

## TOWARDS IMPROVED DRAINAGE PERFORMANCE IN PAKISTAN<sup>1</sup>

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### Abstract

Review of the performance of drainage systems in Pakistan shows that the installed tubewell and pipe drainage systems are capable of controlling the water table. Moreover, the soil salinity status has improved in many systems also. Nevertheless, there have been problems, e.g. with the choice of technology, and the operation and maintenance of the systems. Current practice is that the Government funds operation and maintenance, within its limitations. This cannot continue forever, and the users will have to take their share as well.

The Government of Pakistan and the World Bank have prepared a National Drainage Program, NDP, with objectives to: (i) Improve the management of public expenditure in drainage; (ii) Strengthen key drainage institutions; (iii) Initiate changes in the legal and regulatory framework to facilitate implementation of a new strategy. This strategy includes surface and pipe drainage schemes, small schemes to alleviate drainage and public health problems, mitigatory measures to protect the environment and increase the drainage efficiency.

A development concurrent to the NDP is the participatory approach to drainage, as started by IWASRI, in cooperation with NRAP. After a Workshop on Options to Involve Farmers, a pilot area study was started, in a waterlogged and saline area, where the research team was the first serious contact with the population to address the drainage problem. That is considered the best possibility to move forward as partners in the planning, design and construction of a drainage unit in a participatory way.

The research results have made clear that: (i) the social and economic framework in which the users of (future) drainage systems live, determines their capacity to cooperate towards solutions to the drainage problem; (ii) They should be involved in (future) drainage systems, from the planning stages onward.

### Introduction

In Pakistan 75% of the population depends, directly or indirectly, on agriculture. This sector contributes 50% to the gross national product. Today the Indus Basin has a vast contiguous

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<sup>1</sup> This is a slightly modified version of a paper that was presented at the sixteenth congress of the International Commission on Irrigation and Drainage (ICID), held in September 1996 in Cairo, Egypt

irrigation system, developed over the past 150 years and commanding a net area of 14 million hectares. The climate in the basin is semi-arid to arid, hence the necessity of irrigation to support agriculture. The rapid expansion of the system and the increase in cropping intensities, to cope with the ever increasing population, combined with the flat topography and the lack of well defined natural drainage in the Indus basin has caused serious waterlogging and salinity problems. Since the early sixties the Government of Pakistan has made huge investments to control these problems and to cope with water shortages. By mid-1994, surface and subsurface drainage facilities had been installed in 6 million hectares at a cost of Rs. 21 billion. Ongoing constructions, covering over 2 million hectare require another Rs. 20 billion (NESPAK-MMI, 1995). In spite of these measures, salinity, sodicity and waterlogging problems persist in the Indus basin and threaten the sustainability of irrigated agriculture and, hence, the livelihood of future generations. Monitoring the performance of the completed drainage projects revealed that some had been reasonably successful, whilst others failed to deliver the expected results. Causes for failure are related to: (i) deficiencies in policy and institutional matters; and (ii) low priority given to allocation of resources for the operation and maintenance (O&M) of drainage facilities in favor of initiating new projects (World Bank, 1994).

The O&M of irrigation, drainage and flood protection facilities is the primary responsibility of the Provincial Irrigation Departments. The administrative structure of these departments was primarily established around the extensive canal irrigation systems. With the establishment of deep tubewell-, surface- and sub-surface- drainage systems, separate sections were simply added to the administrative structure and not integrated in the existing set-up. This resulted in an extremely diffusive situation as to the responsibilities for the operation and maintenance of the deep tubewells, the surface drainage system and the horizontal subsurface drainage system (Bandaragoda and Firdousi, 1992). This was further exacerbated by problems concerning the safe disposal of saline drainage effluent. Funds for the operation and maintenance of these various systems kept decreasing in real financial terms; with 63% of the annual budget allocation going to the establishment, and 21% to flood protection embankment maintenance, only 16% remains for the operation and maintenance of the surface drainage system (NESPAK-MMI, June 1993). Hence the deplorable state of this surface drainage system and the far below design capacity operating deep tubewells. In the fresh groundwater zones the public tubewells have been superseded by private shallow tubewells, intentionally to supply additional water for irrigation but at the same time controlling the groundwater table. Given the failure of the Government to mobilize sufficient funds for an appropriate O&M of the various systems to control waterlogging and salinity, the National Drainage Program strongly advocates private sector participation in drainage. This though, would not be a policy that can be implemented easily for the following three reasons. The first reason is that farmers rank water shortage as the major production constraint (63%), while waterlogging comes far second (15%) (Ahmad M. and G.P. Kutcher, 1992). The second reason is that drainage problems are often caused by practices in adjacent areas, hence creating a feeling of unjustness with the farmers if they would have to bear the costs for the system. A third reason is the lack of goal-oriented motivation in the public sector. Henceforth, enormous changes need to be initiated to: (i) convince the farming community that investments in (on-farm) drainage measures will strongly improve agricultural productivity, and (ii) provide incentives to the public sector staff to introduce the enormous changes that increased private participation implies. Anyhow, the government is no longer able to carry the burden of the total costs of operation and maintenance of the systems. For this reason drastic institutional changes, including the participation and direct involvement of the producers are inevitable.

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This paper describes participatory action research on working with farmers to implement on-farm measures to solve waterlogging and salinity problems in a pilot area in Bahawalnagar Tehsil in South-East Punjab (Figure 1).

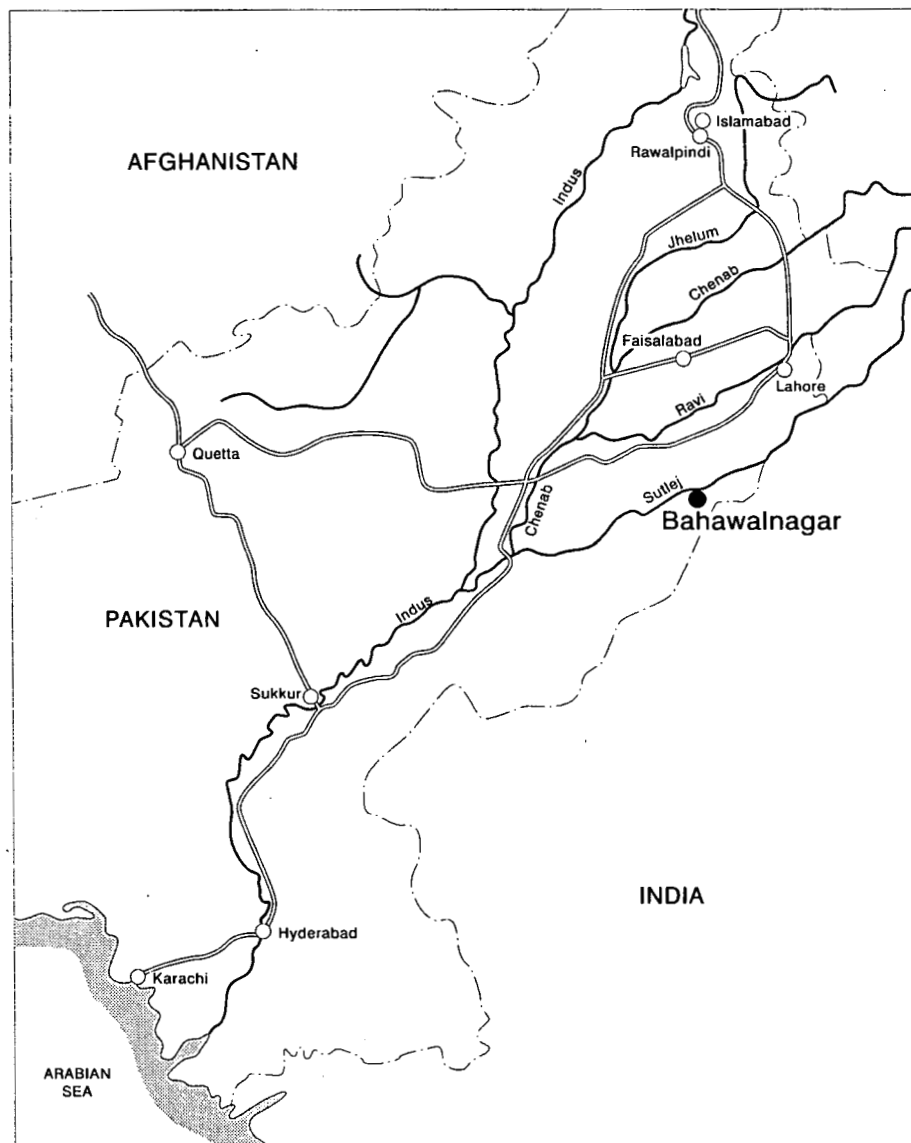


Figure 1. Location of the Bahawalnagar Pilot Area

### Towards participatory drainage research

In addressing the O&M issue, the National Drainage Programme (NESPAK-MMI, 1995) focusses on the sustainability of the irrigation and drainage system. The conceptual framework of the National Drainage Programme mentions three specific objectives: (a) participation of farmers' organizations and the private sector in construction, operation and

maintenance of drainage facilities; (b) targeting government investment on areas in greatest need of drainage; and (c) quicker returns by targeting drainage investments on smaller scale, quicker yielding interventions. The NDP proposes to directly involve farmers in the planning, design, construction, operation and maintenance of on-farm drainage systems. It presents modes for setting up and operating farmers' organizations and stipulates that research should develop instruments to involve the farmers. NDP admits that there is limited experience with direct farmer participation in on-farm drainage in Pakistan and states that initially the technical capacity will be weak. During a transition stage farmers could learn, with assistance and guidance from professionals, either directly or through Non-Governmental Organizations (NGO's).

The International Waterlogging and Salinity Research Institute (IWASRI) embarked, concurrent to the NDP, on participatory action research in drainage, waterlogging and salinity. One of its activities concerns the transfer of research results directly to the end-users, through the Joint Satiana Pilot Project. This project, which is also supported by UNDP, aims at the introduction of salt tolerant trees and shrubs on abandoned saline lands. Another activity, supported by the Netherlands Research Assistance Project, aims at the introduction of non-technical issues in the mainstream research on waterlogging, salinity and drainage. One of the NRAP supported activities is the result of a workshop held at IWASRI on ways and means to start participatory action research in drainage (IWASRI-NRAP, 1995). The favored option, conceived in the workshop, was to start a pilot study in a waterlogged and saline area and implement measures to overcome these problems with full participation of the farmers.

## **Participatory implemented drainage system**

### **How to involve farmers**

Against the background of the gradually decreased capabilities of the government to take effective and efficient responsibility for the operation and maintenance of the system, privatization is advocated as the only way out. The 'aloofness' of the civil service concerning the 'know-how' of the farmers and their belief of farmers' incapability to identify and handle their real problems, has created the so-called credibility and confidence gap. To regain the trust and confidence of the farmers in the government service, the general feeling is that NGO's should be involved to: (1) assist farmers in organizing themselves; in analyzing their real problems and in regaining confidence with the government service, and 2) work on drastically changing the attitude of the service staff towards the farming community, from 'aloofness' and 'depreciation' into appreciation and esteem for farmers' insight in their productive environment and their know-how about its potentials for improvement and development. This idea is based on experience in different countries in the region which has shown that NGO's do understand the social, cultural, economic and political conditions of government and local communities, which enables them to devise modes for building understanding of common interests. Hereto IWASRI/NRAP called-in the assistance of ACTIONAID-Pakistan (AAPk), to involve, communicate with, mobilize and organize the farmers. The NGO had expertise in working with rural communities towards social development and had an interest, in compliance with IWASRI, to start a new programme in a poverty stricken area in the Punjab. One of the attractive points for IWASRI to collaborate with AAPk is their objective to improve demand-based delivery and coordination of services by government agencies to communities, and a fairer allocation of resources by the

government, in response to the real felt needs of rural communities. To build confidence and raise awareness with the community, the NGO required a starter activity around an acute problem threatening the livelihood and well-being of the rural community. The area selected suffers greatly from waterlogging and salinity, large tracts of lands being abandoned, and still cultivated lands suffering from salinity.

IWASRI and AAPk may be convinced though, that waterlogging and salinity are the foremost threat to a sustained livelihood for the rural community, with whom they plan to work towards improvement of their socio-economic conditions, but does the rural community also conceive it that way? If so, will the farmers be prepared to invest in solving the problem? If so, what assistance would the farmers need to get organized, and to mobilize their resources and know-how? To get answers to these questions, and to explore the willingness of the communities to work with the NGO towards development, the technique of Participatory Rural Appraisal (PRA) was applied.

### **Participatory rural appraisal**

Participatory development can only be achieved if the rural communities are willing to: (i) organize themselves in community based organizations; (ii) work together as a group in identifying their real needs, developing solutions to the identified problems, be prepared to discuss the various possible solutions to the problem openly and freely with agency staff, come to an acceptable solution and are committed and willing to work together towards its implementation; and (iii) clarify and agree on their contribution towards the full-fledged implementation and their acceptance of their own responsibilities towards the operation and maintenance activities.

At this point it is important to note that AAPk's objective is to build capacity in communities to become fully involved in planning and implementing their own development that is sustainable in social, economic and environmental dimensions. Its strategy consists of three components: (i) long-term involvement; (ii) developing community organizations for participation: a viable Community Management Structure will be central in identifying needs, selecting the type of program and its design, implementation, and monitoring and evaluation, as well as detailing the different responsibilities of the different actors involved; (iii) enhancing community capacity through entry point activities: the program content would be based on the communities' assessment of their needs and priorities. An essential entry activity could be based on the principal activities of IWASRI in the selected pilot areas.

The need-assessment analysis with the community through the PRA investigation process would not necessarily yield waterlogging and salinity as the primary problem conceived by the community. One of the drawbacks of a first and open contact of outsiders with rural people, not accustomed to being listened to and their opinion asked, will definitely raise their expectations. But with the long-term interest of AAPk in working with the communities, this was not considered a problem. AAPk, in consultation with IWASRI, decided to hold a first exploratory PRA in 6 villages of two Union Councils in Bahawalnagar District. The team members, who would conduct the ten days field work, received first a two day training in PRA-techniques and held a one day brainstorming session to determine key questions, main and sub topics, sources of information and tools to be applied to acquire the information. The field work was carried out in ten days by three teams of 4 people each, in a mixed composition of NGO and IWASRI staff, and 2 specialist moderators. The PRA was

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exploratory as AAPk itself was only recently introduced to the people in the area. It requires time to build confidence with the people. The PRA attempted to explore the perspective of the community on the waterlogging and salinity problems as caused by the irrigation system. The community was involved as: (i) providers of relevant knowledge and information based on several PRA tools (map, trend lines, cropping calendars and water need periods, ranking, pie charts); (ii) analyze the problems related to irrigated agriculture with help of cards and flow charts which visualized causes, effects and possible solutions; and (iii) cross-checking of information received through triangulation. Some conclusions of special interest to IWASRI/NRAP in their aim to develop on-farm drainage measures with the farmers are: (i) organizational: dominance by certain feudal families is a major issue in the area as this impedes the introduction and evolution of democratic norms and collective decision making and action; (ii) gender imbalances: women in the area are an unrecognized, though vital, human resource and have little say in decisions taken, many of which have a direct impact on them; (iii) environmental degradation: the irrigation system put into place in the early sixties, has brought the evils of waterlogging, salinity and sodicity, rendering large tracts of land unproductive, threatening the livelihood of the rural people.

The NGO will continue its contacts with the people and in doing so will build trust and confidence, which is a necessary prerequisite for participatory development. These regular interactions with the people will further contribute to clarifying the picture on the socio-economic conditions and the organizational setting of the local communities.

The increasing loss of agricultural lands due to waterlogging, sodicity and salinity is considered by the communities as one of their biggest problems. People are of the opinion that once this problem would be solved, many related problems - such as health and rural water supply - could then easily be overcome.

### **Selection of pilot area**

Given the limited financial resources to both organizations it was decided that the pilot area to start the participatory action research should not be larger than 100-150 ha. Criteria agreed upon for the final selection of the pilot site were: (i) community should be poverty stricken; (ii) area severely degraded by waterlogging and salinity; (iii) area with many small holdings and no feudal dominance; (iv) area easily accessible for demonstration impact; and (v) land ownership. Field visits and a walk-through were conducted before a final choice for the pilot area could be made. These visits were carried out initially by NRAP/IWASRI and AAPk staff. Later, staff of the Irrigation and Agricultural Departments joined in the site selection. Criteria for site-selection were defined during the learning process of getting to grips with: (i) the general topography and hydrology of the area; (ii) the possibilities of temporary evacuation of the drainage water; (iii) the land tenure situation; (iv) the potential solutions to the problem, manageable and operable by the beneficiaries; and (v) the willingness to cooperate of representatives of the community and local Government Agencies.

When the potential site was selected, meetings were held with the farmers of those lands. In these meetings, attended by all actors involved, the possibilities of solving the waterlogging and salinity problem were discussed with the farmers. Farmers explicitly made clear that they were willing to work with the NGO and Government Agencies in solving these problems. The area was also selected because, according to the land tenure survey, these

lands are cultivated by many small landholders (114) all residing in one village. According to the PRA, there are no feudal families dominating this village, which under the prevailing social and cultural conditions in the Punjab would make the formation of a farmers organization extremely difficult (Merrey, 1986).

### **Development of working relations with government agencies**

One of the objectives of both the NGO and IWASRI is to draw upon the services of the Government Agencies present in the area and in doing so, create an awareness among their field staff on the need for attitudinal changes in dealing with the farmers. Hereto contacts were made with the On-Farm Water Management Directorate in the Fardwah Eastern Sadiqia (South) Irrigation and Drainage Project, Agricultural Extension of the Punjab Department of Agriculture, and the Sadiqia Division of the Punjab Irrigation Department, all at Bahawalnagar. All organizations expressed their willingness and interest to work with the NGO and IWASRI on the Pilot project and assist with the technical surveys. From each organization a staff member participated in the walk-through and in the meetings with the farmers.

### **Development of community management structures**

To enhance the capacities of communities to identify and exploit resources for development, the NGO is to develop and strengthen accountable and equitable community management structures, which can sustain development initiatives and redress societal discrimination. This will be done by strengthening the community based organization or by developing new community management structures taking into account existing social structures.

### **Technical survey of the pilot area**

The technical survey could not start before final selection of the pilot site and farmers expressed willingness to work together towards a solution to their waterlogging and salinity problems. A detailed proposal was prepared for the technical survey, based on a rapid appraisal of potential solutions to the waterlogging and salinity problem in the selected area, and discussed with the NGO and farmers representatives of the village concerned. Farmers expressed their willingness to assist in the field survey. But a disadvantage was the timing of the field surveys, at a time that farmers were busy with their regular farming activities, like harvesting of wheat and land preparation and sowing of the successive cotton crop. Nevertheless, farmers showed an interest in what was going on in their fields by sending some representatives to assist whenever possible. In the long run it is felt to be extremely important that farmers do not feel overruled or cut-out from any step taken along the long road leading towards a participatory implemented drainage system. In the end they should really consider it their own system, created by themselves, only assisted and guided therein by the governmental agencies.

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### **Formation of a farmers organization.**

Formation of a Farmers Organization (FO), as a sub-unit of the CBO (community based organization), for the anticipated drainage unit. This may require communally developed and accepted solutions to such questions as: (i) need for cooperation between different classes (land owners, tenants, share-croppers); (ii) need for cooperation between different kinship groups; (iii) need for cooperation between members of different villages; and (iv) need for cooperation between farmers of different water courses.

Still there remains another set of questions to be resolved: (i) from experience on FO's it has been proven that the social group cohesion is more sustainable if based on kinship relations (Merrey, 1986). But will this imply the complexities of more than one FO-responsible for one drainage unit?; (ii) it has been proven in irrigation management that FO's based on hydraulic units function more efficiently than social based FO's. But will this complicate the social cohesion sustainability of the group?; and (iii) how do or do not watercourse command areas coincide with the hydraulic boundaries of drainage units? If not, will it further complicate matters as to one FO for both functions? If an area has strong village councils (community based organizations); they may be able to take-up drainage, alongside other activities such as roads, health, education. Probably it is wise to have only one set of community (village) based organizations.

Experience in organizing farmers in Pakistan have shown that (NESPAK & MMI, 1995): a) successful farmers' organizations are best based on social structures of kinship relations; b) authoritarian views are not conducive with farmers' participation. Relevant local knowledge and skills should be drawn upon; and c) success in participation often stems from input of NGO's, who work in close collaboration with the people in the project area.

Experience in other countries with farmers' participation has shown that the following attributes are desirable: (i) Felt Need: the farmers must be convinced that there will be a definite and tangible gain for them by cooperating and taking responsibilities for irrigation and drainage activities and investments; (ii) Accountability: the farmers' organization should be solely and fully accountable and transparent to their farmers; (iii) Sustainability: there must be a certain degree of social cohesion within the farmers' organization to be able to survive the reliance on outsiders during the initial formation and establishment period; and (iv) Accessibility: the farmers' organization must have easy and ample access to the technical advice and expertise related to the tasks to be performed, either among its own members or by employing or hiring technical staff (Coward, 1986 and Uphoff, 1986).

As these questions of a socio-cultural nature and the more pragmatic ones cannot be resolved beforehand, the process of establishing farmers' organizations, around one or more beneficial activities, will require a gradual approach, needing research and pilot studies to lead the way!

### **Design and action plan**

The next step to be undertaken is the development of different design proposals, which then have to be discussed with the farmers as to which one can be implemented together, within the resources available to the community and IWASRI. An action plan needs to be drawn-up when agreement has been reached on the preferred technical solutions. This plan should

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specify the responsibilities and resource contributions of all stakeholders involved in the implementation of the technical solutions. The final design choices to be implemented have to be agreed upon, fully understood and accepted by the farmers; construction works have to be implemented (when, where, how and by whom); the system has to be operated (why, what and by whom); the system has to be maintained (why, how frequent and by whom). It must be ensured that each different issue is fully understood by the farmers and the plan in all its details will have farmers' consent. Technical staff of the government agencies seriously need to consider any suggestions and comments made by the farmers and modify the plans and planning accordingly, whenever realistic and possible. If suggestions cannot be taken into account on technical-physical grounds, this should be clearly and convincingly be explained to the farmers in such a way that farmers do not feel overruled.

### **Formal agreement of action plan.**

Formal agreements have to be drawn-up between the farmers organization, the NGO and the government agencies before undertaking any implementation activities. These agreement should spell-out the responsibilities, contributions (resources and finances), rights and obligations of each party. The NGO-support organization should ensure that the farmers organization fully understands and accepts the agreement; if this is not the case it needs to be modified until all parties find it acceptable.

### **Financial contributions**

Collection of the financial contributions from the farmers will be the responsibility of the farmers organization. These funds together with the contributions of IWASRI are to be deposited in a FO's Bank Account.

### **System construction**

Construction works can only be started if full consent is reached on proposed works; its layout; right of way has been secured; funds and materials have been secured; pending issues have been dealt with; an implementation plan has been worked out and is accepted by all parties concerned; and there is clear understanding of each party's role and contribution during the implementation process.

At this stage it cannot be stipulated how and by whom the different works will be implemented. It is for example conceivable that part of the works (a shallow surface drain) will be constructed by the farmers with advice and technical guidance of the government agencies. It needs to be looked into, whether horizontal pipe drainage systems can be installed by the farmers or will have to be contracted out. If works have to be contracted out, it is still too early to decide on whether the work-contracts can be made-up by the farmers organization or whether the government agencies still have to take charge of it. If the latter will be the case, the government agency must ensure that a construction supervision committee (of FO representatives) is established and that the government agency only provides advice and technical guidance to the committee.

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### **Training in operation and maintenance of the system**

When all construction works have been completed to the full satisfaction of all parties concerned, the operation and maintenance of the system will be handled independently by the farmers' organization. Beforehand the government agency, with assistance and guidance of the NGO-support organization, ensures that relevant members of the farmers organization or their staff will have received the proper training in all aspects of the operation and maintenance of the system and operations and maintenance manuals have been compiled.

### **Follow-up services**

The government agency commits itself to remain responsible for assisting the farmers in solving any technical design flaws which may surface during the normal operation and maintenance of the system. The government agency though, cannot take any responsibility for problems arising from gross neglect by the farmers organization or caused by malfunctioning of the farmers organization. The duration of this follow-up period, that should include monitoring as well, needs further consideration and will also depend on the technical complexity of the solutions chosen.

It should be realized that the above course of actions is by no means a blue-print that has to be followed exactly. Each step will provide new insight in the situation, circumstances and conditions one has to deal with. Hence, based on the experience acquired, the next step in the process can be determined more precisely. These steps merely provide a rough guidance for what will have to be done and can be expected in the process of developing drainage measures to combat waterlogging and salinity in participation with the farmers.

With this research approach IWASRI aims at developing guidelines for the replication of this pilot study at a much wider scale. Therefore, it is of the utmost importance that all field level activities are properly documented. The focus of this documentation should not only concern the project-related activities of the farmers, but also those of the Government Agencies Drainage Service Staff and the field support staff of the NGO.

### **Conclusions and summary**

The direct involvement of small farmers in solving their waterlogging and salinity problem is a totally new concept in Pakistan. It is the politically accepted view that there is an urgent need to involve the private sector in the operation and maintenance of not only the irrigation but also the drainage system. The Government is no longer in a position to carry the whole burden. The National Drainage Programme I advocates a widespread privatization of the irrigation and drainage infrastructure. But the Government Agencies are bureaucratically entrenched in a system developed over the last 150 years. The recurrent expenditure for the establishment puts a large drain on the governmental resources, such that little is remaining for an appropriate operation and maintenance of the facilities implemented over the last 35 years.

IWASRI has embarked on a study to find ways and means to overcome the serious waterlogging and salinity problems in full participation with the farming community. It is too early to draw conclusions and come-up with recommendations, as this research approach in

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drainage has been taken-up only recently. The PRA revealed that: (i) the social and economic framework in which the users of (future) drainage systems live, determines their capacity to cooperate towards solutions to the drainage problem; and (ii) farmers should be involved right from the planning stage in any future drainage implementation activities.

This new approach may contribute to improved efficiency and effectiveness of the huge investments made in Pakistan to combat waterlogging and salinity, and may have a great impact on the sustainability of agriculture.

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## Discussion

A summary of the discussion following Ir. Knop's presentation is given below:

Question: In organizing farmers for irrigation management, it is sometimes advocated to organize farmers at the distributory level, rather than at the water course level. The reason to organize farmers at this higher level is to obtain an organization that is more capable and powerful in dealing with government institutions. Would you recommend the same practice for organizing farmers for drainage?

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Answer: Yes, I would.

Question: You are currently working in an area where farmers have identified drainage as a major problem. However, in many other locations farmers do not yet perceive drainage as a priority problem. What do you intend to do in these areas?

Answer: Our work is a very first start. Once we have some results to show, we can use them in making farmers elsewhere aware of drainage problems and solutions. We could think about making a popular type of movie as a way to increase this awareness.

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## MODELING SALT, WATER AND FINANCIAL BALANCES OF TYPICAL IRRIGATED FARMS IN THE MURRAY VALLEY, AUSTRALIA

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### Abstract

The viability of irrigated agriculture in the Murray Valley is threatened by waterlogging and salinisation induced by rising watertables. By limiting net recharge to the watertable to zero or below, watertable rise can be prevented and the risk of watertable-induced environmental damage can be minimized.

Primary factors affecting the rate of net recharge to the watertable on a farm include: the as determined by soil type and farmer preferences, intensity of irrigation, depth to the watertable, leakage to deeper aquifers. Among these variables, the depth to the watertable and leakage rates are difficult to alter, whereas the landuse and intensity of irrigation can be managed such that net recharge is maintained at or below zero. Such changes to land use and irrigation management must give maximum profits if the farm is to remain a viable enterprise.

To determine the optional land use which give maximum financial returns to the farmer while maintaining net recharge and soil salinisation at zero, we have developed a non-linear programming model - SWAGMAN Farm. SWAGMAN Farm was used to study the effect of leakage, initial depth to the watertable, and landuse restrictions on total gross margin received and optimal intensity of irrigation.

### Introduction

In irrigation areas and districts of the Murray Valley of Australia, agricultural enterprises vary from farm to farm. However, nearly all farms face two environmental problems: waterlogging and salinisation. The primary factor controlling these two environmental concerns is the depth to watertable below the soil surface. Depth to watertable is governed by the net recharge to the watertable and lateral groundwater movements. Therefore by managing net recharge to the watertable, the hazards of waterlogging and salinisation can be minimized. Such a strategy should also result in maximum economic return to the farmer.

In order to determine on-farm land use practices and intensities of irrigation which produce an optimum result (maximum economic returns, zero net recharge, and zero gain of salt in the rootzone), an optimization model, SWAGMAN Farm, was developed. The model takes into account distribution of soils within the farm, potential land uses, crop evaporative

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requirements, current irrigation practices, leaching requirement, annual rainfall, rainfall runoff, leakage to deeper aquifers, depth to watertable, capillary upflow from shallow watertable, salt concentration of irrigation water, groundwater, and rainwater, and the economic returns from potential land uses.

## Model description

The objective of SWAGMAN Farm, subject to recharge and salinity constraints is to maximize total gross margin per farm, i.e.,

$$\text{TGM} = \sum_c \sum_s \text{GMLW}_c - \text{IRRN}_{c,s} * \text{WATPRICE} \quad (1)$$

where,

TGM	Total gross margin (\$)
GMLW	Gross margin of a land use less cost of irrigation water (\$ ha <sup>-1</sup> )
IRRN	Irrigation in use (ML ha <sup>-1</sup> )
C	Land uses considered in a farm
S	Soil types in a farm

Soil types considered in the model were: clay (CLAY), loam (LOAM), and sandy loam (SLOAM). Land uses (C) considered in the model were: rice (RICE), soybeans (SOYB), maize (MAIZE), lucerne (LUCERNE), hay lucerne (HLUCERNE), fababeans (FABA), canola with 4 ML irrigation (CANOLA1), canola with 1.5 ML irrigation (CANOLA2), wheat with 4 ML irrigation (WHEAT1), wheat with 1.5 ML irrigation (WHEAT2), barley with 3 ML irrigation (BARLEY1), barley with 1.5 ML irrigation (BARLEY2), annual pasture (APASTURE), perennial pasture (PPASTURE), dry land wheat (DWHEAT), dry land canola (DCANOLA), and dry land annual pasture (DAPASTURE).

The objective function was solved using a non-linear programming solver, GAMS-MINOS (Brooke et al., 1988), subject to the following constraints.

### Area constraints within the model

- SOYB, MAIZE, LUCERNE, CANOLA1, WHEAT1, BARLEY1, and PPASTURE were not to be grown on clay soils.
- Land uses on a particular soil type cannot exceed total area of the soil type.
- Area of a land use cannot exceed maximum allowable area (PMXA). The maximum limit was set to reflect real world considerations such as enterprise diversification, crop rotations, market demand, and restrictions set by natural resource managers.
- Area of a land use must be greater than minimum required area (PMNA).
- Minimum area of any land use (other than FALLOW) selected by the model must be greater than 10 ha to avoid inclusion of an inefficient area of a land use.

### Salinity constraints within the model

- Salt was assumed to be brought into the rootzone by irrigation ( $0.12 \text{ dS m}^{-1}$ ), rain ( $0.0001 \text{ dS m}^{-1}$ ), and minimum rates of capillary upflow from the static watertable (concentration of groundwater).
- The total mass of salt brought into the rootzone by irrigation and rainfall, and salt brought to the soil surface by capillary upflow, was required to be removed by leaching and runoff, resulting in zero salt gain on the farm.
- The model required that salt brought into the root zone by irrigation water be removed by leaching. Therefore, part of the irrigation water was required to leach the irrigation borne salts. This leaching requirement was determined from the equation below. The leaching water will recharge the watertable, which ought to dissipate by leakage or capillary upflow. We assumed that the concentration of salt in leaching water was  $2 \text{ dSm}^{-1}$ .

$$\text{LREQ} = \text{CIRRN} * \text{IRRN}/\text{CDWATER} \quad (2)$$

where,

LREQ	Leaching requirement, ML
CIRRN	Salt concentration in irrigation water, $\text{dS m}^{-1}$
IRRN	Irrigation amount, ML
CDWATER	Salt concentration of leached water, $\text{dS m}^{-1}$ .

- Salt brought to the soil surface due to capillary upflow was required to be removed by rainfall runoff. Salt at the surface was assumed to be the product of capillary upflow and groundwater salinity. The upper concentration limit of salt in runoff water was set at  $15 \text{ dS m}^{-1}$ . This is consistent with data collected in northern Victoria.

### Net recharge constraints within the model

- Net recharge to the watertable depends on recharge mechanisms (irrigation and rainfall in excess of actual evapotranspiration) and discharge mechanisms (capillary upflow and leakage to deeper aquifers). The net recharge was required to be equal to zero. It was determined using the equations below.

$$\text{RECHARGE} = \sum_{c,s} \text{AREA}_{c,s} * \text{IRRN}_{c,s} + \text{AREA}_c * \text{GRAIN}_c - \text{AREA}_{c,s} * \text{AET}_{c,s} \quad (3)$$

$$\text{DISCHARGE} = \sum_{c,s} \text{AREA}_{c,s} * \text{BRAIN}_c + \text{AREA}_{c,s} * \text{CUFLOW}_s - \text{TAREA} * \text{LEAKAGE} \quad (4)$$

$$\text{NET RECHARGE} = \text{RECHARGE} - \text{DISCHARGE}$$

where,

GRAIN	Rainfall during growing season of land use C ( $\text{ML ha}^{-1}$ )
AET	Actual evaporation use by land use C ( $\text{ML ha}^{-1}$ )
BRAIN	Rainfall during bare season of land use C ( $\text{ML ha}^{-1}$ )
TAREA	Total area of farm (ha)
$\text{AREA}_{c,s}$	Area of land use C on soil S (ha)

LEAKAGE Leakage from watertable to deeper aquifers (ML ha<sup>-1</sup>)  
CUFLOW Capillary upflow (ML ha<sup>-1</sup>)

## Model parameters

### Estimating minimum capillary upflow from a static watertable

Minimum rates of capillary upflow from a static watertable at 1 and 1.5 m depths under a bare soil (CUFLOW) were determined using a numerical model, HYDRUS (Kool and van Genuchten, 1991). Capillary upflow rates for depths in excess of 1.5m were estimates only. Minimum capillary upflow rates determined for Riverina clay, Mundiwa clay loam, and Hanwood loam were considered as the capillary upflow rates for clay, loam and sandy loam (Prathapar and Madden, 1995).

### Estimating actual evaporation (AET)

Initially, monthly reference evaporation (RET) values were used to estimate RET during the growing season of individual crops (Meyer, 1995). The RET value of each crop was multiplied by a seasonally weighted crop factor to obtain seasonal crop evaporative demand (CET). The assumed 'crop factor' for a bare period during average rainfall years was 0.11. This 'crop factor' is considered adequate for summer months but may be too low for the winter period. A better estimate is required to reflect the winter bare-period crop factor.

Actual evapotranspiration (AET) was determined by multiplying the CET by a correction factor (PDFACT). This was to account for irrigation management as well as soil water deficit, and was determined with the equation:

$$\text{PDFACT} = 0.8 - 0.7 * (\text{CET} - \text{WAVAIL}) / \text{CET} \quad (6)$$

where WAVAIL is the sum of irrigation and infiltrating rainfall during the growing season.

The actual evapotranspiration values and estimates of recharge for the land uses are presented in Table 1. Negative values of recharge imply water moving from the watertable to met evaporative requirements of the land use.

## Representative farms

Six representative farms in the Murray Valley were considered for investigation. Characteristics of the six farms are summarized in Table 2.



**Table 1. Estimated AET and recharge for land uses during an average year (mm)**

Land use	AET	Recharge
Rice Clay	1203	293
Rice Loam	1203	493
Rice Sloam	1203	893
Soyb	689	385
Maize	581	486
Lucerne	1188	259
Hlucerne	1188	259
Faba	404	80
Canola1	461	115
Canola2	287	40
Wheat1	474	110
Wheat2	287	40
Barley1	392	85
Barley2	277	38
Apasture	416	187
Ppasture	1115	356
Dwheat	172	-7
Dcanola	172	-7
Dapasture	158	7
Fallow	210	-110

**Table 2. Characteristics of representative farms**

Farm ID <sup>1</sup>	Farm Number	Area (ha)	Clay (ha)	Loam (ha)	Sloam (ha)	GW Salinity <sup>2</sup>	DWT (m)
WKD	1	200	50	100	50	5	1
WKR	2	550	500	50	-	40	4
WKP	3	500	350	100	50	15	3
DNE	4	460	92	368	-	10	4
DNW	5	1000	750	250	-	20	7
BQR	6	284	160	124	-	3	3

<sup>1</sup> WKD: Wakool dairy farm; WKR: Wakool rice farm; WKP: Wakool mixed-pasture farm; DNE: Denemein East mixed farm; DNW: Denemein West mixed farm; BQR: Beriquin rice farm.

<sup>2</sup> Groundwater salinity in dSm<sup>-1</sup>.

## Major determinants of the model

Since the objective of the model is to maximize gross margins while constraining net recharge to zero, the model will initially choose that land use which gives maximum gross margin per unit of recharge. Therefore the primary determinant will be the recharge efficiency ratio (PER). We define recharge efficiency ratio as the ratio between gross margin and recharge for a land use. In general CANOLA, DWHEAT, CANOLA2, and DAPASTURE-D result in higher gross margins per ML of recharge than the other land uses.

Another important controlling factor is the ratio of gross margin to actual evaporation, which will identify land uses that result in maximum gross margin per unit of water used by the crop. Therefore, the secondary determinant will be the evapotranspiration efficiency ratio (ERR). In general, DCANOLA, CANOLA2, MAIZE, and APASTURE-D result in the highest gross margins per ML of recharge.

**Table 3. The recharge efficiency ratio (PER) and evapotranspiration efficiency ratio (EER) of land uses during an average year.**

LAND USE	PER (\$ML <sup>-1</sup> )	Land Use	EER (\$mm <sup>-1</sup> )
DCANOLA	-2759 <sup>1</sup>	DCANOLA	115
DWHEAT	-1218	APASTURE-D	101
DAPASTURE-D	1173	MAIZE	97
CANOLA2	673	CANOLA2	93
DAPASTURE-M	461	SOYB	81
FABA	339	CANOLA1	70
LUCERNE-D	308	LUCERNE-D	67
HLUCERNE	288	FABA	67
CANOLA1	283	HLUCERNE	63
WHEAT2	282	PPASTURE-D	54
APASTURE-D	226	DPASTURE-D	53
BARLEY1	194	DWHEAT	51
RICE-Clay	175	RICE-Clay	43
PPASTURE-D	171	BARLEY1	42
SOYBEAN	146	RICE-Loam	41
WHEAT1	136	WHEAT2	39
BARLEY2	118	RICE-SLoam	37
MAIZE	117	WHEAT1	31
LUCERNE-M	114	APASTURE-M	30
RICE-Loam	100	LUCERNE-M	25
APASTURE-M	68	DAPASTURE-M	21
RICE-SLoam	51	BARLEY2	16
PPASTURE-M	36	PPASTURE-M	12
FALLOW	0	FALLOW	0

<sup>1</sup> A negative value indicates discharge

These two sets of coefficients are the major determinants of the model. However, the final results of individual runs will also depend on specific features and constraints attributed to individual farms. Generally, irrigated crops have higher evapotranspiration efficiency ratios and higher gross margins than dryland crops. This will result in the selection of irrigated crops over dryland crops, provided recharge is not limiting.

## Sensitivity analysis

The model was used to determine the sensitivity of leakage to deeper aquifers, depth to the watertable and minimum rice areas on selected farms.

### Leakage

The model was used to evaluate the sensitivity of leakage rates on gross margins and optimal intensity of irrigation on Farms 1, 2, and 3. The leakage rates used are -0.1, 0, 1, 0.2.25 and 0.4 ML ha<sup>-1</sup> yr<sup>-1</sup>. The following observations were made.

For farm 1, all five runs gave feasible solutions. Optimal irrigation intensity increased from 1.39 ML ha<sup>-1</sup> (leakage = -0.1 ML ha<sup>-1</sup> yr<sup>-1</sup>) to 2.46 ML ha<sup>-1</sup> (leakage = 0.4 ML ha<sup>-1</sup> yr<sup>-1</sup>). The upper bounds set for lucerne and hay lucerne were reached in all runs. This reflects high

returns obtainable for lucerne on dairy farms. As the leakage increased, dry land annual pasture substituted irrigated pasture.

For farm 2, when there was upward leakage it was not feasible to meet salinity and recharge constraints. This farm had a deep water table (DWT = 4), and so the opportunity to discharge water in the form of capillary upflow was not available. Four other scenarios (leakage greater than or equal to zero) gave feasible solutions. Optimal irrigation intensity increased from 0.00 ML ha<sup>-1</sup> (leakage = 0 ML ha<sup>-1</sup> yr<sup>-1</sup>). With an increase in leakage, dryland crops decreased and irrigated crops increased; notably FABA was introduced and DCANOLA was replaced by CANOLA2.

### **Depth to the watertable**

The effect of shallow water tables was studied by raising the watertable to 3 m below the soil surface in Farms 2,4, and 5. This enables capillary upflow to occur.

For farm 2, when upward leakage was 10 mm it was not feasible to meet recharge and salinity constraints, i.e., the capillary upflow rates are still inadequate to offset upward leakage. Recall that the soil type in farm 2 is predominantly clay, which precludes a number of high-value irrigated crops. The optimum intensities of irrigation, without resetting the watertable at 3 m, were 0.0, 0.33, 0.98 and 1.7 ML ha<sup>-1</sup>. In contrast, when the watertable was reset at 3 m, the optimum intensities of irrigation estimated for comparable runs were: 0.09, 0.53, 1.10 and 1.83 ML ha<sup>-1</sup>.

For farm 4, when upward leakage was 10 mm, it was not feasible to meet recharge and salinity constraints. However, feasible solutions were obtained when leakage was zero. Recall that, for such a condition, and without resetting the watertable at 3 m, feasible solutions were not obtained. The optimum intensities of irrigation, without resetting the watertable at 3 m, for runs with positive leakage were 0.33, 0.98 and 1.55 ML ha<sup>-1</sup>. In contrast, when the watertable was reset at 3 m, the optimum intensities of irrigation estimated for comparable runs were: 0.55, 1.14 and 1.62 ML ha<sup>-1</sup>.

### **Minimum rice area requirement**

For this set of runs, minimum area of RICE was set at 40 ha for farms 2,5, and 6. Runs were made with five leakage rates (-0.1, 0, 0.1, 0.25 and 0.4). For farm 2, feasible solutions were obtained when the leakage was 0.4. For farm 5, feasible solutions were obtained when the leakage was greater than 0.25 and the rainfall was average or wet. Farm 6 had no feasible solutions.

Although it is unfeasible to maintain zero net recharge in these farms if rice is grown on 40 Ha, rice remains the preferred crop for most farmers. Watertable rise in these farms may be avoided if groundwater pumping is adopted. For example, in farm 6, where the initial watertable depth is 3 m, growing 40 ha of rice will result in the watertable at a depth of 2.73 m in an average rainfall year. This watertable rise can be avoided if 1.68 ML ha<sup>-1</sup> yr<sup>-1</sup> of groundwater pumping is implemented.

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## **Areas for further development**

We believe that the model has performed in a logical manner for the runs carried out. However, some of the assumptions made in the model could be refined which would improve the model. This section outlines perceived weaknesses in the assumptions.

### **Estimating gross margins**

The model uses gross margins as an indicator of profitability. Gross margins are simply income derived from an enterprise minus the variable costs directly associated with this income. The gross margin is not a profit figure and ideally should only be used to compare activities with similar resource use. As the model recommends optimal land uses, any major changes in a farm plan should be evaluated. This could be done externally to the model.

At present, the yield of a crop does not change as the level of water deficit changes. A crop-specific function needs to be developed to account for this problem.

### **Salt and water balance of the farm**

We assumed that the farms had reticulation systems, so that, irrigation runoff (drainage) was assumed to be zero. This may not be the case in some farms. Further, the levels of irrigation were not changed with changes in weather conditions. For example, RICE was assumed to use 20 ML ha<sup>-1</sup> on a sandy loam, irrespective of weather.

### **Soil hydraulic properties**

The optimal intensity of irrigation depends on minimum capillary upflow rates (CUFLOW) of soil types within a farm. Additional work is required to determine these rates under bare surface conditions and varying depths to the watertable.

## **Role of SWAGMAN Farm in the development and implementation of L&WMPs**

Currently in NSW, Victoria and South Australia there is a move towards privately run irrigation systems, managed by irrigation boards. "For the privatization process to take effect, irrigation boards are required to develop Land and Water Management Plans (L&WMP) which are acceptable to Governments. We believe that SWAGMAN Farm has the following roles to play in the development and implementation of such L&WMPs.

SWAGMAN Farm could be used for educational purposes. Since SWAGMAN Farm accounts for aspects of agronomy, irrigation, salinity, soils, hydrogeology, and economics it can be used to evaluate the impact of a change in any one of the above variables. Therefore, agency personnel, members of irrigation boards, and the farming community at large will be in a position to understand the net effect of a potential change in farming practices.

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Irrigation boards are required to identify and promote best management practices which will contribute to overall enhancement of the irrigated environment. We believe that SWAGMAN Farm could be used to determine guidelines for best management practices. Although SWAGMAN Farm is not comprehensive enough to be a farm management model, it can also be used by farmers to aid planning and management.

## Conclusions

The following general conclusions can be made from this study:

1. The recharge efficiency ratio is the critical controlling factor. As the discharge capacity increased selection of a land use depended on the evapotranspiration efficiency ratio. However, the final solution depended on farm-specific characteristics and constraints.
2. As the leakage increased, total gross margin per farm increased.
3. The optimal intensity of irrigation ( $\text{ML ha}^{-1}$ ) was low when the watertable was at depths below 3 m, the groundwater salinity was high, and the soil type in the farm was predominantly clay.
4. Considering the results of the study we believe that the optimal intensity of irrigation in the Murray Valley is approximately  $2.5 \text{ ML ha}^{-1} \text{ yr}^{-1}$ , conditional on farm type, soil types and depth to the watertable. This compares with a current average rate of  $4\text{-}5 \text{ ML ha}^{-1} \text{ yr}^{-1}$ .
5. When the watertable is deep and highly saline and the soil type is clay, it is advisable to avoid irrigation to prevent watertable rise and salinisation.
6. For a loam soil, when the watertable is deep and moderately saline, irrigation must be combined with groundwater pumping in order to maintain zero net recharge.
7. If area restrictions are not imposed as constraints, total gross margins per hectare received by the farm were high. This was primarily due to the cultivation of crops that had higher recharge and evapotranspiration efficiency ratios.
8. For the farm considered it is not feasible to maintain net recharge at zero and maintain rice area at 40 ha per farm, unless the level of leakage is high.

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## Discussion

Dr. Prathapar's responses to questions from the audience were summarized as follows:

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- Information on leakage is indeed essential for sustainable agriculture in this region. This information can be obtained, due to a well developed piezometer network in the area.
  - Evaporation ponds in this region do not need to be lined, because they leak into an aquifer which is already saline.
  - Agriculture in this region is sustainable, in spite of shallow and saline groundwater. This is possible due to high frequency of irrigation applications (every ten days), which remove the salt.
  - Farmers accept the restrictions imposed on them to make irrigated agriculture environmentally sustainable, because they are consulted in the decision-making process through workshops. The model shows them the financial implications of various management practices. Acceptance is easier when farmers see that they can still make money.
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