The active role of water users’ associations in the modernization of irrigation projects

**Photo 20** Mexico: Rio Fuerte Project. First stage: Modernization of maintenance equipment and office technology
upgraded to remote control. As noted earlier, small-scale canal modernization projects are now widespread throughout the western United States. For example the gates of the composite check structures of the Dolores project have been automated. (Composite structures consist of a combination of one or two automated gates and long-crested weirs.) Several terminal reservoirs were built in the Coachella project, still operated for gravity application, to allow the farmers to convert from surface irrigation to low volume application methods. The Sevier River water user association in Central Utah has installed low-cost solar-powered automatic gates and SCADA. This user association has adopted the principles of gradual upgrading and retrofitting of existing infrastructure that are generally adopted for the modernization of irrigation systems in the western United States. None of these upgrading/modernization tools were applied in developing countries to improve the performance of gated projects. The 175-km-long main canal serving the 90 000 ha Phitsanulok project in Thailand is a case in point (Box 8).

**Box 8: The Phitsanulok project in Thailand**

The Phitsanulok main canal is equipped with 24 manually checked structures. It was designed and built without any provision for remote monitoring. Recent studies show large discrepancies between operating rules and actual operations. On average the levels upstream of check structures are about .7 metre below the target levels. Because of the variations in water level, flows diverted to secondary canals are poorly controlled. There is inequitable distribution at macro and micro scales. Constant-head orifices, of which there are more than 1100 at the field channel heads, are used neither for measurement of flow nor for fine adjustment to deliver a varying rate of discharge. The farmers have responded to the deficiencies in the operation of the gravity Phitsanulok irrigation systems by installing individual wells during the last decade. The average density of wells estimated by a survey in 1996 was nearly 20 wells per 100 ha. The development of groundwater has given farmers a greater level of control over their crop calendar. They do not have to wait for water to be available and they can plant their crops at times that seem best according to their own situation. Groundwater development was also observed in the Northern Chao Phraya and Mae Khlong projects in Thailand.
In 1991, the Bureau of Reclamation issued a manual on canal system automation. The preface of this manual points out that the earliest designs of canals were based on the maximum flow conditions (known as full supply). This design does not provide the requisite flexibility to operate a canal efficiently. The first canal automation was crude but it was immediately successful. Advances in the operation of canals through the use of automation have paralleled the development of the electronics industry.

This statement is of major relevance to the canal systems in developing countries designed for maximum flow conditions; they simply cannot work as designed. Unfortunately, the signal sent by the Bureau of Reclamation on the limitations of old designs was ignored by many design engineers. Institutional reforms alone, including participation irrigation management, will not change this situation.

**D. CROSS-COUNTRY TRANSFER OF TECHNOLOGY**

Transferring any technology from one environment to another should be approached with caution. Great caution is particularly needed in the irrigation sector where the site conditions are specific and the success of the transferred technology depends on physical, social and economic factors. Horst points out in his recent book that “many donors stipulated that foreign consultants were to be involved in the planning, design and supervision of construction. These consultants came from different parts of the world with different irrigation technologies and traditions. Each of them was educated and experienced in one of the distinct irrigation schools. Owing to the weak position of the national irrigation departments in terms of experience in planning and design and the dominant role of the donor agencies, the consultants were able to decide on the technology to be adopted, that is to sell or impose their own technology. In other words, [it was] the country of origin of the consultants [that] determined the type of technology, and not the compatibility with the local physical and socioeconomic environment”.
Horst’s observation applies to a number of developing countries which do not have well-established practices of irrigation engineering. In countries with large development of irrigation, the state officials have often entrenched engineering practices. Foreign consultants may face strong resistance from local engineers, sometimes justified, to any proposed change in design of irrigation projects. Irrigation departments in India and Pakistan have rigidly adhered to their design standards for decades. It is only recently that some innovative departments have agreed to adopt new standards. Examples include a few projects in India (such as the Majalgaon project in the state of Maharashtra and the major Narmada project in Gujarat), and the high-level Pehur project and SWABI- SCARP in the North-West Frontier Province in Pakistan.

A number of lessons can be learnt from the examples of failed transfer of experience.

1. India: Transfer of rotational distribution from northwest India to the southern states

Despite the undoubted achievement of irrigation development in India and the success of the Green Revolution in that country, performance of irrigation projects, particularly in the southern states, was far below potential. A strong group of local engineers supported by financing agencies promoted the idea to transfer, with some adjustments, the design package of the northwest states to the southern states, which they considered as the best system in India. This idea materialized in the World Bank-supported National Water Management Project (NWMP) in 1985. The main objective of the project was to improve agricultural productivity through the provision of a more reliable, predictable and equitable irrigation service. The most important element in scheme improvement was the preparation of an operational plan. On the basis of water availability, system characteristics and agricultural options, the plan was expected to define how the system would be operated with respect to the timing and quantities of water deliveries. The project concept was to convert the demand-type systems into supply systems. To ensure equity in water distribution, the “structured design”, an adaptation of
the rigid rotational warabundi delivery combined with ungated canal technology, was developed for the project. The structuring level is the point downstream of which the canal system is ungated. This system was not tested in a pilot project in paddy-growing areas where field-to-field irrigation was traditionally practised. The system does not have the flexibility to adjust to the important variations in rainfall and soil conditions which prevail in southern India. In the warabundi states, soils are rather uniform and rainfall does not contribute much to the total water. More important, groundwater, which is a reliable and flexible supply, accounts for a large portion of the water resource, a critical difference for the farmers of southern India, where groundwater resources are not as rich and widely spread as in the alluvial northern plains.

The project was rated unsatisfactory at completion. During a seminar on modernization of irrigation systems in 1998, IWMI reported the failure of the concept of the structured design and equitable supply technology in the Bhadra scheme, which was part of the NWMP project: “The provision of reliable and equitable supply was not achieved as expected at appraisal. The changes in cropping patterns and agricultural calendars stipulated in the operational plans had not been followed; the advancing of the kharif season could not be implemented” (Sakthivadivel). Lessons from this project were taken into consideration in the formulation of a new generation of projects in India. The thrust is now on improving productivity through system improvement linked to turnover of management of the systems to user associations.

2. Transfer of rotational irrigation from India to Thailand and Nepal

Thailand. An attempt was made in the Nong Wai project in Northeast Thailand in the early 1980s to introduce the warabundi delivery system to irrigation projects in Southeast Asia. This ill-designed transfer of a rigid delivery system got dismal results because of its incompatibility with rice irrigation and the local culture of Thai farmers.
Nepal. Because of the difficulties in operating the Stage-I rehabilitation of the Sunsari-Morang project (58 000 hectares), which was designed as a fully gated, manually operated system, a structured design was adopted for the rehabilitation of Stage II: downstream of the off-takes of the sub-secondary canals, the system is ungated. Tertiary canals are supplied through concrete flow dividers and the watercourses through adjustable proportional modules, as used in northern India. The operation of the Stage II subsystem has been considerably simplified compared to Stage I. However, it has lost flexibility in meeting the variations in demand due to factors such as local variations in rainfall and excessively long staggering of rice cultivation. Towards the end of the growing season, some farmers still request irrigation water while others are ready to harvest. The lack of a drainage system and of operational flexibility in the structured design imposes severe operational constraints, which affect productivity. The duty limitations of the main system (0.7 l/s/ha) and the low flows of the Kosi River during the dry season make this run-of-the-river project very dependent still on monsoon rainfall.

This example from Nepal challenges the opinion shared by some irrigation professionals that farmers prefer proportional distribution. They certainly prefer equity over anarchy but they can also understand that equity and higher productivity can be achieved through improved water control and alternative operational procedures.

If the water user associations in Sunsari-Morang in Nepal were organized before the physical improvements, farmers would have been in a position to formulate their preferences for not freezing the infrastructure into an inflexible distribution system.

3. Transfer of technology to user-managed systems in Indonesia: a case of farmers’ rejection of inappropriate technology

Agro-socio-religious associations in Bali, called subaks, have developed a water division technology throughout the ages. The subak water division technology consisted of institutional
arrangements backed by temple priests and of weirs dividing flows into negotiated shares. These centuries-old subak systems were first disrupted by the arrival of the Green Revolution in the 1970s, which changed the agricultural practices required for cultivation of shorter maturing rice varieties and more dramatically by the government plan to “modernize” the subak systems with the assistance of a financing agency and foreign consultants. The “modernization” project attempted to introduce the technology and water distribution procedures which were the norms in the government-built and -managed irrigation projects in Java. The project consisted in the replacement of the dividing weirs existing at each bifurcation by adjustable structures to be set and reset on the basis of frequent calculations of the crop water requirements. Gates were installed to regulate and measure flows. In general the subak members did not accept this technology. They handled the gates to accommodate the division of water according to their perceptions of water allocation and removed the gates to restore the former fixed-proportion division structures. Towards the end of the project, the state officials reluctantly accepted the subak technology and built new or improved existing proportional division structures.

Curiously neither the change of irrigation technology nor its social implications have been discussed in any of the design reports or even in the completion reports. The technology practised on Java was transferred to Bali with no concern for the opinions and perceptions of the subak members (Horst). This pure engineering approach is unthinkable today, given the emphasis now placed by financing institutions on a participatory approach in the design of irrigation projects.

E. CONCLUSIONS

Different strategies of water delivery and water control have been used for the development of canal irrigation schemes throughout the

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18 Irrigation requirements for irrigation projects in Java are determined by application of the pasten system.
world. Obsolete designs can be found in both developed and developing countries. Many irrigation projects in the United States, Western European countries and Australia built decades ago are inefficient in terms of water and energy use and are in urgent need of modernization. Advanced concepts and electronic-based sophisticated technology have been used for nearly three decades and have been introduced in a number of developing countries such as India (Majalgaon, Narmada), Egypt (the Nile telemetry system), Morocco and Jordan (dynamic regulation). Hydraulic regulation has been used in most Mediterranean countries for about fifty years. Modernization of irrigation, as defined earlier, is not an issue limited to developed countries, as has been stated during some workshops.

The concepts used for the development of irrigation by colonial powers since the mid 1800s in India, Egypt and Sudan were well adapted to the conditions and to the objectives of irrigation in the past. Irrigation was extensive and the water resources were not regulated by large storage reservoirs. Conditions have changed with the intensification of irrigation due to the pressure on land related to the escalating demography and to the construction of regulating reservoirs. Relaxation of the discipline of the users required for an adequate operation of ungated systems in the Indo-Gangetic plain is often mentioned as the cause of poor performance. The diversion of larger volumes of water due to the construction of large dams has exacerbated the problem of siltation, particularly in the smaller canals, which in turn has contributed to the inequity of distribution since the flows diverted through the farm outlets are influenced by the upstream water level. The farmers responded to the economic changes by tapping additional water resources to overcome the limitations of the existing systems, which were undersized for intensive irrigation. Farmers captured more water from the canals by illegal means (Indus basin), replaced animal-driven pumps by motor pumps (Nile valley) and installed a dense system of shallow wells or deep tube wells. Groundwater accounts now for a large proportion of the water used for irrigation in the alluvial plains, which is a normal evolution of irrigation development. The unique feature of the Gezira scheme in Sudan, consisting of night storage in minor canals, makes possible to shift from a rigid delivery to an on-demand system, an
advantage greatly appreciated by the farmers of that scheme in the absence of groundwater or any other water resource, including drainage water in the area.

The design standards adopted in many developed and developing countries after the mid 1900s to deliver water according to crop demand were conceptually more advanced. However, most of them failed to meet that objective because of the deficiencies of the water control technology and complexity of the operational procedures. Managing an irrigation system equipped with manually operated gates at each branching point is a very complex task. In many cases, the systems were designed to be operated at full capacity without consideration for operation at less than full supply. Even with the best vigilance of the operators, operation of these systems is usually inefficient and/or costly in developed countries. Computer-assisted calculations of irrigation targets based on assessments of crop water requirements were developed for use in some countries where centralized scheduling is practised, such as Indonesia. The demands imposed on agency and irrigators to collect innumerable data, to calibrate devices and to control flows often prove beyond their capabilities and interests. Some information which is frequently lacking or inaccurate is data about seepage and percolation, return flows and spatially variable rainfall. Where the inability to take such factors into account renders irrigation targets unacceptably inaccurate, water is distributed based on qualitative judgments by field staff or through interference by farmers. This makes the water delivery system uncertain.

The use of technology with adjustable structures, which has been the norm during the three decades of intensive development of irrigation in developing countries from 1960 to 1990, has badly affected the performance of irrigated agriculture in many countries. It is now impeding the transfer of management to user associations.

With hindsight, the outcome appears to have been inevitable, raising questions about the realism of the foreign consultants’ plans and the Bank support to them. These experiences give the impression of donors and technical assistance teams using the (East Asia) region as
testing ground to try out new designs, with encouragement from agency headquarters, but without a realistic assessment of local management capacities of the incentives for irrigators (Rice). This paper argues that even the best qualified managers and operators would not be able to manage these systems to the highest standards over long periods without the assistance of modern communication systems and/or remote monitoring. The issue is in the deficiencies of the design that imposes very complex methods of operation, not in the organizational weaknesses of the irrigation agencies.

The farmers served by these low-performing manually controlled systems have reacted in different ways to be able to adopt modern cultivation practices and diversified cropping patterns: tampering with control structures, pumping from canals, drains, borrow pits and, more recently, tapping groundwater resources which provide the flexibility and reliability needed for modern irrigation at farm level. These responses from the farmers are inevitable and irrigation agencies are generally passive since they can do very little to stop them. However, it is not a proper use of limited water resources. It is an unacceptable situation with regard to the increasing competition for water and environmental considerations. In some countries, farmers use untreated water which is rich in nutrients and constitutes a reliable resource for yearly intensive cultivation of high-value crops in suburban areas (for example in Punjab, Pakistan).

The development of hydraulic automation in North African countries in the 1950s helped to a large extent the operation of canal irrigation systems by reducing the number of structures requiring readjustments and the frequency of resetting control structures. Automatic downstream control eliminates the need for complex calculations of water releases. It is therefore puzzling that these innovative design standards have not been adopted in other countries. The reasons for the slow adoption of these or any modern techniques are both administrative and behavioural:

- Lack of economic pressure on irrigation agencies;
- Lack of contractual motivation for consultants to introduce new concepts;
• Resistance to change by irrigation managers, engineers and others; risk aversion and adherence to outdated designs;
• Lack of operational experience and service motivation by planners and irrigation departments;
• Lack of sufficient training at all levels, from the university to the field;
• Lack of evidence of the superiority of modern systems in terms of agricultural productivity;
• Failure of some pilot projects for technology transfer (Sidorejo in Indonesia, Cupatizio in Mexico)
• Use of economic tools during the preparation of projects focusing on cost comparisons of different equipment and overlooking the potential benefits to be expected from modernization.

Some transfer-of-technology projects have been unquestionable success stories, such as the Guilan project in Iran or the Muda project in Malaysia. Regrettably these projects have not attracted the attention of international research organizations.

Many transfer-of-technology experiments have failed because of inadequate attention to all the key factors that determine the selection of an appropriate irrigation strategy. For example, the transfer of a rigid method of water allocation from arid zones to rice projects is doomed to fail if the farmers have not been involved in the process which affects their cropping patterns and practices and if they do not perceive some improvement in the quality of service. Replacing fixed water-dividing structures in traditional run-of-the-river schemes without a regulation of the water resources is also doomed to be rejected by the farmers, as was the subak system in Bali.

Suitable water control technology is not enough, however, to achieve high agricultural productivity. It is assumed that the mediocre productivity of irrigated agriculture in Morocco, particularly for cereal crops, is mostly related to the centralized method of irrigation scheduling, with little participation of the irrigators, lack of maintenance of on-farm works, and constraints imposed by the land
consolidation model, possibly in combination with deficient use of non-water inputs. It would be useful to carry out an in-depth analysis of the performance of selected irrigation projects in that country to check the validity of the above assumption.

A last category of projects is those with faulty design, such as wrong selection and combination of control structures which amplify the fluctuations of hydraulic conditions in irrigation canals and those using unrealistically complex procedures to determine irrigation releases.

VIII. THE FORCES OF CHANGE

_Irrigation has well served in the past in supporting the increase in food production, but it must evolve to adjust to the new economic environment_ (Gardner).

In the above chapter, it was noted that the farmers are responding to the changes affecting irrigation in their own environment by looking for more reliable and flexible water supply. Other fundamental and potentially far-reaching changes are challenging some of the basic premises supporting the use of irrigation, as least as traditionally practised. This chapter systematically explores these changes and their effects on the future of irrigation.

The key forces that are going to influence the role and performance of irrigation over the next decades are:

- Population growth, with an even faster growth of the urban population and the continuous prevalence of rural poverty in several regions;
- Competition over water supplies between agricultural and other uses (municipal, industrial, recreational, energy generation, and environmental uses) and the rising cost of developing new resources;
- Globalization of the economy resulting from international and regional agreements (GAAT, NAFTA, European Union) and
rapid advance of the information and communication technologies;
• General public awareness that the environment should be protected;
• Diminishing government implications due to changes in institutional policies; and
• Climatic changes such as a higher recurrence of drought years.

These changes have and will continue to have considerable consequences for irrigated agriculture. The demand for food from irrigated lands will increase, as demonstrated by all models of food-supply predictions. In high-income developing countries, changes in diet patterns from the increased urban population will shift demand for staple food towards processed food obtained predominantly from irrigated fruits and vegetables. For example in Taiwan, rice consumption has declined from 130 to 65 kilograms per capita over the last three decades. In some countries, the governments will gradually eliminate the protection of commodity prices to comply with international agreements. As a result of the globalization of the economy, irrigated agriculture will be driven by market forces and will have to compete on both international and national markets.

The forces of change have and will continue to have serious impact on water supply to irrigated agriculture. Given the increasing competition for water, supply to irrigation is going to decline in some countries. The excessive cost of developing new water resources and the reduction of subsidies to public irrigation systems will contribute to this decline.

Irrigated agriculture is gradually becoming more accountable for the environmental degradation, in particular the degradation of water quality through contamination by salt and agrochemicals. Stronger regulations are required, together with mechanisms to arbitrate conflicts between environmental and irrigation interests.
Response from farmers

In some countries, subsistence irrigation will continue to cover a large share of irrigated lands and provide staple food to poor farmers. However, the general trend towards the modernization and efficiency of irrigated agriculture will apply to small-farmer communities operating now at subsistence level. The objectives will be yield increases, reduction of water consumption and energy costs, and crop diversification.

In some countries irrigated agriculture will predominantly become an economic activity driven by market forces rather than a way of living supported by government subsidies. Increased economic efficiency will be a condition for farmer survival, implying continuous improvement in technology, agricultural practices, farm management and marketing. Savings on water, labour and energy costs will increasingly become major considerations. Confronted with increasing costs of water supply, combined with reduced protection on agricultural prices, farmers will have to react by producing more with less water. They will shift to higher-value crops and crops consuming less water and they will adopt water conservation strategies to reduce water losses.

Farm structures will shift towards well-operated and well-financed units with strong integration in domestic and international marketing and processing industries. This trend took place in OECD countries during the last decades, where the people directly involved in farming activities now represents 3 to 5 percent of the total population. Small farms persist, however, in countries like Japan and Taiwan through weekend farming by aging farmers and highly subsidized agriculture. Irrigated agriculture is in the shrinking phase in some countries, as a result of urbanization and other factors. In Taiwan, irrigated lands decrease from 560 000 to 380 000 hectares over the last three decades.

Some irrigation projects with excessively high operating costs because of high lift pumping or adoption of extensive irrigation with high maintenance costs, which are not sustainable without govern-
ment subsidies, will have to be abandoned unless governments keep a policy of subsidizing irrigated agriculture.

**Response from technology**

Few industries produce the same product in the same way they did fifty years ago and irrigation should not be an exception. However, irrigation technologies have slowly evolved for centuries and age-old practices can still be observed in many rural areas. Significant changes took place in the late 1800s with the construction of large reservoirs providing regulated water to the users and the possibility to balance water supply and demand. A second wave in advance in irrigation technology was the development of more efficient application methods at farm level, including surface methods and pressurized systems. However, application of most of these techniques is still limited in most developing countries. The most striking change in irrigation in the large irrigated areas in Asia during the last two decades has been the phenomenal development of groundwater, which is discussed in Chapter 9.

Because of farm sizes, markets and other factors, farmers in developed countries have readily adopted advanced irrigation technology. This adoption has had a major effect on productivity. Labour, energy and costs of water have considerably influenced the adoption of technologies and the use of water for irrigation in the United States. Since 1968, the total irrigated acreage has increased by 37 percent, but the average water application has decreased by about 15 percent from 6 300 to 5 400 m³ per hectare. Surface irrigation methods that were used on 90 percent of irrigated lands are still the most common methods of irrigation but are now used on only 55 percent of the lands. Sprinkler irrigation is now used on 41 percent of the lands. However, the traditional sprinkler methods, hand moved and solid set, are rapidly loosing ground in favour of centre pivot and linear move, which are now used on one quarter of irrigated lands in the United States.
Labour requirements for irrigation systems vary greatly. Automated systems, such as automated micro-irrigation and centre pivot, have relatively low labour requirements. The recent success of the low-energy precision application labelled LEPA is due to its combined low labour, low energy and water-saving advantages.

The slow adoption of new irrigation technology in developing countries is a perplexing issue. While there have been changes in irrigation technology in the United States, Australia and Western European countries for example, little of this development has affected irrigation in many developing countries. Some of the constraints are obviously the unavailability of capital, low costs of water and energy and pricing policies that fail to provide incentives to conserve water, and the absence or limitations of high-value crop markets and marketing facilities.

However, a main reason for the slow transfer is that the focus of attention in irrigation technology and research in developing countries has occurred at farm level, and not at the level of operation of the main and conveyance systems. Farmers will not invest in water-saving technologies if the service of water is not reliable and if the incentives for saving on water, energy and labour are not strong enough. Bottrall observed in 1979 that “it is only if the main water distribution system is well operated that many other important management objectives can be satisfactorily realized, and it is only then that high returns can be obtained from agricultural extension advice and the increased application of other complementary inputs”.

Response from agricultural research

The agricultural research centres deserve credit for their contribution to the achievements of the Green Revolution. The Irrigated Rice Research Institute estimates that their new rice varieties have increased water productivity threefold through increased yield and reduced crop duration. IRRI and CIMMYT are optimistic that they can develop high-yielding drought-tolerant varieties. However, development of reliable irrigation is crucial to realizing the benefits
of high-yielding modern varieties. Growing crops under a mild water deficit requires a high degree of water control and farmers’ confidence in the irrigation system (Molden).

Advances in genomics and genetics will certainly contribute to the challenge of food and water production but would have to be associated with improvement in water delivery.

**Response from the governments**

As a consequence of diminishing implication of governments in irrigation management, stakeholders and the private sector will take an increasing share of responsibilities at all stages of irrigated agriculture. The governments will support the establishment of new policies, legislation and institutions. The decisions about water allocation and planning will be gradually made at the river-basin level through a consensual process among users.

The governments will continue shifting from supporting the construction and rehabilitation of large irrigation infrastructure towards establishing new policies to support private-sector participation, water conservation and environmental protection.

The forces of change discussed in this section will force the irrigation engineers to design more efficient and responsive irrigation systems.

**IX. THE EXPLOSIVE EXPLOITATION OF GROUNDWATER RESOURCES**

The contribution of irrigated agriculture to food and fibre production has continued to increase despite the lower level of investments for developing new irrigable areas and the focus on rehabilitation of existing schemes. One of the reasons is the exceptional increase in groundwater development in recent decades. Declining extraction costs due to advances in technology and in many instances government subsidies for power and pump installation have encouraged
private investment in tube wells. Groundwater in India now supplies more than 50 percent of the irrigated area. Due to higher yields in groundwater-irrigated areas, groundwater is central to a significantly higher proportion of the total irrigated output.

The significance of groundwater in the Indian economy is due to the fact that agricultural yields are generally higher – by one third to one half – in areas irrigated by groundwater than in areas irrigated from other sources. Groundwater offers greater control over the supply of water than do other sources of water. As a result groundwater irrigation encourages complementary investments in fertilizers, pesticides and high-yielding varieties, leading to higher yields (World Bank 1998). It is the reliability of groundwater that allows farmers to take the risk of investing in fertilizers, which substantially increase their crop productivity (Ahmad).

In Pakistan, groundwater development through private tube wells has grown exponentially, especially in Punjab. According to a 1991 survey, about 46 billion m$^3$ of groundwater are used for irrigation in the Indus basin, 85 percent of which comes from private tube wells. However, salinity continues to present a threat to the sustainability of agriculture because of the recycling of large quantities of poor-quality groundwater from the top of underlying aquifers.

Groundwater exploitation for irrigation is not limited to arid or semi-arid countries. The explosive use of diesel pumps in the Chao Phraya and Mae Khlong river basins in Thailand has responded to the increase demand for dry-season cultivation of high-value crops and the unreliable supply from the large gravity irrigation systems. Commenting on the changes that have affected the Phitsanulok project in Thailand, Manuiddin pointed out the advantages of groundwater over canal water: “With an average of one well for 5 hectares, virtually all the farmers now have access to groundwater. The development of groundwater has given farmers a high level of control over their crop calendar. They do not have to wait for the availability of canal water, and they can plant their crops at the time that seems the best according to their own situation. The benefits that the changes have brought to farmers include increased quantity of
water, increased reliability of water and freedom for the families to choose their own crop strategies.”

The rapid development of groundwater has recently been observed even in some projects that were designed to meet the full requirements needed for intensive irrigation and to provide reliable service. About 9,000 private deep wells have been installed in the 40-year-old Tadla project in Morocco during the last five years, i.e. nearly one well for 10 hectares. The main reason for this recent farmer initiative might be the higher frequency of dry years that affects annual water allocation and the constraints imposed by the current water allocation strategy.

Overexploitation and an associated decline in water quality have been occurring in many parts of the developing world, particularly in the arid and semi-arid regions. Water tables are falling at an alarming rate – often 1 to 3 metres per year. These regions include some of the world’s main grain production areas such as the Punjab in India and the North China Plain. About two thirds of farmlands in North China are facing serious problems of groundwater exploitation (Shah).

Groundwater has played a critical role in food production by agriculture over recent decades. However, groundwater is a major emerging problem in many parts of the world. Some areas have reached the point where overexploitation is posing a major threat to the environment, health and food security. The potential of groundwater development for irrigation may be reached soon. Seckler pointed out that “many of the most populous countries of the world have literally been having a free ride over the past two or three decades by depleting their groundwater resources” and he concluded that “the results could be catastrophic for these countries and, given their importance, for the world”. The explosion of groundwater irrigation in some countries is a farmers’ response to the lack of flexibility and, in the worst cases, to the unreliability of the canal irrigation systems. “Water recycling and the conjunctive use of groundwater are rarely considered in the original design of irrigation projects. They mostly happen as a desperate response from farmers who are unable to obtain their share of irrigation water from the canal or from system managers as a way to rectify problems
of management capacity and shortcomings of the original design” (Bhuiyan).

These brief considerations on groundwater use in irrigation lead to the conclusion that there is an urgent need to improve the quality of service from water surface systems and for a well-thought conjunctive use of both surface and groundwater. The present passive attitude is no longer acceptable.

X. THE PLANNING PROCESS: A GLOBAL GAME PLAN

Definition of modern design

Several definitions of modern design have been proposed. The following definition was adopted during an FAO seminar on modernization held in Bangkok in 1996: “Modernization is a process of improving resource (labour, water, economic and/or environmental) utilization by upgrading (as opposed to merely rehabilitating) the hardware and software in irrigation projects, while maintaining or improving water delivery service to farms.”

Another definition was proposed during another FAO-supported workshop on the valorization of irrigation water in the large-scale irrigation schemes of North Africa in 1999: “Modernization is a process of rehabilitation of irrigation systems during which substantial modifications of the concept and design are made to take into consideration the changes in techniques and technology and to adapt the irrigation systems to the future requirements of operation and maintenance. Delivery of water should be as flexible as possible, with demand irrigation being the ideal solution.”

These two definitions slightly diverge on the technical aspects. The first one focuses on the shift from supply to service-oriented and the second one on future requirements of operation and maintenance. The first one suggests the use of advanced concepts of hydraulic engineering, the second of new techniques and technology, which may include modern equipment for remote control. The main
difference is that institutional and organizational changes, including more active farmer participation, are attached to the first definition. The principles attached to the 1996 definition have been elaborated in a number of publications. These principles are summarized in the next section.

Principles of modern design

The overriding principle of modern irrigation is that irrigation is a service to farmers which should be as convenient and efficient as possible. Farmers ultimately have to generate the benefits which keep the system functioning. Modern irrigation schemes can be conceived to consist of several subsystems or levels with clearly defined interface, where water is measured and controlled.

- Each level is as financially autonomous and hydraulically independent as possible.
- Each level is technically able to provide reliable and timely water delivery to the next lower level. At each level there are the proper types, number and configurations of gated turnouts, measuring devices, communications systems and other means to control flow rates and/or water levels as desired.
- Each level is responsive to the needs of its clients. Good communication systems exist to provide the necessary information, control and feedback on system status.
- Each level of delivery has confidence, based on enforceable rights, in the reliability, timeliness and equity of the water which will be supplied from the next higher level. Effective mechanisms for conflict resolution are in place.
- The hydraulic design of the water delivery system is created with a well-defined operational plan in mind. The operational plan is established with a clear understanding of the needs of the end users.
- The hydraulic design is robust, in the sense that it will function despite changing dimensions, siltation, and communication breakdowns. Automatic devices are used where
appropriate to stabilize water levels in unsteady flow conditions.

- Motivated and trained operators are present at all levels of the system. They are not necessarily the farmers themselves but preferably hired staff. Instructions for individual operators are well understood and easy to implement.

- Maintenance is the obligation of each level. Maintenance plans are defined during design and are adequately funded and implemented.

- There is a clear recognition of the importance and requirements of agriculture and of the existing farming systems. Engineers do not dictate terms of water delivery; rather agricultural and social requirements are understood at all levels and in all stages of the design and operation process.

A modern design is the result of a thought process that selects the configuration and physical components in light of a well-defined and realistic operational plan that is based on the service concept. A modern design is not defined by specific hardware components and control logic, but use of advanced concepts of hydraulic engineering, irrigation, agronomy and social science should be made to arrive at the most simple and workable solution.

The most important issue and the one that often receives superficial attention during project preparation and appraisal is the ability of the system to achieve a specific level of operational performance at all levels. A precondition for high performance is that the design must reflect the objectives and requirements of the future operation. As long as the design of irrigation systems is understood as a classical engineering task of designing structures, essential operational questions will not be addressed.

A proper operational plan is one that combines the various perspectives and helps reconcile conflicting expectations between the users, the project manager, the field operators and the country’s policy objectives. The two preliminary steps in the planning of
irrigation projects are the definition of objectives and the associated decision about water deliveries.

**Project objective:** A preliminary step in the planning of an irrigation project or its rehabilitation is the definition of project objectives that depend on the country policy for irrigated agriculture. The objective could be to maximize the value of production by unit of water or unit of land. Project designs vary whether the project objective is to develop export-oriented commercial farming or to support rural population, alleviate poverty in rural areas and limit rural migration to urban centres. The original design of a project may no longer be compatible with the forces of change, which are affecting irrigated agriculture in many countries.

**Water delivery:** The second step in the planning of an irrigation project is the decision about water delivery. This can be described as the frequency, rate and duration of water deliveries at all levels of an irrigation system. The various systems of water delivery are described in the literature (FAO, Clemmens): rotation, arranged schedule, limited rate demand and centralized scheduling. Most traditional delivery systems have no or little flexibility built into them. They do not attempt to match water deliveries to crop needs. The stated objective is to obtain equity through simplicity of design, although poor design, maintenance and operational problems may prevent from achieving the objective. Modern irrigation projects are designed with the stated objective to deliver water according to crop requirements. At a minimum, the frequency and sometimes the duration of irrigation should be adjustable.

As noted earlier, a water delivery schedule does not necessarily imply a specific design or technology. A fairly rigid schedule of water delivery to the farm turnouts may use modern irrigation hardware and computerized decision support systems to make the water delivery reliable and equitable. A primary advantage of using modern design and equipment is that the operators can choose the flexibility offered at various levels of the system. For example, the different methods of water distribution in modern irrigation systems in Morocco are variations of centralized scheduling (with the choice
given farmers on duration and timing), although the systems have the capability to be operated on an arranged schedule. The reverse is not possible. A project designed for rigid rotation through simple non-adjustable structures or for proportional distribution cannot be operated for flexible water distribution.

The most important step in the design of an irrigation system is water control defined by three strongly related elements: the configuration of the distribution system, the control strategy and the hydraulic equipment.

**Configuration**: The configuration of an irrigation system is obviously determined by the relation of land and water resources, the topography and economic considerations. The design should incorporate as much as possible features that facilitate operation and provide flexible irrigation service, such as buffer reservoirs and on-farm reservoirs and use of low-pressure pipes instead of canals for tertiary distribution. Buffer reservoirs are widely used in mid and south China, in what is known as the “melon on the vine” system. Buffer reservoirs can be located alongside main systems or at the interface between two levels of management, such as between main and secondary canals. The incorporation of reservoirs reduces to some extent the need for sophisticated water control methods of the main systems.

**Water control strategy**: The designer has the choice between many control strategies for the operation of the system:
- Upstream, downstream control or controlled volume
- Local versus remote monitoring and control
- Proportional versus adjustable control

The designer has also the choice between various configurations for the automation of the canal systems:
- Distributed control in which control is achieved through independent automatic units;
- Centralized control in which control is achieved through a master station; and
Supervisory control combining distributed automation under master supervisory control\(^{19}\). This configuration is known as SCADA (supervisory control and data acquisition). These three systems are depicted in Figure 2 a, b and c showing the same canal system equipped with different types of control structures. The advantages and disadvantages of these different configurations are discussed in technical publications. Under distributed control, the system manager is not in a position to supervise or control the entire canal system. Centralized automatic control makes possible the use of highly efficient control logics but the operation depends on the reliability of a communication system. Under supervisory control, the central station makes decisions on the lower-level strategy based on the data received from the local controllers, also known as remote terminal units or programmable logics controllers. These local controllers make changes to the control devices according to the target instructions received from the master station, such as maintaining a target flow rate or water level. This system is less susceptible to communication system failure. The centralized and supervisory control methods can involve varying levels of participation of the master station personnel in making decisions from manual to computer-directed control, which uses specially developed computer programs using data from the entire canal systems and modelling studies. Computer-directed control is applicable to the most complex systems involving a number of canals, reservoirs, pumping and/or power stations.

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\(^{19}\) Supervisory control is defined by the Bureau of Reclamation as the control of a system from a centralized (master station) over a communication system and using remote terminal units at the canal structure sites.
Figure 2 Alternative configurations of canal automated systems
The selection of water control strategies can have very different effects on day-to-day operations. Certain control strategies eliminate the need for advance scheduling of water deliveries, the need to know exactly the flows at various sections of the canals, the determination of lag time and the estimation of seepage and operational losses. This is the main advantage of the basic downstream control compared to the upstream supply-oriented control methods, which require elaborate and complex predictions of irrigation requirements. However, downstream control is not necessarily associated with demand delivery. It is essentially a control strategy often used to greatly simplify the operation of very long canal systems, which is very complex under upstream control. Demands from the next lower level of secondary canals can be either under rigid rotation or flexible.

A single strategy is rarely used for an entire irrigation system. Most projects combine two or more control strategies. A main canal can be under downstream control and the distribution system under upstream control; or the main canal can be under upstream control and the distribution under proportional control (structured design in Nepal). Many examples of combination of control strategies could be provided to illustrate the wide number of solutions. The Narmada system is designed for remote central control and the tertiary system for proportional control using the structured design standards. The King Abdullah canal in Jordan is operated by remote control under dynamic regulation although rigid rotation is used for the distribution of water from the pressurized pipe systems. The Coachella project in California is operated under upstream control with the assistance of a remote monitoring system. A large buffer reservoir at the end of the canal absorbs the daily differences between orders and deliveries. This reservoir supplies open pipelines which receive rigid deliveries during 24-hour periods. Farmers have built numerous reservoirs on their farms to increase the flexibility of irrigation required for the mix of on-farm irrigation systems most suitable to the variety of crops.

The selection of a control strategy has a major impact on several aspects of the future performance of an irrigation system: ease of
operation, ability to provide a high quality of customer service, and general efficiency. Projects designed for proportional division of water through rigid and passive structures are the easiest to design, construct and operate, but provide the least flexible service to the users. Manually operated gated systems are the most complex to operate to provide both quality of service and efficiency. Modern design makes possible to improve service and efficiency but requires more design skills and higher quality of construction and installation.

![Figure 3](image)

**Figure 3** Complexity of different control strategies at design, construction and operation stages

**Some guiding principles for selecting a control strategy and equipment**

No control strategy and no equipment is ideal for all situations found in irrigation projects. Many physical and institutional factors have to be taken into consideration by the planners and designers. However, there are some general principles, which are summarized here:

- The delivery service should be as much as possible user-oriented. Reliability and equity of water delivery are the basic features of irrigation service. However, providing some form of flexibility in duration, flow and interval of irrigation should be considered during the planning stage.
• Different control strategies could be combined within an irrigation system. The degree of flexibility could differ from one level to another level of a canal system.

• A key objective should be the ease of operation – not necessarily the simplicity of design or installation. This principle is widely applied by other industries.

• Automatic downstream control is well suited for long canals because it eliminates the need for advanced scheduling and a number of estimations. Use of downstream control for large canals does not mean on-demand delivery at farm level. Efforts to convert existing systems to downstream control through the use of control algorithms have generally failed. However, adoption of downstream control with the use of automatic float-gates has been successful in new projects.

• Manually operated gated systems are the most complex irrigation systems to operate with high efficiency and reliability. Using simple hydraulic principles and equipment could make operation simpler.

• Hydraulic automation requires a minimum of skills and training, compared to electronic-based automatic controllers.

• Proportional-division systems are the easiest to operate and design. Basically these systems provide no flexibility in water delivery. They cannot respond to agricultural changes. However, some improvements in the design of proportional dividers make it possible to easily adjust the sharing of incoming flow.

In summary, the selection of a control strategy is not limited to a simple choice between gated and ungated systems, as implied in the oversimplification of the 1994 World Bank irrigation review. There are a number of options available for each level of a canal system and they can be combined to define the most desirable global solution in order to provide ease of operation and a higher level of service. These options are summarized in Figure 4.
Control equipment: The last step is the selection of control equipment that fits with the selected control strategy. A number of publications provide detailed description of the equipment available to control flows in canal systems. The 1993 ICID publication on *Automation of canal irrigation systems* presents the salient features and fields of application of the various types of equipment which may be used, including:

- Passive regulators: long-crested weirs, flow dividers, level controllers;
- Conventional gates: leaf gates, drop-leaf and flap gates;
- Automatic controllers: electro-mechanical and electronic controllers;
- Self-operating gates for automatic level control: float-operated gates;
- Instrumentation: position, level and flow sensors;
- Means of communications: radio and cable methods; and
- Equipment for remote monitoring and control master stations.

A number of physical, social and institutional factors, which are discussed in Chapter 11, should be considered in the selection of control strategy and equipment. Questions such as the possibility of
crop diversification or conversion to crops with higher irrigation requirements, the risk of silting of canals operated under variable flows, the capabilities of the field staff to operate and maintain electronic equipment, the acceptance of the operating rules by the farmers and their understanding of how the structures function should all be considered. The answers to some of these questions are beyond the scope of responsibilities of a design engineer. However, it is his responsibility to select control structures that are robust, easy to operate and interact with the other structures in the vicinity to minimize the fluctuation of hydraulic conditions.

One of the most important points is the right selection of the combination of check structures and turnouts. Clustered structures react differently to fluctuations of upstream level and flows depending on their characteristics. The sensitivity of these structures and the hydraulic flexibility of the different combinations of overshot and undershot gates are discussed in detail in several reference books (Ankum and Horst). Figure 5 shows the sensitivity of overshot and undershot hydraulic structures (weirs and orifices) and the effect of a twofold increase of the head on the flow rates.

The World Bank review of the Indonesian irrigation sub-sector (1990) rightly observed that “very often the solution adopted has been sluice-gated controls along the parent canal combined with Rominj gated off-takes (overshot gates). Unfortunately this is the worst of all combinations from the hydraulic viewpoint since it is extremely unstable. Small deviations have a proportionally great effect”. The negative effect on the operational stability of a system was overlooked when selecting the Rominj gate, which has excellent metering potential when considered in isolation. Figure 2 shows the best and the worst combinations of hydraulic devices to minimize the fluctuation in water levels and diverted flows.

The constant-head orifice gate, found in many schemes throughout the world, is a flow-control and measuring structure which is particularly difficult to operate. Very few field operators and gatekeepers are familiar with the functions of the two gates. In practice,
these devices are rarely used for water measurement despite their good capability in laboratory conditions.

**Figure 5** Flow rate fluctuations through weir and orifice control structures

*Note:* When the relative head doubles, the relative flow rate increases by 180 percent over a weir and only by 40 percent through an orifice.

**Detailed design and construction drawings** are the last steps in the design of irrigation projects. The design process moves from art to conventional structural engineering, which is the domain of civil and mechanical engineers. The emphasis is on the dimensioning of the structures and reinforcements and the mechanical and structural integrity analyses. Manuals and guidelines are widely used during this phase.

The configuration of an irrigation system and the selection of control strategies are the design steps that require the most imagination.
Although there are economic considerations to select among various options, there are no design manuals that can be applied as in structural engineering. The selection of the control equipment requires up-to-date skills to keep up with the developing technology. The principles of hydraulic regulation, including passive and reactive regulators, although developed half a century ago, have not widely been used outside the Mediterranean countries, because of a lack of awareness of these techniques and in many cases resistance and aversion to innovation. Computer-assisted operation and telecommunications entered the irrigation sector about two decades ago and have been used to improve the performance of old systems under manual operation.

**Figure 6** Combination of check and turnout structures
Modernization of existing schemes

Modernization of irrigation schemes raises major challenges for designers and policymakers. How much of the existing infrastructure can be saved? Which level of investments can be supported by the users? How much can be achieved by substituting hydraulic infrastructure by management inputs? The first step in this modernization is an in-depth diagnosis of the present performance of the system. The objective of this diagnosis is to identify the changes that have taken place since its original design, and the deficiencies in design and management. The diagnosis should determine the best approaches to solving the problems and if changes in water deliveries and system control strategy are desirable or necessary. The rapid appraisal process presented in Chapter 13 proves to be a very successful diagnosis tool.

After the diagnosis of an existing scheme is complete, a master plan needs to be developed. The master plan needs to define short-term and long-term improvements. A list of priorities must be developed based on realistic financing availability. Of major importance is the choice of the configuration of the automation system between distributed, centralized and supervisory control.

Changes or improvements in control strategy are difficult to test in real conditions without disrupting the operation of canals. The development of digital computers and advances in numerical methods in recent years has gradually helped to solve this problem. Flow simulation models in recent years have made possible to develop and test various control strategies (Mutua). Two approaches have been adopted to make use of these new tools.

Simulation of canal response for different scenarios: This approach has been used in recent years by IIMI and other researchers to simulate different operational scenarios for improving the operation of complex canal systems, for example the Chasma Right Bank canal in Pakistan, affected by high silt content, and the Gal Oya canal in Sri Lanka, which has a large number of gated cross regulators. The complex operational rules derived from these studies
have not been fully adopted by the agencies responsible for the operation of these canal systems. A simulation study of the Pyramid Hill No 1 canal in Victoria State in Australia concludes: “Operational scenarios to improve manual operation yielded only marginal improvements in the operational performance, thus reinforcing the view that significant gains in the quality of operation cannot be attained under manual operation.”

The studies show that canal operation can be considerably improved by adopting the SCADA model because of the advantages of real-time information on water levels and flow rates and the possibility to respond to fluctuations more accurately and timely.

**Centralized automatic control systems:** A number of problems have been reported with centralized automatic control making use of control logics. Although a number of different control algorithms and automatic devices have been used, the desired results have not always been attained. Balogum states that some projects have failed and even led to unstable control because of the failure to take into account the dynamic properties of canal systems. Some specialists do not recommend to use these models for real-time control but to use them for defining operational procedures. Several efforts were made in Alberta, Canada, to achieve downstream control; but to date none has been satisfactory due to control algorithm limitations (Ring). As stated earlier, this method should be used for the most complex systems because of the complexity of design and equipment and the skill level required which is not always available in either developed or developing countries.

An emerging approach to the modernization of existing systems is the basic low-cost, incremental SCADA model. This model is commonly adopted by the irrigation districts in the United States for the modernization of old manually gated systems. Based on financing availability, four or five sites are equipped every year. For example, the proposed SCADA system for the Yuma irrigation district serving about 4 500 hectares provides for the automation of 20 sites, including the head of main canal, laterals, waste way and
supply wells, which have been given five levels of priority. The total cost estimate is about US$350,000.

Box 9: Turlok irrigation district, California: the modernization process

The 62,500-ha Turlok project serves 6,500 customers in the San Joaquin Valley. The Irrigation District owns and manages more than 400 kilometres of canals. Most of the land is flood irrigated. The district is progressively modernizing the infrastructure through the construction of long-crested weirs and installation of supervisory control.

As discussed earlier, some developing countries have adopted or developed modern design standards, but very few have converted from conventional to modern design standards for the modernization of existing schemes. One remarkable exception is the modernization of the irrigation system in the Nile River delta, which is at the cutting edge of the technology by attempting to solve the problem of night storage within the secondary canals, a solution imposed by the constraints on land availability for the creation of farm reservoirs. Another example is the modernization of irrigation in the Jordan Valley, where the originally manually operated main canal has been converted to dynamic regulation and the canal distribution to pipelines. In Asia, modern designs are being used for the construction of the High-level Pehur canal in Pakistan, for the Narmada main canal and for the GAB project in Turkey. After a long period of failed attempts to install automated systems, Taiwan has now successfully placed most of its large irrigation districts under basic SCADA control. Malaysia has commissioned a study on “Modernization of irrigation water management systems in granary areas of Peninsular Malaysia”. The 20-year-old remote monitoring system of the MUDA project has been recently converted to a SCADA system.

XI. PARAMETERS INFLUENCING PLANNING AND DESIGN OF IRRIGATION PROJECTS

The design of a project configuration and the selection of an irrigation strategy and of control equipment to meet that strategy depend on a number of physical, social, managerial and economic
considerations. Not all of these are of equal importance in different projects, but all should be considered during the planning stage.

**Water resources**

Water resources and their variability are the critical elements in the determination of the irrigable areas. Studies on the balance of water supply and demand form the main part of the conventional feasibility studies of irrigation projects. Simulation model programming techniques have made it possible to examine various alternative solutions for different cropping patterns and seasonal or multi-year storage considerations.

The less reliable the water supply, the less feasible it is to adopt a water control strategy to meet precise crop irrigation requirements. There is little need for precise flow and water-level control. It is for this very reason that most traditional run-of-the-river projects have a proportional control strategy. The main objective is the equitable distribution of diverted natural flows that respond rapidly to the local variations of rainfall. The adoption of another strategy is doomed to fail. A case in point is the modernization of the *subak* projects in Bali, Indonesia. Farmers or groups of farmers can, however, improve the dependability of available water by constructing farm reservoirs, as was done in China before the construction of large reservoirs, or by tapping groundwater.

**Groundwater resources**

The development of groundwater in surface irrigation projects is a relatively recent phenomenon. The original objective may have been the mobilization of additional water resources, particularly in projects where canal systems were designed for extensive irrigation. However, the prevailing incentive for farmers to develop groundwater may now be the flexibility and reliability of that resource. Groundwater now accounts for about 40 percent or more of the total irrigation resources available in some originally water-surface projects. The contribution of groundwater has changed the overall game plan. Irrigation strategies adopted in the past to support
a drought protection policy should be reassessed. In some cases, use of groundwater can be limited to drought years, if the canal capacities and surface resources can meet the requirements in normal years (United States). In other cases, such as in the Indus basin in Pakistan, conjunctive use is needed year round to satisfy the intensification of irrigation. The poor quality of irrigation service in the middle and lower sections of these systems frequently requires the use of groundwater for precise irrigation for high-value crops, and even for pre-germination rice-seeding techniques.

The two positive and obvious effects of groundwater exploitation that have led to its rapid development are that it is an easy means to get access to a huge extra resource and, when developed privately, it provides the ideal flexible water delivery service. At the same time, these developments have had negative side effects that have important consequences for the future planning of irrigation development:

- The development and use of groundwater as an additional source of irrigation water has often served to indemnify the irrigation agencies responsible for canals systems from bad or poor water deliveries, effectively taking away the incentives and need to improve their systems and service;
- The exploitation of groundwater has often escaped the regulation measures of allocation and scheduling, thus facilitating its overexploitation. This situation requires an integrated approach in the planning and design of future irrigation developments.

How the integrated management of both ground and surface water resources can best be integrated in the design of the delivery and conveyance system still remains a challenge. The recent increased attention paid to integrated management of surface and ground water at the river basin level has also brought about new concepts of irrigation management. The aquifer can be regarded as a reservoir that can be refilled with surface water. Some imaginative solutions could also be developed to improve the performance of the old-fashioned surface systems designed for protective irrigation. These
systems could deliver multiple services ranging from a basic proportional delivery to a highly flexible demand delivery, for example if operated under the refusal operation mode. In surface projects designed for meeting full crop requirements, groundwater could be saved for dry years if the farmers are satisfied with the quality of service and particularly the flexibility offered by the surface system.

The strategy to be adopted for conjunctive use of surface and groundwater strongly depends on the quality of groundwater. If groundwater is brackish or saline, one way is to alternate its application with application of surface water of better quality; another way is to blend good-quality water with brackish water in order to extend the water supply, gaining quantity at the expense of quality (Hillel). The choice depends on the tolerance of crops to brackish water, the degree of salinity of groundwater and the type of soil. The cyclic strategy allows the soil to be flushed from time to time.

Hillel points out the great importance of the frequency of irrigation in salinity management. If irrigation is applied frequently, the concentration of salts in the soil solution is maintained at a level close to that of the applied water, and the progressive build up of salinity is prevented, which points to the need for modern irrigation at farm level.

**Silt load**

The problems and challenges associated with silt-laden water in irrigation are frequently poorly understood, and underestimated, by irrigation specialists. There is an inherent conflict between flexible delivery operation and maintenance costs of schemes with a high sediment load. Flexible delivery results in unsteady flow conditions and occasionally low flow velocities, thus increasing the risk of siltation of canals. Unstable channels put enormous strains on maintenance and undermine the operation of canals. The problem of silt management was underestimated in designing the Chasma Right Bank canal in Pakistan, possibly because of optimistic assumptions on the silt trap effect of the upstream reservoir. As indicated earlier,
considerable studies using computer simulation models were later carried out by IWMI to determine how to manage silt and operation of this canal at less than full supply. Techniques and management procedures to reduce substantially the silt load should be developed.

**Rainfall**

The variability and intensity of rainfall require flexibility in the operation of irrigation systems to achieve overall efficiency. The system should be able to respond quickly to a sudden fall in demand of irrigation water. Operation of irrigation schemes in arid regions is usually easier because smaller variations in demand require fewer provisions to regulate unsteady flows. In humid areas, the system should be able to satisfy the total evapotranspiration requirements in case of dry spells during the wet season.

It is still normal practice to use the concept of excess probability of rainfall in the calculations of crop requirements, as recommended in FAO Paper No 24. A more realistic method would be to use the actual data rainfall for each 10-day period of the entire period. The conventional method has the disadvantage of smoothing out the deficits of water during the drought periods. Irrigation departments in China use the more precise method of actual rainfall for each period. The capacity of computer modelling is no longer an obstacle to the wide adoption of that method.

The underestimation of water deficits due to the use of rainfall probability for the calculations of canal capacity contributes to the discontent of farmers in humid areas, as they try desperately to save their crops during dry spells.

**Soil conditions**

Differences in soil conditions influence on-farm irrigation requirements. Crop evapotranspiration is equal in well-managed fields on sandy and clay soils. There are major differences between these soils, however, with regard to optimum frequency flow rate and duration. Sandy and clay soils have different holding capacities and water
intake rates. Coarse soils have a low water-holding capacity and a high intake rate. Fine soils have a high water-holding capacity and a low intake rate. Sandy soils must be irrigated frequently. No single irrigation schedule (rate, duration and interval) is optimal for all soil types. Recognition of the importance of customizing water deliveries to different soil types is a main reason why modern irrigation schemes provide as much flexibility in water delivery as possible, rather than forcing the users to adapt to a rotation with a specific flow rate, duration and frequency.

**Crop diversification**

There are inherent differences among crops in relation to needs for water at particular growth stages, root depths, optimal frequency of irrigation, and drought resistance. For example, grain crops are very sensitive to water stress during the critical periods of pollination and milking of grains. Vegetables are particularly sensitive to water stress because of shallow root zones. Water supply must be very reliable to meet the quality requirements of high-value markets.

Rice cultivation has particular water requirements: high flow rates are required during land preparation. Low design capacity of canals increases the time of land preparation and imposes its staggering over too long a period to benefit from the optimal use of rainfall. During the growth period, most farmers prefer the traditional method of continuous supply of water, which enables them to maintain the desired level in the paddy fields to reduce weed problems. Attempts to introduce rotational irrigation in rice schemes have failed in many countries, such as Thailand and the southern states of India, because of farmer resistance. By contrast, water-saving irrigation (WSI) techniques are practised in many projects in Southern China where distribution of water from terminal reservoirs is fairly reliable. WSI techniques involve maintaining a very thin water layer in the field and alternate wetting and drying. Bhuiyan observes that “WSI techniques as those applied in China, however, require a high degree of management control and infrastructure at both the farm and system levels. For much of developing Asia, management capacity to implement such strategy does not exist. More supervision and labour
are required. Adoption may also be hampered by farmers’ concern about not having access to water when they need it because of lack of reliability in the system water supply performance”.

The very high capacity of irrigation canals for paddy irrigation in Western Africa, over 3 l/s/ha in some cases, where high yields are obtained, contrasts with the limited flows used for the design of projects in South Asia – for instance, the Sunsari-Morang project in Nepal, where main canals were designed on the basis of Indian standards. At the end of the growing season, conflicts arise between farmers who still require irrigation water and those who are ready to harvest. There is no management solution to this situation in a structure design scheme in the absence of drains. Undersized capacity of canals imposes the staggering of cultivation over too long a period. It is not only a question of management capacity as argued by Bhuyian.

**Existing infrastructure**

To a large extent, the layout, original design criteria and standards used for an irrigation project limit the options for its rehabilitation and modernization. The slope of the main canals, if too steep (over 15/20 cm per kilometre), determines whether or not operation can be converted from upstream to downstream control. The relative design capacity also is a major constraint, unless remodelling of the canals is found to be economically viable. In extensive irrigation projects with the objective of spreading water thinly, the design capacity decreases from upstream to downstream since only seepage losses are considered. In responsive irrigation projects, the design capacity increases when moving downstream to accommodate the need for flexibility.

Considerable imagination is required of the designers to modernize the existing infrastructure of irrigation projects since in most cases there are severe constraints. Construction of collectors and buffer reservoirs, conversion to pressurized systems and modifications of cross regulators are some of the tools available for the modernization of the configuration and control technology.
Land tenure and consolidation

Modern principles of irrigation scheduling and water application methods require specific arrangements of farm boundaries. Ideally plots have to be arranged within a geometric grid, with the proper choice for their orientation and slope for the application of surface irrigation methods. Since the 1960s, the policy of the Ministry of Agriculture in Morocco has been to systematically consolidate irrigable lands before the construction of any modern irrigation system. Design of the distribution system layout and of the blocks within which consolidated plots will be arranged is the first step in the design process. Ideally each plot should have a direct outlet from/to the irrigation and drainage system.

Basically, two land consolidation models have been tested and later adopted in a few developing countries. These two models reflect two different ideologies of irrigated agriculture: planned economy or liberalism. Under the former model, the irrigation blocks are divided into equal crop strips, crossing the farm boundaries, for semi-collective farming activities. Governments largely impose the cropping pattern. This model is used, for example, in the Gezira project in Sudan, in most of the modern systems in Morocco and in some smallholder systems in Zimbabwe. Irrigation in principle should be organized by crop and not by farm. Under the latter model, the farm plots are arranged so that each farm has individual access to the tertiary canal. Distribution of water is organized by turns of individual farms, not by crop strips.