# THE COLLABORATION BETWEEN IIMI AND CEMAGREF IN PAKISTAN

## Proceedings of a one-day workshop
### October 3, 1997
### International Irrigation Management Institute, Lahore

Organized and Edited

by

Pierre Strosser

# TABLE OF CONTENTS

# FOREWORD

The French research center for agricultural and environmental engineering (Cemagref) and the International Irrigation Management Institute (IIMI) began a joint research program during 1987 in Sri Lanka. This program was expanded in 1993 to include Pakistan.

The major research activities have focused upon: the hydraulic operation of canals and branch canals, including decision support systems for irrigation managers; water transactions by farmers of both canal and tubewell water, along with water market policies; the use of Geographical Information Systems (GIS) and Remote Sensing (RS) for temporal monitoring and spatial analysis of irrigation system performance, as well as developing new RS techniques to delineate saline and sodic lands using satellite imagery and developing an integrated approach that is being applied to Chishtian Irrigation Subdivision located in southeastern Punjab. In addition, we are working on the development of a generic model for unsteady flow sediment transport, which can be applied to canal operation.

For the time period 1995-97, the French Embassy has also provided funding to strengthen this Cemagref-IIMI collaboration, which has fostered a strong linkage with the Watercourse Monitoring and Evaluation Directorate (WMED) of WAPDA, along with assisting the International Sedimentation Research Institute, Pakistan (ISRIP), with both organizations being under the federal Water and Power Development Authority (WAPDA).

With modest funding from the French Government and the French Embassy in Islamabad, a highly productive research program has evolved. There have been frequent professional interchanges between both organizations, both in terms of planing and conducting the research. Also, a number of Pakistani and French students have participated in this program, which has been mutually beneficial.

Most importantly, I consider the Cemagref-IIMI relationship as a role model for international collaboration and working with national partners. This has really facilitated the development of IIMI's Pakistan National Program. We all look forward to continuing this valuable partnership.

Gaylord V. Skogerboe, Director
Pakistan National Program
International Irrigation Management Institute

# THE IIMI-CEMAGREF COLLABORATION IN PAKISTAN - GENERAL PRESENTATION

Thierry Rieu, Gaylord V. Skogerboe and Patrice Garin

## The IIMI-Cemagref Collaboration

The International Irrigation Management Institute (IIMI) and Cemagref, the French Research Center for Agricultural and Environmental Engineering, have been working on joint research activities since 1987. Joint research activities were initiated in Sri Lanka and started in Pakistan in 1993. In 1994, a five year Memorandum Of Understanding was signed between the two institutes and a mid-term evaluation was conducted in Colombo in April 1997.

The joint research studies have been defined within the framework of IIMI's research programs as defined in its Medium Term Plan and Cemagref's Strategic Plan. More specifically, the proposed research studies fall under the following programs:

- Performance Assessment : In applying advanced information techniques (use of remote sensing data, for example), the objective is to provide a framework that would improve the use of information to improve the management of the irrigation system.

- Design and Operation :
  1. For the design and operation of irrigation systems, it is essential to understand the hydraulic processes and related management rules. The development of simulation models facilitates the identification of existing constraints in canal operation and the testing of scenarios to improve water deliveries.
  2. Part of the research activities focus on sustainability issues. Investigating salinisation processes is required in order to identify appropriate indicators for the monitoring of irrigation systems, and to propose management recommendations that would mitigate salinity.
  3. The development of new methodologies to analyze irrigation systems in a muti-disciplinary and more holistic way for the analysis of the impact of management and policy options for the irrigation sector has been included as a joint research study.

- Policy, institutions and management: in the context of scarce water resources and the potential need to reallocate water resources among users/sectors, research activities focus on water management reforms. Emphasis is given to the development of methods to analyze the economic and social impact as well as to investigate the political and institutional feasibility of these reforms.

H 22401

The Government of France supports IIMI through the secondment of two researchers (one in Sri Lanka, one in Pakistan) of the French Ministry of Agriculture. Since 1991, an associate-expert (CSN) is also seconded to the IIMI-Pakistan National Program. The financial support of the Government of France is divided into a contribution to IIMI core funds and a direct support by the Ambassade de France in Pakistan to IIMI's National Program. The overall financial contribution is around 1.2 million French Francs per year.

## The IIMI-Cemagref Collaboration in Pakistan

*Research Themes*

In Pakistan, the main research topics that have been investigated in the context of the IIMI-Cemagref collaboration are:

1. **Decision-support systems for the operation and maintenance of irrigation canals;**

2. **Development of methodologies to estimate the economic impact of irrigation sector policies;**

3. **Use of remote sensing (RS) and Geographic Information Systems (GIS) for spatial analysis and temporal monitoring of irrigation system performance; and**

4. **Development of integrated approaches to estimate the impact of management and policy changes on irrigation system performance in terms of water, agricultural production and the environment.**

*Reinforcement of the IIMI-Cemagref: A Project Supported by the Ambassade de France in Pakistan*

The IIMI-Cemagref collaboration in Pakistan has been reinforced since 1995 by a direct financial contribution of the Ambassade de France in Pakistan. This initiative is part of a broader program which aims at developing a cooperation between France and Pakistan in the field of irrigation management.

The main objectives of this reinforcement project are:

1. To reinforce the scientific collaboration between IIMI-Pakistan and Cemagref, by strengthening the research team and promoting exchanges of researchers of the two research institutes ;

2. To associate Pakistani institutes to the collaborative research programs. For example, the Watercourse Monitoring & Evaluation Directorate (WMED) in the field of RS/GIS, or the International Sediment Research Institute of Pakistan (ISRIP) in the field of sediment transport as part of the research on decision-support systems;

3. To develop training activities to transfer methodologies and results to Pakistan partners; and

4. To disseminate research results in Pakistan, France and the international community through report and research papers, workshops and seminars.

## Means

A large number of researchers from IIMI have been associated to the collaborative research program. Cemagref researchers have been visiting Pakistan frequently, and IIMI researchers have also been visiting the Irrigation Division of Cemagref frequently. A large number of M.Sc. and Ph.D. students have been involved in research activities which are jointly supervised by IIMI and Cemagref researchers. Table 1 summarizes the Cemagref human contribution to the collaboration.

**Table 1.** The Involvement of Cemagref Researchers in IIMI-Cemagref Activities in Pakistan (4- year period).

| | Topic 1 Decision-Support Systems | Topic 2 Methodologies for Economic Analysis | Topic 3 GIS/RS | Topic 4 Integrated Approach |
|---|---|---|---|---|
| Researchers (no.) Man-month Missions to Pakistan | 2 10 4 | 1 10 6 | 3 3 1 | 5 10 5 |
| Ph.D Students (number) Masters' Students (No.) | 2 14 | 1 10 | 1 2 | 9 |

Also, researchers from other French research institutes have been involved in the collaboration and have complemented Cemagref's involvement in Pakistan. For example, researchers from CIRAD and CNEARC have participated in joint research activities related to the analysis of physical processes related to sodicity, and the social aspects of water management at the local level.

## Research Studies

The specific research studies that have been undertaken in the context of the IIMI-Cemagref collaboration include:

**1. Decision-Support Systems for the Operation and Maintenance of Irrigation Canals**

- Management Information Systems and use of the ILIS software (in collaboration with the Punjab Irrigation and Power Department)

- Analysis of the operation and maintenance of primary and secondary canals in the Chishtian Sub-division
- Use of hydraulic models to analyse the operation of the Chashma Right Bank Canal (Stage I)
- Sediment transport in irrigation canals through the review of literature, analysis of data and development of simulation models (in collaboration with ISRIP)

## 2. Development of Methodologies to Estimate the Economic Impact of Irrigation Sector Policies

- Analysis of the potential for water market development in Pakistan as in the example from the Chishtian Sub-division
  - ⇒ Analysis of the heterogeneity of farming systems
  - ⇒ Economic modeling of farm decisions
  - ⇒ Economic modeling of current water markets (WTC level)
  - ⇒ Potential economic impact of water market development between tertiary and secondary canals
- Acceptability of water management reforms

## 3. Use of Remote Sensing (RS) and Geographic Information System (GIS) for SpatialAnalysis and Temporal Monitoring of Irrigation System Performance (in collaboration with WMED)

- Use of satellite imagery for land use mapping in the Chishtian Sub-division
- Use of satellite imagery for salinity monitoring in the Chishtian Sub-division
- Analysis of geochemical processes of salinisation and alcalinisation

## 4. Development of Integrated Approaches to Estimate the Impact of Management and Policy Changes on Irrigation System Performance in Terms of Water, Agriculture Production and the Environment

- Identification of methodological issues related to the development of integrated approaches
- Develement of an integrated spatial database in the Chishtian Sub-division
- Analysis of on-farm water allocation and water supply at the tertiary level
- Analysis of management scenarios using the developed methodology

Table 2 summarizes different steps followed for each of the research topics, and specifies the present status of research activities. In Table 2, 6 different levels are defined: methodologies, development of the model, application of the methodology/model to a specific case study, development of a generic methodology/model, dissemination of research results, and training to other users.

**Table 2.** Status of the Different Research Topics

| Topics | Definition of methodologies | Development of model | Application to case study | Generic methodology/ tool | Dissemination of results | Training to users |
|---|---|---|---|---|---|---|
| 1. Decision Support Systems | ████ | ████ | ████ | ████ | ████ | ████ |
| 2. Methodologies for economic analysis | ████ | ████ | ████ | ████ | ████ | |
| 3. GIS/RS | ████ | ████ | ████ | ████ | ████ | |
| 4. Integrated approach | ████ | ████ | ████ | | | |

*Output*

Table 3 summarizes the main research output of the IIMI-Cemagref collaboration for the period 1994-1997.

**Table 3.** Main research output of the IIMI-Cemagref collaboration in Pakistan

| Topics | Methods developed | Software developed | Reports | Working papers and articles | Network activities | Training |
|---|---|---|---|---|---|---|
| 1. Decision -Support Systems | 3 | 3 | 5 | 5 | 5 | 3 |
| 2. Methodologies for economic analysis | 4 | | 6 | 7 | | 2 |
| 3. GIS/RS | | | 2 | | | |
| 4. Integrated approach | 3 | 1 | 7 | 1 | 1 | |

Network activities included in Table 2 mainly represent the organization (Pakistan) and participation to the different workshops (Sri Lanka, Malaysia, Morocco) of the Information Technology for Irrigation Management (ITIS) Network, a major activity that aims at putting together irrigation managers and researchers to discuss and share experiences on the use of information technologies for the management of irrigation systems. Also, a workshop involving around 20 researchers from IIMI and various French research organizations was organized in April 1996 to discuss issues related to the development of integrated approaches for irrigation management research.

Training activities have so far concentrated on the use of RS/GIS for the monitoring and evaluation of irrigation and drainage projects, and sediment transport. For example, training in the field of GIS/RS has included:

- a 1-month training in Montpellier, France, attended by three researchers from IIMI and WMED, on the use of satellite imagery for land use mapping;
- a 1-week training in Lahore, Pakistan, attended by 3 WMED staff, on the use of the ArcInfo software;
- a 3 month on-the-job training in Lahore, Pakistan, attended by one WMED staff, on the use of satellite imagery for crop identification; and
- a 1-week short-course in Lahore, Pakistan, attended by 12 researchers/staff from 8 Pakistani research organizations, on the use of GIS/RS for irrigation and drainage projects.

## Conclusion - Future Plans

At present, the main objective of the IIMI-Cemagref collaboration in Pakistan is to reinforce existing studies, mainly in the field of sediment transport, water allocation and use of RS/GIS, and to further disseminate results obtained so far under the 4 research topics. For example, a workshop will be organized in France during the first half of 1998 to present and evaluate the integrated approach and its preliminary applications. Also, more efforts will be invested to generate complementary funds to develop new activities and associate new partners to the IIMI-Cemagref collaboration.

More specifically, research studies to be continued during1998 are:

1. **Decision-Support Systems for the Operation and Maintenance of Irrigation Canals**
   - Improvement of canal operation (manual operation, IIMIS),
   - Sediment transport
   - ITIS network (meetings, newsletter)

2. **Development of Methodologies to Estimate the Economic Impact of Irrigation Sector Policies**
   - Acceptability of water management reforms

3. **Use of Remote Sensing (RS) and Geographic Information Systems (GIS) for Spatial Analysis and Temporal Monitoring of Irrigation System Performance**
   - Remote sensing and salinity: potential transfer to users and application to the command area of the Fordwah/Eastern Sadiqia (South) Irrigation and Drainage Project
   - Remote sensing and land use mapping: pilot project IIMI-WMED with input from Cemagref in the command area of the Hakrah 3-R distributary

4. **Development of integrated approaches to estimate the impact of management and policy changes on irrigation system performance in terms water, agricultural production and the environment**
   - Dissemination of preliminary results of the integrated approach applied to the Chishtian Sub-division (publication, CD-ROM, workshop)

# IMPROVED OPERATIONAL SCENARIOS FOR REGULATION AND CANAL WATER DISTRIBUTION

Marcel Kuper, Zaigham Habib, Xavier Litrico and Pierre-Olivier Malaterre

## Abstract

This paper summarizes the experiences of the Pakistan National Programme of the International Irrigation Management Institute (IIMI) in the analysis of canal regulation and the impact on irrigation water distribution. The work was carried out in the 70,000 ha Chishtian Sub-division, which forms part of the Indus Basin irrigation system. The research approach consists of three main parts: (1) hydraulic modelling of the water flows in irrigation canals, using a mathematical unsteady state model (SIC); (2) analysis of official and actual rules governing canal regulation, captured in a regulation module (Gateman); and (3) linking hydraulics and management practices in order to determine the scope to improve canal water distribution by changing the operational rules. The ultimate aim of the programme was to provide information and tools to assist irrigation managers in the operation of the irrigation network. The results presented in this paper are a synthesis of a number of papers, which have been published since 1994.

## Introduction

The contiguous Indus Basin Irrigation System irrigates an area of about 16 million ha, diverting about 128 billion $m^3$ of surface water to 43 canal systems annually. Cropping intensities originally envisaged to be about 70% have risen to about 130%, while farmers have changed to producing high yielding varieties (HYV) since the Green Revolution. These developments have put a lot of stress on the scarce surface water resources, even though this is partly compensated for by the exploitation of groundwater (Nespak/SGI, 1991).

Traditionally, the regulation of irrigation canals aims to distribute water according to the official targets set in terms of design or authorised discharge, equitably sharing any shortfall in inflow among the canal commands. Since the demand for water has more than doubled over the years, the irrigation agencies are dealing with a permanent water shortage. To face this challenge, new operational rules have been introduced, which are different from the official rules and are often not transparent. Practically, canal regulation is left mostly to the local gate operators with occasional instructions from the higher levels. Once essential, communication and information systems are largely ineffective, making main canal operations difficult at the managerial level and water deliveries unreliable for farmers.

The International Irrigation Management Institute, in collaboration with the Punjab Irrigation & Power Department (PID), started a programme with the following objectives:
- To understand and quantify the impact of existing operational rules and canal regulation on the water distribution;

H 22402

- To investigate the possible improvements in water distribution by suggesting and comparing alternative operational rules within the existing system constraints, i.e., the absence of an escape, minimum freeboard and an inflow that is highly variable and not sufficient; and
- To develop and field test computer models applicable as research and decision making tools at the main and the secondary canal levels in Pakistan.

The results of the studies were documented in several publications (Kuper et al., 1994; Litrico, 1995; Litrico et al., 1995; Habib and Kuper, 1996; Kuper et al., 1997; Kuper, 1997). In Parallel to this programme, a study on the impact of maintenance on canal water distribution was carried out, for which some of the same models were used (Hart, 1996; Visser, 1996; Van Waijjen et al., 1997). Also, a more field-oriented study on the implementation of an Irrigation Management Information System was conducted, intended to apply some of the results of the studies on canal regulation and on maintenance (Hafiz Ullah et al., 1996).

## Methodology

### Research Locale

The study was carried out on the lower end of the Fordwah Branch canal, which forms part of the Fordwah Canal system, off-taking from Suleimanki Headworks on the Sutlej River in south-east Punjab. The upper boundary of the study area was defined at 61 km of Fordwah Branch canal, going down to its tail at 1·14 km. This coincides with the limits of an hydraulic sub-unit, the Chishtian Sub-division. The width of Fordwah Branch is 35 m at km 61 and 15 m at the tail with an average slope of 1:5000. There are a total of around 500 tertiary units served by 14 secondary or *secondary canal*, canals and 8 minors. A few units are supplied directly from Fordwah Branch. The target discharge of Fordwah Branch at 61 km is 36.3 m³/s in summer and 12.8 m³/s in winter. From 61 km to the tail, there are a total of 6 cross-regulators, generally located just downstream of secondary canal off-takes to ensure a stable supply to secondary canals. A schematic map is given below.

### Research Approach

The research approach consisted of three components:
- Hydraulic modelling of the water flows in irrigation canals, using a mathematical unsteady state model, Simulation of Irrigation Canals (SIC), developed by Cemagref in France (Cemagref, 1992; Malaterre and Baume, 1997);
- Analysis of official and actual operational rules governing canal regulation, captured in a regulation module, Gateman, written in Fortran and linked with SIC; and
- Linking SIC and Gateman in order to be able to undertake a comparative analysis of alternative operational rules and determine the scope for improvement in canal water distribution.

# Layout of Fordwah Branch
## Chishtian Subdivision

RD 199

Daulat

Mohar — 3L

RD 245

Phogan

Khem Gahr — 4L

RD 281

Jagir

Shahar Farid

Masood

RD 316

Soda — WEIR 334

RD 353 — 5L

WEIR 363

Azim — RD 371 — Fordwah

Mehmud

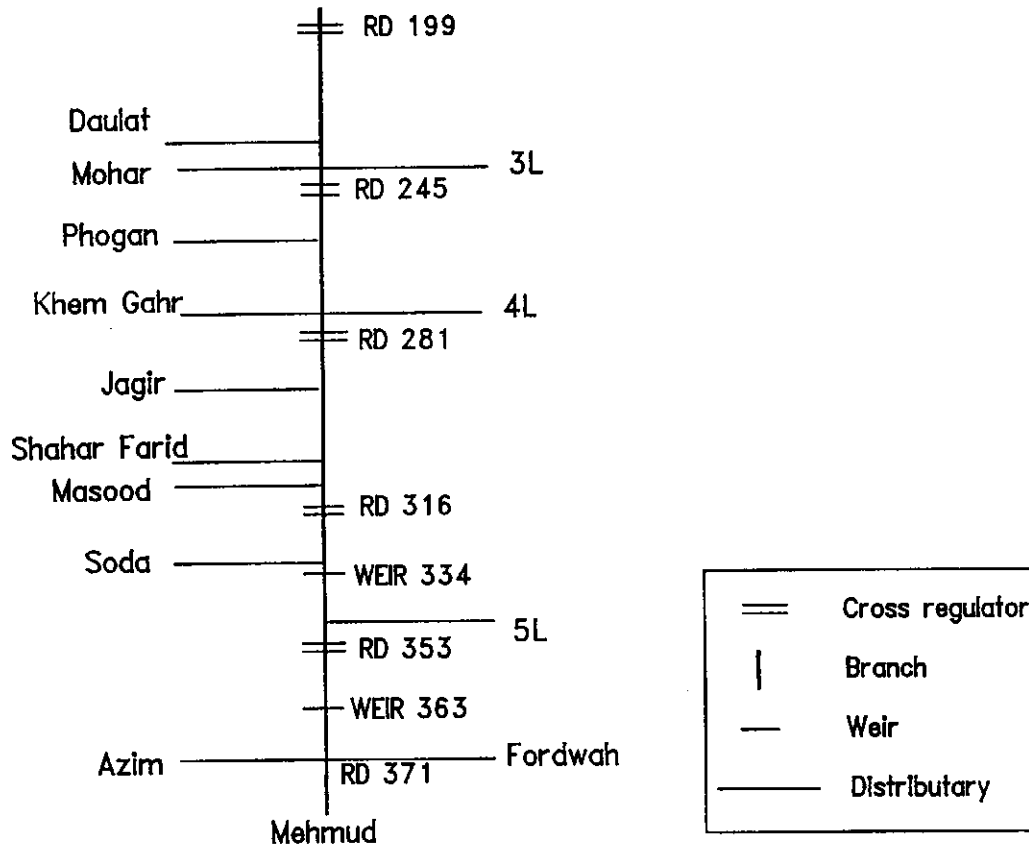| | |
|---|---|
| = | Cross regulator |
| \| | Branch |
| — | Weir |
| —— | Distributary |

**Figure 1. The Hydraulic Network of the Chishtian Sub-division**

Water flows in the Fordwah Branch and deliveries to secondary off-takes were simulated using SIC. SIC has been tested for computational accuracy using the benchmarks developed by the American Society of Civil Engineers, and is presently applied in various countries around the world (Malaterre and Baume, 1997). It consists of three modules, (1) a topography/geometry module, which permits definition of the canal network; (2) a steady state module, which permits definition of canal structures and the calculation of the water line in steady state conditions, using the Manning-Strickler equation, expressed as a differential equation of the water surface profile solved by Newton's method; and (3) an unsteady state unit, which permits the computation of unsteady flow conditions by solving the St. Venant equations numerically by discretizing the equations through a four-point semi-implicit Preissmann scheme.

SIC was successfully calibrated and validated for the Fordwah Branch, comparing simulated water levels and discharges with field observations (Litrico, 1995). Steady state conditions in the field were obtained during a field test carried out in collaboration with PID (Litrico et al., 1995).

The operational rules are captured in a regulation module, Gateman, that was developed especially for this study. Based on earlier work of Malaterre (1989), it was initially developed by Litrico (1995) to simulate manual operations of gate keepers (tactical level). It was modified at a later stage to include the decision-making process of the irrigation manager (strategic level), who has to decide on the operational targets (Kuper et al., 1997). The module is written in Fortran and integrated in the unsteady state module of SIC. At the strategic level, the module generates an order of operational priority for the secondary canals, based on a set of rules, which can be defined in the module. Based on the operational priority and the available inflow on a given day, the module determines which secondary canals should be open, closed, or absorbing the fluctuations. This is subsequently taken up at the tactical level, where the module generates the gate settings that are necessary to achieve the targets that have been defined. The module further generates an action (open or close a gate) whenever the upstream water level (Hu) of a cross-regulator deviates more than 2 cm from a pre-defined Full Supply Level (FSL). Depending on the operational target, the gates of either the cross-regulator or of the off-taking secondary canals can be manipulated. This represents the decision-making process of a gate keeper, whose responsibility it is to maintain a constant water level (generally FSL) upstream of a cross-regulator. The discharge is then calculated based on the gate opening ($G_o$), and upstream and downstream water levels ($H_u$, $H_d$).

Gateman was calibrated and validated in two steps. The tactical component was calibrated and validated through interviews and a special campaign, where the reactions of gate keepers to a varying inflow was determined (Litrico, 1995). The strategic component was calibrated based on a full season of observations of water levels and discharges (Kuper, 1997).

Finally, Gateman and SIC were used conjunctively for a series of studies to determine the scope for intervention in canal regulation, both at the strategic as well as at the tactical level, in order to improve the canal water distribution. The analysis was carried out in two steps; firstly, the existing operations and the management practices were modelled and compared with field observations, while at the second stage, alternative operations and management practices were compared. The results of these studies are summarized in Section 3 and 4.

*Data Collection*

Water levels were monitored daily at all the cross-regulators of the Fordwah Branch as well as the head of all secondary canals. The stage-discharge relationships for all these structures were determined with the help of a current meter in collaboration with PID and the International Sedimentation Research Institute, Pakistan (IIMI, 1995). These data were processed and stored with the help of a computer-based information tool, Irrigation Management Information System (IMIS). For the calibration of SIC, special measurement campaigns were conducted to determine water levels and discharges in the Fordwah Branch canal. Finally, the regulation of irrigation canals was studied during special measurement campaigns, by recording the gate operations of each canal structure and interviewing operators and irrigation managers. This enabled the calibration and validation of the regulation module Gateman.

# Analysis of the Actual Operational Rules

The responsibility of the irrigation agency for regulation is restricted to the main and secondary levels up to the tertiary off-take, while farmers are to share the water amongst themselves in tertiary units through a roster of turns (*warabandi*), whereby a certain farmer is entitled to the entire discharge entering a tertiary unit for a specified amount of time. The warabandi is generally defined for a 7-day period. The operational management of irrigation canals can be divided into two levels, the strategy level, where objectives are defined and translated into targets, and a tactical level, where gates are operated to meet the targets. In the Chishtian Sub-division water is delivered to the minor secondary canals mostly according to the demand, while a rotation is implemented between the four larger secondary canals. The operational targets are set by the system managers. At the tactical level, local operators are responsible for the operations at a regulation point, which generally comprises of one cross-regulator and two to three off-taking secondary canals. When one of these secondary canals is in the first priority, the gates of the cross-regulator are operated to maintain the upstream water level, followed by much smaller operations of another secondary canal at the same location, if required. If the downstream discharge of a cross-regulator is in first priority, the gate keeper will manipulate the gates of the secondary canals, off-taking at this point. No regular information is given to the gate keepers about the inflow, so, their actions are governed by local regulation requirements, knowledge and interference. In the following sections, the actual operational rules will be determined, both at the strategic as well as at the tactical level.

*Determining the Strategic Operational Rules*
*(Based on Kuper and Kijne, 1993; Kuper et al., 1997; Kuper, 1997)*

In order to achieve an efficient and equitable water supply, certain operational rules have been defined to guide the irrigation manager in the regulation of canals. These rules are documented in the Manual of Irrigation Practice (PWD, 1961), and those pertaining to the study are summarised here:

- The water supply to a secondary canal should be ensured for a full cycle of warabandi, i.e., eight days, including one day to stabilise the inflow;
- Target discharges are based on the official allowances; they can be adjusted downwards during the irrigation season if demand is less than the supply; these allowances vary over quite a large range;
- A canal should not receive less than 70% of the official target discharge in order to avoid siltation and maintain equity; and
- The discharge to a secondary canal should not exceed 110-120% in order not to surpass the carrying capacity of a secondary canal.

Implementation of these rules is often delegated to the gate operators, who, on the basis of instructions from the irrigation managers, operate the gated cross-regulators in main canals, as well as the gated head regulators of secondary canals. Gate keepers generally maintain water levels upstream of a cross-regulator at a pre-defined *full supply level* (FSL) in order to enable stabilising the supply to off-taking secondary canals, or the on-going parent channel.

The system manager and his staff do not always follow the official operational rules that were defined above for various reasons. When looking at the observed values of deliveries to secondary canals, the following **actual** operational rules can be identified:

- Reduction in the rotation time from 8 days to 4 days;
- Change in target discharges of the secondary canals;
- Continued implementation of a rotation between the four major secondary canals, Daulat, Shahar Farid, Fordwah and Azim; the other secondary canals are not involved in this rotation; and
- Rotation between Azim and Fordwah secondary canals.[1]

These rules were programmed in Gateman. By running the composite model, the discharges to the different secondary canals could be compared with the actual measured data of Kharif 1994. The results of the simulations, presented in Table 1, show that the definition of the operational rules yields a water distribution that on average resembles reality (in terms of volumes) with an average difference of less than 5%.

**Table 1.** Simulated and Measured Volumes Delivered to Secondary Canals in the Chishtian Subdivision, Kharif 1994.

| Canals | Volume Measured in 100,000 m$^3$ | Difference Simulated with Measured % |
|---|---|---|
| Inflow | 3674.2 | + 2.2 |
| Daulat | 677.6 | + 3.5 |
| Mohar | 90.2 | + 2.9 |
| 3-L | 46.6 | + 4.1 |
| Phogan | 100.0 | - 16.9 |
| Khemgarh | 89.9 | + 4.6 |
| 4-L | 47.4 | - 7.5 |
| Jagir | 102.9 | + 6.5 |
| Shahar Farid | 488.5 | + 1.6 |
| Masood | 138.3 | + 4.8 |
| Soda | 216.9 | - 0.7 |
| 5-L | 27.5 | - 5.5 |
| Fordwah | 500.7 | + 2.0 |
| Mehmud | 56.9 | + 8.5 |
| Azim | 468.3 | - 3.9 |
| Seepage and direct outlets | 622.6 | + 8.8 |

---

[5] This is due to physical limitations of the system, whereby it is quite dangerous to supply water simultaneously to both large secondary canals at the tail. Any fluctuation in discharge would in this case lead to breaches.

The reasons for differences between measured and simulated values are manifold; errors in discharge estimation (equation used, field measurements), the punctual measurement (once a day) versus a simulation with a time step of 10 minutes, an inflow pattern that may deviate, errors in levels, and dimensions of structures, etc. A difference of 10 % in delivered volumes seems, therefore, allowable. Only in the case of Phogan Secondary canal, where a small ungated channel is not attended by a gate operator, the difference exceeds 15%. An error in the crest level cannot be excluded in this case, as farmers have tampered with this intake on various occasions.

Particularly for Shahar Farid and Azim, simulated values match measured values very well. In the case of Daulat and Fordwah, the distribution is somewhat more skewed (more days of supply between 70 and 110%) because of the logic of the model, which attempts either to deliver the targeted discharge to a secondary canal, or is closed. In reality, gate keepers sometimes increase the discharge in times of great demand, while they release less in periods of slack demand.

The shape of simulated hydrographs was compared with the measured values. An example is given in Figure 2. The comparison shows that the measured and simulated discharges correspond reasonably well, and that the shape of simulated curves is quite representative of what has been measured in the field. Note that these results have been achieved with **average operational rules,** without taking the punctual interventions that occur into account. A limitation of the results produced by the model is the fact that in case of a sudden excessive discharge at the tail, when either Azim or Fordwah is closed, the excess discharge is absorbed by the secondary canal that is open, and not passed on to the neighbouring secondary canal. An additional sub-routine in the regulation module would be necessary to address this situation.
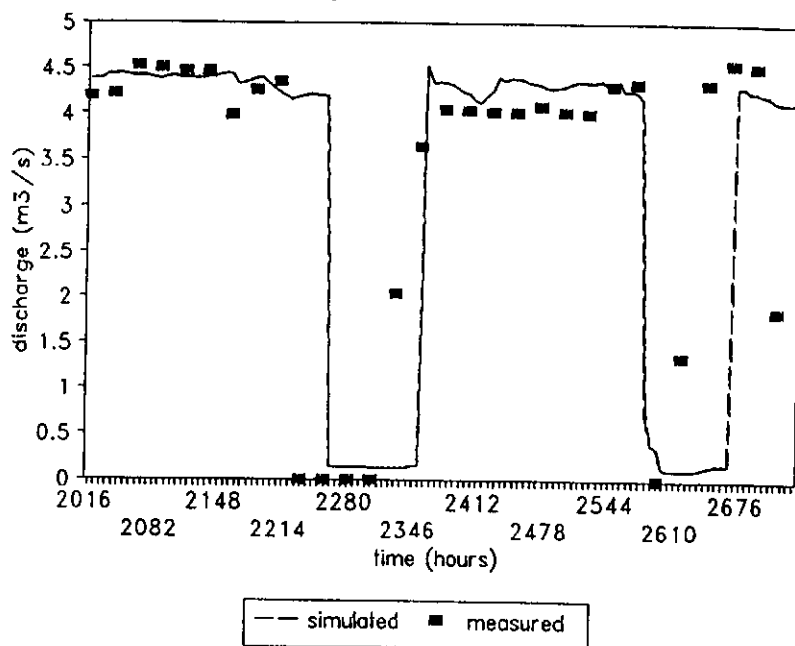


**Figure 2.**     Hydrographs of the Daily Discharge Delivered to Shahar Farid Secondary Canal During Kharif 1994, Simulated Versus Measured.

*Determining the Tactical Operational Rules*
*(based on Litrico, 1995)*

On the contrary to strategic rules, official tactical operational rules are not clearly written on paper, and the way a gate-keeper operates its gate is not easy to derive. The approach used, therefore, is to acknowledge the experience of the operators; their intimate knowledge of the system, due to long practise and experience enable them to operate without written rules. Their objective is mainly to maintain the upstream level close to a pre-specified level, called Full Supply Depth (FSD), using the cross regulator gate in order to ensure constant distribution to off-taking distributaries. The regulation module Gateman uses an hydraulic formula as a reference to « perfect » operation. The gate keeper's operations are then compared to the operations predicted by the formula, and a gate operation ratio is calculated, giving the ratio between predicted and actual operations. If the ratio is close to one, it will show a good prediction capability of the model. Many other parameters are used in the module to reproduce manual operations, such as :

- timing of operations (beginning of day work, duration of day work, time of an operation, time between two operations);
- lower and upper limits for intervention (maximum deviation in upstream level from FSD);
- maximum and minimum openings;
- values for maximum and minimum operations; and
- amplification coefficients for opening and closing operations.

The regulation module was calibrated using a 3-day monitoring period, where water levels, gate openings and gate operations were monitored hourly (Litrico, 1995). The values for the different coefficients are first derived from field observations and interviews before they are refined by trial and error, by running the unsteady state module of SIC linked with the regulation module. The first step of the calibration process gives an idea of the average value of these coefficients. The upper and lower limits of intervention are derived from interviews of gauge readers. The time between two operations is coefficiently taking into account the error generated by the way the module computes the openings; this module looks at the upstream level at one moment to determine the opening, and does not take into account the speed of variation of the water level, or any other kind of information. This means that it does not react to a brutal change in water level well, except if it operates more often.

The time between two operations, the limits of intervention, the amplification coefficients and the FSD, are set to the values derived from the first step of the calibration process. Afterwards a simulation is carried out, with the same inflow as during the monitoring period, and the same operations at off-takes. Parameters are changed in order to match field observations. The process is repeated until a satisfactory level of accuracy is reached.

With such an approach, non-hydraulically justified operations cannot be reproduced, as the module reacts to changes in upstream water level only. These non justified operations are taken into account by the strategic level (for instance by giving priority to a given distributary).
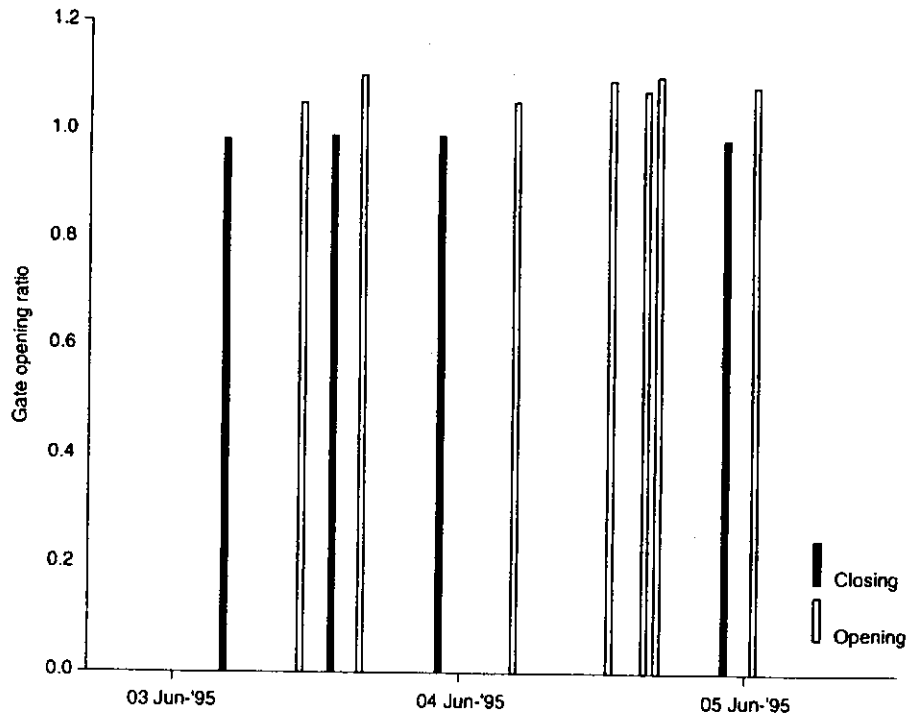
**Figure 3.** Ratios Between Magnitude of Observed and Computed Operations.

As can be seen from the figure, the result given by Gateman is not far away from what an experienced gate keeper does. The discrepancies observed between the output of the model and the measures (ratios larger than 1.5) were mainly due to brutal and unpredicted gate operations, that were not justified by a change in upstream level at a given control point. Other operations were quite well reproduced, allowing the use of the module to simulate manual operations in the usual functioning of the system.

## Improving the Water Distribution

*Alternative Operational Rules at the Strategic Level*
*(based on Kuper et al., 1997; Kuper, 1997)*

Three sets of alternative rules were defined and tested for their impact on the water distribution, using the composite SIC-Gateman model. The aim of these scenarios is to achieve the system objectives of an equitable water distribution, based on the official allowances. The formulated scenarios try to approach the official rules as closely as possible, while taking the system realities into account. The scenarios are presented below.

- Scenario 1: Official rotational plan, whereby all secondary canals receive water whenever the Chishtian Sub-division is in first priority. When in second priority, all secondary canals participate in a pre-defined rotational plan.
- Scenario 2: Four major secondary canals are involved in the rotation, while the small gated secondary canals are open or closed following the major secondary canal. close

15

to which they are located. The target discharges follow the existing management practices.

- Scenario 3: The same rotation as in scenario 3 is adopted. The target discharges are reverted back to the official values.

The results were evaluated with reference to the actual simulated situation, presented in Section 3.1 (Table 1).

The evaluation of the results of Scenario 1 showed that the application of the official rules was not possible for three reasons:

- Even in times of first priority of the Chishtian Sub-division, the inflow is below the target, which means that a rotation among secondary canals is necessary at all times, even when in first priority.
- A rotation involving all secondary canals is impractical, as · small canals with a discharge of less than 1 $m^3 s^{-1}$ cannot absorb the large fluctuations occurring in the Fordwah Branch, often reaching up to 3-5 $m^3 s^{-1}$.
- It is physically very difficult to involve ungated distributaries in a rotation, as it requires the manipulation of wooden planks, bushes, etc.

The results of Scenarios 2 and 3, with reference to the actual (simulated) water distribution is presented in Table 3. The following observations were made:

- It is shown that the inclusion of the small ungated secondary canals in the rotation increases the water delivery to Azim Distributary by almost 30%; a restoration of the official target discharges further improves the situation leading to a combined improvement of 63%.
- The excessive quantities delivered to small gated secondary canals can easily be curtailed; by including, for instance, Mehmud in the rotation, the delivered volume is reduced by 25%, which is reduced by another 30% if the target discharge is reduced to the official value.
- The excessive quantities delivered to ungated secondary canals (5-L, Phogan) cannot be regulated by changing the operational rules; a physical intervention, such as a reduction in off-take dimensions, would be required
- Including the small gated secondary canals in a rotation (scenario 4) has a dramatic impact on the water delivery to these canals (e.g. Jagir, Masood, and Mehmud).

**Table 3.** Simulated Water Deliveries to Secondary Canals of the Chishtian Sub-division, a Comparison of the Application of Official and Actual Rules.

| Secondary Canals | Actual Water Deliveries (Simulated) Volumes in m³ | Scenario 2 Difference % | Scenario 3 Difference % |
|---|---|---|---|
| Daulat | 70138656 | - 2.1 | -26.4 |
| Mohar | 9279360 | -24.2 | +30.2 |
| 3_L | 4847904 | + 8.1 | +14.8 |
| Phogan | 8308224 | + 2.0 | +13.3 |
| Khemgarh | 9400320 | -23.8 | + 1.2 |
| 4-L | 4378752 | + 4.5 | +14.5 |
| Jagir | 10955520 | -25.5 | -24.3 |
| Shahar Farid | 49620816 | - 6.0 | -17.5 |
| Masood | 14485824 | -24.4 | -28.3 |
| Soda | 21532608 | +11.2 | +23.7 |
| 5-L | 2595024 | +16.7 | +31.8 |
| Fordwah | 51054624 | + 1.1 | + 0.1 |
| Mehmud | 6168960 | -25.9 | -55.9 |
| Azim | 45022608 | +29.2 | +63.2 |

Reverting the length of the rotation back to the official rules has a big impact on the average period of constant water delivery to secondary canals, defined as the time period during which the discharge does not go below 70%. This has been detailed as an example for Scenario 3 with reference to the actual (simulated) water deliveries in Table 4. While the average constant delivery period for Daulat is markedly reduced and brought in line with the other major secondary canals, these periods increase substantially in time for Azim Distributary. Shahar Farid and Fordwah Distributaries are much less affected by the length of the rotation time.

**Table 4.** Simulated Delivery Pattern to Four Major Secondary Canals in the Chishtian Subdivision, Comparison Between the Effect of Actual and Official Rules.

|  | Actual Water Deliveries (Simulated) | | Scenario 3 (Simulated) | |
| --- | --- | --- | --- | --- |
|  | Length of delivery period | Number of periods | Length of delivery period | Number of periods |
| Daulat | 15.8 | 9 | 9.1 | 11 |
| Shahar Farid | 9.4 | 14 | 9.0 | 12 |
| Fordwah | 5.3 | 18 | 6.5 | 15 |
| Azim | 3.5 | 26 | 9.9 | 13 |

*Alternative Operational Rules at the Tactical Level*
*(based on Kuper et al., 1994; Litrico, 1995)*

In order to test the effect of alternative operational rules on water distribution, two different approaches were followed, in which different scenarios were tested:

- one using the hydraulic model SIC, comparing an « improved localized control » to a « centralized feedforward control » (Kuper et al., 1994); and
- one using the regulation module Gateman to test alternative operational rules (Litrico, 1995).

The first approach was based on a 10-day monitoring period, where all the regulation points were monitored on hourly bases in June and July 1994. During this relatively stable period, Chishtian was in second preference with reference to two other upstream sub-divisions, going to the third preference after that. Inflow to the sub-division is fairly stable during this period, and the fluctuations are in the range of 5%. Night operations have not been taken into account, which would have increased the total number of operations by 40%.

Two different scenarios were tested *a posteriori* and compared to measurements:

- The first one is a scenario that assumes that the gauge readers remain decision-makers to make gate adjustments to meet the targets. Their decisions are still based on local variables water level upstream, and downstream of cross-regulator and off-taking secondary canals. These decisions could be optimized to demonstrate the potential for improvement. This scenario will be referred to as "improved localised control".
- The second scenario goes away from the present set-up and assumes a tighter control of the system managers on operations in their (sub)-division. Also, it is assumed that managers have an intimate hydraulic knowledge of their system that enables predicting changes in the hydraulic state of the canal when they instruct a change in gate settings at a certain location. This type of control will be referred to as "centralised feed-forward control".

## *Improved Localised Control*

In order to test this type of control, the actual and improved operations at different regulation points are simulated using SIC hydraulic model, and the results are compared. The inflow and outflow scheme is kept as the actual, hence the modifications made for improvements are small adjustments which will bring the current practices of gate keepers closer to the recommended practice:

- Large gate adjustments, which are usually followed by successive corrective changes in gate settings, are avoided (enhanced responsiveness);
- The gates are not operated when the discharge to the offtaking secondary canals is in the range of 85% to 110% of the target (precision of the action);
- Hydraulically unjustified operations are ignored (correctness of the action); and
- Improved rating curves for the discharge measurements are applied (accuracy of the action).

The above mentioned changes are in fact equivalent to the restoration of official management rules.

## *Centralised Feed-forward Control*

This scenario presumes that future targets are known and that the system manager is aware of future perturbations along the canal, like a change at the head of Fordwah canal, or a shift of priority between two tail secondary canals. The manager also knows, because of an intimate hydraulic knowledge of the system, the effect of specific operations and the global water levels and discharges. In industries, this system usually goes hand in hand with a feedback loop, which gives managers direct feedback on the effect of their operations so that adjustments can be made, if necessary. A similar loop can be easily pictured in the case of canal operations where information on water levels and discharges are not difficult to obtain. However, the scenario presented in this section will not take the feedback loop into account, and only the feed-forward loop will be analysed. The analysis was carried out by simulating a ten-day period using SIC model. The following information are assumed to be known:

- The discharges at the head of the system.
- Target discharges to off-taking secondary canals.
- Target upstream water levels for cross-regulators.

A training period to gain understanding of the hydraulic behaviour of the system is simulated by carrying out a steady flow simulation. All required gate settings for cross-regulators and off-taking (gated) secondary canals were computed using an opening computation mode in order to meet the targets. Upstream targeted water levels at cross-regulators were then adjusted, by trial and error to correctly feed off-taking flumes. An operational print of SIC synthesised the results of the steady flow computation, which formed the basis of the unsteady flow simulation for a 10-day period.

In the unsteady flow simulation, all structures are operated once a day. The maximum difference between supplied discharge and indent is around 10%. The results were even improved by taking into account the time lag of the Fordwah branch. The maximum difference between supply discharge and indent is around 10%.

The results of the study can be summarized as follows :

- The number of gate operations increases towards the tail of the system, allowing to say that operators are reacting to upstream gate operations within the Chishtian Sub-division.
- The first scenario showed that it is possible to improve the local operations, keeping local operators to a large extent responsible for the operations at their regulation points.
- The second scenario showed that a more global approach could reduce the number of operations dramatically, while taking away some responsibility from local operators. This option should also be tested with a feedback loop (performed, for instance, by local operators) in order to react to unpredicted disturbances.

The second approach enabled refining and field-testing some of the options proposed in the first one. Using the regulation module Gateman, different scenarios were tested on the hydraulic model SIC. Five typical situations irrigation staff faces, were identified, and five scenarios were simulated for these situations.

a. Effect of local operations on a real inflow.
b. Increase of discharge at the head.
c. Negative step of discharge at the head.
d. Shift of rotation from Daulat Distributary to Azim Distributary.
e. Local maintenance at RD 363.

The five scenarios simulated were

1. Improved operations: use of regulation module Gateman to simulate local operations, eliminating non-hydraulically justified operations.
2. Buffer capacity: use of the buffer capacity of each reach, allowing the upstream level to fluctuate more, in order to reduce the fluctuations at the tail. This scenario needs the gate operators to be informed of the hydraulic state of the canal.
3. Linked operations at the tail: only the two last gate operators are in communication, and can co-ordinate their actions.
4. Feed-forward control: order in terms of time and amplitude of operations are given to the operators.
5. Automated gates: this scenario, although quite far away from present perspectives, is a possibility in the future.

Scenario 1, tested with a real inflow (situation a.), showed that it is possible to reduce the number of operations, and therefore, reduce the fluctuations in the system, even without having any global information (even with some fluctuations due to the unpredicted opening of a distributary upstream).
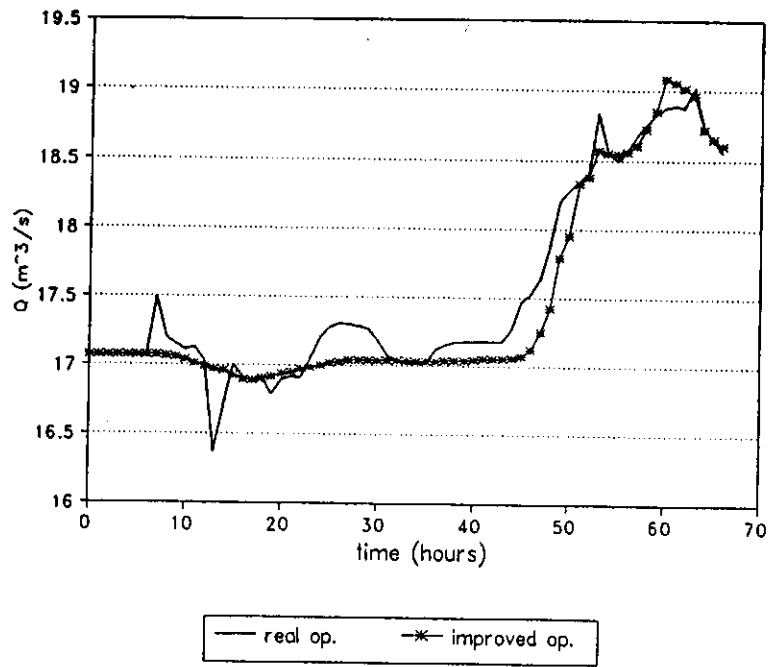
Discharge D/S RD 281
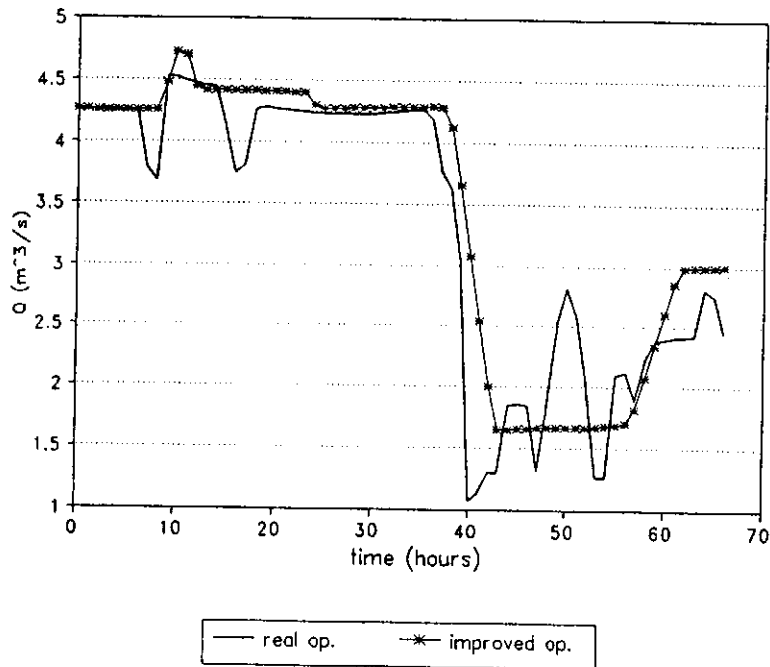


Discharge at Azim disty

**Figure 4.**     Discharge at Azim Distributary, Real Operations Versus Improved operations.

For an increase of discharge at the head (situation b), feed-forward control (Scenario 4) enables the drastic reduction of the number of operations (on average from 10 to 1) compared to improved operations (Scenario 1).



Each block represents the 90h period

**Improved operations**



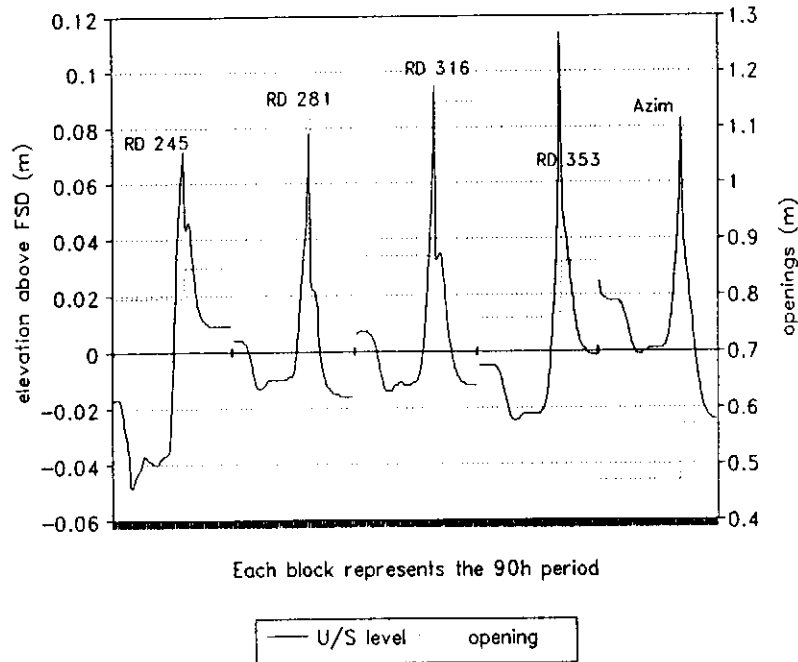Each block represents the 90h period
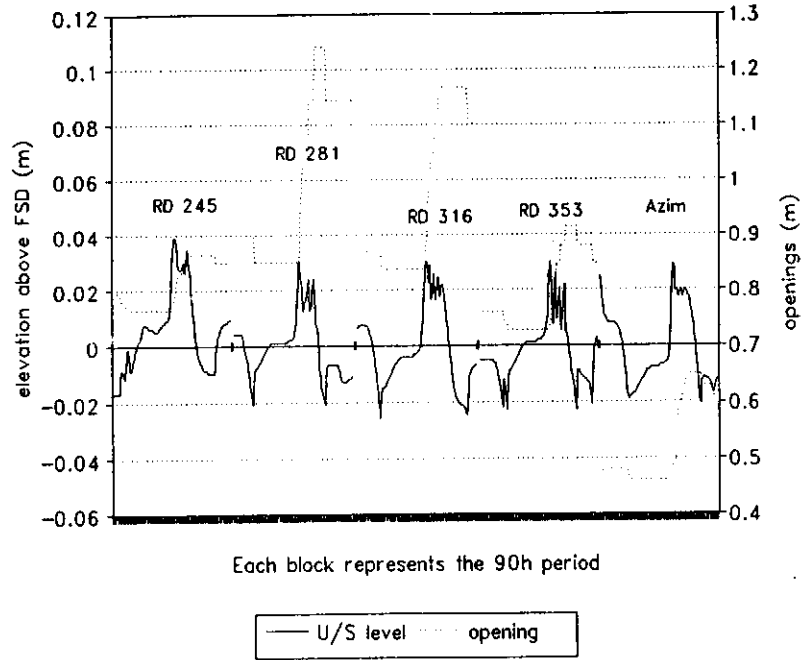
**Figure 5.** Feed forward control.

For a change of rotation from Daulat to Azim (situation d), the number of operations can be reduced up to 18 to 1 (Scenario 1 versus Scenario 4), and can be divided by two, using the buffer capacity of the reaches.

**Table 5.** Number of Operations at Cross-regulators for the Scenarios 1 to 4 (situation d.)

| Regulators | Scenario 1 :<br>Improved operations | Scenario 2 :<br>Buffer capacity | Scenario 3 :<br>Linked operations | Scenario 4 :<br>Feed-forward control |
|---|---|---|---|---|
| RD 245 | 6 | 2 | 6 | 1 |
| RD 281 | 7 | 1 | 6 | 1 |
| RD 316 | 9 | 6 | 8 | 1 |
| RD 353 | 7 | 4 | 4 | 1 |
| RD 371 | 18 | 11 | 10 | 1 |

In summary, the results of the simulations show that:

- the discharge downstream of a regulator can be smoothened by eliminating the operations that are not hydraulically justified;

- it is possible to stabilize the levels and discharge in the canal by passing all the fluctuations to one distributary;

- the introduction of a communication system between gate operators can increase the performance of the system by giving a security margin in case of emergency, and tempering the fluctuations instead of amplifying them;

- on the introduction of an hydraulic model at the manager level, and the implementation of a feedforward command, would have a positive impact on the hydraulic state of the canal, and on the water distribution to secondary canals. This option seems, nonetheless, quite unrealistic, because of all the changes it necessitates in the data collection and evaluation process.

One field test reported (Litrico et al. 1995) was performed on the system during a 4-day period; the canal remained at full supply and in steady flow during more than 36 hours. The gauge readers were given information on the future perturbations coming from upstream, which allowed them to operate much less than usual, and not to amplify little fluctuations, resulting in a steady state for the Chishtian Sub-division of Fordwah Branch. This was achieved using a distributary (Daulat) to take the fluctuations coming from the RD 199, head point of Chishtian Subdivision.

# Conclusions

The operational rules guiding irrigation managers to fix operational targets (strategic level), and gate keepers to manipulate gated structures under their control (tactical level), were analyzed, and their impact on the water distribution determined. Thus, the scope for improvement in water distribution by changing the operational rules, without changing the infrastructure, was determined. The analysis permits us to draw the following conclusions:

- The composite model that was developed, combining the use of a regulation module (Gateman) and a mathematical unsteady state model (SIC), can well represent the official and actual operational rules, and their impact on the water distribution. Simulated deliveries deviated, on average, less than 5% from the observed values for an irrigation season.

- It is possible to improve the water distribution substantially, i.e. better-matched water deliveries with the official objective of *equitable water distribution*, by adapting the operational rules. The changes pertain mainly to changes in the rotational programme and to changes in target discharges (strategic level). However, it is not possible to achieve perfect equitability with the present system constraints, such as the inadequate inflow and the presence of ungated head regulators.

- It is possible to reduce the variability in discharge in the irrigation canals by a better harmonization of the operations of gate keepers substantially (tactical level). By installing a communication network between the different gate keepers, they can be informed of future perturbations, which can then be attenuated by timely operations. At present, these fluctuations are amplified, as gate keepers are reacting to local perturbations with local objectives and local information.

- There is a need for further field work on the implementation of the experiences obtained in this study. In collaboration with PID, a programme could be started targeting the operational rules at the strategic, as well as the tactical levels. The program should consist of the installation of a communication network, and of a monitoring and evaluation component, to verify the improvements in the water distribution. The costs of such a program would be rather low, as the main emphasis is on management practices.

# References

Bandaragoda D.J. and S. Rehman. 1995. Warabandi in Pakistan Canal Irrigation: Widening Gap Between Theory and Practice. Country paper no.7. International Irrigation Management Institute, Colombo, Sri Lanka.

Bhutta M.N. and E.J. VanderVelde. 1992. Equity of Water Distribution Along Secondary Canals in the Punjab, Pakistan. Irrigation and Drainage Systems, vol. 6, no. 2: 161-177

Cemagref. 1992. Simulation of Irrigation Canals: User's Guide and Theoretical Concepts. Cemagref, Montpellier, France.

Habib Z. and M. Kuper. 1996. Performance Assessment of the Water Distribution in the Chishtian Sub-division at the Main Canal Level. Proceedings of the National Conference on Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan, Islamabad, Pakistan.

Hart W.W.H. 1996. Research into the Relationship between Maintenance and Water Distribution at the Secondary Canal Level in the Punjab. M.Sc. Thesis, University of Technology Delft, The Netherlands.

IIMI. 1995. Field Calibration of Irrigation Structures. Technical Report. International Irrigation Management Institute, Lahore, Pakistan.

Kuper M. and J.W. Kijne. 1993. Irrigation Management in the Fordwah Branch Command Area, South-east Punjab. In: Advancements in IIMI's Research 1992, Colombo, Sri Lanka.

Kuper M., Habib Z. and P.O. Malaterre. August 1994. System Objectives and Localised Control: Adequacy versus Equity. Paper presented at the Internal Program Review, International Irrigation Management Institute, Colombo, Sri Lanka.

Kuper M., Litrico X. and Z. Habib. 1997. Analyzing the Impact of Alternative Operational Rules on Water Distribution. Proceedings of the International Conference on the Regulation of Irrigation Canals, Marrakech, Morocco.

Kuper M. 1997. Irrigation Management Strategies for Improved Salinity and Sodicity Control. Published Ph.D. Thesis, Wageningen Agricultural University, The Netherlands.

Litrico X. 1995. Alternative Scenarios for Improved Operations at the Main Canal Level: A Study of Fordwah Branch, Chishtian Sub-division Using a Mathematical Flow Simulation Model. MSc Thesis, Ecole Nationale du Génie Rural, des Eaux et des Forêts, Montpellier, France.

Litrico X., Khan M.A., Rashid M. and S. Ashgar. 1995. Report on the Field Test Performed on Fordwah Branch, Chishtian Sub-division, Bahawalnagar, Pakistan.

Malaterre P.O. 1989. Etude des Possibilités d'Amélioration des Règles de Gestion Manuelles du Canal Principal Rive Droite du Kirindi Oya grâce à un Modèle Mathématique de Simulation des Ecoulements. M.Sc. Thesis Ecole Nationale du Génie Rural, des Eaux et des Forêts, Montpellier, France.

Malaterre P.O. and J.P. Baume. 1997. SIC 3.0, A Simulation Model for Canal Automation Design. Proceedings of the International Conference on the Regulation of Irrigation Canals, Marrakech, Morocco.

Nespak/SGI. 1991. Contribution of Private Tubewells in the Development of Water Potential. Ministry of Planning and Development, Government of Pakistan, Islamabad, Pakistan.

Public Works Department. 1961. A Manual of Irrigation Practice. Government of West Pakistan, Lahore.

Varma B.P. 1917. Canal Outlets. Punjab Engineering Congress, Lahore.

Visser S. 1996. Canal Water Distribution at the Secondary Level in the Punjab, Pakistan. M.Sc. Thesis, University of Technology, Delft, The Netherlands.

Waterhouse J.O. 1918. The Distribution of Canal Water with Special Reference to Outlets. Punjab Engineering Congress, Lahore.

# IMPROVING SEDIMENT MANAGEMENT IN IRRIGATION CANALS OF PAKISTAN

Gilles Belaud, Alexandre Vabre, Pierre-Olivier Malaterre and Ghulam Nabi

## Abstract

This paper presents the joint research program developed by IIMI, ISRIP and Cemagref on the control of sedimentation in irrigation systems of Pakistan. At present, empirical methods are used to design and manage the irrigation systems as far as sediments are concerned. Since 1995, the three research institutes have investigated the possibilities of simulating sedimentation in the channels with two different approaches, systemic and mechanistic, and to propose guidelines for the control of the sedimentation process.

## Introduction

In the early years of the irrigation system, the British engineers were already faced with sediment transport problems. They started to establish empirical laws for the design of stable channels in the late 19th century, such as the famous formulae proposed by Lacey in 1936. These empirical laws are still utilized today for the design of new channels. Known as the *regime theory*, these laws give an unique stable profile for a given water slope (the natural ground slope in fact), sediment size and water discharge. Their application, however, remains limited to average concentrations inflowing into the canal below 500 ppm. Many channels have shown the validity of this empirical approach. Many others, however, have silted up to critical levels showing its limitations. In fact, the conditions under which the irrigation canals are operated are at variance with design conditions: the sediment concentration is often higher than the proposed 500 ppm limit ; the discharge is (in some systems) lower than the expected design discharge; and, the flow is far from uniform

Sedimentation is a slow process, but still large amounts of sand can be deposited within one season. In the Sindh Province, for instance, many distributaries silt up up to 30% of their design depth during the rainy season, when the run-off of the Indus Basin carries large quantities of sand, silt and clay. Obviously, these topographical changes largely affect the water distribution in the system. Farmers at the heads of the canals receive more water due to the rise of the water level in front of their outlet, penalizing tail enders. Desilting is needed whenever a few inches are deposited in a reach (at least in distributaries and minors), but the available funds and machines are generally insufficient to undertake required maintenance activities. Maintenance is also difficult on larger channels (main canals or link canals), and can only be scheduled exceptionally. The example of the Marala Ravi Link Canal, currently redesigned by Halcrow (UK) and Delft Hydraulics, provides a good illustration of the magnitude of the problem; this canal has lost one third of its conveyance capacity due to siltation.

H 22403

The present research program, initiated in 1995, aims at improving the methods used to investigate sedimentation issues. The main questions that are addressed by researchers are:

- Can we improve the design of the canal systems?
- Can we improve/optimize the maintenance of the canals and make it more sustainable?
- Can we minimize the deposition of sediments by modifying the operation of the irrigation system?

The first step of the research is a literature review to understand the sedimentation problem and the physical concepts attached to sedimentation. The second step includes data analysis and model development activities. Data collection has already been done in several large channels in Pakistan, and a sediment transport model has been developed and calibrated. Similar activities (field observations, management practices, measurement campaigns) are also undertaken for smaller canals and area still underway. Two different approaches are then tested:

- A *small scale approach*: sediment transport is modeled with mechanistic models similar to the Simulation of Irrigation Canal (SIC) model and its sediment module SEDI developed by Cemagref;
- A *systemic approach*: a global description and modeling of the sediment deposition areas on the system is undertaken, using information collected through a tracer campaign to monitor the spatial and temporal dynamic as well as distribution of a labeled sample of sediments within a given irrigation system.

The third step of the methodology is the application of the calibrated models to the analysis of the design, operation and maintenance of irrigation canals.

The main output of the research activities will include:

- Computer software for each of the approaches (small-scale, systemic), calibrated and validated under actual conditions;
- Guidelines for the analysis of sedimentation issues in irrigation canals, in terms of data collection protocol and the use of the computer software;
- Guidelines on how to integrate sedimentation issues to improve the design, maintenance and operation of irrigation canals in Pakistan.

It is important to stress that the three research partners do not aim at building new sediment transport theories, but wish to investigate and adapt existing theories to the particular case of irrigation canals. Eventually, the primary goal is to improve the management of irrigation canals faced with siltation problems.

The following sections of the paper will summarize, in more details the activities undertaken and results obtained so far. The paper will then describe planned activities from period 1998 onwards specifying the expected output.

Next >>

# Preliminary Studies

## Literature Review

The problem of the design of stable alluvial canals (section parameters and slope) has been the subject of a wide range of research works since the beginning of the century, and still continues to be explored by different research institutes. The two main concepts for the resolution of the design problem are the *regime method* which was basically developed in the plains of the Indus and Ganges rivers and the *rational method* which was developed in Europe and America. Both of these methods are still under development. The first approach (*regime method*) considers the three components (the fluid, its sediments and the alluvial periphery) as a single whole, while the second one (*rational method*) assesses the independent dynamics through behavioral laws. The regime method is not going to be dealt with in the present paper, and only selected projects related to the rational method are presented. In 1986, a study to establish the hydraulic design criteria for irrigation systems in Pakistan was carried out by the Delft Hydraulics Laboratory under the Irrigation System Rehabilitation Project (ISRP), using the Alluvial Channel Observation Program (ACOP, formerly ISRIP) data. A set of hydraulic and sedimentologic laws have been selected to represent the phenomenons. Later, in 1992, under the Alluvial Channel Redesign Project (ACRP), the *tractive force method* (DuBoys 1879) was tested. The main conclusion of the project was to reject this method as an unreliable alternative tool to design or redesign canals of Pakistan.

## Physical Analysis

The preliminary work entails in analyzing channels affected by sedimentation. This work has been undertaken for the Chashma Right Bank Canal (CRBC), a large irrigation canal shared by the North-West Frontier Province (NWFP) and the Punjab, and also for the Chashma Jhelum Link Canal (CJ Link) in the Punjab, Pakistan's biggest manmade channel, with a conveyance capacity of 21,700 cusecs. Both canals off-take from the Indus River at the Chashma Barrage. To illustrate the importance of issues related to sedimentation in these canals, Figure 1 presents: a) the water and sediment inflow during 1990 (ISRIP and WAPDA measurements), and b) the bed evolution of the CRBC between 1987 and 1993 (4 m of deposition in the downstream part).
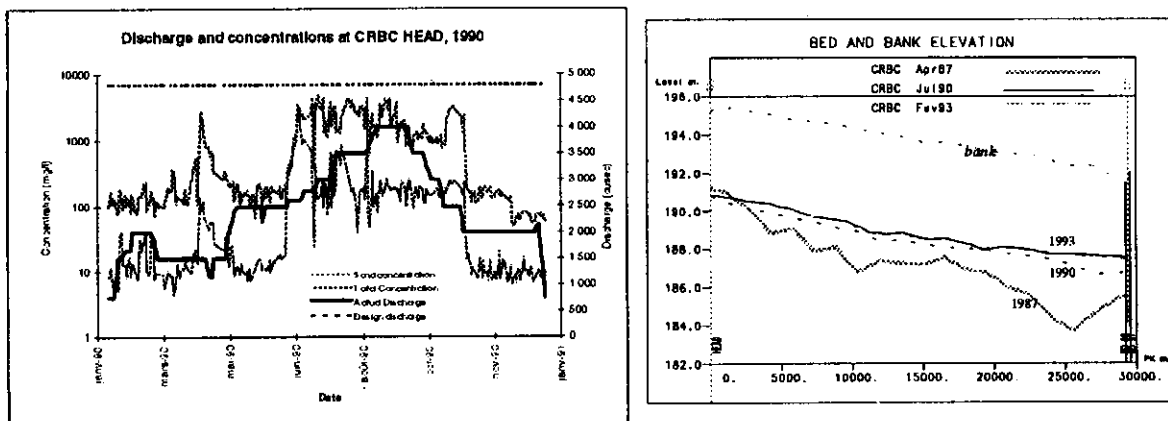


**Figure 1. a) CRBC water and sediment inflow.**          b) Bed variations between 1987 and 1993.

Bed samples were also collected by ISRIP for the CRBC. The medium diameter of the particles is around 100μm (fine sand), except in the downstream portion, where silt and clay (cohesive particles) were also found. The canal was built with very high banks in order to have low velocities, favoring sedimentation of fine particles in order to reduce seepage losses. As depicted in Figure 1.a, the actual discharge is also much lower than the design discharge, whereas the water level is maintained at a high level at the cross regulator. This channel behaves like a settling basin. For the CJ Link, the problem is the opposite. The major phenomenon that takes place along this canal, is erosion that affects the stability of the canal.

The following paragraph presents the mechanistic model that has been developed and tested on these two canals.

*Basic Theoretical Concepts*

The purpose of the mechanistic model is to simulate the sedimentation process in a channel after a given period (one season, one year, several years...). The model combines the hydraulic mode SIC (Simulation of Irrigation Canal) developed by Cemagref and a specific module SEDI that simulate the sedimentation process. The input data of the model are:
- the sediment characteristics and their concentration;
- the initial topography of the channel; and
- parameters that describe the hydraulic behavior of the channel.

We assume that the time period investigated can be well represented by a succession of periods with steady flows. The relevant duration of each steady flow may vary, from a few weeks when the variations of discharges in the canal are low, to a few days when the variations are high. For each steady flow period, the hydraulic quantities are first calculated, then the sedimentologic quantities are estimated. These quantities are then used to update the geometry of the canal before the model computations for the following steady flow period. The hydraulic model is not presented below (to refer to the manual of the SIC software), and a brief description of the sedimentologic computation only, is given below.

Even though sediment transport is generally badly modeled (a good concentrations prediction is accurate within the range 0.5-2 times the measured values), most of the authors use the concept of *equilibrium concentration*, which is the maximum volumetric quantity of sediments that the flow can carry. This equilibrium concentration is highly dependent on the velocity, the flow depth and therefore, the discharge, the water slope, etc. These variables may differ substantially in an irrigation canal due to the presence of off-takes: the water discharge is decreasing from upstream to downstream, the section shape also varies, the water slope may also vary due to regulation, or natural, variations of topography. Moreover, the sediment inflow has no reason to be equal to the equilibrium concentration.

When the sediment concentration in the channel is higher (lower) than the equilibrium, it will decrease (increase) in order to evolve towards the equilibrium value. We use a *loading law* to predict the actual changes over time of the sediment concentration, as illustrated in Figure 2.
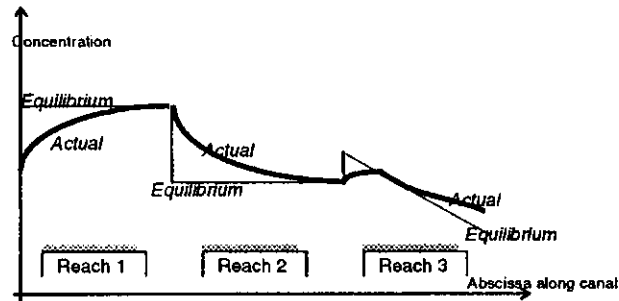
**Figure 2.** Changes Over Time of the Actual Sediment Concentrations in an Irrigation Canal.

A decrease of the sediment concentration from the upstream to the downstream portion of a given reach involves deposition, the quantity of which is calculated from the mass balance equation. Usually, this concept does not apply to finer particles (silt and clay, finer than 62μm) which are known as *wash load* or *self-suspended*, as these particles are transported without any limitation. These particles are indeed in a very low quantity in the bed, meaning they have not deposited, and are not available for scouring. This concept is criticized for irrigation canals as silt and clay can be found in the bed, at least at the tail section of the canals, where the velocity can be very low. In fact, further research is required to understand situations with finer particles better.

*Tests on Actual Systems*

The tests consist of:

- Testing different behavioral laws for the calculation of the sediment deposition;
- Calibrating these laws in order to have the best description of the bed evolutions for a given time period;
- Simulating the sedimentation process for other time periods with the same parameters; and
- Calculating the error of prediction between simulated and measured topographies for these periods.

Each simulation can be described by the following diagram:
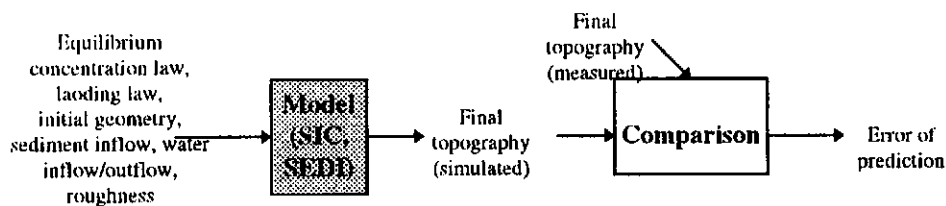


When the model is being calibrated, iterations are done in order to refine the parameters and minimize the error of prediction.

30

These tests have been carried out for three periods of about 2 years each for the CRBC, and for two periods of about 1 year each for the CJ Link canal. A set of six equilibrium laws have been tested.

Figure 3 depicts the bed variations obtained after calibration for a given law of the SEDI module on the CRBC for the 1987-1989 period (left), and obtained for the validation for the 1989-1990 period (right). We can see that both, calibration and validation, give similar results. The error of prediction (percentage of error between deposited volumes within the reach considered) remains quite low, but can be much higher in some cases, even though the zones of deposition and erosion are generally well simulated.
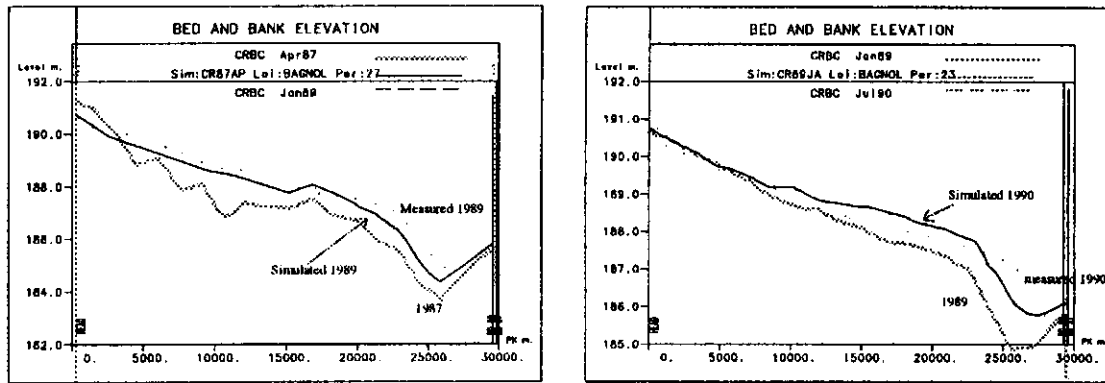


**Figure 3.**     Calibration and Validation of the SEDI Module - Presentation of the Bed Elevation Estimates.

*Application to Irrigation Management*

For the application of the mechanistic models to the management of irrigation canals, a set of schematic irrigation case studies (3) has been chosen. Methodologies for the analysis of issues related to the design, the operation and the maintenance of canals were then developed and tested for the schematic case studies using of the mechanistic models. A preliminary application was then carried out for design and maintenance issues, using a real irrigation canal and its actual conditions.

**Example 1.** Design

The tested scenarios allowed an assessment of the equilibrium bed slope obtained after a given time period of canal operation, to estimate the volumes of sediments deposited in the different reaches, and to evaluate the time duration required to achieve the equilibrium conditions.

An application has been carried out for the Chashma Right Bank Canal (CRBC). The comparison between the model results and those obtained using the Lacey formula, shows that under the Lacey conditions of water flow and maximum discharge ($Q_{max}$) at the head of the canal the year long, the mechanistic model predict an equivalent equilibrium topography for the canal. However, under the actual conditions of water discharge in the canal, varying along the year from 40% of $Q_{max}$ to 100% of $Q_{max}$, the canal silted up by 1 m more than predicted by the Lacey formula. The results of the simulations are presented in Figure 4.
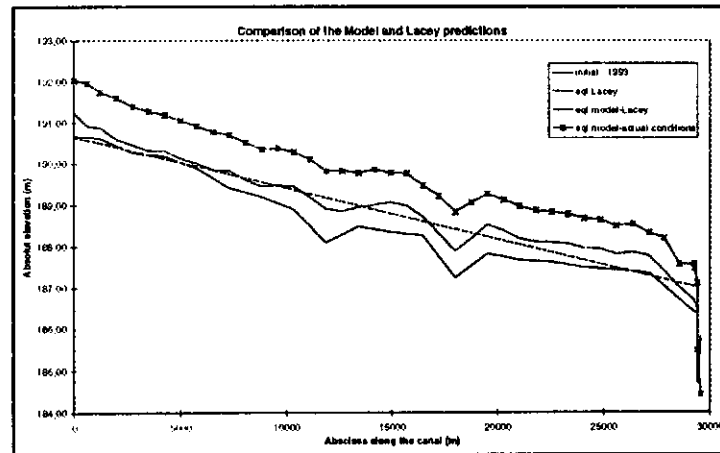


**Figure 4.** Results of Simulation Used for the Analysis of Design Criteria.

**Example 2.** Operation

The tested scenarios for the operations were based on the influence of the modification of the operational modes on the rate and quantity of sedimentation for the case studies. The main idea was to change operational practices (for example the water level upstream from a cross regulator) with a varying hydrology entering the irrigation system, in order to maintain a constant flow velocity in the different reaches of the canal.

Observations yielded that the rate of sedimentation is much higher if the regulated water level is following the actual discharge variations, than when under a constant regulated water level (corresponding to the maximum discharge), as currently performed by the operating agencies managing the canal studied (CRBC).

**Example 3.** Maintenance

Three maintenance scenarios were tested for the schematic cases of irrigation canals.
- *linear excavation*; excavating the whole canal on a constant thickness function of the excavated sediment volume for a given period;
- *rotated excavation*; excavating a portion of the canal on a constant thickness function of the excavated sediment volume for a given period, with maintenance work frequency depending on the size of the maintained portion of the canal; and

- *located excavation*; in excavating a portion of the canal on a constant thickness function of the excavated sediment volume for a given period, with maintenance work consisting of clearing this area from the deposited sediments at a given frequency in order to maintain a free volume, followed by a sediment trap in the upstream portion of the reach.

The third solution has provided the best results in terms of maintaining an acceptable bed level in the canal.

*Conclusions and Lessons for Follow-up*

This preliminary work on the two study cases was quite encouraging even though no firm set of laws and associated parameters were eventually proposed. The first basis of a mechanistic model has been established, and guidelines to use it have been defined. Nevertheless, only two canals have been analyzed, one link canal and one main canal (with no off-take in the studied portions). These systems have given good indications on the sediment behavior within an homogeneous reach, but the diversion component should be introduced in the second stage of the study; some branches and distributaries suffer more from siltation than others, because they draw more silt at their off-takes.

## Towards an Operational Tool

In order to move on from methodologies and tools development to operationalization, the identification of an irrigation system faced with sedimentation problems is important. The physical phenomena, as well as current management practices have to be analyzed. The Jamrao Canal system has been selected for this stage of the research, as it is one of Pakistan's most problematic channels with regards to sediment deposition (8 to 9 feet since its construction in 1932). IIMI and ISRIP are already undertaking research activities in this system as part of the Left-Bank Outfall Drain Project. Sediment data are already available, and have been complemented by a specific measurement campaign that took place during the last monsoon season.

*Field Analysis*

The 1997 campaign intended to study the physical phenomena of sediment transport in small canals, to quantify the bed evolutions during a high concentration period for these canals, and to estimate the sediment drawing capacity of their outlets. This campaign also served as a test for data collection methodologies before selecting a larger system. The sub-system, in the Mirpurkhas Sub-division (Sindh Province), consists of the Sangro Distributary (design capacity of 105 cusecs), one of IIMI's pilot distributaries of the Decision Support System project (DSS), and two of this distributary's minors, as depicted in Figure 5.
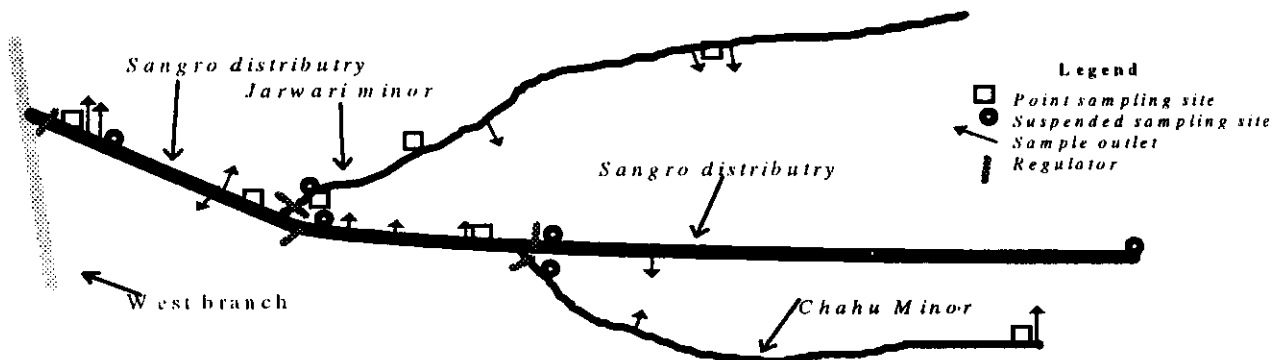
**Figure 5:** Sketch of the Sub-system and Measurement Points.

The campaign lasted 10 weeks, from July 1997 to September 1997. The main data collected include:

- initial and final topographies of the system;
- hydraulic data; off-take calibration, rating curves, regulator calibration; hydraulic measurements have already been done by the DSS research team; and
- Sediment data: 500 have been collected in the field and are being analyzed in ISRIP laboratory.

The sediment data consist of:

- Suspended sampling at six locations in the system, by equal transit rate (ETR) method, measuring the suspended sediment discharge in a channel;
- suspended sampling downstream from 14 selected outlets in the same time as « boiled » sampling in these outlets;
- pump sampling, in order to establish vertical profiles of concentration and understand the diversion process; and
- bed sampling throughout the system, in order to characterize the deposited particles.

All the field work was undertaken by an ISRIP team in collaboration with IIMI and CEMAGREF engineers, who benefited from the 24-year-old field experience of ISRIP. An advantage for ISRIP, is that, for them, this had been the first campaign of its kind. The three institutes have expressed the wish to work together again, less intensively, but for longer time periods. ISRIP, under the LBOD project, will continue collecting suspended samples at the head of the distributary every two weeks until the annual closure of 1998, during which time another topography of the sub-system selected for the study will be taken.

The proposal for the 1998 campaign will be finalized after completion of the analysis of the data already collected. This campaign should focus on a larger part of the system; a portion of the main canal, with its branches, distributaries and minors should be studied. As in 1997, the objectives of the field activities will be multiple.

- Understanding the sedimentation process within the reach selected;
- Understanding the distribution of sediments within the system, and therefore understanding the behavior of the canal off-takes; and
- Calibrating and validating the simulation tools developed for the irrigation system considered.

Since sedimentation is a slow process, the duration of the campaign should be long enough to observe significant bed variations (February to December 1998). Topographies should be taken four times, i.e. at the beginning of the campaign, once before the monsoon season, once after the monsoon period, and one at the end of the campaign. Sediment concentrations should be taken at the head of the system weekly, and also at key locations: downstream diversions, tails of the system. Hydraulic measurements will be undertaken to establish the rating curves of various hydraulic structures. Specific measurements will be taken with nuclear tracers in collaboration with the French research institute, Centre de l'Energie Atomique (CEA), techniques. These techniques should facilitate the cartography of the deposition of labeled sediments in the system during relatively short periods of time.

## *Mechanistic Model*

The mechanistic model SEDI developed in 1997 will be refined, thanks to the experience acquired on the sub-system during the 1997 campaign, and also on the larger system selected for the 1998 campaign. The transient effects will be analyzed in order to validate the approach by successions of steady flows. The modeling of fine sediment transport will be further investigated, particularly to take into account the deposition dynamics at the tail-end of the irrigation canal.

The sharing of sediment through off-takes will also be included in the model. In a first stage, an empirical approach will be adopted. At the same time, a three-dimensional model will be tested on different configurations of outlets in collaboration with the University of Lyon (France). The idea is to keep simple laws for the sharing of the sediments passing through the canal off-takes, but to validate these laws using complex numerical resolution methods.

The data collected in 1996, 1997 and 1998 should facilitate the calibratation and validation of the model for the different scales considered (main canal, distributary, minor), and for each kind of singularity encountered in the system. Eventually, a methodology to collect data, to calibrate and use the mechanistic model, and to assess its accuracy, will be proposed.

## *Systemic Model*

The main objective of this approach is to answer the following questions;

- How a given mass of sediments that enters into the irrigation system during a given period of time is distributed within the system; and

- What the required time period to achieve the equilibrium conditions for the sediment transfer processes is.

The latter question may be diagnoed through the analysis of changes over time of the physical conditions of the system during a long period of canal functioning. In order to evaluate the present sediment processes in the system, a field campaign using nuclear tracers has been jointly designed with CEA. This campaign includes in labeling a sample of sediments (with a chosen distribution size and density), injecting this sample at the head of the system (methodology still to be defined), and collecting samples of the deposited particles all over the system, in order to locate the labeled ones. Drawing a map of the tracer deposition within the system at each collecting moment is then possible, as well as in the equilibrium conditions (when the measure is stable at each collecting point).

The following step of the approach is to build and validate of tool synthesizing the elements of sediment distribution within the irrigation system. This tool may have two principal applications for the irrigation manager:

- to obtain an adequate knowledge of the physical parameters that rule the sediment transport processes in different constitutive elements of the system, and then to propose new operational modes and assess their impact on sediment deposits; and
- to identify the elements of the system that lead to excessive deposition problems, and then to plan adequate maintenance programs to remove/limit the excess of sediment deposition.

## Application to Management

*Design*

For the design of new systems, the hydraulic management, as well as the topography of the command area are imposed. Designing a system requires the design of each reach and each off-take, a process that can be supported by the mechanistic approach described above.

Designing a reach with the model should be consistent with Lacey's empirical rules if the conditions of application are the same. When actual conditions are applied, Lacey's rules may no longer be valid, therefore, the mechanistic approach should bring more satisfactory responses. The small channels (distributaries or tail-ends of canals) have a much smaller sediment transport capacity, which is not taken into account with Lacey. Then the off-takes should be designed for given targeted silt drawing capacities, calculated from empirical or three-dimensional approaches.

At last, a global methodology will be proposed on a schematic system, including big and small channels. Whereas, current systems are designed according to the equi-distribution of sediments, it may be more appropriate to draw more silts at the head outlets in order to decrease the concentration in the parent canal proportionally to its sediment transport capacity.

*Operation*

The operation of the canals may influence the deposition of sediments in the irrigation system. For instance, high water levels at the cross-regulators reduce the flow velocity and the turbulence. Therefore, sediments can settle more easily. Different operation scenarios will be simulated with the mechanistic approach. The effects of these scenarios on the sedimentation process should be quantified with sufficient accuracy in order to provide guidelines to a canal manager. Methodologies to find an optimal management strategy will also be developed and tested under real field situations.

The systemic should provide a good knowledge of the operational and physical parameters of the system to the manager, used as input to modify both, the canal operation and the distribution of sediments.

*Maintenance*

When changes in operation activities are insufficient to meet the targeted water allocation, specific maintenance activities are required. The effects of maintenance have already been studied by IIMI in (4). The feasibility of maintenance modeling with SIC has also been studied (5) and scenarios of maintenance have been, and will be, simulated by IIMI to implement of the Decision Support System research activities in the Punjab (planning of maintenance expenditures). The same scenarios will be run with the mechanistic model, then applied to the system in the Sindh Province. Guidelines for maintenance strategies will be provided.

The systemic approach and model should allow the manager to identify the main constraints in his system, quantify the impact of these constraints on the sedimentation process, and plan maintenance schedules accordingly.

# Conclusion

The preliminary studies have shown encouraging results for the two study cases undertaken in the CRBC and Sindh areas. This year, larger data sets have been collected on different main canals and link canals (ISRIP observations), and on the Jamrao Canal system. Since the measurement campaign of 1997, IIMI and CEMAGREF have also gained a field experience on the monitoring of sedimentation processes for distributaries, and a better knowledge of the physical phenomena and measurement methods. These data will not be sufficient to achieve the calibration and validation of simulation tools. This will be done after the 1998 campaign that will focus on a larger canal than the one analyzed and monitored so far.

## Acknowledgements

## Bibliography

*Useful References*
1- Yalin. 1992. *River Mechanics*, Pergamon Press
2- Pochat, R. *Cours d'Hydraulique Générale* (in French), ENGREF 91-93.
3- Punjab Irrigation and Power Department. 1989. *Workshop on Sediment Measurement and Control, and Design of Irrigation Canals*. HR Wallingford, UK.
4- Lawrence P. 1993. *Deposition of Fine Sediments in Irrigation Canals*. ICID, Den Haag, Q44R105.

*Preliminary Output of the IIMI-ISRIP-Cemagref Collaboration*
1- Vabre, A. 1995. *Suspended Sediment Transport Modeling in Irrigation Canal of Pakistan*. Cemagref 1996.
2- Khan, H. 1996. *Development of Sediment Transport Technology in Pakistan. An Annotated Bibliography*. IIMI blue report R-11.
3- Vabre, A. 1996. *Methodologies for Design, Operation and Maintenance of Irrigation Canals Subject to Sediment Problems: Application to Pakistan*. M.Sc. Thesis, IIMI blue report R-13.
4- Belaud, G. 1996. *Modeling of Sediment Transport in Irrigation Canals of Pakistan: Examples of Application*. M.Sc. Thesis, IIMI blue report R-12.
5- Hart, W. 1996. *Research into the Relationship Between Maintenance and Water Distribution at the Distributary Level in Punjab*. M.Sc. Thesis Techincal University, Delft.

# USE OF SATELLITE IMAGERY FOR LAND USE MAPPING AND CROP IDENTIFICATION IN IRRIGATION SYSTEMS IN PAKISTAN

Yann Chemin, Abdul Rauf and Salman Asif

## Abstract

The size of the irrigation system in Pakistan makes monitoring a difficult process by traditional methods, like the extensive surveys usually conducted in the past. In this context, satellite remote sensing may be an effective way to obtain information on a wide area basis for monitoring and evaluation purposes. The present paper focuses on the use of satellite imagery for land use mapping and crop identification in large irrigation systems in Pakistan. Based on land use mapping and crop identification experiences developed in other countries, a methodology is developed and applied in one irrigation system located in South-Punjab. The results of this application are presented and discussed in this paper to identify existing limitations in the methodology. Based on the lessons from this first application, a follow-up activity is proposed to be undertaken in the command area of the Fordwah/Eastern Sadiqia (South) Irrigation and Drainage project.

## Introduction

With more than 16 million hectares of irrigated land, the Indus Basin Irrigation System represents the largest contiguous irrigation system in the world. The system includes 3 major reservoirs, 43 main canals, 12 link canals (bringing water from the Western to the Eastern part of the country), and a large number of secondary canals, or *distributaries,* that distribute surface water to more than 89,000 tertiary canals, or *watercourses.* Although the size of the system is in itself an authentic achievement of British and Pakistani engineers, it may be one of the reasons that explains the difficulties in tackling current problems encountered in the Indus Basin irrigation system, such as poor canal water system performance, waterlogging and salinity (World Bank, 1994).

The size of the Indus Basin irrigation system also makes it difficult to assess the magnitude of these problems. In the past, large surveys have been undertaken to collect information on physical and economic variables for planning and monitoring purposes[1]. However, these surveys (and the information they produce) are difficult to manage in a given period of time, and cannot be repeated at regular time intervals. Also, sample sizes are often too small to estimate these

---

[1] See, for example, the large surveys undertaken by the Master Planning & Review Division of the Water & Power Development Authority in 1976-77 to prepare the Revised Action Program for Irrigated Agriculture.

# ꝑ aaꝐ0Ꝑ

variables with good accuracy. In this context, satellite imagery may be an effective way to obtain information for large areas of the irrigation system, whether for planning purposes, appraisal, monitoring, and evaluation of irrigation and drainage projects. However, so far, in Pakistan, little has been done to assess the potential for satellite imagery in irrigation management.

## Objectives of the Paper

The present paper focuses on the use of satellite imagery for land use mapping and crop identification in large irrigation systems. The main objectives of the paper are:
- To describe the methodology developed and applied to use satellite imagery for land use mapping and crop identification;
- To present the results of this application in one irrigation system and for one season;
- To identify the limitations of the methodology applied so far; and
- To propose improvements for follow-up activities to be undertaken in another irrigation system.

The research is undertaken in the Chishtian Sub-division of the Fordwah Branch irrigation system, South-Punjab, Pakistan, and is part of the collaboration between the International Irrigation Management Institute (IIMI), Watercourse Monitoring and Evaluation Directorate of WAPDA, and the French research institute, Cemagref. This irrigation system of around 70,000 hectares of Cultivable Command Area (CCA) lies on the left bank of the Sutlej River, and is boarded by the Cholistan Desert to the South, and by the Indian Border to the East. The climate is semi-arid, with a large deficit between the annual rainfall of 260 mm, and the annual evaporation of 2,400 mm.

The main source of irrigation water is surface water distributed to farmers through a network of 14 distributaries and 510 watercourses. Groundwater resources pumped by more than 4,500 tubewells complement canal water. These tubewells have been installed by farmers to compensate for canal water supply inadequacy and unreliability. The main crops cultivated in the area are cotton, rice, sugarcane and fodder during the *Kharif* (or summer) season; and, wheat, sugarcane (annual) and fodder during the *Rabi* (or winter) season[2].

## Methodology for Land Use Mapping and Crop Classification

The different steps of the methodology used for land use mapping and crop classification are summarized in Figure 1. Supervised classification techniques are used for this classification, using maximum likelihood decision rules. The methodology is applied for the *Kharif* 1994 season and the *Rabi* 1994-95 season, using SPOT XS images acquired in October 1994 and March 1995 with a 20x20m spatial resolution[3]. These images are geo-referenced and projected

---

2      For more information on the Chishtian Sub-division, see Kuper and Strosser (1992).

3      Financial constraints have limited the number of satellite images available for the study to one image per season.

with the Lambert Conformal Conic projection system. Ground truth is based on land use data at the field, or *Killa*, level[4]. Two crop surveys were undertaken in September and October 1994 (*Kharif* season) and in February 1995 (*Rabi* season), for all the fields of 31 well-scattered sample watercourse command areas (approximately 6 percent of the total command area of the Chishtian Sub-division).

Specific manipulations are undertaken on the ground truth data prior the classification procedure. *Killa* layout grids are created for each sample watercourse and geo-referenced, using a Geographic Information System (GIS). Then, crop information is attached to this coverage.

Fields/*killas* further sub-divided into sub-units with different crops (totally 40 percent of the total number of fields surveyed) are eliminated at this stage, as it is not possible to spatially reference these sub-units, nor to use them in the following steps of the analysis.
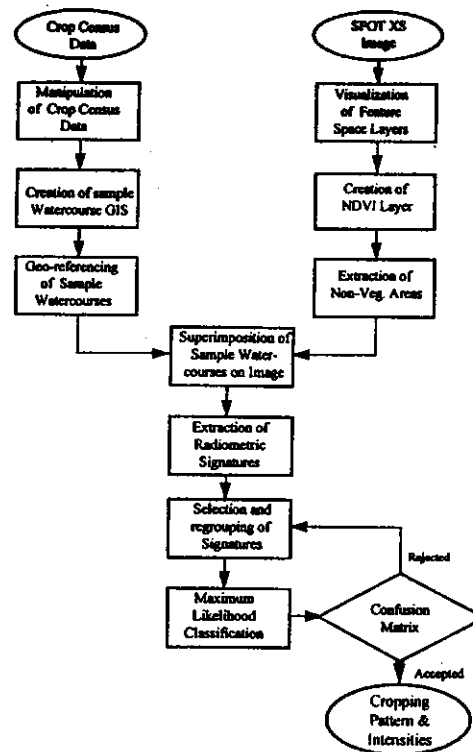


**Figure 1.** Different Steps of the Methodology for Land use Mapping and Crop Identification.

The next step includes the calculation of the Normalized Differential Vegetation Index (NDVI)[5] for each pixel of the image. The classification will be carried out with the original bands XS1 and XS3 of SPOT, along with the computed NDVI[6].

The superimposition of the *Killa* layout grid developed for the sample watercourses and the satellite image allows the extraction of the radiometric signature for the sample fields. This

---

4    Most of the command area of the Indus Basin irrigation system in Pakistan is sub-divided into a regular grid of fields, or *killas* (basic unit of 60 m x 67 m), squares (25 *killas*) and blocks (16 squares).

5    NDVI is obtained from the signature of the bands XS2 and XS3, as expressed by the following formula: NDVI = (XS3-XS2)/(XS3+XS2)

6    The band XS2 is not used in the classification procedure, as it is strongly correlated to the band XS1.

signature contains statistical information for each polygon (field or group of fields with the same crop) such as the number of pixel, the average values and standard deviations of the radiometric response for XS1, XS3 and NDVI.

The most homogeneous polygons (i.e. with standard deviations lower than a specific level) are then selected for the classification itself, and are grouped according to the crop type. The use of scatter plots to visualize the signature of different crops already highlights the large degree of confusion existing between crops. For the final classification, the Maximum Likelihood decision rule is used, and classes with mixed crops are obtained. In order to estimate the accuracy of the classification developed (i.e. how well the classification predicts the type of crop grown in *killas* that have not been used for the establishment of the classification), a confusion matrix is developed using all the information that has not been used for the classification itself (around 60 percent of the information available for the 31 sample watercourses).

The results obtained for the *Rabi* 1994-95 season are presented in the following section.

## Results and Discussion

Five different classes have been identified as the result of the classification for the *Rabi* 1994-95 season. The percentage of each crop in these classes is presented in Figure 2, showing that only Class 1 and Class 3 are pure crop classes representing wheat and fallow/barren. The remaining confusion between barren and fodder in class 2 may be explained by fodder areas that have been harvested in the middle of the season. The confusion between the area under sugarcane and fallow or barren (expressed by the mixed Class 4, and



**Figure 2.** Composition of Final Land Use Classes Obtained; Supervised Classification of Satellite Imagery.

also by the low level of User Accuracy for sugarcane in the confusion matrix of Table 1) is related to the fact that sugarcane is planted in February/March, and looks like fallow in March when the satellite image has been taken.
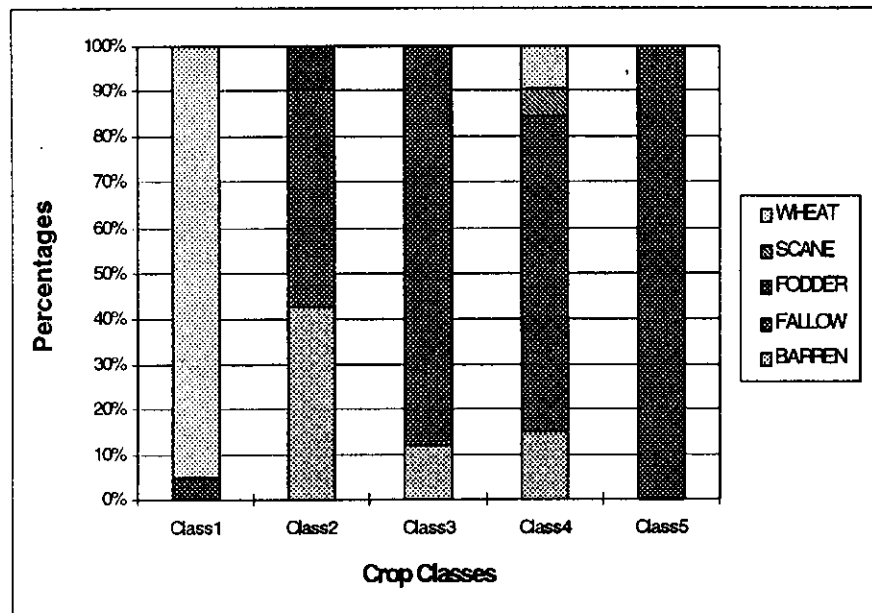
The confusion matrix is presented in Table 1. The overall accuracy of the classification is equal to 82 percent, with problems arising mainly with Class 2 and Class 5.

**Table 1.**    A Confusion Matrix to Assess the Accuracy of the Supervised Classification

| Land Use Type | Class 1 | Class 2 | Class 3 | Class 4 | Class 5 | Total | User's Accuracy |
|---|---|---|---|---|---|---|---|
| Barren | 20108 | 46103 | 21526 | 224620 | 286793 | 599151 | 19% |
| Fallow | 91691 | 286337 | 115455 | 888409 | 641662 | 2023555 | 81% |
| Fodder | 316236 | 69962 | 411 | 65570 | 9484 | 461663 | 84% |
| Sugarcane | 29985 | 73651 | 3181 | 126516 | 51120 | 284452 | 44% |
| Wheat | 4573158 | 541723 | 5265 | 398861 | 57769 | 5576776 | 80% |
| Total | 5031178 | 1017775 | 145839 | 1703976 | 1046828 | 8945597 | |
| Producer's Accuracy | 97% | 11% | 9.1% | 89% | 61% | - | 82% |

No specific reason could be found for the fact that 50 percent of the pixels classified under Class 2 are wheat pixels. The poor status of the wheat crop, and salinity patches in wheat fields that are frequently seen in the Chishtian Sub-division, could be one explanation.

Further analysis of the classes and confusion matrix shows that there is a good accuracy in separating crop and non-cropped area. Although barren land has a very low User Accuracy in the confusion matrix, it is mainly confused with fallow land, a result that is not very surprising. Using the results presented in the confusion matrix, the joint User Accuracy for fallow and barren land is estimated at around 95 percent. In summary, the classification is rather accurate to estimate cropping intensity of irrigated areas, but still remains problematic to estimate the area under different crops.

Using the watercourse coverage of the GIS developed for the Chishtian Sub-division, the results of the classification are used to estimate distributary and watercourse level cropping intensities[7] for the *Rabi* 1994-95 season. The watercourse level information obtained for the Sub-division is presented in Figure 3.[8].

---

[7] The cropping intensities computed are obtained by dividing cropped area over the total Gross Command Area (GCA) of each watercourse. Thus, the values computed are expected to differ from cropping intensities obtained by dividing the total cropped area by the Cultivable Command Area (CCA).

[8] In this paper, no attempt is made to explain this spatial distribution of cropping intensities along the distributary. Analysis is currently undertaken to investigate the relationship between canal water supplies, soil types, salinity, etc. and seasonal and yearly cropping intensities.
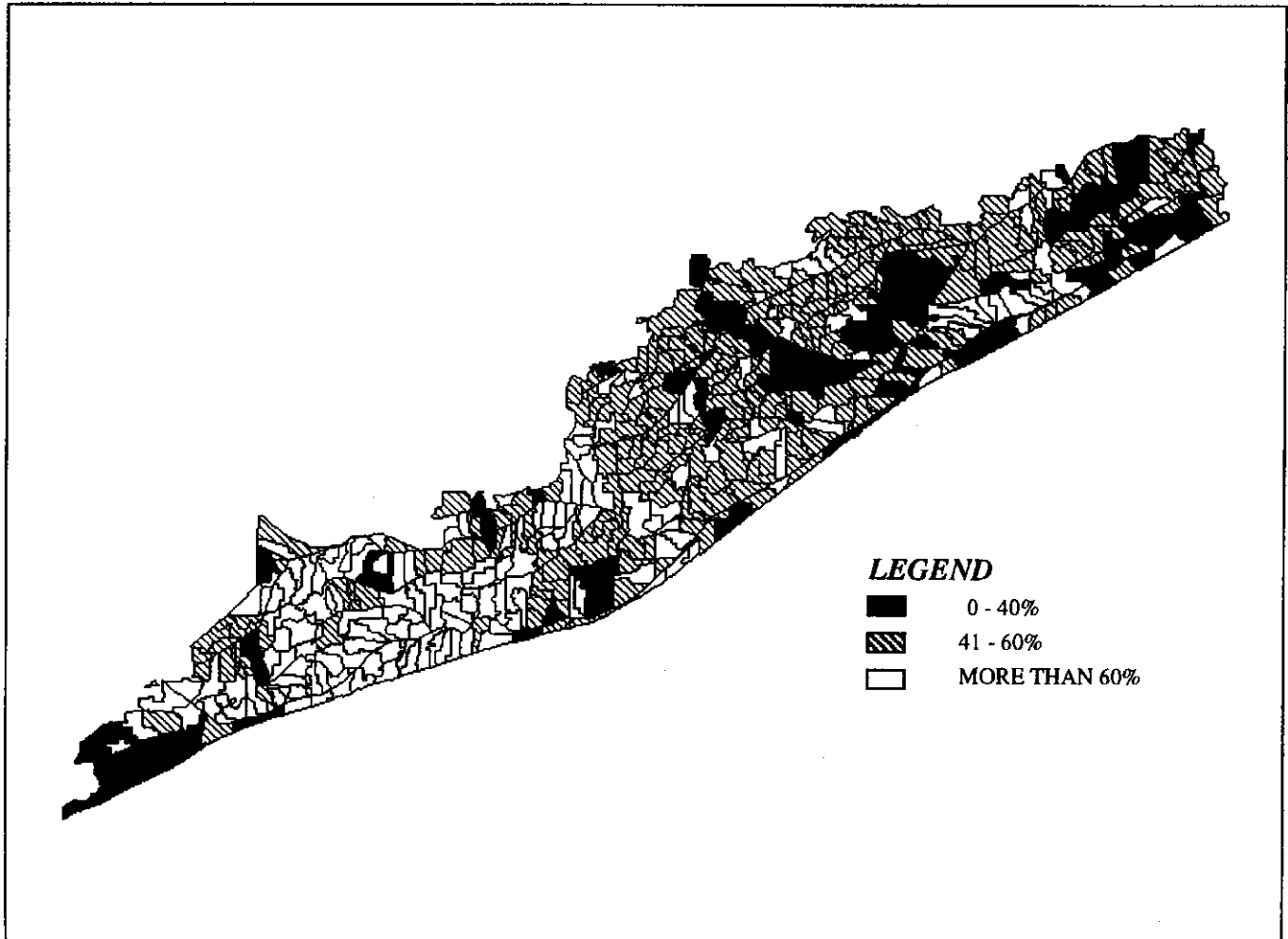
**Figure 3.** Seasonal Watercourse Level Cropping Intensities for the Chishtian Sub-division (Rabi 1994-95).

## Lessons Learned

The present study is a first step towards the development of methodologies for land use mapping and crop identification. The results presented for the Chishtian Sub-division and for the *Rabi* 1994-95 season highlights that the distinction between cropped and non-cropped area is possible with a good level of accuracy. However, difficulties remain with the identification of different crops. Similar results have also been obtained for the *Kharif* 1994 season (Jamieson, 1995).

The evaluation of the initial effort highlights the need to have a larger number of images, instead of only one per season, as acquired during the initial exercise. Also, the sampling frame developed using the watercourse as the basic sampling unit may not be appropriate from a statistical point of view. And, the information collected during the crop survey (i.e type of crop occupying each field of the sample watercourses) has not been sufficient to explain the heterogeneity in signals obtained for given crops.

This initial effort has led to the development of a research work plan for the period 1997-98, which is focused on the development of methodologies for the assessment of irrigation system performance using satellite imagery. This work, presented below, will be undertaken jointly by WMED, IIMI and Cemagref.

## Towards an Appropriated Methodology to Use Satellite Imagery for Land Use Mapping and Crop Identification

In consideration of the cost involved, there is a need to provide satellite imagery to potential users with the required information and expertise, that will allow them to better identify methodologies to be implemented that fulfill their requirement in terms of information and accuracy. This will enhance the allocation of financial resources, particularly scarce for monitoring and evaluation of irrigation system performance in developing countries, like Pakistan.

*Objectives of the Planned Study*

To tackle methodological issues related to the use of satellite imagery for assessing irrigation system performance, a specific research activity is proposed for the *Kharif* 97 season. The overall objective of this activity is:

**The identification of appropriate methodologies to use satellite imagery for assessing irrigation system performance.**

By appropriate methodology, we mean the right combination of satellite images with specific spatial and spectral resolutions, time of satellite image acquisition, and ground truth survey, to obtain performance indicators at a specific scale of the irrigation system (*killa*, watercourse, distributary, project area) with a given accuracy.

At present, as a result of discussion between the collaborators involved in the study and the needs of WMED, only two performance indicators have been selected; cropping pattern and cropping intensity. The study will provide results in two steps. First, the research will establish whether it is possible to identify crops (and at which scale) with the use of satellite imagery. Second, the research will provide information that will allow users to select the appropriate methodology in terms of satellite images and ground truth information that is adapted to the required accuracy level.

*Selection of Study Site*

The site selected for the study is the command area of the Hakra 3-R Distributary, off-taking from the Hakra Branch canal. The Cultivable Command Area of this distributary is equal to 28,468 ha, partly irrigated through 3 minors; 1R Qazi Wala Minor, 1-L Jourkhan Wala Minor and 2L Fazal Minor. This distributary has been selected because WMED already monitors 5 watercourses in the command area as part of monitoring activities undertaken in the context of the Fordwah/Eastern Sadiqia (South) Irrigation and Drainage project.

45

*Planned Methodology and Activities*

The methodology is based on a systematic assessment of the various technical options that have an impact on the accuracy of the results obtained through classification. The various options (range of options) to be tested include:

- Number of satellite images: from 1 image for the season to 4-5 images per season;
- Date of image: comparing results obtained with images taken at different months (or combination of images taken at different months);
- Resolution and number of bands available on different satellites: comparison between information obtained from the satellites IRS, SPOT and Landsat for a given date;
- Number of crop surveys undertaken in the field: from 1 field visit to 3 field visits;
- Information collected through crop survey: from simple information such as the crop name for each field, to information related to agricultural and irrigation practices, and parameters influencing crop growth (salinity, soil type, etc.); and
- Sampling frame: statistically drawn sample of square (10 ha) segments versus a sample of 5 watercourses; different sampling ratio from 2% to 8% of the total CCA.

Initially, each satellite image will be processed separately. Then, computer-intensive manipulation will take place to combine the information obtained from different images, classify pixels, and develop confusion matrix to assess the accuracy of the classification developed. The end result will be a three-dimensional matrix that specify for different combinations of images and ground truth data collection the accuracy obtained for cropping pattern and cropping intensity indicators.

# Conclusion

Follow-up research activities are undertaken jointly by staff from WMED of WAPDA, IIMI and Cemagref, in the context of the Fordwah/Eastern Sadiqia (South) Irrigation and Drainage Project. A whole set of variables factors will be analyzed, an attempt to sketch methodologies that can be optimum for one given objective, i.e., area under a crop type with a given accuracy level. The evaluation of the methodologies developed for the 3-R Distributary will be further undertaken at the level of the Fordwah/Eastern Sadiqia Irrigation and Drainage project area, providing a first operational assessment of these methodologies. Although the initial efforts concentrate on two indicators only, namely, cropping intensity and cropping pattern, it is clear that similar efforts would be of interest for other performance indicators, such as crop yields, evapo-transpiration, water stress, etc.. Such indicators may also be investigated in the future as a result of collaborative efforts with IIMI-HQ researchers.

# References

Jamieson, J. 1995. *A Study of the Agricultural Land use of an Irrigated Area of Pakistan Analyzed in Terms of the Volume of Water Available with the Aid of satellite Imagery*. M.Sc. Thesis, Ecole Nationale du Génie de l'Eau et de l'Environnement, Strasbourg, France.

Kuper, M. and P. Strosser. 1992. *The Appropriateness of Irrigation Water Supplies: the response of the Farmers - A Case Study in the Fordwah/Eastern Sadiqia Area, Punjab, Pakistan*. Discussion Paper No.6, International Irrigation Management Institute, Pakistan Division, Lahore, Pakistan.

World Bank. 1994. *Pakistan - Irrigation and Drainage Sector Issues and Options*. The World Bank, Washington D.C., U.S.A.

# SALINITY ASSESSMENT IN IRRIGATION SYSTEMS USING REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM
## Application to the Chishtian Sub-division, Pakistan

Alain Vidal, Dunia Tabet, Mobin-ud-din Ahmad, Salman Asif, Daniel Zimmer, Pierre Strosser

## Abstract

The present paper summarizes the main results of the research activities undertaken by IIMI and Cemagref in the use of satellite imagery and Geographic Information Systems for salinity monitoring in irrigation systems. The paper describes the physical phenomena involved in the salinization process, investigating the way the understanding of these processes can explain the radiometric properties of salt-affected and sodium-affected crops or soils. Three applications of the use of remote sensing are then presented; (i) the assessment of the dynamics of salinity and sodicity; (ii) the quantitative assessment of salinity and sodicity in cropped areas; and, (iii) the quantitatve assessment of salinity and sodicity in bare soils. The final section of the paper summarizes the lessons learnt from three years of research on the use of satellite imagery for salinity and sodicity assessment.

## Introduction

Among the 270 million hectares of irrigated surfaces, it is admitted that 100 million have been, or will soon be, brought out of cultivation due to waterlogging and/or soil salinisation as a result of irrigation (Smedema, 1995). Accurate information to assess the magnitude of these problems for specific irrigation schemes and to identify solutions for improvements is rare. Thus, satellite remote sensing represents a great potential for salinity assessment.

Since 1994, Cemagref and IIMI have been cooperating on the development of an integrated approach to assess the impact of changes in irrigation management on agricultural production and salinity. The approach is currently developed and tested in a large irrigation system in Pakistan, a country with 16 million hectares irrigated, where soil salinisation concerns around 20 percent of the irrigated area. The irrigation system selected to test the integrated approach is the Chishtian Sub-division of the Fordwah/Eastern Saddiqia irrigation system, South-Punjab. With a command area of 70,000 hectares, the Chishtian Sub-division is fed by the Fordwah Branch canal, which includes a mix of perennial (receiving canal water the year round) and non-perennial (receiving canal water during the *Kharif*, or summer, season only) rainfall in secondary canals or *distributaries*. Surface water is complemented by groundwater of lower quality (higher salt content), pumped by more than 4,500 private tubewells installed by individual farmers.

An important part of the activities developed has focused on the analysis of the spatial heterogeneity of the main parameters and variables within the Chishtian Sub-division. Most of the required information on water, agricultural production and environmental parameters was collected, stored in a geographic information system, and analyzed. Regarding environmental variables, this meant an assessment of the extent of waterlogging, salinity and sodicity within the entire sub-division. As there is no information readily available for salinity and sodicity, a specific methodology was required to establish the spatial distribution of these parameters. Thus, part of the research efforts concentrated on assessing the *potential for using satellite imagery to assess salinity and sodicity* levels for the irrigation system considered.

More specifically, the objectives of the research conducted on this theme are:
1. to identify how salinity and sodicity affect the radiometric properties of the soil-plant continuum; and
2. to derive and define image and geographic information processing methods to:
    - locate saline/sodic areas;
    - quantify the level of salinity / sodicity; and
    - eventually evaluate the risk of degradation due to a possible increase in salinity and sodicity.

This paper presents the results obtained and lessons learnt in the assessment of soil salinity using remote sensing techniques. The paper describes the phenomena involved, and how their knowledge can explain radiometric properties of salt-affected and sodium-affected crops, or soils. Three applications of the use of remote sensing are then presented:
    - assessment of the dynamics of salinity and sodicity;
    - quantitative assessment of salinity and sodicity in cropped areas; and,
    - quantitatve assessment of salinity and sodicity in bare soils.

Finally, the lessons learnt from three years of research on the use of satellite imagery for salinity and sodicity assessment are presented.

## Description of Phenomena and Associated Radiometric Properties

Salinity is usually defined as an excess of ions in the soil profile yielding to chemical toxicity for plants and surface crusts, and thus, to a degraded crop growth (Figure 1a). Sodicity is defined by an unbalanced amount of monovalent (+) and bivalent (++) ions in the soil profile, yielding to clay dispersion and slaking, surface or subsurface crusts, and thus, to a degraded soil hydrodynamics that will affect crop watering through the root system (Figure 1b).
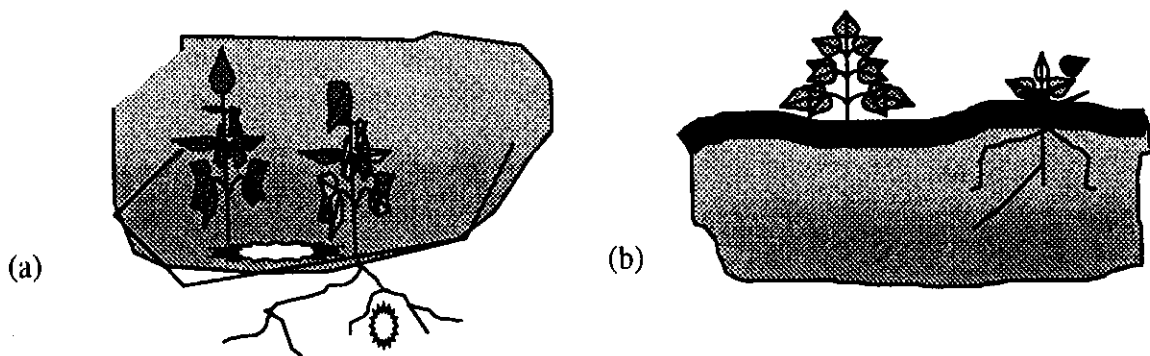
**Figure 1.** Impacts of Salinity and Sodicity on Soils and Plants
(a)salinity yields chemical toxicity, surface crusts and reduced crop growth; and
(b) sodicity yields clay dispersion and slaking, surface thick crusts, and a reduced soil
and plant hydrodynamics.

Though salinity and sodicity often coexist, involving combined effects on soil and plants, there are usually two ways of salinization, neutral or alkaline, the result of which will be that salinity or sodicity will be dominant. In the case of the Chishtian Sub-division, it has been observed that sodicity was the major constraint (Condom, 1997). The main indicators for on-field measurements of these processes, are the electric conductivity EC (dS/m) for salinity, and the Sodium Absorption Ratio SAR for sodicity.

Another important element of salinization and sodification processes is that water is the vehicle for salts and sodium. Water includes drainage water, saline groundwater with capillarity, and sodic irrigation (tubewell) water (the most important source of salts in the Chishtian Sub-division). Finally, two types of salinity and sodicity usually co-exist; a primary salinity, mainly due to the existing sub-stratum containing salts, and/or sodium; and, a secondary salinity induced by agricultural and irrigation practices, that may vary over time.

Radiometric properties of salinity-affected soils and crops depend on the type of effect induced by salinity and sodicity.

- In the solar domain, i.e., when the surface reflectance is the considered variable (SPOT, Landsat MSS or TM), these properties can cover a wide range of situations. Vegetation patches yield a decrease of the high reflectance in the near infra-red band. Bright white salt crusts yield a very bright reflectance in all bands. And, dark salt crusts (usually related to the accumulation of sodium) yield a very low reflectance in all bands (See Figure 2a).

- In the larger optical domain, including thermal infrared, when both surface reflectance and surface emission are considered, sodicity-induced water stress might be detected by combining the fractional vegetation cover derived from reflectance measurements, and the surface temperature derived from thermal infra-red bands (See Figure 2b).
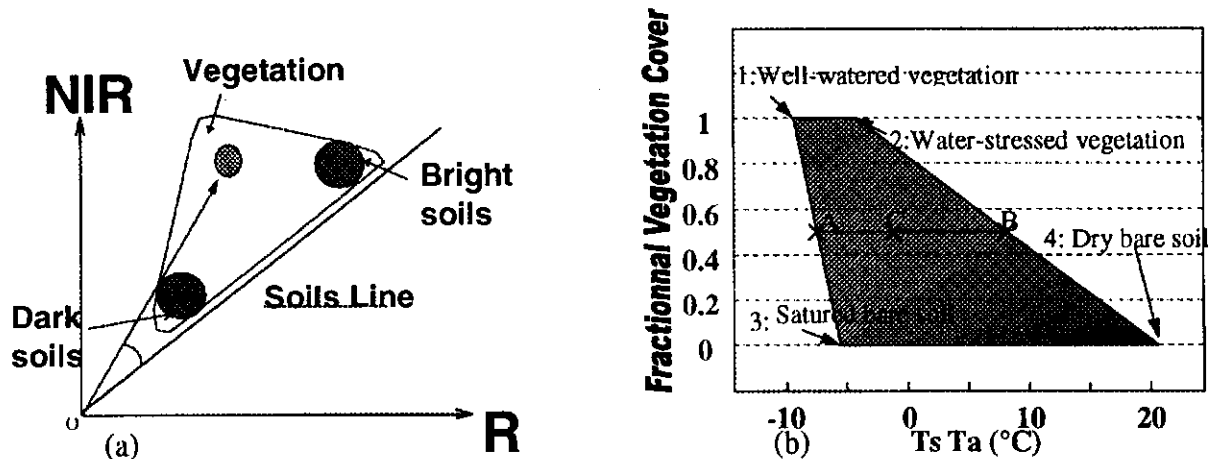
**Figure 2.** Radiometric Properties of Salinity-and-sodicity-affected Soils and Plants

    (a) in the solar domain, ranging from dark to bright salt crusts (red spots), up to poorly-developed vegetation (green spots); and

    (b) in thermal and solar domain, sodic soils and plants characterised by a higher water stress, located in the right part of the trapezoid.

## Example 1: Understanding the Dynamics of Salinity

A first innovative result of this research was the knowledge of saline areas provided by the analysis of *space maps,* as presented in Figure 3, i.e. geo-referenced SPOT images, including a minimal set of geographic features such as roads, main villages, rivers and canals. The location of very saline areas, appearing in bright white on the space map of March 1995, already gives some key information on the genesis of these areas, corresponding to old abandoned meanders and depressions, where probably a high evaporation of the closer groundwater table has occurred.
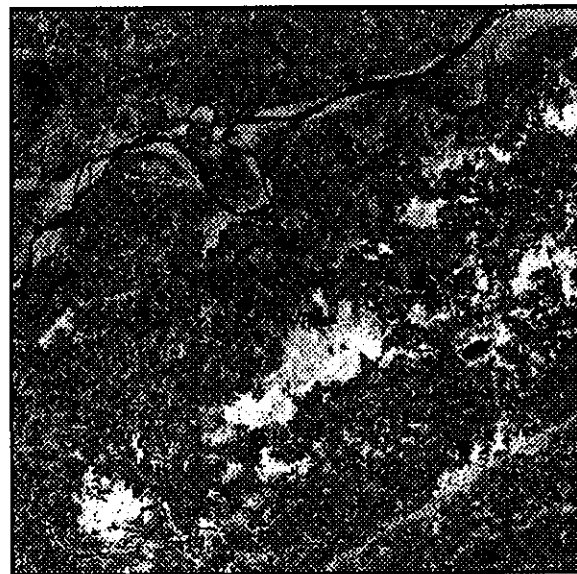


**Figure 3.** SPOT Derived Space Map of March 1995 (clearly showing strongly saline areas appearing in white in the image. Crops appear in red, bare soils and sand dunes in blue).

The superimposition of the space maps with the limit of tertiary units further enhances the understanding of the genesis of the observed salinity patches; primary salinity when the salinity patches location are not directly related to the shape of the tertiary unit; secondary salinity when their location appears at the tail of the unit.

Furthermore, the analysis of a multi-temporal data set of space maps can also be of value to reconstitute the historical evolution of salinity and sodicity. It is possible to compare present images with Landsat MSS images from 1973 and 1980, and SPOT images from 1986. This analysis, still under way, is limited by the lack of coherent ground-truth calibration data from one date to another, the salinity maps used, or ground-truthing being derived from field surveys undertaken following different methods. The first results, however, show a global reduction in areas severely affected by salinity, though some saline areas have extended locally.

## Example 2: Quantifying Salinity in Cropped Areas

Whereas, many applications of remote sensing are based on image classification, where pixels are affected to a given statistical class identified in the field, the bibliography already showed that classifications were of low efficiency in the case of salinity and sodicity. The original method developed by Tabet (1995) relates the vegetation and brightness indexes derived from SPOT XS to visual observations, similar to the ones collected by the Directorate of Land Reclamation (DLR) of the Punjab Irrigation and Power Department. The aim of the visual observations is to classify fields into 4 categories of salinity (S0, S1, S2 and S4). The principle of the image classification method is close to the tree-classification used for the visual classification (Figure 4).
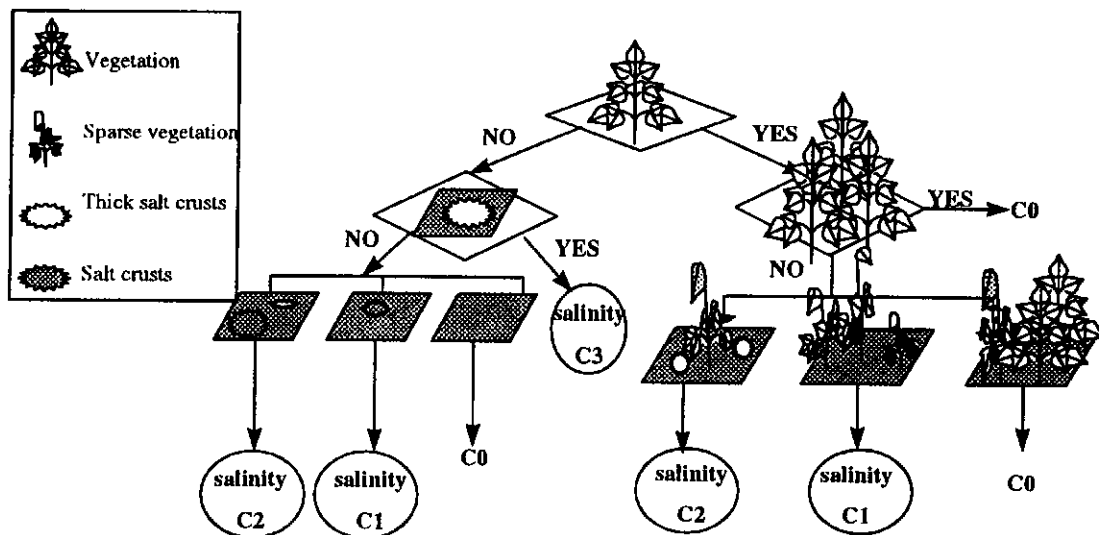


**Figure 4.** Representation of the Salinity Visual Classification (Reproduced by using vegetation and brightness indexes derived from SPOT XS data. Fields are classified into 4 categories;C0, C1, C2 and C4).

The classification developed allows a good identification of the areas with high salinity levels (66% of well-classified fields), and of the non-saline areas (80% of well-classified fields). However, the areas with low to medium salinity levels are more difficult to identify. Confusion about salinity classes are related to a combination of factors, as listed below.

- field sizes are close to the resolution of the satellite, and confusion between crops appear since most pixels are mixed;
- due to the crop cycle variations from one field to another, a change in the radiometric properties of a given crop might be due to differences in the phenological stages rather than to differences in salinity levels;
- salinity and sodicity are not the only limiting factors for crops development; water stress and lack of fertilisers are also limiting factors that may explain differences in crop signatures; and
- finally, the NDVI derived from the red and near-infra-red reflectances reach a saturation value for biomass of more than 0.8 kg/m$^2$ (Tucker, 1979). Thus, this indicator will not show the effect of salinity or sodicity on biomass if its value is higher than 0.8 kg/m$^2$, the most common situation, as demonstrated by field measurements (Tabet, 1995).

The introduction of the Landsat TM image of February 1995, combined with a SPOT image of March 1995, was also explored. The added-value of the thermal infra-red was rather low, since it did not bring additional information on sodicity, as expected from the water stress induced by sodicity. This could be easily explained by the combined effects of insufficient irrigation, and of sodicity. However, the combination of the 2 dates slightly improved the classification. These results still need to be refined by a more complete analysis that will be completed by late 1998.

## Example 3: Quantifying Salinity of Bare Soils

As explained above, highly saline and sodic bare soils are easily identified on satellite images. This constitutes the most obvious historical information, related to old abandoned meanders, with low temporal dynamics.

Furthermore, one part of the research (Tabet et al., 1997) concerned the definition of an optimal observation date, and concluded that March was this optimum, compared to other observation periods (May, October). This period corresponds to the period when the maxima precipitation and crystallization of salts can be found in the field. Also, gradients in soil brightness appeared at this date to be well-related to salinity intensities measured in the field (see Figure 5).
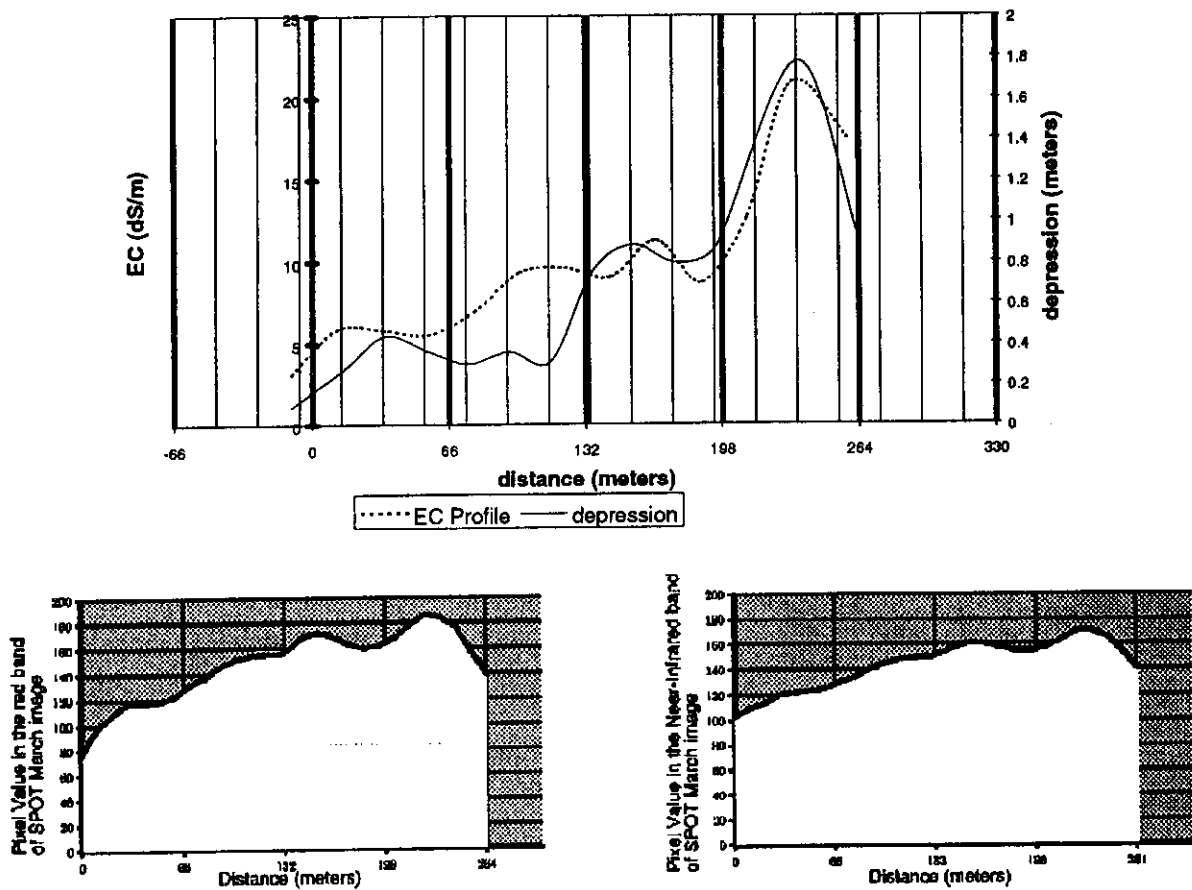
**Figure 5.** Spatial Variation of Soil Salinity Associated to Micro-topography Along a Transect Crossing a Highly Saline Depression (Spatial variations of reflectances in red and near-infra-red in March 1995 are shown below (Tabet et al., 1997).

## Lessons learned and Conclusions

In terms of the knowledge of related physical phenomena, the present research has allowed progress on the understanding of the phenomena involved, and its associated radiometric properties. Though this knowledge can be considered good for salinity (mainly geo-chemical phenomena), it remains insufficient for sodicity (physical soil degradation, hydrodynamics, polymorphism of radiometric effects), the major problem in the Chishtian Sub-division.

Space maps help to understand the dynamics of salinity in space and in time. Also, salinity and sodicity intensities can be mapped:

- For cropped areas, differentiating 2-4 classes, with a global accuracy of 72 %, but preferably with 2 images during the same cropping season; and
- For bare soils, where a good evaluation of the salinity gradients can be obtained, but only in March, where bright crusts appear on the soil surface.

Major advances have thus been accomplished in:
- Salinity and sodicity physics and radiometric properties;
- Salinity and sodicity mapping in cropped areas; and
- Determination of the optimal date for mapping highly saline areas, and monitoring the dynamics of the salinity/sodicity processes.

This analysis will be completed in 1998, mainly for the command area of the Chishtian Subdivision. The analysis will integrate information collected in 1994-95 on farming and water management practices. A further study could be initiated in the command area of the Fordwah/Eastern Sadiqia (South) Irrigation and Drainage project, but only after an analysis of the major phenomena (salinity vs. sodicity, waterlogging, farming practices) encountered in this area.

# References

Condom, N. 1997. *Salinisation, Alkalization, and Sodification on Irrigated Areas in Pakistan; Characterization of the Geochemical and Physical Processes and the Impact of Irrigation Water on these Processes by the use of a Hydro-geochemical Model.* DEA ENGREF-USTL, IIMI Report n°22, 111p.

Smedema, L.K., 1995. Salinity Control of Irrigated Land. Proceedings of the CEMAGREF-FAO Workshop on the *Use of Remote Sensing Techniques in Irrigation and Drainage, Montpellier, 2-4 November 1993*, FAO Ed., Water Reports n°4, 155-164.

Tabet, D. 1995. *Le suivi de la salinité dans les périmètres irrigués par télédétection et systèmes d'information géographique: Application au périmètre de Fordwah, Pakistan.* Rapport du DEA National d'Hydrologie, Montpellier, 174 p.

Tabet, D.; Asif, S.; Aslam, M.; Kuper, M.; Strosser, P.; Vidal, A. and D. Zimmer. 1997. Soil Salinity Characterization in Irrigation Schemes: A Case Study in the Punjab (Pakistan). Proceedings of ISPRS 7th International Symposium *Physical Measurements and Signatures in Remote Sensing*, Courchevel, France, 7-11 April 1997.

Tucker, C.J. 1979. Red and Photographic Infra-red Linear Combinations for Monitoring Vegetation. *Remote Sensing Environ.*, 8 (2), 127-150.

# ANALYZING THE LINK BETWEEN THE IRRIGATION ENVIRONMENT AND AGRICULTURAL PRODUCTION; EXAMPLES FROM THE CHISHTIAN SUB-DIVISION

Jean-Daniel Rinaudo, Pierre Strosser and Thierry Rieu

## Abstract

A number of interventions are proposed to increase agriculture production and productivity in irrigation systems in Pakistan. However, limited evidence supports the claim that proposed interventions will effectively lead to an increase. This paper presents a methodology to estimate the impact of changes in irrigation management and irrigation sector policy on agricultural production. The water-production relationship is analyzed at three different levels (field, farm and watercourse level) through case studies conducted in the Chishtian Sub-division. Economic models using linear programming techniques are developed, and then used to estimate the impact of a reduction, or increase, in canal water supply on cropping pattern and farm income. The models are also used to assess the impact of tubewell water markets in the command area of sample tertiary units.

## Introduction

The productivity of irrigated agriculture in Pakistan is one among the lowest in the world (World Bank 1994). To improve agricultural productivity, various interventions in the agricultural and irrigation sectors have been, and are, proposed. To increase surface water supplies at the farm through watercourse lining, to subsidize input use or to keep electricity prices low and to encourage farmers to tap groundwater resources, are examples of such interventions. More recently, options have included the institutional reform of the irrigation sector, the transfer of responsibilities to water users, and the development of water markets.

In a large number of cases, limited evidence supports the claim that proposed interventions will effectively increase agricultural production. This results partly from the fact that the relationship between irrigation water, agricultural production and productivity remains understudied. Thus, rough estimates are used to justify the economic and financial feasibility of large projects that often do not reach their targets in terms of increase in agricultural production.

The present paper advocates for more research on the economics of irrigation water and the link between irrigation water supply and agricultural production, as a prerequisite for the identification of appropriate solutions to improve the performance of irrigated agriculture in Pakistan. It presents the example of the application of the methodology developed in the context of the collaboration between the International Irrigation Management Institute, Pakistan National Program, and the Irrigation Division of the French research institute, Cemagref, to assess the impact of water markets on agricultural production and productivity.

## Research Framework

The analysis of the relationship between water and agricultural production can be undertaken at different *spatial and temporal scales*, based on the level of details required to define policies, information available, and agricultural production indicator targeted.

- At the *field* level, where the relationship between irrigation water applications and crop stress and crop yield can be investigated;
- At the *farm* level where the access to water resources and expected water supplies influence crop choices, cropping pattern and expected total agricultural production;
- At the farm level again, where the irrigation water supplies effectively received during a given season, or year, influence crop yields & overall farm agricultural production and income;
- At *higher scales of the irrigation system* (from tertiary unit to canal command area) the link between total water allocations and aggregated agricultural output is also of interest, and is inter-linked with output market issues and the analysis of supply and demand of agriculture/food product.

The analysis also requires further specification of different characteristics of water that influence farmers' decisions, and are being considered. Those include *quantity*-related characteristics, as listed below.

- *Surface water* supplies, defined not only in terms of average, or total, *quantities* received for a season, or a year, by individual farmers or tertiary units, but also in terms of *temporal variability* of these supplies between months, or within months. Also, it is important to differentiate between *expected* water supplies (based on previous years' supplies) and *actual* water supplies, and investigates related *timeliness* aspects.
- Access to *groundwater* resources is an important element that influence farmer's decisions and relates to tubewell ownership and control over groundwater resources, as well as to the possibility of purchasing tubewell water from neighboring tubules. The availability of groundwater resources may be limited as a result of few tubewells within the command area of a watercourse, or as a result of the preference given by tubewell owners to their own crops. Similar to canal water supplies, a certain element of uncertainty is attached to access to groundwater resources.

*Price*-related characteristics are also included. For canal water, water charges are related to the area cultivated and crop selected, and may be considered as a land tax. In some cases, however, extra costs may be involved as a result of the acquisition of extra canal water supplies. For tubewell water, farmers have to pay for the operation and maintenance costs of their own tubewell, or pay a given price for tubewell water purchases. *Quality*-related characteristics are also considered in the decisions taken by farmers.

The research framework is further based on the recognition of two important elements related to the investigation of farming systems issues.

- The *rationality of farmers' decisions*, based on profit maximization as the major objective, but constrained by other objectives, such as risk aversion, minimum income, or minimum wheat requirement. Under a given set of circumstances, a farmer is expected to

follow a given strategy consistently. Only then does it become possible to develop economic models that reproduce farmer's decisions.

- Recognition of the *heterogeneity of the farm population* within an irrigation system depends upon different objectives, production strategies, farm constraints (economic or related to the physical environment), and the need for investigating to enable the analysis of the relationship between water and agricultural production.

As the analysis undertaken in the context of the IIMI-Cemagref collaboration concentrates is on allocation and re-allocation of surface water resources, the main focus of the research developed in this collaboration, is on farmers, planning decisions related to cropping intensity and crop choices, and based on *expected* surface water supplies. The approach selected includes the following elements:

- The analysis of the heterogeneity in farming systems within tertiary units of the irrigation system; and
- The development of economic models for different types of farms and tertiary units to assess the impact of canal water supplies on crop choices, cropping intensity and groundwater use.

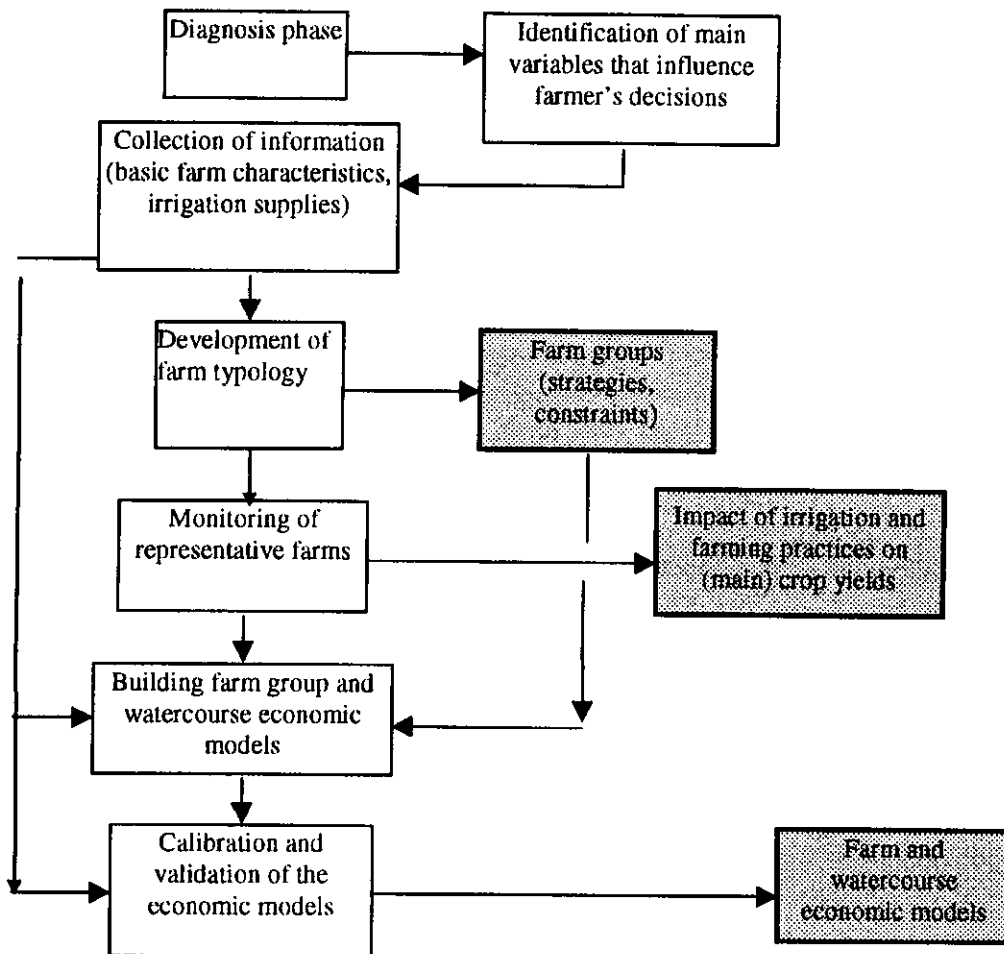Different steps of the methodology developed are summarized in Figure 1.



**Figure 1.**    Methodological Framework to Analyze the Relationship Between Irrigation Water Supplies and Agricultural Production.

The following section of the paper presents the results obtained through the application of these different steps to one case study. The sample sites selected for this application are the command areas of 8 sample tertiary units located along two secondary canals of the Chishtian Sub-division, South-Punjab. These secondary canals or *distributaries* are the Fordwah Distributary, perennial, and receiving canal water supplies the year round; and the Azim Distributary, non-perennial, and receiving canal water supplies during the *Kharif* season only. The irrigation system is located in the cotton-wheat agro-ecological zone of Pakistan, but records a sizable portion of its command area under sugarcane cultivation. Conjunctive use of surface and groundwater are a common practice, and the average tubewell density in the Chishtian Sub-division is around 5-6 tubewells per 100 ha of CCA.

## Analyzing the Diversity of Farming Systems

The objective of the farm typology undertaken in the 8 sample watercourses of the Fordwah and Azim Distributaries is to identify homogeneous groups of farms in terms of access to resources and constraints. The production strategies of each group are then analyzed by investigating the relationships between the decisions made by farmers, in terms of cropping pattern, land use, and input use on one hand, and farm resources, farm constraints and the physical environment on the other.

An important step in the development of a farm typology is the selection of variables used to differentiate farms, and to classify them into groups. Assuming that the production strategies can be fully explained by variables describing the farm structure (Boussard, 1987), the typology which was undertaken relies only on variables describing farm resources, farm constraints and farmers' attitude towards risk.

- *Farm characteristics* incorporate owned area, land tenure status, family labor, tractor and oxen ownership, tubewell ownership;
- *Physical environment* incorporates importance of salinity, cotton and wheat yields used as a proxy for soil and irrigation quality;
- *Risk aversion* is the number of crops in the cropping pattern used as indicator of risk aversion; and
- *Access to water resource* encompasses tubewell ownership, the adequacy indicator (see definition below) for canal water supply.

Information related to most of the variables was collected for all farms in the eight sample watercourses through a formal farm survey. The adequacy indicator for canal water supply at the farm level compares the design duties and actual canal water supplies, computed on information obtained through daily monitoring of water deliveries at the head of each sample watercourse, as well as measurements of conveyance losses between the watercourse outlet and farm gates.

In order to classify farms into farm groups or types, a cluster-analysis method was selected and applied using the SOLO statistical software. For $N$ farms and $P$ variables, the user specifies first the number of clusters ($K$). Using standardized variables, individual farms are sorted according to distances to the overall mean (gravity center) of the population. For cluster $C$, with $C=1$ to $C=K$,

the [1 + (*C*-1) * *N/K*]th farm is chosen as the initial center of the cluster. The algorithm allocates each farm to its closest center, minimizing the square distance between the farm and the cluster center.

The statistical classification of the farms has led to the identification of 9 homogeneous farm groups. The production strategies of these groups are differentiated by their access to, and integration into, input and output markets, the level of intensification reflected by cropping intensities and crop yields, and, the level of diversification expressed by the importance of crops other than wheat and cotton in the cropping pattern. These production strategies are described below.

- Farm with auto-consumption strategy

The main objective of these farms is to produce wheat for auto-consumption. Limited assets, important cash flow and credit constraints, and limited access to input and output market explain an *extensive strategy*, leading to a low average cropping intensity (122%), and low cotton and wheat yields. The importance of fodder in the cropping pattern (19% of the operated area in *Kharif*) stresses the importance of *livestock* as a production activity, but also as a mean of saving.

- Market-oriented farms with cotton specialization

⇒ Very *small owner-cultivators* with an average operated area of 1.5 ha. Those farms, sizes being a result of land fragmentation due to inheritance, have adopted an *intensive strategy* leading to high cropping intensities (180%), and high cotton and wheat yields. This intensification is allowed by a good availability of family labor, joint family tubewell management, and a very good canal water supply.

⇒ Although *pure tenants* with sharecropping of fixed rent arrangements operate smaller holdings (4.5 ha) along the Fordwah Distributary than along the Azim Distributary (6 ha), their production strategies are rather similar, with a very high specialization in wheat and cotton production. As a result of perennial canal water supplies, combined with better soil conditions, Fordwah tenants obtain higher yearly cropping intensities, and significantly higher cotton and wheat yields, than tenants located along the Azim Distributary. Good access to groundwater resources is obtained as part of contracts with landowner-tubewell owners.

- Diversification in cropping pattern

⇒ *Medium size farmers:*

    ✓ With credit constraints and limited access to input and output markets, these farmers are closer to auto-consumption strategies without having to adopt cotton specialization strategies. When they are in close proximity to sugar-mills (reduced transportation costs for sugarcane), their good canal water supply allows them to grow *sugarcane,* which represents 10% of the operated area. Wheat is grown for auto-consumption only. The cropping intensity is medium (135%) as a result of the competition over water resources between sugarcane and other crops, and the credit constraints that limit farmers' purchases of tubewell water.

    ✓ With an excellent canal water supply, and within the proximity of a sugar-mill, these farmers cultivate *sugarcane* in 28% of their operated area. Competition for water and

other inputs remains important and leads to reduced area under cotton, wheat and fodder, and to a relatively low yearly cropping intensity (138%).

✓ With no credit constraints as a result of joint management of resources (*joint tubewells*, for example), farmers from this group can compensate for their low canal water supply and cultivate crops with high water requirements. *Sugarcane* is grown in 10% of the operated area and processed into raw sugar to generate cash, whereas *rice* is also included in the crop rotation to mitigate *salinity problems* which affect a significant portion of the operated area. Although relatively high levels of input are used, crop yields remain at a medium level as a result of the poor quality of the soils.

⇒ *Large, to very large, commercial farms* (groups 8 & 9) have very good access to short and long term credit, and are, therefore, the ability to have an intensive use of inputs, as well as investing in tractors and single-owned tubewells. To increase the profitability of these investment and to maximize the farm income, these farmers rent in large areas, and permanent labor is also hired to complement family labor. The intensive use of inputs leads to high cotton and wheat yields, with 50 to 60% of the production being sold on the market. Control over groundwater resources has also led to the development of sugarcane and rice cultivation.

This analysis of the diversity of farm strategies stresses the differences in terms of main farm strategies and constraints that exist within the command areas of the 8 sample watercourses of the Fordwah and Azim Distributaries. A change in water supply characteristics (quantity or price of surface or ground water) is, therefore, not expected to have uniform impact in terms of a change in cropping pattern and farm income for all the farm groups.

## Analyzing the Relationship Between Access to Water Resources and Agricultural Production and Farm Income

The present section describes the economic models developed for the 9 farm groups identified in the 8 sample watercourses of the Fordwah and Azim Distributaries. Based on data obtained through monitoring of representative farms for two seasons (*Rabi* 1993-94 and *Kharif* 1994), these models have been developed to estimate some of the technical coefficients of the economic models, as well as farm survey data for specific farm constraints and objective function parameters.

*Development of the Farm and Watercourse Economic Models*

The choice selected for the present study is to build linear programming models for each farm type. The model investigates farmer's choice in terms of area under each crop and monthly tubewell water use. Based on a given canal water supply, the model maximizes an objective function under a given set of constraints related to land, water and credit, and identifies the optimum cropping pattern and related monthly tubewell water use. The objective function is the farm gross income, defined as the sum of the crop gross margins (total production multiplied by prices, minus total variable costs), plus the proceeds from tubewell water sales (for tubewell owners only), minus the operation and maintenance costs related to own tubewell use (tubewell owners) and tubewell water purchases (non-tubewell owners).

Risk is also a consideration in the linear programming models, and risk aversion parameters are included in both, the objective function of the economic models to account for cotton and wheat yield variability, and in the canal water supply constraint to account for canal water supply variability. More specifically, the canal water supply constraint is split into a monthly canal water supply, and the temporal variability of daily volumes supplied to watercourses or farms. The relationship between irrigation water supplies and crop yields for cotton and wheat is established using the results of the detailed monitoring of representative farms (Pintus, 1995; Meerbach, 1996). These results are then integrated into the economic models. Figure 2 presents a schematic representation of the linear programming models developed for each farm group.

The farm group models are built by aggregating resources for all the farms of a given farm group. Using these farm group models, watercourse models are developed as combinations of the farm group models, based on the relative importance of each farm group in the watercourse command area considered. Also, specific links are established between the farm group models to set total tubewell water sales, equal to total tubewell water purchases. In addition, limits in tubewell water availability and tubewell water sales are fixed, based on the total number of tubewells in the watercourse command area, the importance of joint tubewell owners, and the percentage of time sections of the main watercourse is free from canal water supplies
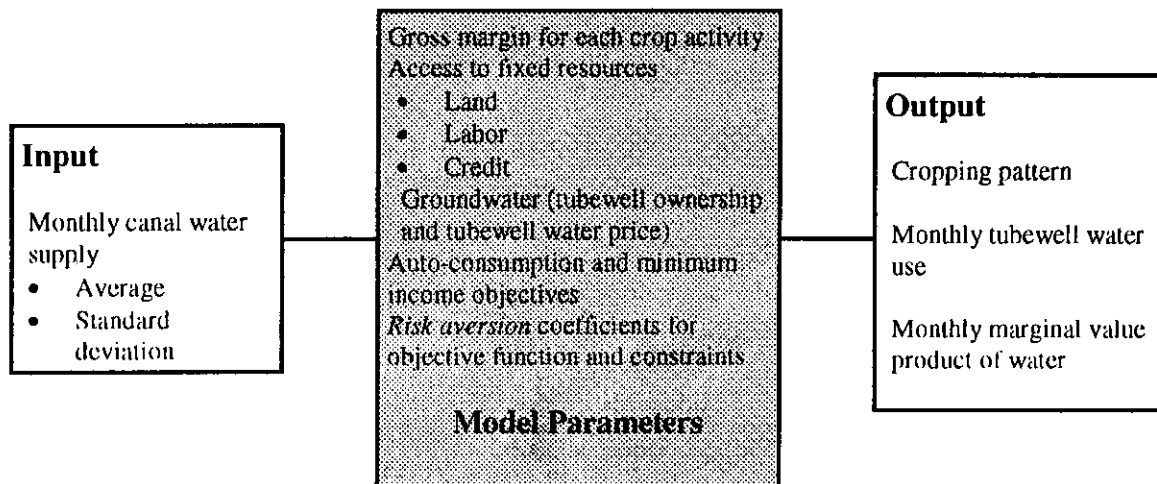


**Figure 2.** Schematic Representation of the Linear Programming Farm Models Developed for Farmers from the 8 Sample Watercourses of the Fordwah and Azim Distributaries.

The calibration of the farm group models is first undertaken for 4 sample watercourses only. The calibration process specifies the values taken by the different risk aversion parameters included in the models, and refine the gross margin of rice and sugarcane to account for differences in these parameters according to the proximity to a sugar-mill (farms closer to the sugar mill face a higher sugarcane gross margin as a result of reduced transportation costs), and the importance of salinity in the watercourse command area.

Using the parameters established through calibration, the farm group models are then validated for the remaining 4 watercourses where they face different canal water supply, tubewell availability, and tubewell water price situations. The overall accuracy of the aggregated watercourse linear programming models was computed at an average of 5% for seasonal cropping intensities, and 8% for the area under the main crops, except sugarcane. Problems were still faced with an over-prediction of the area under sugarcane for most of the farm groups and watercourses analyzed.

The following sections of the paper illustrates the potential use of the economic farm and watercourse models to investigate the impact of changes in the access to surface and groundwater resources on farmer's decisions, agricultural production, and tubewell water use.

*Impact of Change in Average Canal Water Supply on Agricultural Production and Farm Income*

The first example investigates the impact of a change in canal water supply on cropping pattern and farm income. Figure 3 shows changes in the area under wheat and cotton, and the cropping intensity predicted by the economic model developed for the FD 130 watercourse for different levels of canal water supply, expressed in percentages of the actual canal water supply (actual situation = 100).
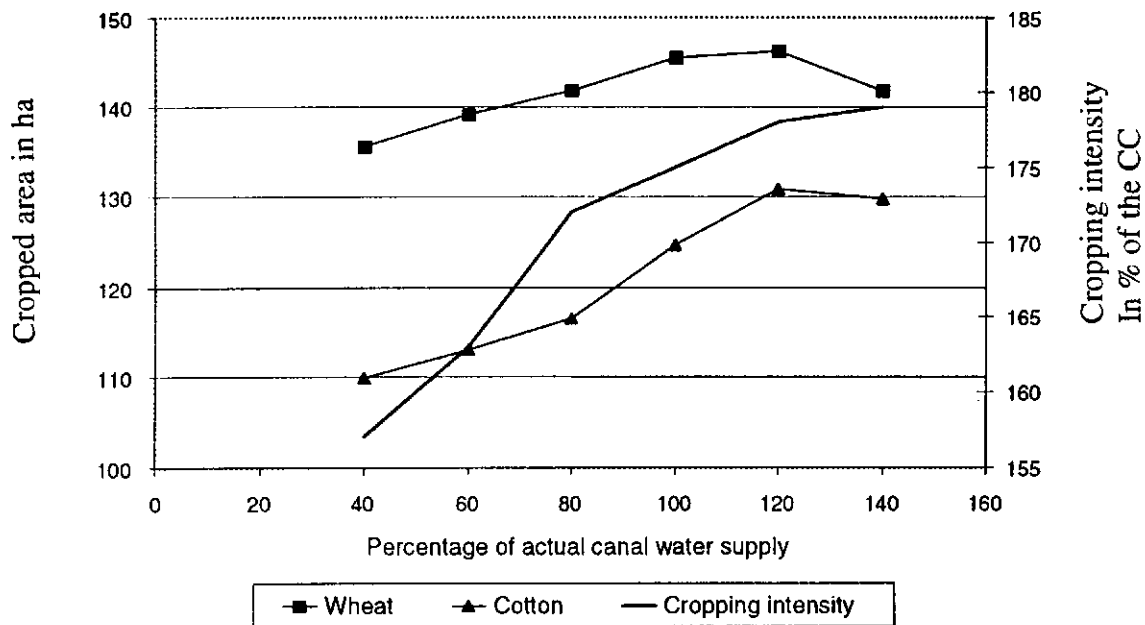


**Figure 3.**    Changes in Cotton Area (ha), Wheat Area (ha), and Cropping Intensity Predicted by the Economic Model Developed for the FD 130 Watercourse under Different Canal Water Supply Conditions (expressed in percentages of actual canal water supply).

Figure 3 emphasizes the non-linearity of the relationship between the canal water supply and the area under wheat and cotton. In fact, as the canal water supply increases from 120 to 140 percent of the actual canal water supply, the area under wheat decreases. This is the result of the increase in the area under sugarcane (not shown on the present figure), and the competition over water resources between wheat and sugarcane during the *Rabi* season.

Figure 4 compares the impact of a change in canal water supply on aggregated farm gross income for 4 sample watercourses. This figure highlights differences in watercourse behavior, with watercourses such as AZ 63 having a rather linear trend in aggregated farm gross income for the range of canal water supplies considered, while AZ 20 watercourse shows a quadratic trend. Similar differences are recorded between changes in farm gross income for different farm groups. Farms with auto-consumption strategies, and with tubewells record limited changes in cropping pattern and farm income as a result of changes in canal water supplies, as compared to farms with diversification strategies and constraints in the access to groundwater resources.
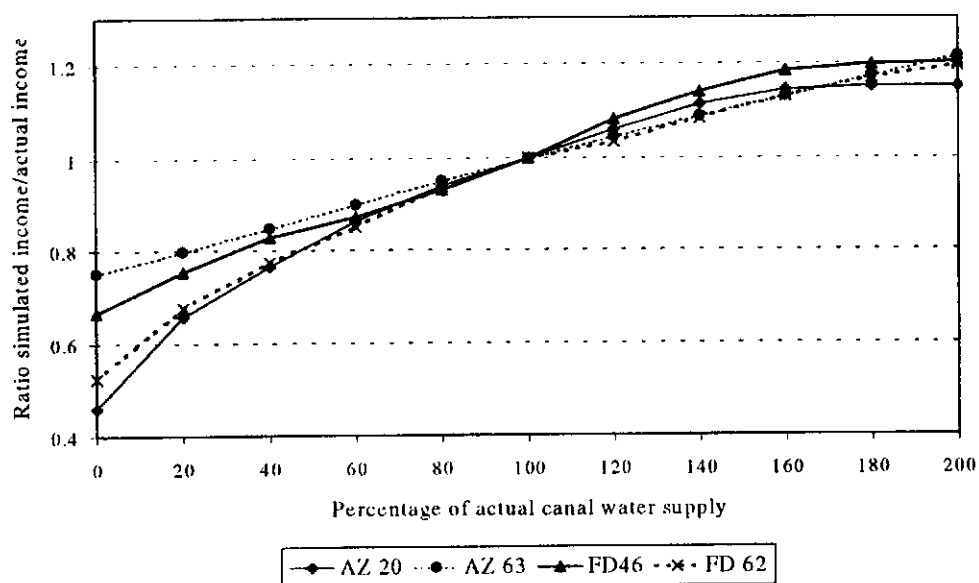


**Figure 4.** Changes Farm Gross Income (Expressed in Terms of Ratio And Actual Farm Gross Income) Resulting from Changes in Canal Water Supply (Expressed in Percent of Actual Canal Water Supplies) for 4 Sample Watercourses of the Fordwah and Azim Distributaries. (Results from simulations with the watercourse economic models).

An important stress is that the range of canal water situations that have been modeled and presented in Figure 4 is rather wide. The limited robustness of the results of simulations for the two extreme portions of the curves is acknowledged.

## Impact of Tubewell Water Markets on Agricultural Production

The second example concentrates on existing tubewell water markets that have developed within the command areas of the sample watercourses. Tubewell water markets have been reported under a large number of physical and socio-economic environments in Pakistan.

Too little estimation has been afforded to the impact of tubewell water markets. Strosser and Kuper (1994) found an impact of tubewell water markets on cropping intensities, with tubewell water purchasers obtaining similar cropping intensities as that of joint tubewell owners. Meinzen-Dick (1996) further investigated the relationship between tubewell water markets and crop yields, and identified the marginal impact of tubewell water markets on wheat yield and gross margin. The economic models developed for the 8 sample watercourses are used to estimate the impact of existing tubewell water markets on cropping pattern, cropping intensity, and farm gross income. Two scenarios are compared that is:

- The actual situation with tubewell water markets developed between tubewell owners and non-tubewell owners; and
- A scenario where tubewell water transactions are banned within the watercourse command areas. Thus, non-tubewell owners rely solely on canal water supplies for agricultural production.

Table 1 presents the results obtained from simulations with the watercourse economic models.

**Table 1.** Impact of Tubewell Water Markets on Irrigation Tubewell Water Use, Agricultural Production, and Gross Income. (Aggregated results obtained by means of the economic models developed for the 8 sample watercourses of the Fordwah and Azim Distributaries).

| Variable | | Actual situation | No tubewell water markets | |
|---|---|---|---|---|
| | | | Estimate | % of change |
| Water | Tubewell Water Use | 10.4 Mm3 | 5.3 Mm3 | -49% |
| Agricultural Production | Yearly Cropping Intensities | 163% | 107 % | - 34% |
| | Wheat | 1030 ha | 620 ha | -40 % |
| | Cotton | 920 ha | 590 ha | -36% |
| | Sugarcane | 160 ha | 90 ha | -44% |
| | Rice | 70 ha | 50 ha | -29% |
| Economic Output | Total Gross Income | 17.8 Million Rs. | 10.7 Million Rs. | -40% |

The comparison between the different performance indicators related to water supply, agricultural production and economic output clearly stresses the importance of tubewell water markets. Overall, for the 8 sample watercourses aggregated, tubewell water markets increase the total farm income by Rs. 7.1 million, equivalent to 40% of the actual total farm gross income. The relative increase in cropping intensity is in the same order of magnitude. Overall, tubewell water use is doubled as a result of tubewell water markets, which in turn is expected to have an impact on mining of the aquifer and secondary salinization on areas with poor groundwater quality.

# Conclusion

The reforms which are currently being discussed in Pakistan emphasize the importance of using policy instruments such as water pricing, or water markets, that produce economic incentives for farmers to use water in a more efficient manner. The approach presented in this paper could generate some answers to questions related to the impact of such instruments on the overall agricultural productivity. The comparison of estimated benefits with the cost required to implement the reforms, could generate some elements about the economic feasibility of proposed changes. The simulation tool could also be used to estimate the consequences of such changes on the distribution of income among farm groups.

# References

Boussard, J-M. 1987. *Economie de l'agriculture*. Economica. Paris.

Meerbach, D. 1996. Impact of Irrigation, Salinity and Cultural Practices on Cotton Yield : A Study of the Fordwah/Eastern Sadiqia Area, Punjab, Pakistan. M.Sc. Thesis, Wageningen Agricultural University, Wageningen.

Meinzen-Dick, R. 1996. Groundwater Markets in Pakistan : Participation and Productivity. Research Report No. 105, International Food Policy Research Institute, Washington D.C.

Pintus, F. 1996. Impact of Irrigation, Salinity and Cultural Practices on Wheat Yield : A Study of the Fordwah/Eastern Sadiqia Area, Punjab, Pakistan. M.Sc. Thesis, *Centre National d'Etudes Agronomiques des Régions Chaudes, Montpellier*.

Strosser, P and Kuper, M. 1994. Water Markets in the Fordwah/Eastern Sadiqia Area. Working Paper No.30, International Irrigation Management Institute, Colombo.

The World Bank. 1994. Pakistan Irrigation and Drainage - Issues and Options. Report No. 11884-PAK, the World Bank, Washington D.C.

# IMPLEMENTING AN INTEGRATED APPROACH TO ASSESS THE IMPACT OF INTERVENTIONS ON IRRIGATION SYSTEM PERFORMANCE

Marcel Kuper, Frédéric Labbé and Pierre Strosser

## Abstract

Drastic changes in irrigation sector policies have been proposed to improve irrigation system performance in Pakistan. Little is known, however, on the potential impact of these interventions. This paper presents an integrated approach, developed in collaboration by IIMI and Cemagref, to assess the impact of management and policy changes on water supply, agricultural production and farm income, and salinity and sodicity. To illustrate its potential use, the integrated approach is applied to the analysis of the reallocation of surface water supplies between tertiary units to mitigate salinity and sodicity risk. Selected issues related to the development and application of the integrated approach that may be of relevance for similar research efforts, are summarised in the final section of the paper.

## Introduction

Recently, there have been many discussions about the performance of Pakistan's irrigation system in the context of a disappointing agricultural production (World Bank, 1994). The key question that needs to be answered is how the available water resources can be better managed to provide farmers with the right amount of water at the right time. An improvement of the irrigation system performance requires interventions, but before doing so, one must know which intervention or package of interventions would have the highest pay-off under the present physical and socio-economic conditions. Also, improving agricultural production is important, but sustainability issues should not be overlooked, and are a major element to be considered for the identification of new irrigation sector policies. Such issues include salinity, sodicity, the mining of the groundwater, and waterlogging (Kijne and Kuper, 1995).

At present, no methodology and/or tool are available to investigate the scope for changes in canal water deliveries, and to determine the impact of such changes on enhancing the farmers' capability to improve agricultural production and its sustainability. There is a need for the development of such tools to support policy makers and irrigation managers in assessing the impact of management interventions, and to evaluate whether a better canal irrigation management could reduce the need for high cost works on infrastructure.

IIMI and Cemagref, in collaboration with several other research institutes, have designed a research programme *to develop and apply an integrated approach to assess the impact of irrigation policy and management interventions on water supply, agricultural production, salinity and sodicity.* This approach should provide information to policy makers, irrigation managers, and other actors in an irrigation system to increase their understanding of how the irrigation system functions, and to enable a comparison of the impact of various interventions before the selection and implementation of any of these interventions.

H 22407

The approach is applied in the Chishtian Sub-division, an irrigation system in the south-east Punjab with a command area of 75,000 ha. The Chishtian Sub-division is part of the Fordwah-Eastern Sadiqia irrigation system. The main crops are cotton and rice in the summer, and wheat in the winter. Sugarcane and fodder are also cultivated in the area. The climate is (semi-) arid, with annual evaporation far exceeding the rainfall. The area is served by the Fordwah Branch canal and 14 secondary canals that supply surface water to around 520 tertiary units. Farmers augment canal water supplies by tapping the groundwater through shallow tube wells. In total, there are about 4,400 private tubewells in the command area of the Chishtian Sub-division. Groundwater table depths range from 1 to 6 metres, but are mostly below 2 metres. Salinity and sodicity are important concerns in the area. The use of poor quality groundwater is seen as a threat for further salinization and sodification.

The following section of the paper presents the main elements of the integrated approach developed in the Chishtian Sub-division. To illustrate the potential of the integrated approach, an application is presented, and is focused on the analysis of the link between the allocation of surface water supplies between tertiary units and environmental variables, such as salinity and sodicity. The last section, and conclusion, discusses selected issues related to the development and application of the integrated approach.

# Methodology

## *General*

The overall methodological framework, or *integrated approach*, developed to assess the potential impact of management and policy changes on irrigation system performance, is presented in Figure 1. More specifically, this framework includes:

- The understanding of the complexity of the irrigation system where a large number of inter-linked biophysical and decisional processes take place. This analysis leads to a *representation* of the irrigation system that is accepted, and recognised, by researchers from different disciplines.
- The investigation of the *main bio-physical and decisional processes*, based on the analysis of the existing situation, and the development of simulation models, to test the impact of changes in input variables on the output of these processes.
- The analysis of the *spatial diversity* of the main variables and parameters of these processes.
- The *operationalization* of the integrated approach with the development of links between the simulation models developed for different processes, and between these models and the database that account, for the spatial diversity of the environment under study. These activities lead to the development of an *integrated tool* that can be used to assess the impact of changes in a given variable, or parameter, on output of the various processes selected for the analysis.

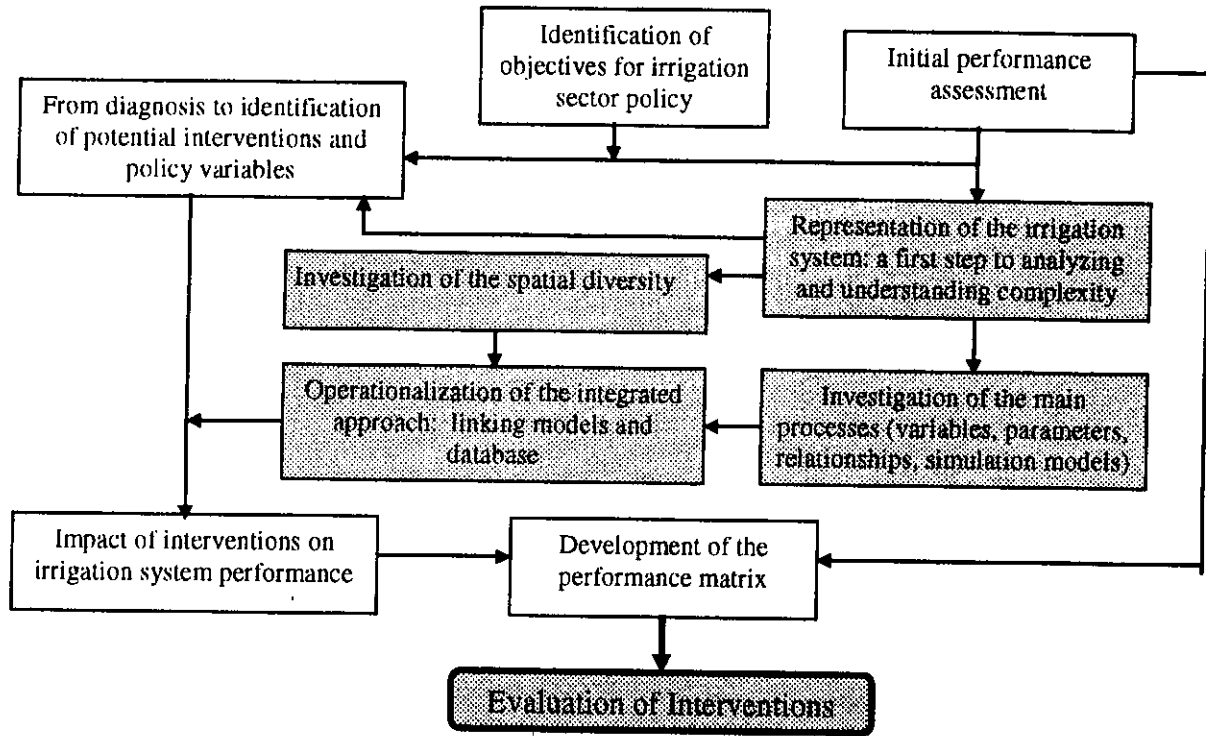**Figure 1.**     The Integrated Approach: Analytical Framework to Assess the Impact of Management Interventions on Irrigation System Performance (Source: Strosser 1997).

*Selection of Processes and Models*

The main processes that have been investigated in the Chishtian Sub-division, along with the different simulation models developed for the analysis of these processes, are summarised in Table 1.

**Table 1.** Processes Investigated and Models Used for the Development of the Integrated Approach in the Chishtian Sub-division (Adapted from Strosser, 1997).

| Process | Name of model/software | Type of model | Spatial unit of analysis | Model/software developed by | Source |
|---|---|---|---|---|---|
| Water allocation and distribution at main canal | SIC version 2.1 + Gateman | Hydro-dynamic hydraulic model | Main canal | Cemagref, Cemagref-IIMI | Malaterre (1997), Litrico (1995), Kuper (1997) |
| Water allocation and distribution at secondary canal | SIC version 2.1 | Hydro-dynamic hydraulic model | Secondary canal | Cemagref | Malaterre (1997), Kuper (1997) |
| Canal and tubewell water allocation/distribution along the tertiary unit | Stochastic linear programming model for tertiary units (Micro-LP software) | Linear programming model | Tertiary unit | IIMI | Strosser (1997) |
| Impact of canal water supply on agricultural production | Stochastic linear programming farm model (Micro-LP software) | Linear programming model | Farm | IIMI | Strosser (1997) |
| Impact of water supply on sodicity | Empirical sodicity equation (spreadsheet) | Statistical model | Field, tertiary unit | IIMI | Kuper (1997) |
| Impact of water supply on salinity | SWAP93 | Hydro-dynamic solute-transport model | Field, tertiary unit | Wageningen Agricultural University | van Dam et al. (1997), Smets (1996), Kuper (1997) |

## Analysis of the Spatial Diversity

To investigate the spatial diversity that exists within the irrigation system is an important element of the integrated approach, required to:

- Understand the heterogeneity that exist within the irrigation system for the variables and parameters of importance for the main bio-physical and decisional processes investigated;
- Identify representative areas with specific characteristics and constraints that are to be analysed in detail, and for which simulation models will be developed, calibrated and validated; and
- Specify the values of parameters of simulation models for use of these models in areas other than the ones for which they have been calibrated and validated.

In the Chishtian Sub-division, the main variables that have been investigated include :

- Physical environment: encompassing groundwater quality, soil type;
- Irrigation: encompassing position within the irrigation system, lining within the tertiary unit, estimated surface water supply, and importance of private tubewells;

- Socio-economic characteristics, encompassing farm size, tenancy status, level of mechanisation; and
- Agricultural production, encompassing the importance of different crops, importance of fallow and barren land.

Using this information, several classifications have been performed, including:

- Based on a detailed analysis of the soils in the Chishtian Sub-division, a classification with 4 soil classes is proposed. The SWAP93 model is then calibrated and validated for each soil class.
- Typology of farms was identified using different strategies and constraints expected to influence farmer's decisions and the impact of changes in canal water supply on cropping pattern. Nine types of farms with different farm strategies and constraints have been identified, using statistical techniques. Economic stochastic linear programming models have been developed for each type of farm.
- Classification of tertiary units was enabled by the large heterogeneity within the Chishtian Sub-division in terms of physical characteristics, socio-economic characteristics of farmers, access to output markets, and position within the irrigation system and canal water supply, is analysed at the scale of the tertiary unit. A typology of tertiary units is performed using statistical techniques. Different classes of tertiary units are identified and stochastic linear programming models are built for each class of tertiary unit.

The information collected for the Chishtian Sub-division is stored in a Geographic Information System (GIS). This GIS will also be used to display the output, and results, of the different scenario simulations.

*Operationalizing the Integrated Approach*

The operationalization of the integrated approach includes the development of links between the different simulation models presented in Table 1, and the development of links between these models and the spatial database. A schematic diagram of the integrated tool developed in the Chishtian Sub-division is presented in Figure 2.

The integrated tool was built using a MATLAB platform, which allows easy linking between models and intermediary control of process. Most of the models were programmed with the MATLAB language, except the SIC model, which remains external, and linked to the MATLAB software. In order to link the models, a common time and space step was selected. Spatial models were either aggregated at the scale of the tertiary unit (watercourse), or used directly at this scale. The month is taken as the time step to link hydraulic, economic and salinity models. The global architecture is then organized around the models presented in Figure 2, and the different parameter, input and output data sets/files.

The models are run consecutively generating temporary output files that may be used as the input for consecutive computational steps. Based on the daily inflow at the head of the main canal, the SIC model, coupled with the Gateman module that specifies operational rules, computes a daily

inflow at the head of each secondary canal. Using this information, the SIC models developed for secondary canals computes monthly canal water supplies (average and standard deviation) to each tertiary unit. For each tertiary unit, based on the appurtenance of this unit to a watercourse class, on the percentage of the watercourse area covered by each farm type, and on the individual farm models developed for each farm type, an aggregated stochastic linear programming model is built. For a given canal water supply obtained from the SIC model, these aggregated models estimate the seasonal cropping intensities, the area under the main crops, the total tubewell pumpage, and the importance of tubewell water sales and purchases. The next step is the assessment of salinity and sodicity risk using the canal and tubewell quantities and qualities as input. The SWAP93 model determines the resulting water and salt balance for the soil profiles, while an empirical equation determines the sodicity risk for each tertiary unit.
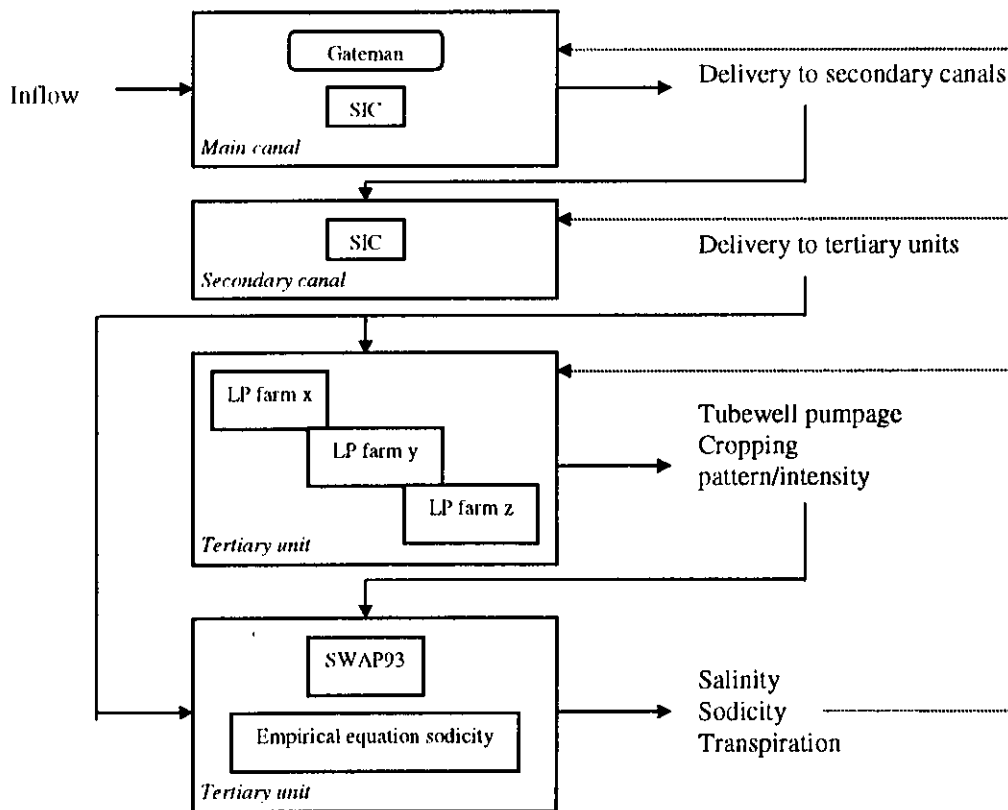


**Figure 2.**   Linking Physical and Decision-making Models to Assess the Impact of Irrigation Management Interventions on Agricultural Production, Salinity and Sodicity (Source: Kuper 1997).

A graphical interface has been developed for the integrated tool which allows the user to select the data file names, to choose the units for which simulations will be performed (all the watercourses of the scheme, all watercourses of a particular secondary unit, a particular watercourse), and to control the information process after each computational step. The interface also allows the selection of the scenario, or interventions, to be investigated. At present, the tool

estimates the impact of interventions on surface water supply, tubewell water use and sale, agricultural production and farm income, and salinity and sodicity. Interventions that can be tested include changes in irrigation sector policy, such as a change in the price for water, and changes in the hydraulic environment, such as the maintenance of the canal system, or a change in outlet dimensions. Table 2 summarizes the different types of interventions that can be investigated using the integrated approach developed in the Chishtian Sub-division.

**Table 2.**   Example of Interventions that can be Tested Using the Integrated Approach Developed in the Chishtian Sub-division.

| Intervention | Main canal | Secondary canal | Tertiary unit/farm |
|---|---|---|---|
| Construction | Lining | Lining | Lining<br>Construction of public tubewells |
| Management | Change in inflow pattern<br>Change in operational rules | Maintenance<br>Change in surface water allocation | Improved irrigation practices and change in irrigation efficiency |
| Change in the enabling environment | | | Change in water pricing<br>Establishment of water markets<br>Changes in output prices |

The following section of the paper presents the application of the integrated approach to a specific case study, i.e. the analysis of the impact of a change in canal management on salinity and sodicity.

## An Application: Impact of Canal Management on Salinity and Sodicity for the Fordwah Distributary

*Presentation of the Case Study*

With the importance of tubewell water use (more than 40% of total irrigation water), salinity and sodicity are seen as an important threat to the sustainability of irrigated agriculture in the Chishtian Sub-division. To reallocate and increase surface water supplies of good quality, an intervention similar to the reclamation activities of the Directorate of Land Reclamation of the Punjab Irrigation and Power Department, is a potential option that is expected to mitigate this threat.

The potential for surface water reallocation to mitigate salinity and sodicity is analysed for the command area of the Fordwah Distributary located at the very tail of the Chishtian Sub-division. This distributary has a command of 14,000 hectares, and supplies water to 80 tertiary units.

## Analysis of the Existing Situation

The actual situation is analysed using the integrated tool presented in Figure 3. The simulations are done using information collected for a one-year period, i.e. *Rabi* 1993/1994 and *Kharif* 1994.

In reaction to the expected canal water distribution, farmers in the Fordwah Distributary decide on a cropping pattern and intensity, for which they need to obtain a certain amount of tubewell water. Both, canal deliveries and tube well water use for the different tertiary units, are presented in Figure 3. The tertiary units are presented from head to tail of the Fordwah Distributary. The canal water supplies were simulated using the SIC-Gateman model, while the tubewell pumpage is predicted using the stochastic linear programming models developed for each tertiary unit.
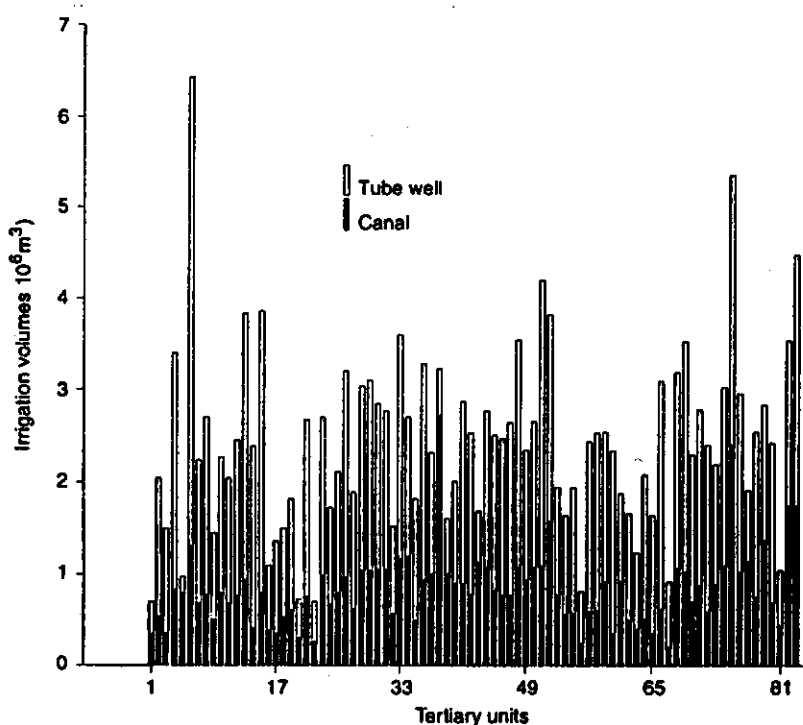


**Figure 3.**   Simulated Canal Water Supply and Predicted Tubewell Water Use During One Year in the Tertiary Units of the Fordwah Distributary for the Reference Scenario (Source: Kuper 1997).

The stochastic linear programming models also predict the cropping intensities. The output of the models were verified with data obtained through remote sensing for the study area (Vidal et al., 1996). In this way, it can be investigated whether the coupling of individual models has amplified errors, or not. The results of the comparison are presented in Figure 4. The results for the Fordwah Distributary seem quite coherent with the values estimated using remote sensing data. The pattern of predicted and measured cropping intensities match quite well, and only for a few tertiary units, larger differences can be observed.
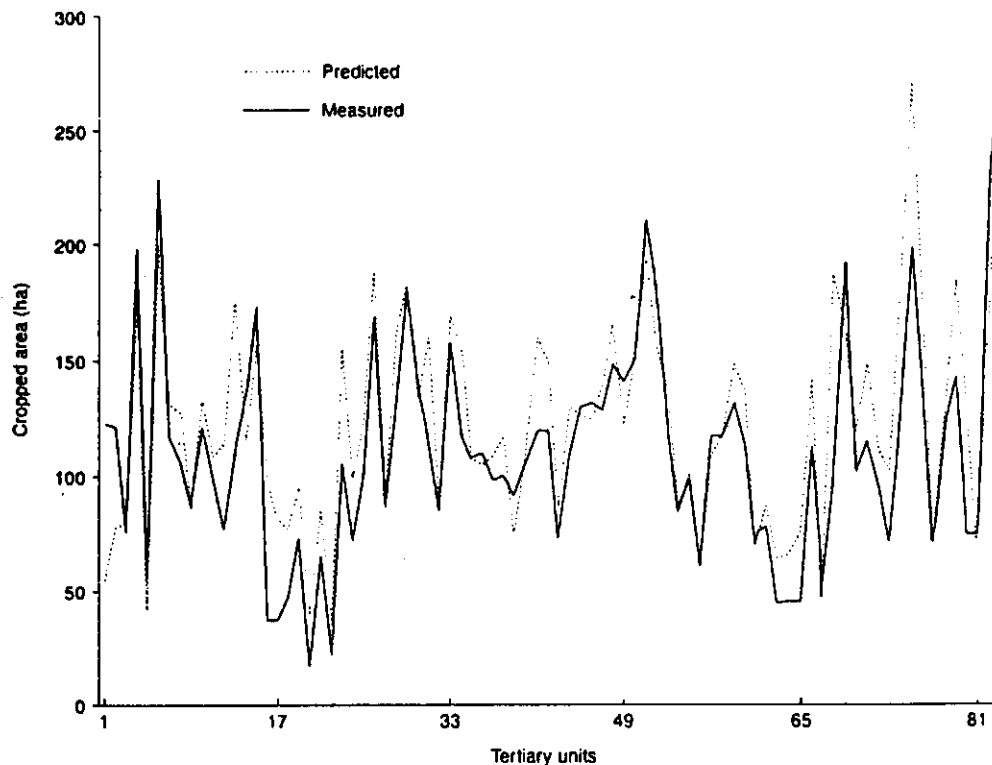
**Figure 4.** Comparison Between Measured and Predicted Cropped Area for the *Rabi* 1994-95 Season for all the Tertiary Units of the Fordwah Distributary for the Reference Scenario (Source: Kuper 1997).

The sodicity risk is represented by the SAR levels, depicted in Figure 5. The figure shows quite a variety in sodicity risk. A number of tertiary units face a risk of high levels of SAR. An area of about 3,300, ha or 25% of the command area of the Fordwah Distributary, is confronted with an SAR higher than 13, the threshold value provided by the Punjab Agricultural Department. The large differences in sodicity risk that are found between tertiary units can be explained by the spatial heterogeneity of the groundwater quality and the soils, by the different access to canal water, and also, differences in the volume of tubewell water used by farmers to complement surface water supplies.
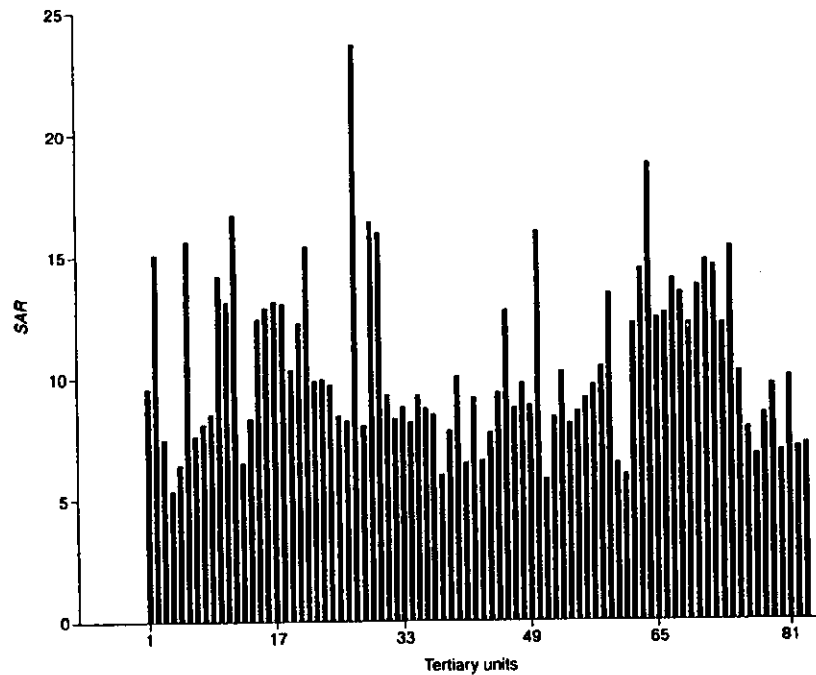
**Figure 5.** Sodicity Risk for the Tertiary Units of the Fordwah Distributary, for the Reference Scenario (Source: Kuper 1997).

*Improving the Salinity Control for the Fordwah Distributary*

Twelve outlets with the highest SAR level were selected for an increased allocation in canal irrigation supplies. The width *b* of these outlets was increased by 100%. To compensate for this increase, twenty outlets with the lowest SAR values were decreased in size by about 25%. In addition, extra canal water supplies were scheduled for the Fordwah Distributary.

Two effects of the increase in canal water supplies can be discerned. Firstly, farmers may reduce their tubewell water use and substitute tubewell water with canal water. Secondly, farmers may increase their cropping intensities and modify their cropping pattern. These effects are not instantaneous, but would, in fact, take place gradually once the interventions have been implemented. In the particular case of reallocation between tertiary units, the predictions of the stochastic linear programming models show little impact on cropping intensities. A much more significant impact, however, is predicted on soil salinity and sodicity. The impact on the sodicity level for the tertiary units of the Fordwah Distributary are depicted in Figure 6.
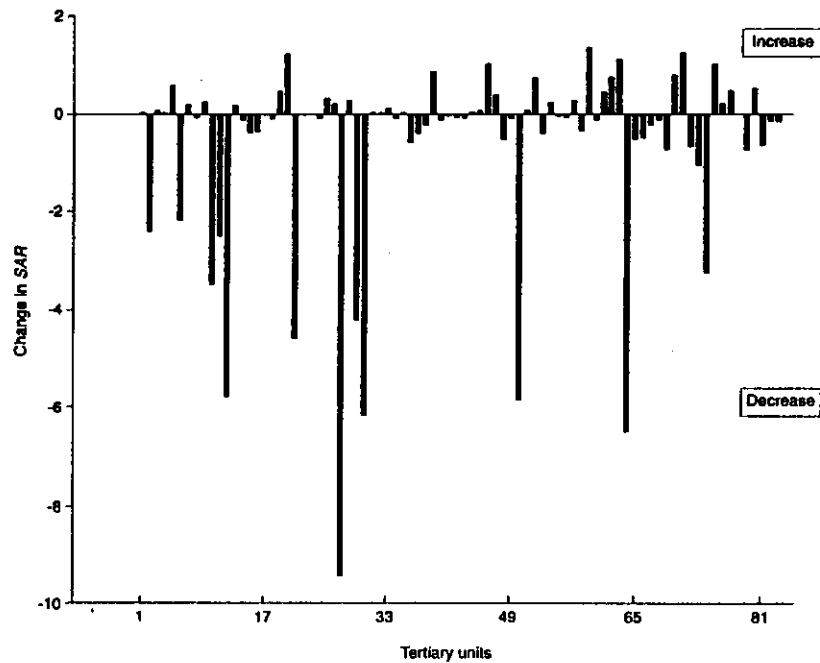
**Figure 6.**    Comparison of the SAR levels of the Tertiary Units of the Fordwah Distributary Between the Intervention and the Reference Scenario. (The results represent the SAR level after intervention, minus the SAR level for the actual situation) (Source: Kuper 1997).

The tertiary units that have a high risk of soil sodicity in the actual situation, show a considerable decrease in SAR level. Since the reductions in canal water supplies were done for tertiary units where the groundwater quality is relatively good, they are able to pump more tubewell water without doing much harm in terms of soil sodicity. In the actual situation, about 3300 ha have an SAR higher than 13. After intervention, this area is reduced by almost 40%, or 1,400 ha. At the same time, an increase in the SAR level is recorded for around 600 hectares that move from an SAR smaller than 7 to a SAR ranging from 7 to 13. This is the trade-off to be paid by reallocating surface water supplies for reducing the areas with a considerable risk of sodicity. Eventually, the end-result is a more equitable sodicity status for the Fordwah Distributary.

The time period that is required for these new sodicity levels to develop can only be given as indicative values. Condom (1996), and van Dam and Aslam (1997), show that within a year's time, the upper 30 cm of the soil profile is impregnated with sodium when irrigating with poor quality irrigation water. However, it takes a few years for the deeper layers to be affected. The reclamation of sodic soils is also a lengthy process. Farmers say they are able to reclaim most of these soils within 3-5 years, provided canal water of good quality is available.

# Discussion and Conclusions

*Follow-up Research Activities*

The development of the integrated approach has taken several years, with a large number of researchers from IIMI, Cemagref and other institutes involved in related research activities. Follow-up activities will include:

- Finalizing the development of the interface of the model . This would increase the potential number of users of the model, for research, and also for training purposes;
- Refining some of the individual models that have been linked into the approach;
- Evaluating the integrated approach that has been developed in the Chishtian Sub-division with other researchers, and potential users of the information, and of the approach;
- Testing a wider range of interventions to illustrate the potential of the integrated approach in order to provide information for policy-making processes, and to further test the robustness of the approach; and
- Disseminating the approach and results.

*Looking at the Research Process*

The integrated model, however, is only part of the integrated approach. More important, is the process itself that leads to the development of such an approach. With the increasing scarcity of water resources, the competition between users and uses, and the need to identify appropriate policies for the management of water resources, the need for integrated approaches, and the demand for information, on the impact of potential interventions, is certain.

However, the implementation of an integrated approach is often difficult. Different disciplinary teams need to co-ordinate the research, and in doing so, to harmonize research objectives and methodologies. In addition, some of the choices that need to be made for one discipline will be constrained by the needs of other disciplines. This relates, for example, to the choice of the study area, the sampling frame, or the time frame.

To achieve a successful integration, the process should start as early in the flow of research as possible. Combining research results and tools cannot be left to the last minute when it is discovered that important relationships have not been studied, and that required information is missing. The importance, for example, is that the representation of the irrigation system and the selection of the main processes that will be studied in detail, are undertaken by different researchers jointly. Also, to develop a simple integrated model in the early stages of the research, helps to identify the important variables and parameters, and to understand the trade-offs that exist between complexity and simplicity. However, an integrated approach will need to leave sufficient room for disciplinary studies to carry out their own studies.

An important aspect of the development of an integrated approach relates to information. Information requirements are relatively high, as it is important to obtain, at the same time, detailed information for the main processes and information for all the basic units of the irrigation system analysed. To decrease these information needs, it is important to carry out proper sensitivity analysis. Also, advanced techniques (statistical methods for interpolation, extrapolation, classification) will be required. Finally, the importance of the spatial variability of the main parameters and variables makes GIS an important element of the database development and management.

*Perspectives*

So far, the approach has been developed by researchers from IIMI and Cemagref. The transfer of the approach to other potential users remains an important issue. Such a transfer could take place within the context of on-going irrigation and drainage projects that offer some room for research studies, and with a direct link to the policy making-process in Pakistan. Examples of such projects include the Fordwah/Eastern Sadiqia (South) Irrigation and Drainage Project, or the National Drainage Program.

# References

Condom, N. 1996. *Salinisation, Alcalinisation et Sodifisation sur un périmètre irrigué du Pakistan*. M.Sc. Thesis, *Ecole Nationale du Génie Rural, des Eaux et des Forêts*, Montpellier, France.

Dam, J.C. van; Huygen, J; Wesseling, J.G.; Feddes, R.A.; Kabat, P. and P.E.V. van Walsum. 1997. *SWAP Users Manual. Simulation of Transport Processes in the Soil-Water-Plant Environment*. Wageningen Agricultural University, Wageningen.

Dam, J.C. van and M. Aslam. 1997. *Soil Salinity and Sodicity in Relation to Irrigation Water Quality, Soil Type and Farmer Management*. Consultancy Report No. 7, International Irrigation Management Institute, Lahore.

Kijne, J.W. and M. Kuper. 1995. Salinity and Sodicity in Pakistan's Punjab: A Threat to Sustainability of Irrigated Agriculture? *Water Resources Development*, Vol.11.

Kuper, M. 1997. *Irrigation Management Strategies for Improved Salinity And Sodicity Control*. Ph.D. Thesis, Wageningen Agricultural University, Wageningen.

Litrico, X. 1995. *Alternative Scenarios for Improved Operation at the Main Canal Level : A Study of the Fordwah Branch, Chishtian Sub-division, Using a Mathematical Flow Simulation Model*. M.Sc. Thesis, *Ecole Nationale du Génie Rural, des Eaux et des Forêts*, Montpellier, France.

Malaterre, P.O. and J.P. Baume. 1997. *SIC 3.0, A Simulation Model for Canal Automation Design*. Proceedings of the International Workshop on Regulation of Irrigation Canals: State of the Art of Research and Applications, April 1997, Marrakech.

Smets, S.M.P. 1996. *Modeling the Effects of Irrigation Management on Soil Salinity and Crop Transpiration at the Field Level*. M.Sc. Thesis, Wageningen Agricultural University, Wageningen.

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*. Ph.D. Thesis, Wageningen Agricultural University, Wageningen.

Vidal, A.; Maurel, P.; Durand, H. and P. Strosser. 1996. *Remote Sensing Applied to Irrigation System Management: Example of Pakistan*. EURISY Colloquium on Satellite Observation for Sustainable Development of the Mediterranean Area, Frascati, Italy.

World Bank. 1994. *Irrigation and Drainage - Issues and Options. Pakistan Sub-sector Report*. The World Bank, Washington D.C.

# About the Authors

Mobin-ud-Din Ahmad, Water Resources Engineer, IIMI Pakistan National Program

Salman Asif, Geographic Information System Specialist, IIMI Pakistan National Program

Gilles Belaud, Ph.D. Student, Irrigation Division Cemagref and IIMI Pakistan National Program

Yann Chemin, Associate Expert (Geographic Information Systems and Remote Sensing), IIMI Pakistan National Program

Patrice Garin, Research Program on Integrated Irrigation Management, Irrigation Division, Cemagref

Zaigham Habib, Systems Analyst, IIMI Pakistan National Program

Marcel Kuper, formerly Associate Expert, IIMI Pakistan National Program, currently Researcher at the Hydrology Laboratory, ORSTOM

Frédéric Labbé, Research Program on Integrated Irrigation Management, Irrigation Division, Cemagref

Xavier Litrico, Ph.D. Student, Irrigation Division, Cemagref

Pierre-Olivier Malaterre, Research Program on Regulation and Canal Operation, Irrigation Division, Cemagref

Ghulam Nabi, On-farm Water Management Department, seconded to IIMI Pakistan National Program

Abdul Rauf, Senior Agronomist, Watercourse Monitoring & Evaluation Directorate, Water and Power Development Authority

Thierry Rieu, Head, Irrigation Division, Cemagref

Jean-Daniel Rinaudo, Ph.D. Student Irrigation Division Cemagref and IIMI Pakistan National Program

Gaylord V. Skogerboe, Director, IIMI Pakistan National Program

Pierre Strosser, formerly Agricultural Economist, IIMI Pakistan National Program, currently Researcher at the Irrigation Division, Cemagref

Dunia Tabet, Ph.D. student, Irrigation Division, Cemagref

Alexandre Vabre, Ph.D. student, Irrigation Division Cemagref and IIMI Pakistan National Program

Alain Vidal, remote sensing applied to irrigation management and international network, Irrigation Division, Cemagref

Daniel Zimmer, head, drainage division, Cemagref

# List of Workshop Participants

| Name | Designation | Organization |
|---|---|---|
| Zaigham Habib | Systems Analyst | IIMI-Pakistan |
| Dr. G. S. Khan | Director | Soil Survey of Pakistan |
| Neeltji Kielen | Associate expert | IWASRI |
| Dr. Muhammad Aslam Chaudhry | Dean | Faisalabad Agriculture University |
| Dr. S. A. Prathapar | Research Coordinator | IIMI-Pakistan |
| Saeed ur Rehman | Agricultural Economist | IIMI-Pakistan |
| Dr. Muhammad Jamal Khan | Chairman, Water Management Department | Agricultural University N.W.F.P. |
| Dr. Manawar Hashmi | Principal Engineer | NESPAK |
| Muhammad Aslam | Principal Soil Scientist | NESPAK |
| Ch. M. Ramza Arshad | Principal Agronomist | NESPAK |
| J. D. Rinaudo | Ph. D. Student | IIMI-Pakistan/Cemagref |
| Abdul Rauf | Senior Agronomist | WMED, WAPDA |
| Yann Chemin | Associate Expert | IIMI-Pakistan |
| Thoyer Sophie | Lecturer | ENSAM, France |
| M. Badruddin | Sr. Executive | IIMI-Pakistan |
| Sanjeye Bandaragoda | Research Assistant | NRAP/IWASRI |
| Paul W. Vehmeyer | Associate Expert | IIMI-Pakistan |
| Olivier Gilard | Senior Scientist | Cemagref |
| Rieu Thierry | Head, Irrigation Div. | Cemagref |
| Gaylord V. Skogerboe | Director | IIMI-Pakistan |
| Bille Raphael | Scientist Attaché | French Embassy |
| Alain Vidal | Senior Scientist | CEMAGREF |
| M. Sadiq Hassan | Project Director | WMED, WAPDA |
| Dr. Muhammad Latif | Director | CEWRE, UET, Lahore |
| Dr. M. Akram Kahlown | Project Director | MONA Project, WAPDA |
| Mehmood-ul-Hassan | Field Research Social Scientist | IIMI-Pakistan |
| Dr. Muhammad Asghar Cheema | Sociologist | IIMI-Pakistan |
| Abdul Rehman | Sr. Engineer | IIMI-Pakistan |
| Raza-ur-Rehman Abbasi | Secondment PID | IIMI-Pakistan |
| Samia Ali | Research Assistant GIS/RS | IIMI-Pakistan |
| Cris de Klein | Associate Expert | IIMI-Pakistan |
| Robina Wahaj | Agricultural Engineer | IIMI-Pakistan |
| Amir Wazir | Hydraulic Engineer | IIMI-Pakistan |
| M. Shabbir Baig | Deputy Director | Soil Survey of Pakistan |
| Dr. M. Anwar Baig | Associate Professor | CEWRE, UET, Lahore |
| Pierre Strosser | Agricultural Economist | IIMI-Pakistan |

# IIMI-PAKISTAN PUBLICATIONS
## RESEARCH REPORTS

| Report No. | Title | Author | Year |
|---|---|---|---|
| R-1 | **Crop-Based Irrigation Operations Study in the North West Frontier Province of Pakistan** Volume I: Synthesis of Findings and Recommendations | Carlos Garces-R D.J. Bandaragoda Pierre Strosser | June 1994 |
| | Volume II: Research Approach and Interpretation | Carlos Garces-R Ms. Zaigham Habib Pierre Strosser Tissa Bandaragoda Rana M. Afaq Saeed ur Rehman Abdul Hakim Khan | June 1994 |
| | Volume III: Data Collection Procedures and Data Sets | Rana M. Afaq Pierre Strosser Saeed ur Rehman Abdul Hakim Khan Carlos Garces-R | June 1994 |
| R-2 | Salinity and Sodicity Research in Pakistan - Proceedings of a one-day Workshop | J.W. Kijne Marcel Kuper Muhammad Aslam | Mar 1995 |
| R-3 | Farmers' Perceptions on Salinity and Sodicity: A case study into farmers' knowledge of salinity and sodicity, and their strategies and practices to deal with salinity and sodicity in their farming systems | Neeltje Kielen | May 1996 |
| R-4 | Modelling the Effects of Irrigation Management on Soil Salinity and Crop Transpiration at the Field Level (M.Sc Thesis - published as Research Report) | S.M.P. Smets | June 1996 |
| R-5 | Water Distribution at the Secondary Level in the Chishtian Sub-division | M. Amin K. Tareen Khalid Mahmood Anwar Iqbal Mushtaq Khan Marcel Kuper | July 1996 |
| R-6 | Farmers Ability to Cope with Salinity and Sodicity: Farmers' perceptions, strategies and practices for dealing with salinity and sodicity in their farming systems | Neeltje Kielen | Aug 1996 |
| R-7 | Salinity and Sodicity Effects on Soils and Crops in the Chishtian Sub-Division: Documentation of a Restitution Process | Neeltje Kielen Muhammad Aslam Rafique Khan Marcel Kuper | Sept 1996 |
| R-8 | Tertiary Sub-System Management: (Workshop proceedings) | Khalid Riaz Robina Wahaj | Sept 1996 |
| R-9 | Mobilizing Social Organization Volunteers: An Initial Methodological Step Towards Establishing Effective Water Users Organization | Mehmoodul Hassan Zafar Iqbal Mirza D.J. Bandaragoda | Oct 1996 |
| R-10 | Canal Water Distribution at the Secondary Level in the Punjab, Pakistan (M.Sc Thesis published as Research Report) | Steven Visser | Oct 1996 |
| R-11 | Development of Sediment Transport Technology in Pakistan: An Annotated Bibliography | M. Hasnain Khan | Oct 1996 |

| Report No. | Title | Author | Year |
|---|---|---|---|
| R-12 | Modeling of Sediment Transport in Irrigation Canals of Pakistan: Examples of Application (M.Sc Thesis published as Research Report) | Gilles Belaud | Oct 1996 |
| R-13 | Methodologies for Design, Operation and Maintenance of Irrigation Canals subject to Sediment Problems: Application to Pakistan (M.Sc Thesis published as Research Report) | Alexandre Vabre | Oct 1996 |
| R-14 | Government Interventions in Social Organization for Water Resource Management: Experience of a Command Water Management Project in the Punjab, Pakistan | Waheed uz Zaman D.J.Bandaragoda | Oct 1996 |
| R-15 | Applying Rapid Appraisal of Agricultural Knowledge Systems (RAAKS) for Building Inter-Agency Collaboration | Derk Kuiper Mushtaq A. Khan Jos van Oostrum M. Rafique Khan Nathalie Roovers Mehmood ul Hassan | Nov 1996 |
| R-16 | Hydraulic Characteristics of Chishtian Sub-division, Fordwah Canal Division | Anwar Iqbal | Nov 1996 |
| R-17 | Hydraulic Characteristics of Irrigation Channels in the Malik Sub-Division, Sadiqia Division, Fordwah Eastern Sadiqia Irrigation and Drainage Project | Khalid Mahmood | Nov 1996 |
| R-18 | **Proceedings of National Conference on Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan** | M. Badruddin Gaylord V. Skogerboe M.S. Shafique (Editors for all volumes) | Nov 1996 |
| R-18.1 | Volume-I: Inauguration and Deliberations | | |
| R-18.2 | Volume-II Papers on the Theme: Managing Canal Operations | | |
| R-18.3 | Volume-III: Papers on the Theme: Water Management Below the Mogha | | |
| R-18.4 | Volume-IV: Papers on the Theme: Environmental Management of Irrigated Lands | | |
| R-18.5 | Volume-V: Papers on the Theme: Institutional Development | | |
| R-19 | Detailed Soil Survey of Eight Sample Watercourse Command Areas in Chishtian and Hasilpur Tehsils | Soil Survey of Pakistan IIMI-Pakistan | Nov 1996 |
| R-20 | Unsteady Flow Simulation of the Designed Pehur High-Level Canal and Proposed Remodeling of Machai and Miara Branch Canals, North West Frontier Province, Pakistan | Zaigham Habib Kobkiat Pongput Gaylord V. Skogerboe | Dec 1996 |
| R-21 | **Salinity Management Alternatives for the Rechna Doab, Punjab, Pakistan** | Gauhar Rehman Waqar A. Jehangir Abdul Rehman Muhammad Aslam Gaylord V. Skogerboe | May 1997 |
| R-21.1 | Volume One: Principal Findings and Implications for Sustainable Irrigated Agriculture | | |
| R-21.2 | Volume Two: History of Irrigated Agriculture: A Select Appraisal | Gauhar Rehman Hassan Zia Munawwar Asghar Hussain | Jan 1997 |

| Report No. | Title | | Author | Year |
|---|---|---|---|---|
| R-21.3 | Volume Three: | Development of Procedural and Analytical Links | Gauhar Rehman<br>Muhammad Aslam<br>Waqar A. Jehangir<br>Abdul Rehman<br>Asghar Hussain<br>Nazim Ali<br>Hassan Zia Munawwar | Jan 1997 |
| R-21.4 | Volume Four: | Field Data Collection and Processing | Gauhar Rehman<br>Muhammad Aslam<br>Waqar A. Jehangir<br>Mobin Ud Din Ahmed<br>Hassan Zia Munawwar<br>Asghar Hussain<br>Nazim Ali<br>Faizan Ali<br>Samia Ali | Jan 1997 |
| R-21.5 | Volume Five: | Predicting Future Tubewell Salinity Discharges | Muhammad Aslam | Jan 1997 |
| R-21.6 | Volume Six: | Resource Use and Productivity Potential in the Irrigated Agriculture | Waqar A. Jehangir<br>Nazim Ali | Feb 1997 |
| R-21.7 | Volume Seven: | Initiative for Upscaling: Irrigation Subdivision as the Building Block | Gauhar Rehman<br>Asghar Hussain<br>Hassan Zia Munawwar | Apr 1997 |
| R-21.8 | Volume Eight: | Options for Sustainability: Sector-Level Allocations and Investments | Abdul Rehman<br>Gauhar Rehman<br>Hassan Zia Munawar | Apr 1997 |
| R-22 | Salinisation, Alkalinisation and Sodification on Irrigated Areas in Pakistan: Characterisation of the geochemical and physical processes and the impact of irrigation water on these processes by the use of a hydro-geochemical model (M.Sc Thesis published as Research Report) | | Nicolas Condom | Mar 1997 |
| R-23 | Alternative Scenarios for Improved Operations at the Main Canal Level: A Study of Fordwah Branch, Chishtian Sub-Division Using A Mathematical Flow simulation Model(M.Sc Thesis published as Research Report) | | Xavier Litrico | Mar 1997 |
| R-24 | Surface Irrigation Methods and Practices: Field Evaluation of the Irrigation Processes for Selected Basin Irrigation Systems during Rabi 1995-96 Season | | Ineke Margot Kalwij | Mar 1997 |
| R-25 | Organizing Water Users for Distributary Management: Preliminary Results from a Pilot Study in the Hakra 4-R Distributary of the Eastern Sadiqia Canal System of Pakistan's Punjab Province | | D.J. Bandaragoda<br>Mehmood Ul Hassan<br>Zafar Iqbal Mirza<br>M. Asghar Cheema<br>Waheed uz Zaman | Apr 1997 |
| R-26 | Moving Towards Participatory Irrigation Management | | D.J. Bandaragoda<br>Yameen Memon | May 1997 |
| R-27 | Fluctuations in Canal Water Supplies: A Case Study | | Shahid Sarwar<br>H.M. Nafees<br>M.S. Shafique | June 1997 |
| R-28 | Hydraulic Characteristics of Pilot Distributaries in the Mirpurkhas, Sanghar and Nawabshah Districts, Sindh, Pakistan | | Bakhshal Lashari<br>Gaylord V. Skogerboe<br>Rubina Siddiqui | June 1997 |

| Report No. | Title | Author | Year |
|---|---|---|---|
| R-29 | Integration of Agricultural Commodity Markets in the South Punjab, Pakistan | Zubair Tahir | July 1997 |
| R-30 | Impact of Irrigation, Salinity and Cultural Practices on Wheat Yields in Southeastern Punjab, Pakistan | Florence Pintus | Aug 1997 |
| R-31 | Relating Farmers' Practices to Cotton Yields in Southeastern Punjab, Pakistan | P.D.B.J. Meerbach | Aug 1997 |
| R-32 | An Evaluation of Outlet Calibration Methods: A contribution to the study on Collective Action for Water Management below the Outlet, Hakra 6-R Distributary | Arjen During | Aug 1997 |
| R-33 | Farmers' use of Basin, Furrow and Bed-and-Furrow Irrigation Systems and the possibilities for traditional farmers to adopt the Bed-and-Furrow Irrigation Method. | Nanda M. Berkhout<br>Farhat Yasmeen<br>Rakhshanda Maqsood<br>Ineke M. Kalwij | Sep 1997 |
| R-34 | Financial Feasibility Analysis of Operation and Maintenance Costs for Water Users Federations on three distributaries in Province of Sindh, Pakistan. | Amin Sohani | Sep 1997 |
| R-35 | Assessing the Field Irrigation Performance and Alternative Management Options for Basin Surface Irrigation Systems through Hydrodynamic Modelling. | Ineke Margot Kalwij | Oct 1997 |
| R-36 | Socio-Economic Baseline Survey for Three Pilot Distributaries in Sindh Province, Pakistan. | Yameen Memon<br>Mehmood Ul Hassan<br>Don Jayatissa Bandaragoda | Nov 1997 |
| R-37 | Socio-Economic Basline Survey for a Pilot Project on Water Users Organizations in the Hakra 4-R Distributary Command Area, Punjab. | Muhammad Asghar Cheema<br>Zafar Iqbal Mirza<br>Mehmood Ul Hassan<br>Don Jayatissa Bandaragoda | Dec 1997 |
| R-38 | Baseline Survey for Farmers Organizations of Shahpur and Mirwal Small Dams, Punjab, Pakistan. | Muhammad Asghar Cheema<br>Don Jayatissa Bandaragoda | Dec 1997 |
| R-39 | **Monitoring and Evaluation of Irrigation and Drainage Facilities for Pilot Distributaries in Sindh Province, Pakistan** | | |
| R-39.1 | Volume One:    Objectives, Stakeholders, Approaches and Methodology | M.S. Shafique<br>B.K. Lashari<br>M. Akhtar Bhatti<br>Gaylord V. Skogerboe | Dec 1997 |
| R-39.2 | Volume Two:    Bareji Distributary, Mirpurkhas District | B.K. Lashari<br>Waryam Balouch<br>Ghulam Mustafa Talpur<br>Muhammad Nadeem<br>Asghar Ali Memon<br>Badrul Hassan Memon<br>M. Akhtar Bhatti<br>M.S. Shafique<br>Gaylord V. Skogerboe | Dec 1997 |
| R-39.3 | Volume Three:    Dhoro Naro Minor, Nawabshah District | B.K. Lashari<br>Abdul Rehman Soomro<br>Nizamuddin Bharchoond<br>Muneer Ahmed Mangrio<br>Parvez Ahmed Pirzado<br>Fateh Mohammad Mari<br>M. Akhtar Bhatti<br>M.S. Shafique<br>Gaylord V. Skogerboe | Dec 1997 |

| Report No. | Title | Author | Year |
|---|---|---|---|
| R-39.4 | Volume Four: Heran Distributary, Sanghar District | B.K. Lashari<br>M. Naveed Khayal<br>Niaz Hussain Sial<br>Abdul Majeed Ansari<br>Abdul Jalil Ursani<br>Ghulam Shabir Soomoro<br>M. Ghous Laghari<br>M. Akhtar Bhatti<br>M.S. Shafique<br>Gaylord V. Skogerboe | Dec 1997 |
| R-40 | **Maintenane Plans for Irrigation Facilities of Pilot Distributaties in Sindh Province, Pakistan.** | | |
| R-40.1 | Volume One: Dhoro Naro Minor, Nawabshah District | Abdul Rehman Soomro<br>Munir Ahmed Mangrio<br>Nizamuddin Bharchoond<br>Fateh Muhammad Mari<br>Parvez Ahmed Pirzado<br>Bakhshal Lashari<br>M. Akhtar Bhatti<br>Gaylord V. Skogerboe | Dec 1997 |
| R-40.2 | Volume Two: Heran Distributary, Sanghar District | Abdul Majeed Ansari<br>Niaz Hussain Sial<br>Abdul Jalil Ursani<br>Ghulam Shabir<br>M. Ghous Laghari<br>M. Naveed Khayal<br>Bakhshal Lashari<br>M. Akhtar Bhatti<br>Gaylord V. Skogerboe | Dec 1997 |
| R-40.3 | Volume Three: Bareji Distributary, Mirpurkhas District | Asghar Ali Memon<br>Waryam Balouch<br>Ghulam Mustafa Talpur<br>Muhammad Nadeem<br>Badrul Hassan Memon<br>Bakhshal Lashari<br>M. Akhtar Bhatti<br>Gaylord V. Skogerboe | Dec 1997 |
| R-41<br><br>R-41.1 | **Preliminary Business Plans**<br><br>Volume One: Dhoro Naro Minor, Nawabshah District | Pervaiz Ahmad Pirzada<br>Mohsin Khatri<br>Syed Daniyal Haider | Dec 1997 |
| R-41.2 | Volume Two: Bareji Distributary, Mirpurkhas District | Muhammad Nadeem<br>Mohsin Khatri<br>Syed Daniyal Haider | Dec 1997 |
| R-41.3 | Volume Three: Heran Distributary, Sanghar District | Niaz Hussain Sial<br>Mohsin Khatri<br>Syed Daniyal Haider | Dec 1997 |
| R-42 | Prospects of Farmer-Managed Irrigated Agriculture in the Sindh Province of Pakistan. LBOD Project Final Report | D.J. Bandaragoda<br>Yameen Memon<br>Gaylord V. Skogerboe | Dec 1997 |
| R-43 | Study Tour of Pakistani Pilot Project Farmer-Leaders to Nepal | Mehmood Ul Hassan<br>Yameen Memon | Jan 1998 |
| R-44 | Self-Help Maintenance Activities by the Water Users Federation of Hakra 4-R Distributary | Waheed uz Zaman | Feb 1998 |

| Report No. | Title | Author | Year |
|---|---|---|---|
| R-45 | Semi-Detailed Soil Survey of Chishtian Irrigation Sub-Division | Soil Survey of Pakistan IIMI-Pakistan | Mar 1998 |
| R-46 | Tenancy and Water Management in South-Eastern Punjab, Pakistan | Annemiek Terpstra | Mar 1998 |
| R-47 | The Collaboration between the International Irrigation Management Institute and Cemagref in Pakistan: Proceeding of a one-day workshop | IIMI Cemagref | Apr 1998 |