-	-
	Wheat	-	-	-	-	40.6	-3.8	-	-
Grp 7	Sugarcane	-	-	-	-	-	-	-	-
	Rice	-	-	-	-	-	-	8.1	-27.7
	Cotton	-	-	-	-	-	-	30.2	+21.3
	Wheat	-	-	-	-	-	-	41.0	+4.1
Grp 8	Sugarcane	12.4	+47	-	-	-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	52.8	+3.1	18.2	-1.1	-	-	-	-
	Wheat	49.7	-12.0	18.2	-2.1	-	-	-	-
Grp 9	Sugarcane	-	-	2.1	+75.0	-	-	11.6	+3.6
	Rice	-	-	-	-	-	-	13.7	+34.0
	Cotton	-	-	10.6	+4.7	29.2	-3.9	85.0	-4.1
	Wheat	-	-	10.1	-3.8	29.2	-2.7	101.0	+25.0
Total per WC	Sugarcane	35.6	+15.6	4.5	+18.0	23.3	+1.4	11.6	+3.6
	Rice	-	-	-	-	12.9	-2.7	21.8	+1.4
	Cotton	150.7	+4.5	124.7	-2.0	64.4	-2.5	128.4	+1.6
	Wheat	162.5	+7.9	145.6	+21	81.2	-0.1	160.7	+17.4

The calibration accuracy of the models is also computed in terms of the total area cropped, or cropping intensity, for each season and for each watercourse. Table A3.20 presents the relative difference in percent between actual total cropped area and cropped area estimated by the models.

Table A3.20. Relative difference (%) between actual and estimated cropping intensities for the kharif and rabi season for the four watercourses used for calibration of the farm group models.

Watercourse	Kharif cropping intensity	Rabi cropping intensity
FD 14	+5.4	+8.0
FD 130	-1.7	+18.6
AZ 20	-1.7	+0.1
AZ 111	+1.4	-5.4

The various risk-aversion coefficients estimated are presented in Table A3.21.

Table A3.21. Risk aversion coefficients for nine farm groups: results of model calibration.

Risk aversion related to	Grp 1	Grp 2	Grp 3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
Variability in cotton gross margin in the objective function	-0.1	-0.5	-1.35	-0.5	-0.35	-0.85	-1.1	-0.7	-0.5
Variability in wheat yield in the objective function	-0.4	-0.5	-	-0.85	-	-0.85	-0.5	-0.85	-0.5
Variability in wheat yield in the minimum wheat requirement constraint	-	-	-0.4	-	-1.4	-	-	-	
Variability in canal water supply	0.5	0	0.5	0.5	0.5	0.5	0	0	0

The main modifications and changes that have been brought into the group models relate to the relative level of sugarcane gross margin, that has been increased for most of the watercourses as compared to values originally presented in Table A3.2, but more significantly for AZ 20 watercourse as a result of the proximity of this watercourse to the sugar mill of the Chishtian Sub-division.

3 Validation of the farm models

As explained in Section 2.2, the four remaining watercourses (AZ 43, AZ 63, FD 46 and FD 130) are used to validate the farm group SLP models as these watercourses present different situations in terms of canal water supply, tubewell water constraints, and tubewell water price. Using the risk aversion parameters obtained from the calibration step, farm models are developed and aggregated according to their respective importance in terms of operated area in each of the four watercourses.

Conveyance and irrigation application efficiencies are specified for each watercourse according to values presented in Table A3.11. Average tubewell water prices are also set accordingly. Specific modifications are made in the sugarcane and rice gross margin to take into account local variability and differences such as soil type and proximity to the sugar mill.

The models are then run for the four watercourses. The output of the models in terms of area under each crop is summarized in Table A3.22. Model results are presented farm group-wise watercourse-wise, in absolute terms (ha) and as a percentage of the actual area under each crop.

Table A3.22. Validation of the farm models in FD 46, FD 62, AZ 43 and AZ 63 command areas: estimated area (ha) under sugarcane, rice, cotton and wheat, and relative difference in percent between the actual situation and model prediction.

Group	Crop	FD 46		FD 62		AZ 43		AZ 63	
		Ha	%	ha	%	ha	%	ha	%
Grp 1	Sugarcane	-	-	-		-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	-	-	-	-	-	-	-	-
	Wheat	-	-	-	-	-	-	-	-
Grp 2	Sugarcane	-	-	-	-	-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	-	-	-	-	-	-	-	-
	Wheat	-	-	-	-	-	-	-	-
Grp 3	Sugarcane	-	-	-	-	-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	15.3	+1.3	16.6	+13.7	-	-	-	-
	Wheat	18.9	+25.1	17.6	-5.4	-	-	-	-
Grp 4	Sugarcane	3.7	+2.8	-	-	13.8	-2.1	7.7	+157
	Rice	-	-	-	-	-	-	-	-
	Cotton	19.2	+2.7	-	-	29.0	-11.6	50.9	-2.5
	Wheat	21.3	+15.1	-	-	26.8	+10.0	52.9	+20.2
Grp 5	Sugarcane	7.8	+90.2	-	-	-	-	0.4	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	53.0	-11.8	28.8	-34.0	-	-	15.2	-2.6
	Wheat	71.0	+0	57.5	+21.6	-	-	15.8	-3.1
Grp 6	Sugarcane	-	-	-		-	-	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	-	-	-	-	-	-	-	-
	Wheat	-	-	-	-	-	-	-	-
Grp 7	Sugarcane	-	-	-	-	7.7	+20.0	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	-	-	-	-	11.9	-5.3	21.8	+9.0
	Wheat	-	-	-	-	11.0	+68.0	23.0	+8.5
Grp 8	Sugarcane	3.7	+132	12.0	+67.0	7.9	-7.6	-	-
	Rice	-	-	-	-	-	-	-	-
	Cotton	12.2	-9.6	42.1	+10.2	17.1	+63	-	-
	Wheat	11.2	-13.8	39.1	-15.9	15.5	-10.0	-	-
Grp 9	Sugarcane	-	-	-	-	18.3	-30.0	12.3	+18.8
	Rice	-	-	-	-	-	-	-	-
	Cotton	-	-	11.0	+85.0	22.8	+40	147.7	+14.4
	Wheat	-	-	11.0	+139	18.3	+45	92.1	-0.2
Total per WC	Sugarcane	15.2	+53.5	12.0	+50	40.0	-27	20.4	+54
	Rice	-	-	-	-	-	-	-	-
	Cotton	99.2	-7.8	87.5	-14.1	63.9	-10	235.7	+5.4
	Wheat	123.4	+5.3	115.5	-1.3	56.4	-3	183.8	+5.7

Table A3.23 presents the difference between actual and estimated cropping intensities for the kharif season and rabi season for the four watercourses used for validation.

Table A3.23. Relative difference (%) between actual and estimated cropping intensities for the kharif and rabi season for the four watercourses used for validation of the farm group models.

Watercourse	Kharif Cropping intensity	Rabi cropping intensity
FD 46	-2.2	+8.0
FD 62	-8.5	+1.7
AZ 43	-16.4	-13.7
AZ 63	+7.5	+8.2

As part of the validation procedure, more attention was given to the prediction ability of the watercourse models regarding total tubewell water use. As tubewell information collected through monitoring for the year 1992-93 was not available, tubewell operation information for the Kharif 1994 and Rabi 1994-95 was used to check the accuracy of model predictions in total tubewell water use. Several issues arise when comparing model predictions and tubewell water use:

- The farm operated areas used in the models are not the same as the command areas for which actual tubewell water use is collected as out-of-command areas are also considered;
- Similarly, cropping intensities and cropping patterns are expected to be different;
- Total tubewell water use predicted by the model relates partly to an effective increase in quantity for irrigation (similar to what is obtained through tubewell monitoring data), and partly for an insurance that is accounted for at the planning stage to compensate for variability in canal water supply;
- Capillary rise has not been considered in the watercourse models, while it is an important element of the water balance for some watercourses, more particularly FD 14 and AZ 20 (Waijjen, 1996). Thus, watercourse models are likely to predict higher tubewell water use.

Table A3.24 presents the results of the comparison between the 1994-95 data and the prediction of the watercourse models. Information obtained after each computational step is included in this table for better understanding these steps. Overall, the difference between actual tubewell pumping aggregated for the eight watercourses and tubewell pumping predicted by the watercourse models is equal to +18%, showing that the predictions from the models in terms of tubewell pumping are realistic as compared with the actual situation. As illustrated by Table A3.24, however, the predictions are rather good for five watercourses out of eight but are not in concordance with monitoring data for FD 46, FD 130, and AZ 20.

For FD 130, the higher cropping intensity predicted by the model directly explains the higher tubewell pumping predicted by the model. For FD 46, the difference pertains to a higher predicted area under sugarcane as compared with the actual situation. Finally, the higher tubewell water pumping estimated by the model may be related to an underestimate of canal water supplies for this watercourse located at the head of the Azim Distributary that may benefit from temporary illegal supplies from the distributary. For all watercourses, however, it is important to remember that two different years are compared, and that out-of-command areas for which canal water supplies are unknown have been included in the model. Both elements are likely to explain part of the observed inaccuracies in tubewell water use.

Table A3.24. Comparison between actual yearly tubewell water use in 1994-95 and model predictions based on the 1992-93 situation (m^3).

Variable	**Fordwah**				**Azim**			
	FD 14	FD 46	FD 62	FD 130	AZ 20	AZ 43	AZ 63	AZ 111
A. Actual yearly tubewell water use (1994-95)	422800	167800	277000	1170982	121400	168100	429400	1229300
B. Model predictions for total yearly tubewell water use	2459291	738604	772336	1363433	600122	857936	1726020	1908826
C. Model prediction for tubewell water to increase quantity	1057495	664743	695102	1336164	534108	394650	1104653	1660678
D. Model prediction modified to account for differences in areas	801405	703604	494378	1848962	517580	183250	368014	837375
E. Model prediction modified to account for capillary rise	448787	415126	346065	1848962	258790	183250	368014	837375
F. Relative difference between actual and predicted tubewell water use ((E-A)/A)	+6%	+147%	+25%	+58%	+113%	+9%	-14%	-32%

4 Conclusion

The overall accuracy of the farm and watercourse models is rather good in terms of cropping intensity and cropping pattern, as the area under a given crop for a given farm group in a given watercourse are estimated with an average accuracy of 10%. The main weaknesses of the models remain related to the area under sugarcane that remains rather volatile for some farm models and under specific canal water supply situations. Also, model predictions appear less accurate for watercourses with high canal water supplies. Under such situations, water may not be the main constraint anymore. Other constraints that have not been specified well enough in the models would become predominant. An example of such constraints is labor that would become a constraint with large areas under sugarcane. The absence of labor constraint in the models may already explain higher predictions in terms of area under sugarcane as compared with the actual situation.

Although appropriate information on tubewell water pumping is not available for the period considered, preliminary validation of tubewell pumping predicted by the watercourse models is performed. It shows that tubewell pumping predictions are rather appropriate for five watercourses out of eight. For the eight watercourses aggregated, the overall accuracy of tubewell pumping predictions is equal to + 18%, better for the Azim Distributary watercourses (-15%) than for the Fordwah Distributary watercourses (+ 48%).

Samenvatting

Om de consequenties van beleids- en beheersinterventies in een irrigatiesysteem *a priori* te beoordelen is een integrale aanpak ontwikkeld. In dit proefschrift is deze geïntegreerde aanpak toegepast in een irrigatiesysteem in Pakistan om de effecten van beleidsmaatregelen ter bevordering van watermarkten te analyseren en de consequenties voor gewasopbrengsten te kwantificeren. In een parallelle studie, is deze aanpak toegepast om de gevolgen van ingrepen in het irrigatiewaterbeheer op bodemverzouting, sodificatie en gewasproduktie te kwantificeren (Kuper, 1997). In het eerste deel van deze samenvatting worden de bevindingen van de analyse van watermarkten in een irrigatiesysteem Pakistan samengevat en worden conclusies getrokken. De lessen uit beide toepassingen van de geïntegreerde aanpak, zullen worden behandeld in het tweede deel.

Mogelijkheden voor de ontwikkeling van watermarkten in irrigatiesystemen in Pakistan: wat zijn de antwoorden?

De noodzaak van watermarkten voor het beheer van de irrigatiesector

De toenemende druk op watervoorraden en financiële middelen heeft recentelijk geleid tot een algemene erkenning van het belang van de economische dimensies van water als hulpbron, en de noodzaak om de economische waarde van water op te nemen in nieuwe beleidsstrategieën voor de irrigatiesector. Op de aanbodzijde gebaseerde interventies, zoals grote infrastructurele projecten, waren lange tijd de meest geliefde ingrepen in de irrigatie sector. Deze interventies zijn echter niet langer geschikt, of mogelijk om vraagstukken op te lossen op het gebied van de watergebruiksefficiëntie en duurzaamheid van financiële middelen en watervoorraden.

Erkenning van water als economisch goed heeft echter nog niet geleid tot een belangrijke verschuiving in de keus van de vereiste economische instrumenten om de efficiëntie van watergebruik te vergroten. In plaats daarvan is de nadruk van recente interventies komen te liggen op veranderingen in de institutionele context: het overdragen van taken en verantwoordelijkheden naar de watergebruikers. Hoewel de invloed van deze overdracht op het financieringstekort van de overheid helder is, zijn de effecten op watergebruiksefficiëntie en duurzaamheid nog niet duidelijk aangetoond.

Het verbinden van een kostprijs aan water is het klassieke voorstel om de efficiëntie van watergebruik te vergroten. Recentelijk wordt er meer aandacht besteed aan de mogelijkheden voor watermarkten ter verbetering van de efficiëntie van waterverdeling en watergebruik. Hoewel er een groot verschil is tussen de vereiste theoretische voorwaarden voor optimaal functionerende watermarkten, en de bestaande condities, is het functioneren van watermarkten in de literatuur beschreven voor diverse socio-economische en fysische omgevingsfactoren, en vormen deze watermarkten wellicht een beter alternatief dan de bestaande situatie.

Als gevolg van het slechte functioneren van de irrigatiesector en de noodzaak tot het terugdringen van het financieringstekort, zijn er ingrijpende veranderingen in de Pakistaanse irrigatiesector op komst. De ontwikkeling van watermarkten wordt als een optie gezien, waardoor de watergebruiksefficiëntie kan worden verbeterd en waardoor een groei van de agrarische produktie kan worden gerealiseerd, die de bevolkingsgroei evenaart en voldoet aan aan de vereiste vraag naar voedsel.

Het doel van dit proefschrift is het evalueren van de mogelijkheden voor, en invloed van de ontwikkeling van watermarkten in irrigatiesystemen in Pakistan. Hiertoe wordt gebruik gemaakt van elementen uit de in samenwerking met Kuper (1997) ontwikkelde integrale evaluatiemethode van beleids- en beheersinterventies. Deze integrale benadering omvat een analyse van de complexiteit van het irrigatiesysteem, de identificatie van fysische processen en besluitvormingsprocessen, welke een directe invloed hebben op de watervoorziening, verzilting, sodificatie en agrarische produktie, en een analyse van de bestaande heterogeniteit en ruimtelijke diversiteit van de belangrijkste parameters en variabelen die een rol spelen in deze processen. Onderdelen van dit onderzoek die betrekking hebben op het waterbeheer op tertiair niveau, en op de relaties tussen het aanbod van kanaalwater en de agrarische produktie worden in meer detail behandeld. Het onderzoek richt zich op de Chishtian Sub-division, Zuid-Punjab, en in het bijzonder op acht tertiaire vakken van twee secundaire kanalen: Fordwah en Azim. Het irrigatiesysteem is gelegen in de katoen-tarwe-zone van Pakistan, en kenmerkt zich door complementerend gebruik van grond- en oppervlaktewater.

Bestaande watermarkten binnen tertiaire eenheden van het irrigatiesysteem

In alle acht de bestudeerde tertiaire vakken komen oppervlaktewater- en grondwatermarkten voor. Door nauwkeurige registratie van het watergebruik is meer inzicht verkregen in de transacties van kanaalwater, welke in werkelijkheid frequenter voorkomen dan is beschreven in de literatuur. Handel in kanaalwater vindt voornamelijk op korte termijn plaats doordat boeren gedeeltes van waterbeurten aan- en verkopen. Deze transacties compenseren de variabiliteit in het debiet aan de inlaat van een tertiair vak. Transacties van grondwater, opgepompt met behulp van kleine, door boeren geïnstalleerde pompen, hebben een tweeledige functie: zij vergroten de beschikbare hoeveelheid water per boerenbedrijf, en tevens compenseren zij de variabiliteit in het aanbod van kanaalwater.

Het functioneren van watermarkten is afhankelijk van de kwantiteit en kwaliteit van de beschikbare watervoorraden, en van de beperkingen en produktiestrategieën van boeren. Indien de aanvoer van kanaalwater onbetrouwbaar is, de transportverliezen hoog zijn, en de toegang tot grondwatervoorraden goedkoop is, ontwikkelen boeren binnen een tertiair vak een intensieve handel in kanaalwaterbeurten per week of per seizoen.

De invloed van grondwatermarkten op het bruto inkomen van boeren is aanzienlijk en bedraagt ca. 40% van het huidige bruto inkomen gesommeerd over de acht bestudeerde tertiaire vakken. Grondwatermarkten hebben een aanzienlijke daling van de grondwateraanvulling tot gevolg, en verhogen het risico op verzouting en sodificatie. De invloed van grondwatermarkten op sodificatie is echter minder uitgesproken dan die op de grondwateraanvulling en op verzouting.

De invloed van bestaande kanaalwatermarkten op de agrarische produktie is moeilijker in te schatten. Transacties van kanaalwater worden gekenmerkt door een grote flexibiliteit op de korte termijn en zijn dus moeilijk te registreren. De invloed van korte termijn transacties op het aanbod van irrigatiewater binnen een groeiseizoen is verder moeilijk vast te stellen met de in deze studie gevolgde werkwijze en ontwikkelde modellen.

Mogelijkheden voor de ontwikkeling van watermarkten

De potentiële ontwikkeling van watermarkten is op verscheidene ruimtelijke schaalniveaus van het irrigatiesysteem onderzocht: binnen tertiaire vakken, tussen tertiaire en tussen secundaire vakken. Op elk schaalniveau is de invloed op de agrarische produktie en op de fsische omgeving geanalyseerd. Tevens worden de operationalisering en de technische haalbaarheid van de voorgestelde watermarktscenaio's besproken. Waterrechten zijn gedefinieerd als een volume met een vaststaande maandelijkse verdeling van kanaalwater.

De marginale groei van het bruto bedrijfsinkomen binnen een tertiaire vak, voortvloeiend uit een betere werking van kanaal- of grondwatermarkten bedraagt voor de acht bestudeerde tertiaire vakken ca. 5-6%. Een combinatie van beter functionerende kanaal- en grondwatermarkten zal dus naar verwachting een aanzienlijke toename van het bruto bedrijfsinkomen opleveren. Bovendien zijn er geen significante negatieve effecten op de omgeving te verwachten. Verschillen tussen tertiaire vakken blijven echter belangrijk. Door een betere werking van grondwatermarkten in het tertiaire vak Fordwah 130, zal bijvoorbeeld de verzouting met ca. 8% toenemen ten opzichte van de huidige situatie. Een vergelijkbare toename van het sodificatieniveau is te verwachten bij een betere werking van kanaalwatermarkten in het tertiaire vak Fordwah 62.

Door de herverdeling van oppervlaktewater, gedefinieerd als een jaarlijkse volume met een vaststaande maandelijkse verdeling, wordt op hogere schaalniveaus in het irrigatiesysteem een minder grote groei verwacht van het bruto bedrijsinkomen. Als gevolg van de herverdeling van water tussen de tertiaire vakken van het Fordwah- en Azim-kanaal, zal het bruto bedrijfsinkomen met 3-4% toenemen. De volumes kanaalwater die door marktwerking van Fordwah naar Azim worden herverdeeld zijn groot. Deze herverdeling van de jaarlijkse hoeveelheid kanaalwater leidt echter tot een groei van het bruto bedrijfsinkomen van slechts 2%.

De herverdeling van kanaalwater tussen tertiaire en secundaire vakken zal naar verwachting een toenemende druk op de grondwatervooraden veroorzaken, wat zal leiden tot verdergaande uitputting van de aquifer. De herverdeling van kanaalwater tussen tertiaire vakken zal tot een verbetering leiden van het gemiddelde verzoutings- en sodificatieniveau van de acht beschouwde tertiaire vakken. De herverdeling van water tussen de secundaire vakken leidt naar verwachting tot een algemene (maar beperkte) toename van verzouting en sodificatie, in het bijzonder voor de tertiaire vakken FD14 en FD130, waar het grondwater van slechte kwaliteit is.

De bestaande infrastructuur is waarschijnlijk geen belangrijke beperking voor de verdere ontwikkeling van watermarkten. Binnen het voorzieningsgebied van tertiare vakken zijn de operationele problemen beperkt. Bovendien tonen tertiaire vakken met intensieve kanaalwatermarkten aan dat boeren over de organisatorische capaciteiten beschikken om dergelijke markten te ontwikkelen. Herverdeling van kanaalwater tussen tertiaire vakken kan de plaatsvinden door de dimensies van de tertiaire inlaatwerken aan te passen. Ook voor de tertiaire vakken die niet betrokken zijn bij de herverdeling worden veranderingen in het wateraanbod voorzien. Aangezien de kunstwerken sub-proportionele hydraulische eigenschappen bezitten, zal de invloed hiervan beperkt blijven.

De herverdeling van kanaalwater wordt beperkt door de maximale en minimale afvoeren van de secundaire kanalen. Het probleem is voornamelijk gerelateerd aan de minimale afvoeren, daar deze leiden tot problemen bij de verdeling van kanaalwater over de secundaire kanalen. De problemen betreffende de maximale afvoeren kunnen gemakkelijk worden opgeheven of verminderd door versterking van de kanaalpanden in de secundaire kanalen. Uit de analyse van herverdeling in de secundaire kanalen door marktwerking blijkt dat er problemen met de waterverdeling ontstaan bij de verwachte afname in de aanvoer naar het Fordwah kanaal. Tevens doen zich problemen voor bij de voorspelde toename van de aanvoer naar het Azim-kanaal vanwege de slechte fysieke condities van dit kanaal.

De definitie van hetgeen verhandeld wordt, heeft directe invloed op de mogelijke ontwikkeling van watermarkten. Uit de studie blijkt dat er beperkte mogelijkheden zijn voor de herverdeling van waterrechten, indien deze gedefinieerd zijn als de vaststaande maandelijkse verdeling van kanaalwater. In feite impliceert deze definitie een onderlinge afhankelijkheid tussen de maandelijkse aangevoerde volumes kanaalwater. Door deze rigide maandelijkse verdeling is de invloed van herverdeling slechts beperkt. Indien waterrechten echter als een jaarlijks volume worden gedefinieerd, zijn de verwachte opbrengsten van herverdeling aanzienlijk hoger. Dit wordt geïllustreerd aan de hand van de herverdeling tussen twee tertiaire vakken: met een vaststaande maandelijkse verdeling van kanaalwater, is de invloed van de herverdeling ca. 5% van het bruto bedrijfsinkomen; de invloed van herverdeling van een jaarlijkse volume kanaalwater (zonder de rigide verdeling over de maanden) tussen dezelfde twee tertiaire vakken is ruim twee keer zo groot, namelijk ca. 13%. Echter, om de herverdeling van kanaalwater in de tijd mogelijk te maken zijn drastische aanpassingen van de infrastructure noodzakelijk en dient het bergend volume van het systeem te worden vergroot.

In de bestudeerde herverdelingsscenario's tussen de twee secundaire vakken, is de herverdeling van kanaalwater tussen de tertiaire vakken binnen een secundaire vak niet in beschouwing genomen. Deze ruimtelijke afhankelijkheid tussen de tertiaire vakken onderling, resulteert eveneens in een kleinere invloed van de herverdeling tussen de secundaire vakken. De combinatie van watermarkten tussen tertiaire en secundaire vakken zal waarschijnlijk een grotere invloed op het bruto bedrijsinkomen hebben. Dit gecombineerde scenario dient echter nog te worden getest met de beschikbare simulatie- en optimalisatiemodellen.

Algemene toepassing van een geïntegreerde aanpak in irrigatiewaterbeheer

Het gebruik van de geïntegreerde aanpak: toekomstverwachtingen

De geïntegreerde aanpak is getest in twee casestudies, waardoor waardevolle inzichten zijn verkregen in het functioneren van het irrigatiesysteem, in de effecten van beleids- en beheersinterventies en in aspecten met betrekking tot de ontwikkeling en toepassing van een geïntegreerde aanpak. De belangrijkste stap voor de toekomst is het verdere gebruik van de ontwikkelde aanpak. In samenwerking met de actoren in het irrigatiesysteem kunnen verschillende scenario's worden geformuleerd en gesimuleerd met het huidige gecombineerde model. Dit kan de basis vormen voor toepassingsgerichte discussies met de betrokken actoren om het functioneren van het huidige systeem te verbeteren in een meer actiegerichte fase. Een dergelijke toepassing kan de conclusies van de beide casestudies enerzijds bevestigen en versterken, en kan anderzijds leiden tot een bijstelling van bepaalde aspecten in de geïntegreerde aanpak. Gebaseerd op de huidige ervaringen kunnen al een aantal verbeteringen worden aangegeven. Ten eerste zullen analyses van de terugkoppelingen tussen verschillende processen, zoals de invloed van verzouting op de beslissingen van boeren, kunnen worden toegevoegd aan de aanpak. Ten tweede dient het draaien van verschillende scenario's te worden vergemakkelijkt. Daarnaast kunnen verbeteringen in het modelleren van individuele processes worden overwogen, bijvoorbeeld het inbrengen van een geo-chemisch model of het analyseren van een groter aantal bedrijfsbeperkingen van boeren. Deze verbeteringen kunnen relatief gemakkelijk worden aangebracht door de modulaire opzet van het gecombineerde model. Tenslotte, zal een diepergaande nauwkeurigheidsanalyse moeten worden uitgevoerd. In de huidige configuratie blijken fouten niet te worden geamplifieerd, hetgeen uiteraard een goede zaak is. Dit fenomeen zou echter beter moeten worden geanalyseerd en getest voor een groter aantal scenario's. Er moet echter worden benadrukt dat al deze verbeteringen op zich wenselijk zijn, maar dat de eerste prioriteit zal moeten liggen bij het gebruik van het huidige model binnen het grotere geheel van de geïntegreerde aanpak.

Procesmatige aspecten

Een geïntegreerde aanpak wordt als concept door vele onderzoekers toegejuicht, maar blijkt nog zeer weinig te worden toegepast. Dit wordt waarschijnlijk veroorzaakt door problemen in de uitvoering. Verschillende disciplinaire teams moeten daartoe hun onderzoek coördineren en hun onderzoeksdoelstellingen en methodologieën harmoniseren. Daarnaast worden deze teams beperkt in de onderzoekskeuzes door het interdisciplinaire verband. Dit heeft te maken met practische aspecten, zoals de keuze van het onderzoeksgebied, het bemonsteringsschema en de tijdsplanning van het onderzoekstraject. Het is wellicht ook gerelateerd aan de keuze tussen de relatieve zekerheid van een disciplinaire uitkomst en de onzekerheid van wat een integrale aanpak zal bieden. De uitgevoerde casestudies laten echter zien dat het zeer wel mogelijk is om disciplinair en geïntegreerd onderzoek naast elkaar uit te voeren.

In de diepte of in de breedte ? Om tot een succesvolle integratie te komen, zou deze zover mogelijk bovenstrooms in het onderzoekstraject plaats moeten vinden. Het combineren van onderzoeksresultaten en modellen levert waardevolle informatie op en moet niet tot het laatst worden bewaard, waarbij men tot de ontdekking komt dat bepaalde belangrijke relaties niet zijn bestudeerd. Het is aan te raden om een gecombineerd model op te stellen in de aanvangsfase van het onderzoek in de context van de integrale analyse, zelfs als dit model zeer gesimplificeerd is. Dit model kan dan vervolgens worden aangepast en verbeterd, want het geeft al in een vroeg stadium signalen af ten aanzien van de processen welke moeten worden bestudeerd, de zwakke punten van een aanpak, en de variabiliteit van belangrijke procesvariabelen. De geïntegreerde aanpak moet echter voldoende ruimte laten voor de disciplinaire teams om hun studies uit te voeren, omdat voldoende diepgang in de bestudering van belangrijke processen moet worden bereikt. De waarde van de geïntegreerde aanpak hangt af van de rigueur van de samenstellende delen. Het is moeilijk om de balans tussen diepte en breedte te vinden en te handhaven.

Bij de uitvoering van een integrale aanpak is het informatiebeheer van groot belang. Bij een onderzoek dat zich in verschillende ruimte- en tijdschalen afspeelt en waarbij de resultaten van het ene proces gebruikt worden om een ander proces te analyseren, moeten afspraken worden gemaakt over gemeenschappelijke ruimte- en tijdstappen, en gemeenschappelijke gegevensbestanden.

Heterogeniteit en variabiliteit

De ruimtelijke heterogeniteit van fysische factoren en de temporele variabiliteit van verschillende processen, alsmede de diversiteit in boerenbedrijven, zijn inherent aan de analyse van irrigatiesystemen. Dit is een nadeel omdat het diepgaande (geo-)statistische analyses vereist van de ruimtelijke en temporele ordening in een systeem, hetgeen een groot aantal gegevens vergt. Het betekent ook een nadeel voor beleidsmakers en voor de waterschappen, die graag met interventies zouden komen met een uniforme uitwerking.

De heterogeniteit/variabiliteit kan echter ook gezien worden als een voordeel dat grote vooruitzichten biedt. Heterogeniteit en variabiliteit zijn sterke punten aangezien het systeem beter bestand is tegen ongunstige externe omstandigheden. Tevens biedt het vooruitzichten omdat er in potentie mogelijkheden bestaan om tot een herverdeling van goederen te komen, zulks met wederzijds voordeel. Dit wordt geïllustreerd in beide casestudies. Deze dissertatie laat zien dat door gebruik te maken van seizoensinvloeden, een herverdeling van water zal leiden tot een algemene verhoging van de gewasproductie. Kuper (1997) toont aan dat bij een heterogeniteit van de kwaliteit van het grondwater en bodemtypes, een herverdeling van water kan leiden tot een afname van het areaal dat wordt bedreigd met verzouting en sodificatie.

De uitdaging ligt dus in het begrijpen en kwantificeren van de bestaande heterogeniteit/variabiliteit teneinde deze te gebruiken bij het formuleren van nieuwe beleids- en beheersinterventies.

Interventies

De beleids- en beheersinterventies die zijn geanalyseerd in de beide case studies beslaan een breed kader. In deze studie worden voornamelijk beleidsinterventies geanalyseerd, terwijl in d studie van Kuper (1997) meer de beheersinterventies worden geëvalueerd. In de praktijk hebben beleidsmakers en waterschappen uiteraard de keuze in het toepassen van een combinatie van dergelijke ingrepen. Een logisch vervolg op de beide casestudies is dus een geïntegreerde analyse van deze ingrepen. Dit is zeer wel mogelijk vanwege de uitgebreide analyses die zijn uitgevoerd, en de configuratie van het huidige gecombineerde model, waardoor het mogelijk is een groot aantal variabelen te veranderen. Door een integrale analyse uit te voeren ten aanzien van de complementariteit van de verschillende interventies, is het tevens mogelijk een afweging te maken van de effecten van deze ingrepen op de gewasopbrengsten en de duurzaamheid van de geïrrigeerde landbouw.

Overdraagbaarheid

Het feit dat de ontwikkelde geïntegreerde aanpak de complexiteit van een irrigatiesysteem goed benadert, en dat een groot aantal interventies kunnen worden geëvalueerd, maakt de aanpak ook interessant voor toepassing in andere gebieden, of eventueel bij andere vraagstukken. Bij deze toepassing moet echter goed in de gaten worden gehouden dat niet alleen de modellen worden overgedragen. Het zijn juist aspecten als diagnose, identificatie van relevante processen en parameters, en discussies met actoren, die van groot belang zijn voor het uiteindelijke nut van een integrale aanpak. Deze fasen van het onderzoek bieden namelijk inzichten voor een goed begrip van de fysische en menselijke relaties. Op deze manier kan de aanpak gericht blijven op het begrip van het huidige functioneren van een systeem en op de voorbereiding van de toekomst door het vergelijken van de effecten van verschillende interventies.

Résumé

Une approche intégrée est proposée pour estimer l'impact de nouveaux modes de gestion et de politiques du secteur irrigué sur l'offre en eau, la salinité, la sodicité et la production agricole. Cette approche est appliquée à l'analyse du fonctionnement et impact des marchés de l'eau (existants et potentiels) dans les périmètres irrigués au Pakistan. Dans une étude développée en parallèle, cette approche est également utilisée pour l'analyse des effets d'un changement dans la gestion des canaux sur la salinité, la sodicité et les rendements des cultures. Les résultats obtenus par l'application de cette méthodologie à l'analyse des marchés de l'eau sont presentés dans la première partie de ce résumé. La deuxième partie discute d'une manière plus générale de l'approche intégrée et des lecons apprises suite a son application aux deux cas d'étude considérés.

Quel potentiel pour les marchés de l'eau au Pakistan: résultats du cas d'étude dans la Sous-Division Chishtian

Le rôle potentiel des marchés de l'eau dans la gestion du secteur irrigué

La pression croissante sur les ressources en eau, ainsi que la compétition entre secteurs économiques pour l'allocation de ressources financières, renforcent la nécessité de prise en compte de la valeur économique de l'eau dans les nouvelles politiques du secteur irrigué. Les grands projets d'infrastructure ne sont plus adaptés aux problèmes croissants de rareté de la ressource en eau, et il est nécessaire de mettre en place de nouvelles approches de gestion qui favorisent une utilisation plus efficace des ressources en eau existantes.

Bien que l'importance de la valeur économique de l'eau soit de plus en plus reconnue, il n'y a pas eu de changement majeur récent dans le choix des instruments économiques de gestion pour améliorer l'efficacité d'utilisation des ressources en eau. En effet, les changements proposés et mis en place dans de nombreux pays se concentrent sur les aspects institutionnels et le transfert de responsabilités vers les usagers. Ces changements permettent naturellement de réduire les déficits budgétaires des gouvernements concernés, mais leur impact sur l'efficacité d'utilisation des ressources en eau et sur la durabilité des périmètres irrigués n'a pas encore été clairement démontré.

Des changements dans la tarification de l'eau sont les options le plus souvent considerées pour améliorer l'efficacité d'utilisation des ressources en eau. Plus récemment, un interêt accru s'est porté sur les possibilité de développement de marchés de l'eau, pour améliorer à la fois l'allocation entre

usagers des ressources en eau existantes, ainsi que l'efficacité d'utilisation de ces ressources. Bien que des différences importantes existent entre les conditions théoriques nécessaires à un fonctionnement efficace de marché et les caractéristiques du secteur de l'eau, des marchés de l'eau se sont developpés sous des conditions physiques et socio-économiques variées et peuvent représenter une alternative réelle a l'amélioration de la gestion des ressources en eau.

Au Pakistan, la faible performance des périmètres irrigués face a croissance importante des besoins alimentaires, ainsi que la nécessité de réduire le déficit budgétaire, ont conduit à une remise en question de la gestion actuelle des périmètres irrigués. Le transfert de certaines responsabilités de gestion des canaux secondaires vers les usagers, la mise en place d'organismes de gestion financièrement autonomes, et le développement de marchés de l'eau, ont été proposés. A l'heure actuelle, peu d'éléments permettent de comprendre ce que seraient ces marchés de l'eau, et leur impact sur la production agricole du pays reste une inconnue.

L'objectif de cette thèse est d'évaluer les possibilités de développement de marchés de l'eau au sein des périmètres irrigués du Pakistan. Une approche intégrée, développée conjointement avec Kuper (1997), est appliquée à l'analyse de l'impact de marchés de l'eau sur la performance des périmètres irrigués. Cette approche est construite à partir de plusieurs études disciplinaires, i.e. hydraulique, sciences du sol, agronomie, économie. Elle inclue une analyse de la complexité du système irrigué et des liens entre les différent processus bio-physiques et décisionnels qui affectent l'offre en eau, la salinité et sodicité, et la production agricole, ainsi qu'une analyse de l'hétérogénéité et diversité spatiale des paramètres et variables qui influencent ces processus.

Un périmètre irrigué du Sud-Pendjab, la Sous-Division Chishtian, est choisi comme cas d'étude pour l'application de l'approche integrée à l'analyse des possibilités de développement des marchés de l'eau au Pakistan. Ce périmètre, situé dans la zone agro-climatique cotton-blé du pays, se caractérise par une utilisation conjointe des eaux de surface et eaux souterraines. L'analyse détaillée des processus bio-physiques et décisionnels est développée à partir d'information collectée dans les zones irriguées par huit canaux tertiaires.

Marchés de l'eau existants au niveau des canaux tertiaires

L'étude montre que les marchés d'eau de surface et d'eau souterraine sont actifs le long des huits canaux tertiaires considérés. Les données utilisées, obtenues par un suivi journalier de la distribution d'eau le long des canaux tertiaires, permettent de montrer que les échanges en eau de canal sont plus importants que ce qui avait été décrit dans la littérature. Ces échanges sont principalement des échanges a court-terme, compensant partiellement la variabilité des débits distribués à la tête des canaux tertiaires. L'achat d'eau souterraine permet à la fois d'augmenter les quantités disponibles pour l'irrigation, et de compenser les fluctuations de débits d'eau de surface.

Le fonctionnement des marchés de l'eau est influencé par les caractéristiques (quantité, qualité) des ressources en eau, ainsi que par les stratégies de production et contraintes des agriculteurs. Sous certaines conditions extrêmes de variabilité élevée de l'offre en eau de canal, de pertes de distribution élevées, et d'accès bon marché à une eau souterraine de bonne qualité, des marchés d'eau de canal plus intensifs se développent au sein des unités tertiaires. Ces marchés mettent en jeu des ventes et achats de tours d'eau, soit pour une semaine, soit pour une saison complète.

L'impact des marchés d'eau souterraine sur la production agricole est significatif, estimé pour les huits canaux tertiaires à 40% des revenus agricoles bruts actuels. Ces marchés réduisent la recharge nette vers la nappe souterraine, et augmentent les risques de salinisation et sodification. Cependant, l'impact des transactions d'eau souterraine sur la sodicité est moins important que celui estimé pour la recharge nette et la salinité.

L'impact des échanges a court-terme sur la production agricole est plus difficile à estimer. Ces échanges augmentent la flexibilité du système de distribution et permettent aux agriculteurs de mieux adapter offre et demande en eau. Mais les modèles de simulation et optimisation développés et utilisés dans le cadre de cette étude ne sont pas adaptés pour analyser et quantifier l'impact de ces échanges.

Quel potentiel pour le développement des marchés de l'eau

Le potentiel de développement des marchés de l'eau est étudié à différentes échelles du système irrigué: le long des canaux tertiaires entre agriculteurs, entre canaux tertiaires le long d'un canal secondaire, et entre canaux secondaires. A chaque échelle, l'impact des marchés sur la production agricole et l'environnement physique, la mise en place de ces marchés, et leur faisabilité technique sont discutés. L'analyse se concentre sur les transferts de droits d'eau définis par un volume d'eau total et une distribution mensuelle de ce volume pré-définie.

Au sein des canaux tertiaires, une intensification des marchés de l'eau existants, soit d'eau de surface, soit d'eau souterraine, conduirait à une augmentation du revenu brut agricole de 5-6% pour les huits canaux tertiaires considérés. Une combinaison des deux types de marchés, eau de surface et eau souterraine, aboutirait donc à une augmentation apréciable de la production agricole. L'analyse montre également que l'impact de tels marchés sur le milieu physique serait limité pour l'ensemble des unités tertiaires etudiées. Certaines unités tertiaires, cependant, seraient négativement affectées par une réallocation des ressources en eau. Par exemple: une augmentation de salinité de 8% est estimée pour l'unité tertiaire FD 130 suite à un développement plus important des marchés d'eau souterraine; de même, un développement plus important des marchés d'eau de surface entrainerait une augmentation de sodicité de 10% pour l'unité tertiaire FD 62.

A des échelles supérieures, une réallocation des ressources en eau de surface entrainerait une augmentation du revenu brut agricole plus limitée. Une augmentation du revenu brut agricole de l'ordre de 3-4% est obtenue par reallocation de l'eau de surface entre unités secondaires le long de Fordwah et le long de Azim. Entre canaux secondaires, des volumes importants seraient réalloués suite a la mise en place de marchés de l'eau. Mais cette réallocation n'aboutirait qu'à une augmentation limitée de la production agricole et du revenu brut des exploitations, de l'ordre de 2% seulement.

La réallocation des ressources en eau de surface entre canaux secondaires et canaux tertiaires entraine une augmentation conjointe de la pression sur l'eau souterraine, et pourrait accentuer les problèmes de rabattement des nappes.

Une réallocation d'eau de surface entre unités à différentes échelles du périmètre ne semble pas poser de problèmes majeurs liés à l'infrastucture de distribution. Au sein des unités tertiaires, ces contraintes sont quasi inexistantes, et les exemples de marchés intensifs d'eau de surface montrent que les agriculteurs ont une capacité organisationnelle suffisante pour développer de tels marchés. Entre unités tertiaires, un changement des dimensions des ouvertures a la tête des canaux est nécessaire pour réallouer l'eau de surface. Ces changements entraineraient une modification de l'offre en eau des unités tertiaires qui ne participent pas aux transactions (externalités positives ou négatives).

La réallocation d'eau de surface entre canaux secondaires est limitée par des contraintes en débit maximum et débit minimum. La contrainte en débit maximum peut être réduite relativement facilement par des activités de renforcement des berges. La contrainte la plus forte provient du débit minimum à fournir aux canaux pour éviter les problèmes de distribution le long des canaux secondaires. L'analyse de la réallocation entre les canaux secondaires Azim et Fordwah montrent que des rotations complexes seraient nécessaires pour fournir des quantités réduites d'eau de surface à Fordwah et éviter les problèmes de distribution le long de ce canal secondaire. Pour Azim, des problèmes se poseraient suite à l'état délabré des berges de ce canal.

L'analyse effectuée montre l'influence de la définition des droits d'eau sur l'impact potentiel des transactions. L'impact réduit des scénarios de reallocation est expliqué en partie par la définition des droits d'eau utilisée dans cette étude, i.e. un volume d'eau annuel et une distribution temporelle associée pour tenir compte des contraintes de distribution liées au système physique existant. En fait, cette définition entraine une inter-dépendance entre volumes mensuels reçus par les agriculteurs, et explique les caractéristiques volume-élevé faible-impact des marchés etudiés. Des droits d'eau définis uniquement par un volume annuel permettraient d'obtenir des augmentations du revenu agricole brut bien plus élevées. Une analyse détaillée des possibilités de réallocation entre deux unités tertiaires montre que la rigidité imposée par l'inter-dépendance entre volumes mensuels réduit de moitié l'impact d'une réallocation de droits sur la revenu brut des exploitations agricoles.

Dans le scénario de réallocation entre canaux secondaires, les possibilités de réallocation entre canaux tertiaires n'ont pas été inclues. Cette inter-dépendance entre canaux tertiaires est également un facteur important qui limite l'impact des transactions sur la production agricole. La variabilité des valeurs marginales de l'eau le long d'un canal secondaire montre que des réallocations sont possibles entre unités tertiaires, et aboutiraient à des augmentations de revenu agricole plus importantes que celles estimées dans cette étude. La quantification de l'impact combiné du développement de marchés entre canaux secondaires *et* entre canaux tertiaires devra cependant être testé avec les outils de simulation et d'optimisation developpés pour cette étude.

Approche intégrée et gestion du secteur irrigué

Application de l'approche intégré

L'approche intégrée développée à partir des deux cas d'étude a conduit à comprendre le fonctionnement actuel du système irrigué, à estimer l'impact d'interventions sur la performance de ce système, ainsi qu'à identifier les problèmes qui se posent lors de l'application d'une telle approche. Pour mieux comprendre la valeur ajoutàe d'une telle approche, un plus grand nombre de scénarios sera analysé. En collaboration avec les différents acteurs impliqués dans la gestion des périmètres irrigués, d'autres scénarios seront identifiés et leur impact testé grâce aux modèles existants.

Une application grandeur réelle de l'approche integrée permettrait de mieux evaluer la pertinence de cette approche à répondre aux questions posées par différents acteurs, et conduirait à une amélioration de l'approche existante. A partir des deux cas d'études présentés, certaines améliorations peuvent déjà être identifiées. Premièrement, des interactions rétro-actives entre processus et modèles associés peuvent être prises en compte. Prendre en compte la salinité dans les décisions des agriculteurs des modèles économiques est une voie d'amélioration à poursuivre. Deuxièmement, l'environnement informatique peut être amélioré pour faciliter l'utilisation des modèles et de la base de données associée. Troisièmement, les modèles individuels peuvent également être améliorés. Le développement d'un modèle géo-chimique prenant en compte les réactions chimiques du sol qui influencent la salinité et la sodicité, ou la prise en compte d'un plus grand nombre d'objectifs et de contraintes dans les modèles économiques, représentent de telles améliorations. Enfin, une analyse de la propagation des erreurs au cours des simulations d'un processus à l'autre est nécessaire. L'utilisation de l'outil integré pour les deux exemples considérés montrent que les boucles de calcul mises en place n'amplifient pas les erreurs. Cependant, ce phénomène est à analyser pour un grand nombre de scénarios, et pour des configurations non-linéaires du modele integré.

Bien que les améliorations des differents modèles individuels soient importantes, la priorité d'amélioration reste dans l'utilisation et l'amélioration de l'outil integré dans le context plus general de l'approche integrée.

Quel démarche pour une approche intégrée

La notion d'integration est un concept partagé par tous mais mis en pratique par quelques uns seulement. Les difficultés rencontrées au cours de la mise en place d'une approche integrée peuvent expliquer cette différence. Des équipes mono-disciplinaires doivent coordiner leurs activités de recherche, harmoniser objectifs et méthodologies, choisir des sites d'étude et des plans d'échantillonage communs, allouer des ressources financières et décider de priorités. Le choix entre un résultat scientifique disciplinaire certain et un résultat multi-disciplinaire plus incertain, qui de plus est difficilement valorisable, peut également expliquer le nombre limité d'expériences d'intégration.

Pour aboutir à une integration effective des activités de recherche et disciplines, le processus d'intégration doit débuter dès la phase de préparation de ces activités. La combinaison de résultats et d'outils ne peut se faire à la dernière minute. En effet, le risque est grand de négliger des processus et liens entre processus importants, et de ne pas avoir accès à l'information nécessaire pour extrapoler les résultats des études disciplinaires à différentes échelles spatiales. Développer un modèle integré simple aux cours des phases initiales de recherche semble être une etape pertinente conduisant à une approche integrée plus robuste. En effet, ce modèle simple permettra d'identifier rapidement les processus importants demandant une analyse fine, les faiblesses de l'approche developpée, et les besoins en information à des échelles spatiales et temporelles différentes.

Une approche integrée, cependant, ne peut se constuire qu'à partir d'études disciplinaires rigoureuses. La valeur de l'approche integrée dépendra en effet fortement de la solidité des éléments disciplinaires, et le succès de l'approche integrée dépendra de l'équilibre entre recherche disciplinaire et intégration.

La collecte et organisation de l'information est une étape essentielle du développement d'une approche integrée. La demande en information est relativement élevée, mais des analyses de sensibilité permettent de réduire d'une maniere significative cette demande. L'information doit être accessible à tous, et partagée par des personnes/chercheurs/acteurs s'intéressant à des processus, des échelles spatiales, et des échelles temporelles différents.

Hétérogénéité et variabilité

L'hétérogénéite de situations, la variabilité spatiale des paramètres physiques, la diversité des systèmes agraires, ainsi que l'évolution temporelle des variables, sont des éléments importants à considérer au cours de l'analyse des périmètres irrigués. Cette hétérogénéité et variabilité représentent un coût plus important pour le chercheur, car il est nécessaire de l'analyser en collectant plus d'information et appliquant des méthodes d'analyse plus sophistiquées pour extrapoler, interpoler, classifier. Pour les décideurs politiques et gestionnaires de périmètres irrigués, l'hétérogénéité est également synonyme de plus faible efficacité des politiques globales.

Cependant, hétérogénéité et variabilité représentent des opportunités d'amélioration de la performance actuelle du périmètre. En effet, hétérogénéité et variabilité augmentent la capacité d'adaptation à des chocs externes du système consideré, et offrent des possibilités de réallocation spatiale et temporelle des ressources disponibles. Les deux cas d'études permettent de souligner ces possibilités. L'analyse des marchés de l'eau presentée dans cette thèse discute des possibilités de réallocation spatiale des ressources en eau, et souligne les potentiels d'une réallocation temporelle. L'analyse presentée dans Kuper (1997) montre qu'une réduction importante de la sodicité est possible par une réalloaction des ressources en eau de surface entre unités tertiaires.

Le challenge reste donc la compréhension et quantification de l'hétérogénéite et variabilité existante pour différent facteurs et variables à différentes échelles spatialles et temporelles pour identifier les changements de gestion et de politique qui utiliseraient cette heterogeneite d'une manière optimale.

Identifier des interventions appropriées

Les changements de gestion et de politique du secteur irrigué proposés et analysés dans cette etude, ainsi que dans l'étude par Kuper (1997), couvrent un vaste champ d'interventions possibles. L'étude par Kuper (1997) se concentre sur des changements de gestion qui modifient l'offre en eau d'irrigation (i.e. changement des règles de distribution entre unités secondaires, ou modification de la taille des ouvertures des unités tertiaires). L'étude presentée dans cette thèse se concentre sur des modifications de la demande en eau d'irrigation (i.e. développement des marchés de l'eau). Cependant, l'analyse du potentiel des marchés de l'eau souligne déjà la complémentarité de ces différents types d'interventions, et la nécessité de considerer simultanément les aspects liés à l'offre et a la demande en eau d'irrigation.

En pratique, les decideurs politiques et gestionnaires de périmètres irrigués ont une palette large d'interventions possibles pour améliorer la performance des périmètres irrigués. La complémentarité de ces interventions reste un sujet peu etudié et représente une voie d'analyse future. L'outil integré offre la possibilité d'une telle analyse et la comparaison de l'impact d'interventions diverses sur la production agricole et sa durabilité.

Transférer une approche intégrée

L'application de l'approche integrée aux deux cas d'étude permet une analyse de la complexité du système irrigué et de l'impact d'interventions diverses sur la performance de ce système, grâce à la prise en compte simultanée de plusieurs processus biophysiques et decisionnels et d'un nombre relativement important de variables dans les modèles développés. L'approche proposée a également un intérêt pour des chercheurs, décideurs et gestionnaires d'autres systèmes irrigués. Cependant, le transfert d'une telle approche ne peut se limiter à reproduire un outil integré, mais doit se construire à partir de phases de diagnostic et de sélection de processus et variables clés en interaction avec les différents acteurs. Ces étapes sont des éléments essentiels à une phase d'apprentissage de la compréhension de la compléxité des systèmes irrigués et des relations physiques et humaines qui conditionnent la performance de ce système irrigué. La situation actuelle reste le point de départ d'analyse, et l'application de l'approche integrée permet alors de préparer les décisions futures par l'analyse de différentes interventions, plutôt qu'à prédire d'une manière fine l'évolution de variables choisies.

About the author

Pierre Strosser
Born at Strasbourg, France, on March 1, 1966

Ingénieur Agronome, Institut National Agronomique Paris-Grignon, 1989
M.Sc. in Agricultural Economics, Wye College, University of London, 1990
Ingénieur du Génie Rural, des Eaux et des Forêts, Paris, 1990

Agricultural Economist at the International Irrigation Management Institute, Pakistan National Program, Lahore, from May 1991 to September 1997

Currently researcher at the Irrigation Division, Cemagref, Montpellier, France