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Guidelines on spate irrigation

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Frank van Steenbergen - Constructing a large river diversion structure - earthworks and gabions - in Wadi Labka, Eritrea.

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Table of contents

List of figures

List of tables

List of boxes

Glossary and abbreviations

Ala'ala fala'ala	Irrigation sequence giving upstream users priority (Yemen).
Algamas	Canal entrance formed by two conical stone structures, with a circular base having a diameter of 3–4 m (Yemen).
Aqm	Earthen diversion bund constructed across a wadi bed. Also used to describe traditional diversion spurs (Yemen and Eritrea).
ARV	Annual runoff volume (m^3).
Base flow	Part of the streamflow that results from precipitation infiltrating the ground and eventually moving to the stream channel. Also defined as groundwater return flow.
Bund	Embankment constructed from soil or wadi bed sediments.
Command area	The area of the spate irrigation scheme that can be irrigated (provided that water is available) and is fit for cultivation.
D_{84}	The size of the sediment of which 84 percent of the material is finer (m).
ERR	Economic rate of return.
Floodwater diversion	The act of diverting floodwater from the seasonal channels into adjacent embanked fields for direct application or into storage.
Gannda	Earthen diversion bund (Pakistan).
Gham	Contribution of land owner to maintenance (Pakistan).
Kharif	Summer cropping season (wet season).
MAF	Mean annual flood peak discharge (m^3/s).
MAP	Mean annual precipitation (mm)
MAR	Mean annual runoff (mm).
Mekemet	A conservation tillage practice of the Sheeb area of Eritrea.
Numberwar	Rule describing an irrigation sequence (Pakistan).
Peak flow	Maximum discharge of a flood event (m^3/s).
O&M	Operation and maintenance.

Q	Discharge or runoff (m^3/s).
Rabi	Winter cropping season (dry season).
Rada'ah'	Irrigation sequence giving upstream users priority (Yemen).
Rod-Kohi or Sailaba	Form of spate irrigation practiced in Pakistan.
Saroba paina	Rule describing the irrigation sequence (Pakistan).
Seguia	Irrigation canal (Morocco).
Spate flow	Runoff regime characterized by rapid changes in the levels of discharge and large variation in the size and frequency of flood events.
Spate irrigation	An irrigation practice that uses the floodwaters of ephemeral streams (wadi) and channels guided through short, steep canals to bunded basins where cropping takes place (sometimes referred to as floodwater harvesting).
Streamflow	Flow or discharge of water that moves along a river or channel (m^3/s).
T	Return period of a flood of a given magnitude (years).
TDA	Tihama Development Authority (Yemen).
Wadi	The bed or valley of a seasonal stream in arid or semi-arid areas that is usually dry except for a short time after spate flow events (a few hours to a few days).
Wakra	A local term in Pakistan that refers to an earthen bund for diverting spate flow from a secondary canal to a field.
Waqf	Land belonging to religious trusts (Pakistan).
WUA	Water users' association.
Zakat	Religious tax (Pakistan).

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This work is dedicated to the memory and inspiration of two giants in the field of spate irrigation: Robert Camacho and Berhane Haile Ghebremariam.

Preface

Spate irrigation is an ancient practice by which floodwater is diverted from its river bed and channelled to basins where it is used to irrigate crops and feed drinking-water ponds, serve forest and grazing land and recharge local aquifers. It has evolved over the centuries and provided rural populations in arid and semi-arid regions with an ingenious way to cope with the aridity of their climate. It is thought that spate irrigation started in present-day Yemen, where it has been practised for around five thousand years.

Today, spate irrigation covers more than 3 million hectares across the world. Although its extent is relatively minor compared to other types of irrigation, it represents a unique option for the management of scarce water resources in support of agricultural production and rural livelihoods in many arid regions.

Spate irrigation has been largely neglected in the technical literature. There are no available guidelines that discuss the specificities of spate irrigation. Yet it is different from conventional irrigation in many ways and therefore needs special skills and approaches of which practitioners are not always aware. In particular, standard design approaches cannot appropriately take into account the level of uncertainty related to floods, the hydraulic challenge of guiding flood flows, the heavy sediment loads, the exceptional nature of the water rights, or the management and maintenance models that are specific to spate irrigation.

The main objective of this publication is therefore to assist planners and practitioners in designing and managing spate irrigation projects. It covers hydrology, engineering, agronomy, local organizations and rules, wadi basin management and the economics. It is designed to be both a practical guidance document and a source of information and examples based extensively on experience from around the world in areas where spate irrigation is practised.

Chapter 1

Introduction

DEFINITIONS AND CONCEPTS

Spate irrigation is a unique form of water resource management that has been practised in arid and semi-arid regions where evapotranspiration greatly exceeds rainfall. In the report of an Expert Consultation on the subject, *UNDP and FAO (1987)* have defined spate irrigation as "an ancient irrigation practice that involves the diversion of flashy spate floods running off from mountainous catchments where flood flows, usually flowing for only a few hours with appreciable discharges and with recession flows lasting for only one to a few days, are channelled through short steep canals to bunded basins, which are flooded to a certain depth". Subsistence crops, often sorghum, are typically planted only after irrigation has occurred. Crops are grown from one or more irrigations using residual moisture stored in the deep alluvial soils formed from the sediments deposited in previous irrigations.

A simpler definition of spate irrigation was given by *Mehari et al. (2007)* as "a resource system, whereby flood water is emitted through normally dry wadis and conveyed to irrigable fields". *ICID (2010)* distinguishes floodwater harvesting within streambeds, where channel flow is collected and spread through the wadi where the crops are planted, from floodwater diversion, where the floods – or spates – from the seasonal rivers are diverted into adjacent embanked fields for direct application. In all these cases, spate irrigation is characterized by the arid environment in which it takes place, the unpredictable nature of flood water to be harnessed, high sediment loads and a complex social organization.

Sedimentation is a major factor in spate irrigation. Spate systems grow their own soils, and rely on nutrients transported with sediments from upstream catchments to maintain soil fertility. High sediment loads cause command areas to rise and block intakes and channels, but sedimentation processes can be manipulated for the benefit of farming. Spate irrigation is as much about sediment management as it is about water management.

Spate irrigation is the main source of livelihood for large numbers of economically marginal people in areas as varied as the Near East, Africa, South and Central Asia and Latin America, and is mostly practised outside the formal state-managed irrigation sector. Generally, it is a subsistence activity, with low returns, generating highly variable incomes between good and bad years. It requires high inputs of labour to maintain intakes, canals and field systems and, in places where more reliable and rewarding livelihood opportunities are available, farmers tend to abandon their schemes, local management structures are undermined, and spate irrigation systems tend to decline and disappear. This has been the case in some richer countries such as Saudi Arabia. On the other hand, spate irrigation also remains at the heart of places like the bread basket of Yemen – the Tihama – and it is on the upsurge in several countries, for instance in the Horn of Africa.

This type of water management is very risk-prone and requires high levels of cooperation between farmers to divert and distribute flood flows. The uncertainty stems from the unpredictable numbers, timing and volumes of floods, the occasional very large floods that wash out diversion structures, and the frequent changes to the wadi channels from which the water is diverted. Substantial local wisdom has developed in setting up and constructing intakes, organizing water distribution and managing the flood waters and their heavy sediment loads. In some locations, large irrigation systems have developed over centuries, first with rudimentary diversions and canals providing high water diversion efficiency and a fair measure of equity between upstream and downstream water users. Command areas may range from anything between a few hectares to over 30 000 ha, and some spate schemes rank amongst the largest farmer-managed irrigation systems in the world. While spate irrigation has been primarily developed for cropping, it rarely serves only agriculture. In many instances, it also sustains rangelands and local forestry, and helps recharge groundwater, thus providing drinking water for humans and livestock.

In many arid environments, the classical approach to water management through storage of river water in reservoirs is not practical owing to the very high sediment loads transported during floods. In such regions, the useful life of reservoirs is usually very short. Spate irrigation offers more attractive development options when appropriate models can be identified. However, only a relatively small number of public programmes to develop and improve traditional spate irrigation have been carried out. One reason has been the difficulty in justifying investments in civil engineering works on systems dominated by low-value subsistence farming. A second reason is that it has been hard to identify successful interventions, as spate schemes, in spite of their apparently simple technologies, are hydraulically and socially complex.

These complexities have not always been sufficiently appreciated. In past improvement and modernization projects, with serious implications for the quality of the results. The overriding point is that the repertoire of potential improvements is often not well known. On the engineering front, for instance, interventions based on improving traditional systems are not part of standard curricula and yet it requires understanding and ingenuity to identify break-through improvements in these systems. As a result, modernization projects have too often applied design and management principles issuing from classical irrigation but not adapted to spate conditions.

Similarly, the potential scope for other contributions to improved spate irrigation – in agronomy and post-harvest technology, in rangeland management and agroforestry, in promoting recharge and reducing potential damage – is often sector-specific and not widely understood. The introduction of irrigation from shallow groundwater in spate-irrigated areas, for instance, is a recent innovation. With the availability of relatively inexpensive pump sets, this technique has become important in some areas in Pakistan, Tunisia and Yemen. In some areas, spate water and shallow groundwater are used together, but in others the introduction of shallow wells has resulted in the abandonment of the spate infrastructure and a move towards perennial cropping, sometimes of high-value cash crops.

HISTORY OF SPATE IRRIGATION

Spate irrigation has evolved and developed over a very long time period. The remains of diversion dams in ephemeral rivers dating from 3000 BC can be seen in Iran and Balochistan (Pakistan). It is thought that spate irrigation started in present-day Yemen, when the wet climate of the neolithic period became more arid, and has been practised there for around five thousand years. The famous Mar'ib dam in Yemen, which irrigated 9 600 ha with spate flows diverted from the Wadi Dhana, was first constructed during the Sabian period in the third millennium BC (see Box 1.1).

It is reported that large volumes of sediment were scoured out of the dam when it was breached. *Hehmyer (2000)* suggests that the dam builders could have constructed a permanent masonry dam but chose an earthen impounding structure that would fail when overtopped by historic floods, to prevent very large flows from damaging the irrigated area.

One can only speculate as to how the practice spread across the world. However, the intense development of trade after the Islamic period may have helped to spread innovations from the Yemen area. Yet it is likely that spate irrigation technology has

BOX 1.1

Mar'ib dam, Yemen

It is believed that construction of the Mar'ib dam commenced in about the third millennium BC, and was completed in stages over the next 500 years. The structure had very well constructed stone abutments and irrigation offtakes on both banks, which have partly survived. The dam itself was constructed from rock and soil and was breached on five or six occasions between the fourth and seventh centuries BC, when the final catastrophic breach, which is described in the Holy Koran, occurred. In its final form the dam was about 18 m high and 700 m long, and irrigated farmland supporting a population of between 30 000 and 50 000, growing maize, millet, barley and other crops. The dam was intended to divert water from spate floods, rather than to store water over long periods, as storage of flood waters would have resulted in fairly rapid sedimentation. It thus functioned more like a diversion barrage than a dam. The remains of the dam abutments and the 60 m^3/s irrigation outlets can be seen in the figure below.

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sprung up independently in several areas – particularly as it is found in areas as diverse and remote as West Africa, Arabia, Central Asia and Latin America. In some areas the interest is recent. The development of spate irrigation in Eritrea is for instance traced back to the arrival of Yemeni migrants 80-100 years ago (Haile *et al.*, 2003). In several other parts of Africa, such as Ethiopia, spate irrigation is now just emerging, in response to increased population pressure in the highlands.

In Yemen, large traditional spate systems consisting of numerous individual intakes and canals irrigating areas of up to 30 000 ha were developed in individual wadis. Sophisticated water sharing arrangements were formalized, with rules relating to water rights that exist in written records dating back at least 600 years. In Pakistan, spate irrigation has been practised for a long period and it was the basis of important agricultural production systems until the end of the nineteenth century, when the development of perennial irrigation received an important impetus under the British colonial administration – essentially by a reorganization of the water management arrangements. Spate water from about 26 wadis in the northwest coastal region of Egypt has been used for irrigation since Roman times, while spate irrigation has been practised in Morocco over a similar period. In central Tunisia, farmers have irrigated their fields with diverted spate water since the second half of the nineteenth century *(Van Mazijk, 1988)*. In Iran, spate irrigation has a history of many millennia and can be seen in many forms, often combined with groundwater drainage galleries, so-called *qanats*.

Spate irrigation practices are widespread in Iran, as illustrated by the rich terminology used in different parts of the county to describe it. *Darband,* check dams made of dry masonry are called *khooshãb* or *bãgh* in northern Baluchestan, southeast Iran, and *bandsar* in Khorasan, northeast Iran. Diverting floods from ephemeral streams and spreading the water on relatively levelled land is called *degar* in southern Baluchestan; *pal* and *bandsãr* in Khorasan; *ta, goudtak, taghal* and *gaband* in the Izadkhast Plain, Darab and southeast Iran; *goorehband* in Sistan, eastern Iran; and *korband* (silt retainer) in southern Fars, southern Iran, the Persian Gulf coast and the Qeshm Island. *Lavar*

FIGURE 1.1
Area equipped for spate irrigation in selected countries *(FAO-AQUASTAT, 2010)*

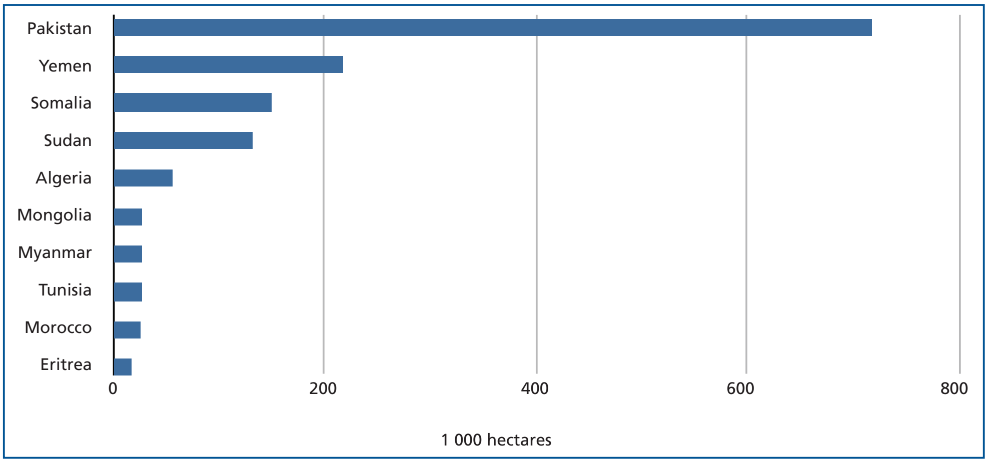
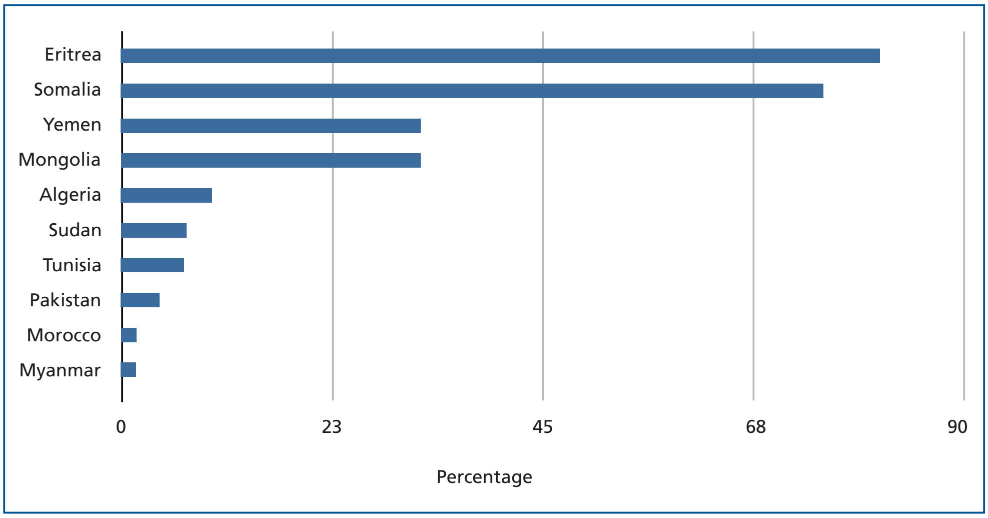


FIGURE 1.2

Spate irrigation as a percentage of total irrigation in selected countries

(FAO-AQUASTAT, 2010)



(silt bringer) is the name given to a spate-irrigated farm field in the Dorz-Sãyehbãn area in southeast Fars. Moreover, the upstream spate-irrigated fields in Mazaijohn, south of the Izadkhast Plain, Darab, are called *bonakhoo*, and those on the downstream end are called *shatmãl* (sheet irrigation) in Darab and *takhtãbi* in Khorasan.

EXTENT AND DISTRIBUTION OF SPATE IRRIGATION SCHEMES

Spate irrigation is found in West Asia, Central Asia, the Near East, North Africa, the Horn of Africa and Latin America. The country with the largest area under spate irrigation is Pakistan. In some areas – such as North Africa - the area under spate irrigation has been reduced in the last twenty years, partly as a result of reservoir construction on several of the ephemeral rivers. In contrast, however, in the Horn of Africa the area under spate irrigation is expanding rapidly, especially in Ethiopia and Eritrea, where population pressure encourages settlement in the vast lowlands which have become more habitable. Another important development is the conjunctive use of groundwater and spate irrigation, giving rise to relatively highly productive systems, where possible.

Owing to the nature of spate irrigation, a substantial level of uncertainly exists on the extent of spate irrigation across the world. The most comprehensive information on the current extent of spate irrigation comes from FAO's AQUASTAT database *(FAO-AQUASTAT, 2010)*. The database indicates that there are around 3.3 million ha under spate irrigation, spreading over 14 countries and representing 11 percent of their irrigated area, with very large areas listed in Pakistan and Kazakhstan. These data are primarily based on available statistics and do not always capture the smaller, farmer-managed, informal schemes when they are not well documented. They should be taken as indicating an order of magnitude of the importance of spate irrigation and represent probably a conservative measure of the extent of land under spate irrigation. Figures 1.1 and 1.2 illustrate some data analysis based on information available in *FAO-AQUASTAT (2010)*.

Other sources give different estimates, and the definitions adopted to describe spate irrigation vary from one country to another, making statistics difficult to establish. For example, in Pakistan, where spate irrigation is found in all four provinces, alternative estimates of the spate-irrigated areas *(Ahmed, 2000)* are more than twice that indicated in the FAO data.

In several other countries and regions, including central Asia, Afghanistan, western China and parts of Latin America, scattered reports indicate the existence of spate irrigation but no figures are available. Areas of spate irrigation located in Ethiopia, Egypt, Kenya, Mauritania and Senegal, as well as Chile and Bolivia, are not reported. It is testimony to the informal and forgotten nature of spate irrigation that, though the areas may be relatively important, there is no recent accessible reference on spate irrigation in these areas. The uncertainty about the extent of spate irrigation is illustrated in Table 1.1. The table compares the area under spate irrigation as reported in AQUASTAT with estimates provided by participants in an expert meeting organized in preparation for this publication *(FAO, 2010)*.

TABLE 1.1
Large uncertainties that exist in assessing the area under spate irrigation

	Area under spate irrigation	
	FAO-AQUASTAT	Expert meeting 2008
Algeria	56 050	56 000
Eritrea	17 490	17 000
Ethiopia	-	140 000
Iran	-	419 500
Morocco	26 000	165 000
Pakistan	720 000	640 000
Tunisia	27 000	1 000
Yemen	218 000	117 000

Sources: *FAO-AQUASTAT, 2010 and FAO, 2010.*

CLASSIFICATION OF SPATE IRRIGATION SCHEMES

There are several variants of spate irrigation and several terms are used to describe similar practices. Spate irrigation has some similarities with flood inundation and flood recession systems found along alluvial plains, where crops are grown from the residual moisture following floods. The term *water harvesting* is also used to describe the practice in which the flow discharged from a small catchment area after a storm is directed through channels to a nearby field enclosed by bunds, and soil moisture is increased by subsequent infiltration, while *runoff farming* usually refers to *in situ* collection of rainwater in the field to increase moisture in the rootzone. In all cases, the crops take up the supply of water in the soil during the dry periods that follow rainfall and they can survive longer periods without yield losses in places with deeper and heavier soils *(Touer and Humborg, 1992)*.

There are two important features that distinguish spate irrigation from these other forms of flood irrigation. The first is that, in spate irrigation, flood water is physically diverted from wadi channels via canals to bunded fields that may be located at some distance from the water course. The second is that spate irrigation is carried out on a large scale, by groups of farmers rather than individuals, who need to work closely together to divert and distribute flood waters and maintain their intakes and canals. Spate irrigation is also distinct from semi-perennial irrigation, as it depends on short-duration floods, whereas semi-perennial irrigation makes use of flows lasting weeks, even months. In all cases, however, the dividing line is thin.

Common features of most spate irrigation schemes are:

- *ingenious diversion systems*, built to capture short floods but also designed to keep out the larger and most destructive water flows;
- *sediment management*, as the flood water has high sediment loads that would otherwise fill reservoirs and clog intake structures and distribution canals; these sediments are used to build up soil and level the land but can also result in excessive rising of land and loss of command;
- the importance of *soil moisture conservation*, especially as floods often come ahead of the sowing season;
- a sophisticated *social organization* to manage the sometimes complex system, ensure timely maintenance of the structures and channels and oversee the fair distribution of the flood water, even though it comes in unknown quantities at unpredictable times.

Schemes are usually designed for a given purpose and several classifications of the various types are possible. Table 1.2 presents classifications based on size, infrastructure, management or hydrological regime and source of water. Other classifications are possible, based on the range of crops that are grown or on the way water is distributed.

In these guidelines, scheme size and management arrangements have been used as main classification criteria, as different approaches are required for the different categories of systems. Below four main categories of spate irrigation systems are considered, to which these guidelines refer, together with a short summary of the most common improvement options, which are discussed in detail in the rest of the report.

- **Small schemes under farmer management using traditional diversion practices.**

  These schemes are usually found on small wadis where the flood flows can, for the most part, be easily handled by farmers using relatively simple diversions. For these types of schemes, the main improvement option consists in reducing the amount of labour involved in re-building diversion spurs and bunds.

- **Medium-scale/large-scale schemes under farmer management using traditional diversion practices.**

  These schemes are constructed in larger wadis carrying much larger flood flows. Typically they have numerous intakes ranging from simple deflectors in the upstream part of a wadi to diversion bunds in the lower reaches. Treating these schemes as a series of independent, small systems and providing each independent system with simple, un-gated diversions constructed from gabions, rubble masonry or concrete is to be one of the major improvement options.

TABLE 1.2
Possible classifications of spate irrigation schemes

Characteristic	Class	Description
Size of scheme	**Small**	Range from a few hectares, usually located on tributary wadis in mountain regions, or in plains supplied by small wadis, with areas not exceeding 1 000 ha.
	Medium	Schemes located mostly in plains supplied from small/medium wadis. Command areas ranging from a few hundred up to 5 000 ha. Often a single tribe or social group manages these schemes.
	Large	Substantial systems that may have numerous offtakes irrigating land areas of up to 20 000-30 000 ha. Complex water sharing rules have developed in some cases to control the distribution of flows between intakes operated by different tribes, villages or social groups.
Infrastructure	**Traditional intakes and canals**	Traditional diversions consisting of deflecting spurs or, in flatter plains areas, bunds that are constructed right across the flood channel. Canals are usually short and rarely include a secondary distribution system. Water is usually passed from field to field by breaking field bunds when the ponded water reaches a predetermined depth. In Pakistan, spate-system fields often have their own supply channels.
	Improved traditional systems	Farmer-implemented improvements could include flow throttling structures and rejection spillways near canal heads and drop structures and flow division structures in main canals. In some areas farmers may hire bulldozers to construct diversion bunds. When outside agencies support improvements, bulldozers may be provided at subsidized rates, and simple gabion or rubble masonry structures may be used at diversions. Improved water control structures may also be incorporated in the canal and field systems.
	Modernized and new systems	In large systems, numerous traditional intakes are replaced with concrete diversion weirs, with sediment sluices. Owing to the high costs of permanent structures a single permanent weir often replaces many traditional intakes. In newer schemes, steep canals and sediment management structures are provided to minimize sedimentation. In new schemes, where farmers may not have the traditional skills needed to manage spate flows, a range of diversion types, including large semi-permanent soil bunds and small, simple diversion weirs, are used.
Operation and maintenance	**Traditionally managed**	Farmers manage systems without assistance from outside agencies.
	Managed by farmers with support from outside agencies	In some schemes varying levels of support from government or NGOs is provided to assist in construction and maintenance of intakes, although operation is usually left in the hands of the farmers.
	Agency-managed	In some large, formally farmer-managed systems that have been modernized, the intakes and main canal systems are operated and maintained by irrigation agencies. In Yemen some of these systems are now being handed back to the farmers as part of irrigation management transfer efforts.
Wadi flow regimes and use of groundwater	**Schemes that have access only to spate flows**	At locations where only spates occur, it is necessary to divert water at high discharges if a reasonable proportion of the annual runoff is to be diverted.
	Schemes that have access to significant base flows	High water diversion efficiency can be obtained in wadis where (a) there are small base flows for some months during and following the rainy season; (b) there are large numbers of small and medium floods; or (c) the offtakes are located in flat plains areas where the floods have lost momentum and may last for long periods. In these cases, irrigation of areas located at the head of systems is reasonably assured, and irrigation practices resemble perennial irrigation. Spate irrigation from flood flows is carried out in the middle and lower reaches of the wadi.
	Conjunctive use of spate and shallow groundwater	Where possible, access to groundwater substantially reduces the uncertainty inherent in spate irrigation and allows cropping of cash crops that cannot survive for long periods between watering. Spates are still diverted for irrigation, albeit at unpredictable intervals and volumes. Spate flows enhance the recharge of the shallow aquifers.

- **Large and technically complex schemes.**

  Larger and technically complex systems are only feasible with an element of external management, ranging from full agency management to backstopping and technical support provided by local irrigation or agriculture departments. Where high development costs can be justified economically, permanent diversion and water control structures can be considered. Such schemes may considerably modify the hydrology of the wadi and must therefore be considered against the possible negative effects on downstream water users. There is also the requirement to ensure the funding of adequate levels of maintenance in agency-managed schemes and to avoid potential technical problems related to poorly engineered spate diversion structures.

- **Schemes with access to sufficient shallow groundwater or base flows.**

  Access to groundwater reduces much of the insecurity associated with spate irrigation and allows production of crops that cannot survive long periods between irrigations. In such cases, the provision of incentives or authorizations to allow farmers to dig wells and purchase pumps should be regulated to prevent over-exploitation of groundwater and, in coastal areas, saline intrusion and the destruction of aquifers, and the establishment of community-based groundwater monitoring and management systems may be required. The provision of communal wells to enable poorer farmers to benefit from groundwater irrigation could be considered. Properly conducted regional water balance studies are needed before shallow well irrigation is actively promoted in spate areas.

Aside from these differences, there are common possibilities for improvements in all spate irrigation systems, including stronger management in general, better moisture conservation, improvement in crop varieties and changes in cropping patterns. These improvements are discussed in the different chapters of this publication.

PURPOSE AND SCOPE: HOW TO READ THESE GUIDELINES

Although its importance is relatively marginal in absolute terms, spate irrigation offers scope as a water resources management option in support of agricultural production in many arid countries and represents therefore a viable option to enhance the livelihoods of the rural communities in these regions. Experience from past interventions has shown that improvement of spate irrigation schemes is possible when it is based on the combination of experience and knowledge accumulated by farmers over the years and on ingenious and well adapted design and management solutions.

However, spate irrigation is unquestionably different from conventional irrigation systems and therefore needs special skills and approaches, of which engineers are not always aware. In particular, the use of standard irrigation design approaches that do not take into account the level of uncertainty related to floods, their exceptional nature, and the sediment load challenge is not appropriate. Similarly, management models based on traditional irrigation are unlikely, in most cases, to be adapted to spate irrigation.

Spate irrigation has unfortunately been largely neglected. There are no available guidelines or teaching materials that focus on and discuss the specificities of spate irrigation. The main objective of this publication is therefore to provide insight and guidance, based on the experience gathered in many spate irrigation projects, about potential improvements of traditional spate irrigation systems, while it also highlights their complexity and the inter-connectedness of the different issues to be addressed.

These guidelines are designed to be both a practical guidance document, and a source of information and examples based extensively on experience from across the world where spate irrigation is practised. While it is meant to propose practical ways of designing and organizing the management of spate irrigation, the report also highlights past failures and successes in spate irrigation modernization which have been instructive for project improvement.

The guidelines cover all aspects of spate irrigation design and management: social settings and tenure issues (including water rights), hydrology, engineering design, water and soil management, crop production, farmers' organization, economics and environmental issues. They do not replace standard textbooks in all these disciplines but complement them by providing specific considerations in all these fields that apply to spate irrigation situations.

Each chapter covers one of the above subjects. A summary of the main guiding principles is presented at the beginning of the chapter and outlines the most important features of the subject. The rest of the chapter provides more detailed information and guidance, illustrated by numerous examples from existing spate irrigation schemes.

Chapter 2

The social setting

SUMMARY

An understanding of the socio-economic context in which farmers operate is essential to ensure effective and sustainable improvements in spate irrigation systems. A socio-economic analysis must be performed at an early stage in the design of spate projects, through an in-depth consultation process that covers all livelihood situations in the project area. It will help set the right priorities and avoid unintended negative consequences of spate irrigation improvement interventions.

Of primary importance is the way farmers deal with uncertainty in spate irrigation: with low crop returns and the possibility of crop failures always in the background, farming households adopt a number of strategies to cope with uncertainty that are based primarily on the diversification of the household economy. They include generating additional household income through wage labour, livestock keeping and off-farm activities; the systematic saving of surplus grains from one year to the next; the cultivation of low-yield, drought-resistant traditional crops, such as sorghum, which produce at least some fodder in drought years; and investment in easily disposable property, such as livestock and draught animals in particular, in good years when there is a crop surplus. Understanding and integrating these strategies into spate irrigation improvement projects will help set the right priorities, ensure the relevance of the interventions and avoid unintended negative consequences, as many past spate irrigation improvement projects have demonstrated.

Land tenure in spate irrigation areas varies extensively from one country to another, but it often reflects the complexity of the management of risk associated with spate irrigation. Societies have developed tenure systems that ensure the optimization of return on water, often at the expense of apparent equity in access to the resource. Projects must acknowledge and understand existing tenure systems and consider the implications of any possible intervention on tenure rights and arrangements, both in terms of management and in terms of distribution of benefits. Any changes that would have implications in terms of tenure must be negotiated with the beneficiaries at the outset. In particular, it should be considered that sharecropping is among the most common arrangements in spate irrigation systems. The impact of proposed improvements on the distribution of tasks and benefits between landlords and sharecroppers must be anticipated and agreed upon by all parties.

Careful attention must be given to equity considerations. Spate irrigation improvement projects should be designed and implemented so that poor households can have the chance to increase their incomes. In particular, it is essential that improvements in spate irrigation projects do not increase inequalities and inequitable access to the resources among social groups. While not all projects will have components covering the entire range of livelihood situations, all situations should be considered when projects are being planned and projects need to be screened for their impact on the different groups to ensure that unintended negative consequences are not introduced.

A ‘pro-poor’ approach will seek specific targeting of unprivileged groups. In several spate-irrigated areas there is considerable inequity and groups of ‘have nots’ may exist. These include: farmers who are too poor to farm and have no access to family labour or draught animals to use the water when it comes; people in areas with no, or saline, groundwater and thus without a local drinking water supply; tail-enders who depend on very unreliable spate flow with farming systems at risk of collapse; people living in low-lying areas or on exposed river banks who are in danger of losing all in floods; and the special outcast groups, for instance the Akhdam in Yemen, descendants of very early African migrants who have a long history of an extremely marginal socio-economic position. Poverty alleviation means not only making the local economy work in the remote areas where spate irrigation normally occurs but also making sure the benefits spread far and wide.

Such considerations also apply for the situation within the household. Understanding the distribution of tasks and power balance within the household is an important element of spate improvement projects. While there are major differences between regions, the distribution of tasks and responsibilities between men and women is usually well established, with men often in charge of maintenance of irrigation canals and terraces, and women often responsible for agricultural and harvesting activities, in addition to domestic tasks. It is therefore important that any proposed improvement be assessed in terms of their implications for both men and women and that the benefits of proposed improvements be shared by all. Of particular relevance is the issue of drinking water supply and the implications spate improvement can have on access to a safe source of water for domestic uses. Early consultation processes must ensure that the specific needs and requirements of women are understood and taken into account in the design of spate improvement projects.

Finally, spate irrigation improvement should not be programmed in isolation. To alleviate poverty in spate-irrigated areas, it is not sufficient to focus only on the improvement of spate irrigation. In a situation of a highly diversified household economy, successful alleviation of poverty among poor households in spate-irrigated areas will also depend upon:

- improvement of access to inputs of extension services, credit and marketing for spate-irrigated crops;
- improvement of the productivity of livestock and the processing and marketing of livestock products;
- creation of opportunities for wage labour and off-farm income, in particular for landless households;
- access to credit for well drilling and groundwater pumping or installation of communal wells with pumps, where groundwater development is possible;
- addressing the need for basic amenities – in particular, safe drinking water.

Poverty alleviation will also depend on a good understanding of the threats which spate irrigation systems face and which include their lack of attraction because of high-risk, very labour-intensive work, the excessive burden of maintenance on farming households, the reduced size of landholdings, and, in some cases, the lowering of the water table. When they become too pressing, these threats lead to the abandonment of infrastructure and emigration. It is therefore important that spate improvement projects assess and value these threats and address them to ensure a successful and sustainable impact of projects on people’s livelihoods.

INTRODUCTION

Spate-irrigating communities have developed a range of livelihood strategies to cope with the large and unpredictable seasonal and inter-annual variations in water supply and crop production which are inherent in spate irrigation. An understanding of the socio-economic circumstances of farmers and the coping strategies that they adopt is needed if effective and sustainable improvements to traditional spate irrigation systems are to be developed.

This chapter presents a summary of the socio-economic background of farmers in spate systems, based on information from spate schemes in Yemen, Pakistan and Eritrea. Livelihood and coping strategies adopted by spate farmers vary within and between schemes, regions and cultures.

Most households in spate-irrigated areas are poor, with a per capita income of generally less than US$1 per day. Estimated net household revenues derived from some spate-irrigated systems in Eritrea, Yemen and Pakistan are given in Table 2.1. In most areas economic poverty is amplified by remoteness and lack of access to basic amenities.

TABLE 2.1
Net annual revenues from selected spate irrigation areas

Country	Location	Household net annual revenue (US$)	Note
Eritrea	Sheeb	355	A further US$165 from livestock products giving income of US$520 in a 'good' year.
Pakistan	Toiwar	300	Two-thirds from crop production and one-third from livestock.
Yemen	Shabwah	412	Increases to between US$765–1 000 for households with access to pump irrigation.

Source: Hadera (2000), Halcrow (1993a, 1997, 1998)

These figures are averages and mask large fluctuations between households. For example, farm incomes were reported to vary by a factor of three between upstream and downstream locations in traditional spate-irrigated areas of the Tihama in Yemen, reflecting the farmers' relative access to water *(Tihama Development Authority, 1987)*. While a few favoured landowners located at the head of some schemes generate high incomes from commercial-scale farming, most spate irrigators further downstream are poor subsistence farmers, who lack basic amenities such as potable water and sanitation, electricity and health care. High infant mortality due to malnutrition among children and pregnant women is evident in many locations, as well as anaemia, malaria and other health problems.

LAND TENURE

Spate irrigation systems are used by sharecroppers and tenants as well as by landowners, but there are wide variations in the pattern of tenure. Statistics from selected spate irrigation systems show that the proportion of spate-irrigated land cultivated by landowners may vary from zero to 100 percent (see Table 2.2).

TABLE 2.2

Irrigated areas farmed by landowners, tenants or sharecroppers

Scheme	Percentage of irrigated area farmed by landowner
Kharan District, Balochistan, Pakistan	0
Nal Dat, Balochistan, Pakistan	27
Toiwar, Balochistan, Pakitan	100
Wadi Zabid, Yemen	18
Wadi Tuban, Yemen	49
Wadi Rima, Yemen	50

Source: World Bank (2000a), Makin (1977a), Halcrow (1993, 1994e, 1998)

A common arrangement in many spate-irrigated areas in Pakistan is that of hereditary tenancy. The tenant has a hereditary right to the land but this is contingent on his cultivation of the land. In several places the tenant is called *lathband*, meaning that his responsibility is the maintenance of the field bunds. This shows the importance of field bunds in moisture conservation and at the same time it is an arrangement to tie labour to the land and keep the critical mass required to maintain the systems. In the Anambar Plains in Balochistan, Pakistan, even in the 1990s landowners were actively trying to bond farm labour, for instance by offering farmers loans for bride prices.

An exceptional land tenure situation applies to the main spate irrigation systems in Sudan, the Gash and Tokar. In both systems, land tenure in most of the area is uncertain and land is allocated on an annual basis by the local government. This serves as a severe disincentive for land improvement. Both areas, moreover, suffer from the invasion of mesquite (*Prosopis juliflora*), making land difficult to cultivate and causing the obstruction of flood paths and changes in river morphology.

In some countries, for example Ethiopia, Eritrea and Sudan, all agricultural land is formally owned by the government, while in others, for example Pakistan, individuals' land rights are formally recognized and registered in government-administered cadastral records. In Balochistan (Pakistan), the hereditary tenants acquire partial ownership rights as compensation for developing the land for the original landowners.

Land reforms initiated by the Eritrean People's Liberation Front (EPLF) in the latter half of the 1970s and early 1980s have significantly changed land ownership in Eritrea by allocating small plots of land (0.5–1 ha) to poor families. At present, all land is government-owned, but the farmers have the continuous right to use spate-irrigated land. When the user of the land dies the usufruct right is transferred to the oldest son. Younger sons are allocated their own plots of land by the local administration when they marry.

In Yemen, land can be owned by individuals, government or trusts. In Wadi Zabid, 54 percent of the total command area is privately owned, with the remaining 46 percent belonging to religious trusts. In Wadi Tuban, 20 percent of the total command area is government-owned land, and 10 percent belongs to religious trusts (*waqf* land). Following the independence of South Yemen in 1967, large landholdings were redistributed among new farmers and tenants. After the unification of North and South Yemen in 1991, the farmers working these lands formally lost their legal entitlements to use the land, but the Government has not enforced this change as it would make many households landless.

In general, as indicated in Table 2.3, the average landholdings in spate irrigation systems are rather small. The main exception is in Pakistan, where holdings are generally larger but where command areas are usually overstretched and much of the land has little probability of being irrigated.

TABLE 2.3
Average landholding in selected spate irrigation schemes

Scheme	Average landholding (ha)
Wadi Tuban, Yemen	1.4
Wadi Zabid, Yemen	2.1
Shabwah Governorate, Yemen	2.5–5
Sheeb Eritrea	0.5-1
Balochistan Pakistan	5.4–7.8
Nouael II project Tunisia	1.1
Morocco	1.0

The distribution of land within schemes varies from a relatively egalitarian to a highly skewed distribution, in which a few rich landowners own large tracts in the favoured upstream parts of systems that have first access to water. Only 25 families own 53 percent of the privately owned land in the modernized Wadi Zabid system in Yemen, and their land is mostly located in the upstream areas of the scheme. Another 31 percent of the total command area belongs to family trusts that are often managed by the large landholding families. Only 33 percent of irrigated land is owned by small scale landholders who often have less than one hectare of land, usually located toward the tail of the scheme where irrigation is less reliable.

Land distribution in Wadi Tuban (Yemen) is less skewed, as only 7 percent of the total command area belongs to landlords with more than 5 ha of land, and 49 percent of the total command area is owned by small scale farmers with less than one hectare. Around 55 percent (Wadi Zabid) and 25 percent (Wadi Tuban) of the households living in the spate-irrigated areas do not own or lease any arable land. These landless households usually earn an income as agricultural labourers. Further examples of the unequal distribution of spate-irrigated land, occurring in Balochistan (Pakistan), are shown in Table 2.4.

TABLE 2.4
Distribution of spate-irrigated land in Balochistan (Pakistan)

Scheme	Percent of land area owned by the 25 percent of landowners with the largest holdings
Nal Dat	75
Chandia	55
Marufzai	48

Data cited in Verheijen (2003)

Inheritance and sales usually lead to landholding fragmentation. Inversely, fragmented land-holdings are sometimes amalgamated or enlarged by marriage, inheritance or the purchase of land with remittances from migrants. Land fragmentation may be advantageous when different parts of the farms are irrigated and cultivated at different times, by spreading labour and management demands. Strategies for land distribution to minimize risk in Pakistan, Tunisia and Eritrea are given in Box 2.1.

BOX 2.1

Spatial distribution of land to minimize risk

To cope with the different probabilities of receiving spate water, it is common in small spate irrigation systems in Pakistan for each household to farm different plots of land, with high and low probabilities of irrigation. For instance, most landowners in the Chandia system have plots in different parts of the command area in order to reduce the risk of not receiving any flood water, as this prevents stratification and friction between upstream and downstream users. A similar strategy existed in central Tunisia, where the command areas were divided into three or four sections and each landowner had a plot of land in each section. In this way, each household had access to spate water even if a small flood did not reach further than the first section of the command area. In the 1980s, however, it was no longer possible to allocate a plot of land to each household in each section as some plots had become very small, less than 0.1 ha, because of rapid population growth. (Van Mazijk, 1988).

Another strategy was followed for a period in Eritrea, where the community reallocated land at regular intervals, so as to equalize the probabilities of receiving spate flows over time. The difficulty with this was that farmers were not prepared to invest time in developing and maintaining canals and field bunds when they were shortly to be moved to other plots.

TENANCY AND SHARECROPPING

Landowners engage tenants or sharecroppers to cultivate their lands if they are too old or too ill to cultivate the land themselves or if they are not resident locally. Larger landlords also hire the services of tenants or sharecroppers when they do not have a sufficient labour force to cultivate the fields themselves. Female landowners, such as divorcees and widows, often find it difficult or impossible to cultivate their fields themselves owing to lack of labour and draught animals, as well as cultural or religious constraints. Some landholders may be “too poor to farm” as they do not own draught animals or have access to a tractor for the preparation and repair of the bunds. Furthermore they cannot afford inputs such as seeds to grow crops themselves. As a result, they are forced to rent out their land to tenants or sharecroppers.

Sharecropping is the most common arrangement in spate irrigation systems, but the contractual arrangements between the landowners and the sharecroppers vary considerably, as shown in the examples listed in Table 2.5.

Hereditary tenancy is very common in Balochistan (Pakistan). In the past, owners of large tracts of land used to give plots of land to other persons to develop. As compensation, the developer became a hereditary tenant. As per the customary law, the hereditary tenant loses his rights if he fails to cultivate the land and to maintain the field bunds. Landowners receive between 18 to 25 percent of the harvested crops as rent for the use of the land. The hereditary tenant is responsible for providing all inputs and labour, including the maintenance and repair of field bunds, canals and diversion structures.

TABLE 2.5

Sharecropping arrangements in some spate irrigation schemes

Location	Sharecropping arrangement
Balochistan, Pakistan	Sharecroppers are entitled to 50 percent of the harvested crop and straw if they provide the bullocks for land preparation and labour for planting, weeding and harvesting. Seeds are provided either by the landlords or by sharecroppers. Sharecroppers are responsible for maintenance of field bunds and, in some cases, reconstruction of diversion structures. In areas where it is difficult to find sharecroppers, landlords may provide substantial loans. In some regions this has evolved to a form of debt-bonding, under which sharecroppers have to work for the same landlord until the loan is repaid, with interest.
Wadi Rima and Wadi Zabid, Yemen	Sharecroppers receive one-third of the total output after they have paid 10 percent of the total output as a religious tax (Zakat) and 5 percent to the canal master. The sharecropper contributes proportionally to agricultural inputs and the maintenance of canals, but has to provide all labour, including payment for any wage labour. If major repair works are required, then the landowner and the sharecropper each pay 50 percent of the costs.
Wadi Tuban, Yemen	The sharecroppers' share is 70–75 percent of the harvest, but they have to provide all inputs, irrigation fees and maintenance costs.

Tenancy is also common in Yemen, where substantial spate-irrigated areas are owned by the State and trusts. In Wadi Zabid, some 5 000 tenants cultivate about 46 percent of the total command area, while 1 266 tenants farm 10 percent of the command area in Wadi Tuban. Annual rents may be paid in cash (US$10 to US$15 per hectare) or in kind (5–10 percent of the crop). In Wadi Tuban and Wadi Zabid, the Government and religious trusts lease land to leading community leaders, who then sublease these lands to tenants and sharecroppers for significantly higher rents.

LIVELIHOOD STRATEGIES

With low crop returns even in good years and the possibility of crop failures always in the background, spate-irrigated agriculture makes a precarious living. Farming households adopt a number of livelihood strategies to cope with these uncertainties. The most common is the diversification of the household economy and households in spate-irrigated areas generally depend on multiple sources of income. The coexistence of livestock keeping and spate irrigation is almost universal. Small ruminants in particular are an integral component of the household production system. Other strategies include saving surplus grains from one year to the next, investing in easily disposable property, such as livestock and draught animals in particular, in good years when there is a crop surplus, and earning additional household income through wage labour and off-farm activities.

In spate communities, failed flood seasons often trigger migration of able-bodied male family members in search of labour. Traditional mechanisms of solidarity and mutual assistance also play an important role in such communities. Money, for example, is borrowed from other family members or local moneylenders after a poor season in order to purchase additional food items or to obtain seeds for the next cropping season.

Strategies for coping with risks are summarized in Box 2.2 and discussed more in detail below. An understanding of these coping strategies is essential when spate improvement projects are being planned, to ensure that the proposed interventions are appropriate and do not have unintended negative impacts on aspects of farmers' incomes that are not directly concerned with the spate-irrigated crop production.

BOX 2.2

Strategies for coping with risks in spate irrigation

To reduce the risks of uncertainties in spate irrigation, farmers have adopted a number of strategies:

- Diversification of the household economy: in addition to a highly variable income from spate-irrigated agriculture, households may also have income from livestock keeping and wage labour and to a lesser extent from the sale of handicraft products.
- Spate-irrigated fields may be redistributed annually among all households with land rights.
- Households may have different plots of land with high and low probabilities of spate irrigation.
- Cultivation of drought-resistant traditional crops, such as sorghum, which produce at least some fodder in dry years.
- Practising crop rotation: fields are left fallow during one season in order to reduce the loss of soil fertility.
- Changing of sowing dates to control the outbreaks of pests and attacks by birds.
- Intercropping, whereby two or three different crops with different water requirements and harvesting dates are planted in the same field, so that at least one crop can be harvested in a dry year.
- Linking crop choice with the timing of the first irrigation.
- Use of groundwater as an alternative source for irrigation.

Livestock

Livestock keeping is an integral component of the livelihood strategies of most households involved in the cultivation of spate-irrigated crops (see Figure 2.1). It contributes to households through the provision of:

- Draught power: oxen, and to a lesser extent camels, are traditionally used for the preparation of the fields and the maintenance of the field bunds as well as the reconstruction of the diversion structures in the watercourse beds and the cleaning of the flood canals.
- Transportation: camels and donkeys are used for the transport of crop produce, drinking water and people.
- Food production: cows, goats, sheep and poultry are raised as a source of food. Milk, dairy products, eggs, meat, wool and skins are the main livestock products, mainly used for home consumption but also sold to raise cash.
- Savings: small ruminants, such as goats and sheep, have high reproductive rates and a high degree of resilience to drought conditions. They are an important form of ‘saving’ and can be sold in crisis situations. Oxen are also sold to bridge adverse years.
- Energy: cattle (oxen and bullocks), donkeys and camels provide dung, which farm families use as fuel by making dung cakes and as a building material by mixing it with earth and straw.

The ownership of at least one pair of oxen is a good indicator of wealth. In many households it is difficult to support a pair of oxen because the farm size is too small to produce sufficient fodder to feed them in years with normal floods. At times of drought, oxen and other large ruminants are at risk, and many households do not have any choice other than to sell them, or to move them to areas where fodder is available.

FIGURE 2.1
Bullocks in a spate irrigated area, Ethiopia

Owing to increasing farm mechanization, the number of draught animals in spate-irrigated areas, such as areas in Balochistan (Pakistan) and some other spate-irrigated regions, has diminished significantly, which has had consequences for the livelihoods of many households, and the social organization of the spate-irrigated communities. The sale of bullocks has lost its importance as a mechanism to cope with a crop failure or other crisis. The replacement of bullocks by tractors has in some cases undermined the traditional organization of system maintenance, where every household contributed labour and animals for the reconstruction of the diversion structure and cleaning of the canal system. Some statistics on the ownership of livestock in spate-irrigated areas are shown in Table 2.6.

Sharecropping is also practised in the livestock sector, with owners placing animals in the care of others in return for a proportion of the produce. Small ruminants are usually grazed on rangelands, whereas large ruminants are fed with green fodder and crop residue (i.e. straw and stalks) that are collected from the fields.

Most households use their livestock products for home consumption, although some items may be sold locally to raise cash income. In addition to spate-irrigated agriculture and livestock, beekeeping may be another important source of income. Many households in the Shabwah Governorate in Yemen are engaged in beekeeping, which is also an important secondary source of income among households involved in spate-irrigated agriculture in Konso in Ethiopia.

Wage labour and off-farm incomes

Many households in spate-irrigated areas earn an additional income as agricultural labourers or from other off-farm activities. Most households also have to hire additional labour at critical times, such as harvesting, when family labour is insufficient to carry out all the field activities. The pool of wage labourers may comprise members of landless households, households with landholdings that are too small to sustain the household throughout the entire year, as well as landholding households whose fields could not be irrigated during the last flood season. Nomadic tribes and temporary migrants may also move to spate-irrigated areas during harvest time in search of wage labour.

TABLE 2.6
Livestock ownership in spate-irrigated areas

Country	Scheme/Area	Livestock owned by a typical family (there are wide variations within and across schemes)
Eritrea	Sheeb	On average, a typical household has 1.5–2.7 dairy cattle and 1–2 draught animals. About 30 percent of the farmers do not own bullocks.
Ethiopia	Konso	Thirty-one percent of the landowners in the Yandafero scheme have 1 or 2 oxen.
Pakistan	Chandia, Barag, Nal Dat and Marufzai	An average household owns 3–6 sheep, 5–9 goats, 1.5–3.5 cattle and 1–4 chickens. One-third of the farmers in Chandia possess bullocks and a few households in Barag and Nal Dat have a camel.
	Toiwar	Ninety percent of the households have on average 62 small ruminants and 2 cows.
Yemen	Shabwah Governorate	An average household owns 10–20 small ruminants, 5–10 camels and some poultry, whereas a typical household in the central region possesses 20–30 small ruminants and some poultry.
	Wadi Zabid	An average household has 2 cows, 2 calves, 5 goats and 4 sheep, while a minority of households own 2 oxen.
	Wadi Rima	An average household has 1.5 cows, 7.2 sheep, 1.5 donkeys and 6.4 hens, while about a quarter of the households have 2.1 oxen and about 40 percent have 3.4 goats.

Wage labourers are often paid in kind, receiving a fixed portion of the harvested crop. At Nal Dat, in Balochistan (Pakistan) for example, wage labourers receive one-twentieth of the crop for harvesting, while they get one-tenth of the grain with chaff or one-eighth without chaff for threshing *(Halcrow, 1993e and 1998)*. A majority of households in the Chandia spate-irrigated area in Balochistan have one or more household members in the civil service with low-ranking jobs, such as messengers and workers *(Halcrow, 1993b)*. In the Sheeb area in Eritrea, a typical household accrues 25–50 percent of its average annual income from wage labour *(Halcrow, 1997)*.

Wealthier households may also be engaged in business, trade and transport, whereas poorer households in Eritrea, Pakistan and Yemen generate an income from the production and sale of handicraft products, such as pottery, mats, baskets and sandals *(Makin, 1977; Hadera, 2001; and Nawaz, 2003)*.

Migration

Migration may be needed to move livestock to areas where fodder and water can be found and it may take place annually, or in other cases only in dry years. In the Sheeb area in Eritrea, most of the population migrates every year to the highlands during the summer months in search of fodder and water and to escape the hot climate in the lowlands. Only the male members of each household remain behind to divert the floods in July and August and to plant their fields in September. Although this strategy exploits different agro-ecological zones for acquiring water, food and animal feed, important activities, such as the emergency repairs of the irrigation structures, are usually not undertaken at the right time owing to shortage of labour. In addition, the annual costs of the seasonal migration, both in cash and labour, are substantial and could be as high as a quarter of the annual income of a typical household. A second reason for migration is the search for wage labour by male household members.

Normally seasonal migrants return to their communities before the start of the flood or cropping season to assist in the irrigation and the preparation and planting. Small scale landowners, with land that has a low probability of irrigation, migrate each year, as their landholdings cannot support their households throughout the entire year. Other landowners only have to migrate in search of labour in dry years, as their landholdings produce enough in normal years to sustain their households. In the spate-irrigated areas of Dera Ghazi Khan and Balochistan (Pakistan), seasonal migration is common.

Farmers having spate-irrigated land may also decide to migrate permanently if they can find permanent employment elsewhere. In Pakistan, the existing spate irrigation systems often cannot support entire communities. For example, more than half the landholding households in Marufzai have migrated permanently to other spate irrigation systems in the Anambar valley, where they work as casual labourers, or in some cases as bonded tenants *(Halcrow, 1993b and 1993e).*

Migration abroad, often to Saudi Arabia, was very common in spate-irrigated areas in Yemen until the first Gulf war, when most Yemenis were forced to return. In the Shabwah Governorate, up to 25 percent of extended households had a family member working in the Gulf States in 2002 *(KIT, 2002).*

Depopulation is a general trend in many traditional spate-irrigated areas and a threat to the survival of the systems, as the labour needed to maintain canals cannot be sustained. Ultimately, the remaining farmers may have to abandon the entire spate irrigation system, as has occurred in a number of areas in the Las Bela plains in the South of Balochistan. Migration of adult males and the difficulty in sustaining the traditional systems are cited as one of the justifications for the modernization of the large spate systems located along the Red Sea coastal plain in Yemen.

Credit facilities

Indebtedness is common in spate-irrigated areas as many farmers encounter serious cash deficits during the year, or have to take on debts to survive an adverse year. Friends and relatives are usually the first source of credit. Shopkeepers and traders are another important source as many small scale farmers obtain seeds on credit at the start of the cropping season. The interest charged is often very high, which reflects the risks associated with spate irrigation. In the Chandia system in Pakistan farmers take loans for seeds from shopkeepers at a monthly interest rate of 5–10 percent. Farmers in Barag (Pakistan) purchase seed on credit and pay an 80 percent mark-up. Farmers may also be obliged to sell their produce at low prices to traders, from whom they borrowed money or products *(Halcrow, 1993b and c; Hadera, 2001).*

In the Tihama region in Yemen, the most common form of credit is the traditional system of delayed payment, practised by most merchants, traders and shopkeepers. Interest is not officially charged but different price levels may be negotiated depending on the time delay in payment. Traders in expensive capital equipment, such as tractors and pumps, usually offer credit for up to two years. Shopkeepers and merchants give credit for shorter periods. However, deposits, security and/or a reserve of capital are required for most forms of public and private credit, and this practice precludes poorer farmers from taking advantage of credit for purchase of equipment *(Makin, 1997).*

Farmers in spate irrigation systems rarely have access to formal credit facilities of banks and financial institutions owing to the inherent risks of spate-irrigated agriculture and the low value of the crops that are produced. In Wadi Zabid, Yemen, only large landlords with large holdings have access to credit with subsidized interest rates from the Agriculture Credit Bank, which they mainly use for the installation of tubewells for selling groundwater to smallscale farmers. The latter do not have access to these cheap credit facilities as the bank requires that at least 50 percent of the investment should be self-financed by the farmer *(IIP, 2002).*

Solidarity and mutual assistance mechanisms

Traditional mechanisms of solidarity and mutual assistance exist in the spate-irrigated areas to help people who are in need or struck by a calamity, or during important and expensive social events such as a wedding. However, households facing crop failures cannot rely on mutual assistance when it occurs too frequently, or affects some landowners more than others because of the location of their fields and their access to water.

Among the Tigre population living in the Sheeb area of Eritrea, groups of five to ten farmers work together on a rotation basis, whereby the farmer for whom the labour is performed provides food. Labour and oxen are also mobilized to cultivate the land belonging to widows and very poor households. Mutual self-help groups are spontaneously formed to help during field activities, or the construction of houses.

In Balochistan (Pakistan), it is common that labour and other means of production are shared to a certain extent. Although tractors gradually take over the role of draught animals, bullocks are still lent to poor villagers for a number of days for no rent. Farmers without seeds at the start of the cropping season may ask their more fortunate neighbours to help them out. If a farmer cannot access his field or his field bunds have broken during the flood season, others will come to his aid by either irrigating the field on his behalf or assisting in the repair of the field bund *(Halcrow, 1993 a and e; Van Steenbergen, 1997).*

The prevailing solidarity mechanism in the rural areas of Balochistan is the Islamic duty, *zakat* (charity), to give part of the agricultural produce and livestock as alms to the needy, with preference given to members of the same family or clan. The payment of *zakat* may also be used to finance local religious institutions, such as the mosque or religious school. *Zakat* is either given in cash or kind and the prescribed amount is one-tenth of the harvest of rainfed and spate-irrigated crops, one-twentieth of the harvest of pump-irrigated crops and one-fortieth to one-fifth of the livestock. However, it seems that the actual donations are often less than the prescribed amounts and that not all landowners pay their *zakat* on a regular basis.

Another type of assistance is to allow the poor to pick small amounts of vegetables and melons, or to collect wheat kernels left on the threshing floor, for their home consumption. A less common practice is to give some land in usufruct to a poor relative. Relatives and neighbours offer gifts in cash and kind during special occasions, such as births, weddings and funerals *(Halcrow, 1993 b and e; Halcrow, 1998).*

Basic amenities – drinking water and flood protection

Two issues are of particular relevance to the quality of life in spate irrigation areas: access to drinking water and the risk of flooding. Table 2.7 provides a summary of possible options for improving access to drinking water and addressing flood protection and erosion risks.

TABLE 2.7
Improvements for domestic water and protection against flood and erosion

Improvement	Description	Likely impact	Remarks
	Domestic water improvements		
Improved domestic water ponds	Providing lining of pond; making pond at adequate depth (2.5 m), fencing; sedimentation traps and sand filters	Will increase duration of storage and improve quality of water	Domestic water from ponds may never meet drinking water standards but usually there is no alternative.
Sand dams	Creating an artificial storage by gradually building up a weir and trapping coarse sand behind it	Will provide water supply	
Wells in river beds	Creating conventional wells (dugwells or shallow tubewells) inside river bed or on the river bank	Will provide reliable water supply during dry season	Subject to washout during floods
Including groundwater recharge as an objective in spate water distribution	Spreading water to recharge areas, making use of existing infrastructure or through a system of low guide bunds (Iran)	Will increase the reliability of water supply, especially in dry periods	Extensive experience with flood water spreading in Iran
	Flood and erosion protection measures (see also Chapter 4)		
Village flood protection	Protection bunds to avoid village flooding where agricultural land has risen because of sedimentation	Will avoid loss of residential property and livestock due to uncontrolled irrigation	Important programme in cultivated spate-irrigated areas of the coastal Tihama plains
River bank protection	Vegetative or structural measures	Will prevent river from changing course and causing great damage and will also stabilize intakes of flood channels	In the case of vegetative measures, the protection of trees and shrubs is required.
Dune stabilization	Planting of trees to control tree movements around the command area	Protection of command areas and villages	Care required not to introduce invasive species

Groundwater quality and availability are often an important issue in arid areas. In places, the aquifer is too deep or the quality of groundwater prohibits its use for domestic consumption. In Sheeb in Eritrea for instance, groundwater salinity ranges from 1 200–1 800 μs/cm and in Wadi Labka from 2 250–2 650 μs/cm. Small prisms of fresh water stored in the bed of the spate rivers can be an important source of domestic water supply in areas which have generally saline groundwater and where locally specific recharge measures can be undertaken, such as the construction of artificial aquifers behind check dams on small streams, the use of subsurface dams or low-level recharge weirs, such as those used by farmers in Hadramawt in Yemen, or in some cases the rearrangement of the entire water distribution schedule in order to spread recharge over a larger area.

In addition, improvements may be made in the shape of water ponds for human and livestock use. There are several measures that can improve the services from such ponds, in particular increasing the time they are filled (deepening, silt trapping, using a liner, rationing water) and improving the quality of their water (wells, sand filters, fencing) and the ease of maintenance (introducing steps, controlled inflows – also to reduce sediment intake – and using scraper boards for cleaning out accumulated sediment). These options may secure water supply for a number of months after the flood season and will provide water of low quality, but in many areas there is no alternative.

Progressive elevation of farm land is the result of accumulation of sediments. In some long established systems, the land level has risen above the level of the village itself. This has led to a constant risk of flooding.

GENDER CONSIDERATIONS

Gender issues deserve careful attention for two reasons. First, it is important to understand that no household livelihood improvement strategy can succeed if it does not take women into account and the role they play in the family. Second, it is important to ensure that the proposed improvements in spate irrigation schemes benefit women as well as men and do not modify the balance of power within the household or the burden of work at the expense of women.

Understanding the different roles of women and men and the distribution of tasks within the household is therefore necessary. Women play important roles in spate-irrigated agriculture and in particular in rearing livestock. In poorer households they are often engaged as wage labourers or are involved in producing handicrafts for sale. All domestic tasks are usually the exclusive responsibility of the female household members, including the fetching of potable water and the collection of fuelwood. Women are often members of informal saving groups or other self-help groups at village level. The roles of men and women involved in spate farming vary between regions and cultures. This diversity of situations is illustrated in Table 2.8.

TABLE 2.8
Men's and women's roles in spate-irrigated agriculture

Country	Scheme/Area	Roles of men and women in spate irrigation
Eritrea	Sheeb	Women undertake agricultural activities, such as harvesting, threshing and transport of grains and straw, while men are usually responsible for maintaining and operating the irrigation infrastructure. A number of women are involved in mainly the sale of handicraft products, such as mats and baskets. A few women, usually widows, divorcees or former freedom fighters, run shops. Owing to the policy of the Eritrean Government, women are also active in community affairs, although many men reject these activities outside their houses for cultural reasons. Women have little or no authority over the slaughter or sale of livestock, but are responsible for the distribution of milk and meat to household members as well as the selling of eggs.
Ethiopia	Konso	In periods of drought, when men migrate in search of employment, women are in charge of all agricultural activities, including the maintenance of the stone terraces and irrigation. Women are also involved in petty trade and sale of fuelwood.
Pakistan	Balochistan	Almost all agricultural activities are carried out by women, except the tillage of the land. Women may assist the male members of their households with the supervision of the in-field irrigation and the repair of minor damage to the earthen channels close to their fields during daylight. Animal husbandry is predominantly the domain of women, who are responsible for cutting and transport of fodder, milking goats and cows, preparation of a variety of dairy products and taking care of sick and pregnant animals, as well as the drying of dung for fuel. The grazing and welfare of livestock is the responsibility of men.
	Dera Ghazi Khan	Women have specialized knowledge of the intensity and magnitude of spates and rainfall in their areas, are involved in supervising irrigation, guarding infrastructure, and applying spate water at field level. Men usually carry out the diversion and distribution of spate waters.
Yemen	Shabwah Governorate	Women carry out most crop husbandry activities, including the application of farmyard manure, sowing, weeding, harvesting, threshing and removing of the crop residues from the fields. Men are responsible for the maintenance of the canals and terraces, irrigation, ploughing of the land with tractors, beekeeping and the marketing of crop produce and livestock.
	Wadi Zabid and Wadi Tuban	Men and women undertake most tasks together, including the cleaning of small canals. Generally women are responsible for the more traditional production practices, including spate irrigation, while men specialize in the more modern agricultural practices. Raising livestock is considered to be the responsibility of women and their children. Although women are actively involved in, and often responsible for, most agricultural and livestock activities, the marketing of any produce is exclusively reserved for men.

Table 2.9 proposes a set of questions that help in ensuring that women's needs and priorities are considered in spate improvement projects *(Molden, 2007).*

TABLE 2.9

Checklist of questions on gender and spate irrigation (adapted from *Molden, 2007*)

- How are women's needs expressed and communicated?
- What is the distribution of tasks within the household?
- Do women have recognized access to land and water?
- Are women represented in water users' associations?
- How will proposed improvements affect the distribution of work between women and men?
- How does the project take into account women's need for flexibility?
- How will the project affect and possibly improve domestic and drinking water supply?
- Were women consulted about the location of improved domestic water facilities?
- How will the project and possible changes in cropping patterns affect household food supply and nutritional needs?
- Who is responsible for the livestock? How will the project impact livestock watering? Were women consulted about the location of livestock-watering facilities?
- Are separate financial mechanisms required to take into account specific needs of women?
- Is the importance of backyard gardening recognized and adequately taken into account?
- Have capacity-building components of the project considered specific training for women?

THREATS TO LIVELIHOODS IN SPATE-IRRIGATED AREAS

The livelihood strategies based on the cultivation of spate-irrigated crops in combination with additional incomes from livestock and wage labour are undermined by a number of factors:

- ➢ The importance of spate-irrigated agriculture as a source of income for many households diminishes as the average size of their landholdings decreases through further subdivision due to inheritance. At some stage landholdings cannot sustain a family any longer and if no other option is available some members of the family must emigrate.
- ➢ Spate irrigation is risky, with a low return on labour. Where options for more reliable income exist, farmers will tend to shift their priorities and abandon their land and this leads to rapid degradation of irrigation infrastructure and the impossibility for the remaining families to maintain the system.
- ➢ As more landowners instal their own wells and become less dependent on spate water for the irrigation of their fields, the remaining spate farmers are often unable to mobilize sufficient labour and draught animals for the timely reconstruction of the diversion structure and the cleaning of the flood canals. As a result, the diversion of spate water to their fields becomes more difficult and more landowners have to give up spate-irrigated agriculture. The spate irrigation system thus ceases to function as the capacity to maintain the irrigation infrastructure is no longer available.
- ➢ The groundwater table in many spate-irrigated areas is falling rapidly owing to the installation of an increasing number of dugwells and tubewells, as a strategy for coping with risks which allows farmers to become less dependent upon the unpredictable supply of spate water for irrigation purposes. The result is that older and shallower wells dry up, the quality of the groundwater deteriorates and an increasing number of fields are abandoned. Ultimately, the population of entire villages may have no other choice than to migrate permanently as they have lost secure access to potable water and/or arable land.

- Degradation and widening of the river bed may progress to such an extent that farmers are unable to reconstruct diversion structures that are high and/or long enough to divert spate water into their flood canals. Uncontrolled cutting of trees and bushes as well as overgrazing in and along the river bed may accelerate this natural process.
- In some cases, ill-designed modernization interventions in spate irrigation systems, where traditional diversion structures are replaced by a concrete weir, may have a detrimental impact for farmers in the middle and tail sections of the schemes and make it easier for upstream water users to divert more, if not all, spate water to their fields despite existing rules regarding the allocation and distribution of spate water.

For any spate irrigation improvement project to be successful, these threats need to be understood, valued and assessed in terms of their possible impact on the success of the project. Proposed improvements must focus on increased and more stable earnings, and on solutions for maintenance of infrastructure (in particular in terms of labour required), to reduce uncertainty related to floods and to improve the environmental sustainability of spate systems. A diagnosis based on the above list should be used as a starting point for the design of spate projects, with an understanding, in specific conditions, of the relative importance of each of these threats and the possible options that a spate project can offer.

Chapter 3

Hydrology and sediment transport

SUMMARY

In developing a spate system it is important to understand the entire hydrology of the system – the base flow, sub-surface flow and groundwater and the pattern of spate floods that will dictate the potential yield of spate systems, the design of diversion structures and canals and the area to be potentially irrigated.

Spate hydrology is characterized by a great variation in the size and frequency of floods, which directly influence the availability of water for agriculture in any one season. Spate floods can have very high peak discharges and are usually generated in wadi catchments by localized storm rainfall. Crop production varies considerably because of the large variation in wadi runoff from year to year, season to season and day to day. The extreme characteristics of wadi hydrology make it very difficult to determine the volumes of water that will be diverted to fields and hence the potential cropped areas.

Wadis transport very high sediment loads which can be two or more orders of magnitude larger than those encountered in most runoff river perennial irrigation systems. Management of sedimentation is, therefore, a key factor in spate irrigation and must be given particular consideration in designing spate projects.

Hydrological and sediment transport data are needed to design improved water diversion structures and canals in spate schemes and to estimate the cropped area that can be potentially reached by spate. These data include the annual volumes of water available at the diversion point(s); the probable distribution of spate runoff events; the distribution of flows during runoff events; the proportion of the annual hydrograph that occurs in different flow ranges; wadi bed seepage rates; the magnitude and return periods of extreme discharges for the design and protection of the permanent works; the concentrations and size range of the sediments transported by spate events and their relationship with wadi discharges; and the sediment-transporting capacity of existing canals.

In particular, the distribution of discharges within the annual runoff has a large impact on the water diversion strategy that will be adopted, particularly with regard to the relative importance of seasonal base flows.

In most schemes, the long-term data that would be needed to provide the information listed above is unavailable. Unless a period of hydrological and sediment data collection, combined with numerical flow and sediment transport models is possible, the estimation of the above variables must be made through the use of empirical methods combined with good hydrological judgement. Table 3.1 lists some of the methods used to collect and analyse the hydrological and sediment transport information required to design improved intakes and canal networks. They are described in the following sections.

The calculation of mean annual runoff through a simple runoff coefficient, combined with the use of non-dimensional flow duration curves, makes it possible to estimate the volumes of water that can be diverted and design spate intakes accordingly. Such curves and coefficient depend on the characteristics of the catchments and local climate and care must be taken in applying them to ungauged catchments.

Local knowledge can greatly contribute to the assessment of hydrological characteristics of wadi catchments and is often the only source of information. Farmers in the wadi can provide information on the number and sizes of floods and their variations between years, thus making it possible for the hydrologist to establish flood-frequency curves.

More important is the use of local knowledge for the establishment of potentially cropped areas. In areas where traditional spate irrigation exists, farmers can determine the area to be irrigated on the basis of their past experience and from observation of the quantities of water diverted by any improved diversion and conveyance arrangements. This involves surveys to determine the extent of the existing irrigated areas. Surveys have to be combined with local knowledge and supplemented by interviews with farmers to establish how often fields in different parts of the system are irrigated and how this varies from year to year.

When new areas are being developed, irrigation engineers and agronomists need to determine the potential area that can be irrigated and the capacities of the canals that will be needed through estimates of the proportion of annual runoff that will be diverted, its distribution in time, and the characteristics of the area to be cropped (including soil water-holding capacity). Crop water requirements, while they provide a useful estimate of the maximum volumes of water required, will usually not be the main factor in assessing the potential irrigated area, as farmers will seek to expand their land under irrigation to the maximum possible extent.

Another important characteristic of wadi hydrology is the high rate of infiltration of floodwater in the wadi bed, with many small floods not reaching the lower reaches of the wadi. Seepage in the wadi bed is often the only source of groundwater recharge. Consequently, what is often considered ‘loss’ for spate through seepage may very well be used in a very productive way through groundwater extraction. Similarly, when spate intakes divert a substantial part of the wadi flow, they impact groundwater recharge downstream with possible negative implications for communities relying on groundwater. A river basin approach to spate irrigation planning is therefore necessary, to ensure that any intervention results in an overall increase in benefits for the populations of the wadi, and avoids losses for water users downstream (see Chapter 10).

INTRODUCTION

Spate hydrology is characterized by a great variation in the size and frequency of floods which directly influence the availability of water for agriculture. Wadis are also characterized by very high sediment loads and important groundwater recharge through seepage in the wadi bed. All these characteristics are specific to wadi hydrology. Management of floods and high sediment load therefore require a good estimate of the main hydrological characteristics of the wadi.

This chapter presents a brief description of runoff and sediment transport processes that influence spate irrigation practices and the design of improved spate irrigation schemes. It also provides some simple methods that can be used to derive the hydrological information needed to design intakes and canals for spate irrigation systems. The emphasis is on methods used for small schemes, where little data are available and the specialist hydrological studies that are carried out in support of larger projects are not feasible. The results derived with these methods should be verified wherever possible by comparison with any local or regional data that may be available.

DATA REQUIREMENTS

Hydrological and sediment transport data are needed to design improved water diversion structures and canals in spate schemes. The following information should ideally be available to designers of intakes and canals:

- the annual volumes of water available at the diversion point(s) in terms of seasonal incidence and reliability;
- the probable distribution of spate runoff events in terms of peak flows and flood volumes;
- the distribution of flows during runoff events, particularly the shape of the recession limb of the hydrograph, which provides the bulk of the water that can be diverted to irrigation command areas;
- the proportion of the annual hydrograph that occurs in different flow ranges (flow duration curve);
- wadi bed seepage rates;
- the magnitude and return periods of extreme discharges for the design and protection of the permanent works;
- the concentrations and size range of the sediments transported by spate events and their relationship with wadi discharges; and
- the sediment-transporting capacity of existing canals.

In most schemes, the long-term data needed to provide the information listed above are unavailable. Major spate irrigation improvement projects thus include a short period of hydrological and sediment data collection. The data are often used to assist in validating numerical flow and sediment transport models.

For small- and medium-scale schemes data requirements are smaller, and simpler methods requiring minimal field data are appropriate. Maximum use needs to be made of the local knowledge that farmers have. Table 3.1 lists some of the methods used to collect and analyse the hydrological and sediment transport information required to design improved intakes and canal networks. They are described in the following sections.

WADI HYDROLOGY AND IMPLICATION FOR SPATE DESIGN

The high-intensity rainfall events that generate spate flows in wadis are characterized by a wide variability in space and time. Information on the spatial characteristics of

TABLE 3.1
Hydrological and sediment transport information collection methods

Parameter	Method	Remarks
Seasonal/annual discharge and probabilities of occurrence	Long-term discharge data from flow-gauging station	• Rarely if ever available. • Needs properly sited and maintained gauging station. • Discharge usually computed from continuous water level records and derived rating curve(s). • Velocity measurement in floods is extremely difficult, although surface float tracking is feasible.
	Numerical models verified/ calibrated by short-term discharge data	• Usually only feasible for major studies. • Needs good-quality, long-term rainfall data from catchment. • Some gauging station data desirable for validation.
	Short-term discharge data supplemented by farmers' recollections of numbers of floods occurring and areas irrigated in past years	• Annual and monthly runoff is broadly correlated with the number of floods that occur. • Irrigated areas usually vary widely from year to year, reflecting discharge variations.
	Regional rainfall/runoff relationships/empirical methods supplemented by farmers' recollections	• Method needs to be selected and interpreted by experienced hydrologist.
Design' extreme flood discharges	Analysis of long-term records of annual flood maximum discharges	• Data rarely available.
	Synthetic long-term runoff data derived from stochastic modelling	• Usually only feasible for major studies.
	'Rational' methods	• Need rainfall intensity and other parameters derived from catchment characteristics. • Need verification with measured or slope area estimates of flood maxima.
	Regional flood frequency relationships	• Often the most reliable method as based on large number of station years of measurement. • Need to estimate the mean annual maximum flood in order to use reported growth factors.
	Slope area calculations	• Used to estimate peak discharge of historical floods by means of local informants' estimates of the flood water level.
Discharge capacity of exiting canals	Current metering in floods	• Difficult, need to be on site when large floods occur (often at night), requires heavy equipment.
	Slope area calculations	• Ideally gauge boards/automatic water installed to provide reliable water-level records. • Farmers may provide estimates of water levels when canals have been breached/overtopped.
Sediment transport	Bed material sediment sizes, wadi bed and canals	• Large samples needed when coarse wadi bed material is to be size graded. • Stone-counting methods available for cobble and boulder shoals.
	Pump sampling during floods at discharge-gauging location	• Needs continuous presence on site unless automatic sampling equipment is used. • Measures suspended load component only; bed load is usually derived from empirical relationships. • Needs concurrent measurement of discharges plus size-grading data of bed material.
	Dip samples collected in bottles during floods	• Measures wash load, useful for estimating fine sediment concentrations passed to fields. • Can be supplemented with sediment transport predictors to estimate sand and bed load. • Need concurrent measurement or estimates of discharges and size-grading data of bed material.
	Historical rates of rise of field levels and command levels	• Surveys of field levels, trial pits, upstream movement of traditional diversion structures.

rainfall wadi catchments is limited. Available data, however, suggest a highly localized rainfall occurrence, with the spatial correlation approaching close to zero at distances of between 15 and 20 km *(IHP, 1996)*.

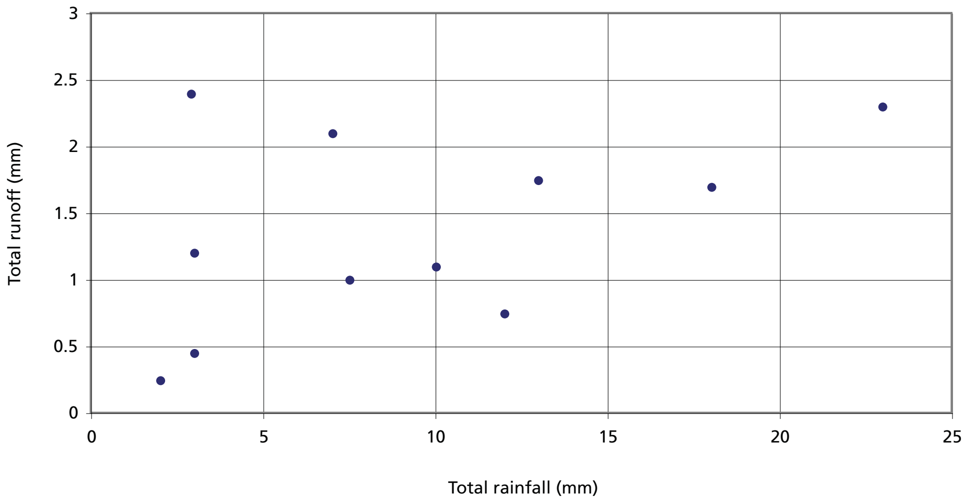
Wadi catchments generally have sparse vegetation cover and thin rocky soils. Soils are exposed to raindrop impact and soil crusting, which results in low infiltration capacity. Storm rainfall generates local overland flow, which converges into wadi channel networks, producing spate runoff events. Runoff generation is usually localized, reflecting the small size of convective rainfall cells. There is some evidence, however, that extreme flood events are sometimes generated by more widespread frontal rainfall, as has been observed in the catchment of Wadi Zabid in Yemen.

Rainfall-runoff relationship

The local nature of rainfall events presents difficulties when attempts are made to link flood events with storm rainfall observed at rain gauges located at the densities found even in relatively well equipped catchments. This is illustrated in the example shown in Box 3.1, which demonstrates the very poor correlation between observed rainfall and runoff that can be expected *(Wheater, 1996)*. Similar conclusions were drawn from a recent study in the catchments of large spate irrigation systems in the Yemen *(Arcardis, 2004)* and a study carried out in Eritrea *(Halcrow, 1997)*. Estimates of flood discharges and runoff volumes derived from conventional rainfall/runoff models are therefore of limited use in spate systems *(IHP, 1996)*.

BOX 3.1
Rainfall-runoff relationship in semi-arid catchments

A comparison of measured flood runoff depths with rainfall derived from five rain gauges located in a 597 km^2 catchment in western Saudi Arabia is shown below *(Wheater, 2002)*. The plot shows no correlation between runoff measured at the catchment outlet and rainfall events observed with the rain gauge network, which have a density of around one per 120 km^2, and the storm with the largest runoff appears to be generated by the smallest rainfall.



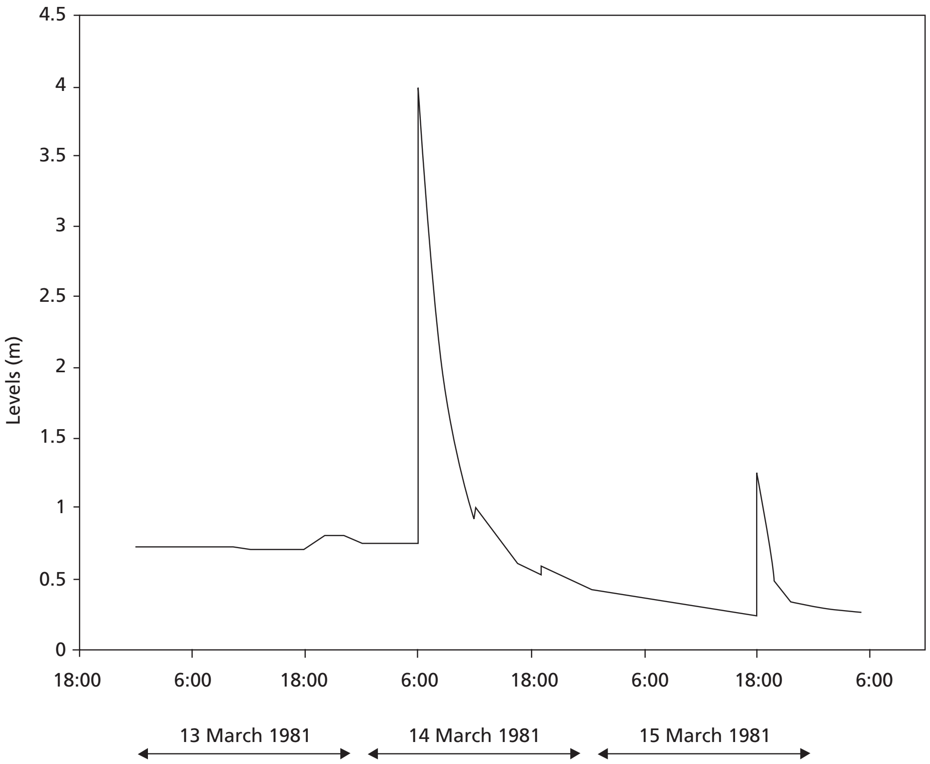
Analysis of discharge data from wadis in Yemen shows an approximate linear correlation between both annual and monthly flood volumes and the number of floods that occur, if a few rare extreme floods are excluded. Similar features were observed in the results from stochastic modelling of spate runoff carried out for Wadi Laba in Eritrea *(Halcrow, 1997)*. This conclusion is very useful as it enables annual flow volumes to be linked, albeit approximately, with the numbers of floods that occur, which will be known by farmers.

Shape of the spate hydrograph

Flows move down the channel network as a flood wave. Runoff from different parts of a catchment converges in the steep wadi channels, sometimes generating multi-peaked spate flows at the water diversion sites in the lower wadi reaches. Flood hydrographs are characterized by an extremely rapid rise in time, followed by a short recession, as illustrated in Figure 3.1. In this case, the discharge at a spate diversion site in Wadi Rima in Yemen increased from less than 1.0 m³/s to about 550 m³/s in around 30 minutes, with a second smaller peak occurring the next day. The lower water surface elevation after the flood is due to bed scour.

FIGURE 3.1

Spate flood hydrograph from Mishrafah, Wadi Rima, Yemen, 1981



Attempts have been made to establish relationships between flood peak discharges, flood durations and flood volumes. Recent studies in Yemen and Eritrea, however, show little or no correlation between peak discharges and flood volumes *(Halcrow, 1997; Arcardis, 2004)*. Floods with a small peak discharge can have a long duration and a large flood volume, while conversely floods with a large peak discharge can have a very short recession and a small flood volume. Floods generated at distant parts of catchments are attenuated by the time they reach a diversion site, and the relationship between flood characteristics depends to some extent on where in catchments the flood-producing rainfall occurred.

As with other hydrological parameters, the distribution of flood peak discharges occurring in wadis is highly skewed. Relatively few large floods occur, and most of the annual flood runoff volume occurs in floods having low or medium flood peak discharges. In some wadis, flood flows are supplemented by spring-fed base flows that may persist for some weeks or months through and after the wet season. Subsurface flows in underlying alluvium may be forced to the surface by a rock bar and appear as a surface flow part way down a dry wadi bed.

The relative proportion of base flows and flood flows in the annual hydrograph has a large impact on the water diversion strategy to be adopted. This is illustrated in Box 3.2, which shows contrasting discharge statistics for wadis flowing to coastal plains located on either side of the Red Sea.

Where most of the annual discharge in wadis occurs at low to medium flow rates, high diversion efficiencies can be obtained by diverting relatively low wadi discharges through the use of simple diversion structures. This is one reason why high diversion efficiencies are obtained in many traditional spate irrigation systems, even though some upstream intakes are regularly washed out in floods.

Over-reliance on diversion of base and low flood flows at a single intake, a strategy adopted in some spate irrigation improvement projects, can be dangerous. In Yemen, it is reported that water abstractions upstream from some diversion sites have substantially increased and the base flows have been reduced or cutoff. In most cases where a new single intake has been constructed as part of a modernization project, farmers have retained their traditional diversions, and in some cases have constructed new ones to capture the flood flows passing a new diversion weir, so as to divert the largest possible proportion of wadi flow to compensate for the limited diversion capacity of the new intake.

Seepage in wadi bed and groundwater recharge

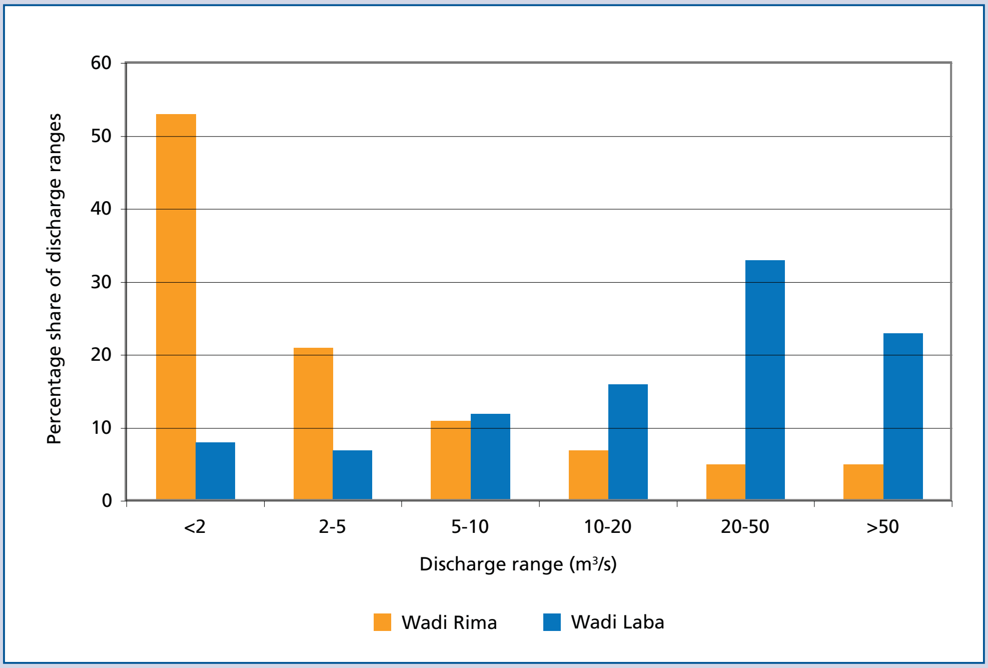
Both channel storage and high infiltration rates into the coarse alluvium that forms the beds of wadis reduce discharges as floods pass down a wadi. Water balance studies carried out for the Tihama coastal plain bordering the Red Sea in Yemen indicate that around 60 percent of groundwater recharge is derived from wadi flows *(DHV, 1988)*. *Komex (2002)* reported that infiltration of wadi flows provides the major source of recharge to the aquifers of both the Abyan and Tuban deltas in Yemen. Apart from a quantity of subsurface inflow, wadi flows provide the only source of replenishment for the aquifers. Other recharge components are merely infiltration of diverted spate flows or recycling of abstracted groundwater. A water balance study carried out for Wadi Turban indicated that approximately 48 percent of the surface inflow recharged the aquifer by infiltrating from wadi beds *(Komex, 2002)*. Infiltration from spate irrigation increased the recharge by only a further 10 percent.

BOX 3.2

Contrasting wadi discharge statistics

The graph shows the percent of the annual runoff volume occurring in different discharge ranges for Wadi Rima in Yemen, and Wadi Laba in Eritrea, from the data reported in *Makin (1977)* and from stochastic modelling carried out by *Halcrow (1997)*.

In Wadi Rima, as in the other large Tihama wadis, spring-fed base flows and low flows occurring at the end of flood recessions provide a large proportion of the annual flow volume. In Wadi Rima, at the time that the measurements were carried out, diverting all the water flowing in the wadi at discharges of less than 15 m³/s was predicted to divert about 90 percent of the annual discharge. The intake discharge capacity of 15 m³/s in this case represented only about 3 percent of the anticipated annual return flood peak discharge in this wadi.



Wadi Laba has a catchment area about four times smaller than Wadi Rima, and has a much lower annual flood peak discharge. As most of the annual runoff is predicted to occur in spate flows, a relatively larger diversion capacity was adopted in order to divert an acceptable proportion of the annual runoff. An intake capacity of 35 m³/s was selected, 23 percent of the estimated annual return flood peak discharge of 150 m³/s.

Estimates of seepage (transmission) losses in wadis have been made using simultaneous flow measurements at different locations. Losses, mostly measured for very low flows, typically range between 1 and 5 percent of the upstream discharge per km *(Lawrence, 1986; Walters, 1990; Jordan, 1977)*. Studies carried out in Yemen in the 1970sv suggest that seepage rates in seasoned traditional canals were much lower than that in the main wadi channels *(Makin, 1977)*. If maximum use is to be made of spate flows, there may thus be advantages in using canals rather than the main wadi channel to convey irrigation flows to the downstream areas of a scheme. However, the use of shallow groundwater for irrigation is increasing in many spate areas and, where this is the case, it can be argued that seepage losses should be enhanced rather than minimized, in order to maximize groundwater recharge.

One important consequence of the role of seepage in groundwater recharge is the need for a river basin approach to spate irrigation design. What is considered 'loss' for spate irrigation through seepage in the wadi bed may well be used in a very productive way through groundwater extraction. Similarly, when spate intakes divert a substantial part of the wadi flow, they impact groundwater recharge downstream, with possible negative implications for communities relying on groundwater. These considerations are discussed in greater detail in Chapter 10.

ESTIMATING MEAN ANNUAL RUNOFF AND POTENTIAL IRRIGATED AREA

The proportion of the mean annual runoff (MAR) that can be diverted to the fields is an important parameter in determining the potential command area, although in spate schemes the areas that are irrigated can vary widely from year to year. MAR is conventionally expressed as a runoff depth from the catchment, in mm, but can easily be converted to a volume by multiplying it by the catchment area. The proportion of the runoff volume that can be diverted for irrigation depends on the diversion arrangements and the patterns of spate flows that are experienced. This is difficult to estimate without extensive long-term site-specific flow data.

In spate schemes the cropped areas are determined in part by the level of risk that farmers are prepared to accept before constructing and maintaining canals and field bunds and preparing their fields. While the fields near the head of a scheme may receive multiple irrigations, those near the tail may only receive water occasionally. In some spate schemes in Yemen, irrigation is reported to be possible as infrequently as once in five years at the downstream end of the irrigated areas. Farmers also adopt differing irrigation strategies. A few attempt to maximize yields by applying multiple irrigations to small areas, while others more commonly spread the water as widely as possible and often grow a crop from a single large water application. Both strategies may be followed at different locations within the same scheme. The relationship between the flows in a wadi in particular seasons and the areas that are irrigated can thus be quite complex and require a large investment in field investigations and farmer interviews if it is to be fully understood.

The operation and management of most systems is carried out entirely by farmers, as well as the decisions concerning patterns of water distribution and the areas that have priority for irrigation. The calculations described in this section are normally not needed, as farmers will determine the area to be irrigated on the basis of their past experience and from observation of the quantities of water diverted by any improved diversion and conveyance arrangements. However, when new areas are being developed, irrigation engineers and agronomists need to determine the potential area that can be irrigated and the capacities of the canals that will be needed. Estimates of the mean annual runoff and the proportion of the runoff that will be diverted need to be made in order to carry out these calculations. Similar calculations are carried out when large existing systems are to be modernized.

Using farmers' knowledge

If estimates of cropped areas are needed when existing schemes are being improved, the most reliable procedure is to base assessments on existing cropped areas. This will involve surveys and analysis of aerial photographs, when available, to determine the extent of the existing irrigated areas. Surveys are supplemented by interviews with farmers to establish how often fields in different parts of the system are irrigated and how this varies between years.

Farmers can also provide information on the numbers and sizes of floods and their variations between years. If surveys of the main canal(s) have been carried out, then slope area calculations described later can be used to convert farmers' estimates of water levels and the periods that canals flow, to make an approximate estimate of the volumes of water diverted from flood events.

Estimates of the impact of improved diversion arrangements can then be based on the additional volumes of water that might be supplied to the fields with improved diversion and conveyance arrangements. However, as many traditional spate irrigation systems are already operating with high water-diversion efficiency, there may not be much scope to increase irrigated areas. The main benefits from spate improvement projects usually stem from a reduction in the large labour requirements needed to operate and maintain the traditional intakes and canals.

Estimating mean annual runoff using a runoff coefficient

The simplest method of estimating mean annual runoff is to apply a runoff coefficient to the mean annual rainfall over the catchment:

$$\mathbf{MAR = k \, . \, MAP}$$

where:

MAR = mean annual runoff (mm)
MAP = mean annual precipitation (mm)
k = runoff coefficient

Runoff coefficients for catchments of wadis typically range between 0.05 for larger catchments and 0.10 for smaller catchments. However, runoff coefficients can vary considerably, even between adjacent catchments and, if this approach is used, then a hydrologist with knowledge of the local catchments should select an appropriate runoff coefficient. More sophisticated methods for estimating mean annual runoff are available, but these need to be applied by experienced hydrologists, preferably with a good knowledge of local conditions.

Calculation of runoff volumes

The annual volume of runoff from a catchment is calculated as the product of the MAR and the catchment area. Catchment areas should be measured on 1: 50 000 maps, after marking the intake location(s) and the catchment boundaries, by using a digitizer, planimeter or squared overlay sheet.

$$\mathbf{ARV = MAR \, . \, A \, . \, 1\,000}$$

where:

ARV = annual runoff volume (m^3)
MAR = mean annual runoff (mm)
A = catchment area (km^2)

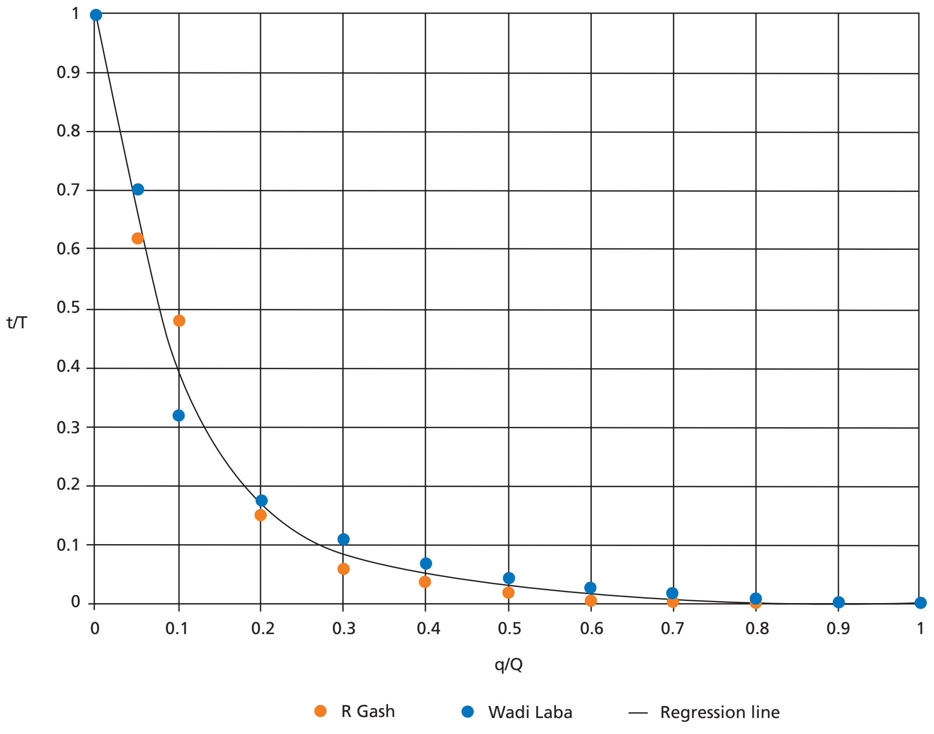
Estimating the proportion of annual runoff that is diverted

As mentioned earlier, the proportion of the MAR that is diverted depends on the diversion arrangements and the pattern of flows that occur and is very difficult to estimate without long-term flow data collected at or near to the diversion site. Very few measurements have been carried out in spate schemes, but information from traditional systems in Yemen suggests that high diversion efficiencies were achieved when numerous intakes were used. Although large floods destroy upstream deflectors, water could usually be diverted downstream where the flood peaks had diminished. Only rarely did exceptionally large floods pass the last diversion structure.

For new schemes with a single diversion point, approximate estimates of the proportions of flows diverted for a range of intake capacities can be derived from non-dimensional flow duration curves when these are available or can be developed from regional hydrological data. An example for two spate rivers in Eritrea is shown in Figure 3.2. In this form of the duration curve the number of hours a wadi flows in different discharge ranges is plotted against the wadi discharge representing the discharge range. The curves are made non-dimensional by dividing discharges by the mean annual flood discharge (Q) and times by the total time that a wadi flows in the year (T). In the absence of more specific local information, non-dimensional flow duration curves developed for one catchment may be transferred to another catchment of similar size in the same region if they are in similar rainfall zones and it can be assumed that the relative distribution of discharges within an annual runoff hydrograph will be similar.

Curves like those shown in Figure 3.2 can be used to estimate of the proportion of the annual flows that would be diverted from a wadi for different ratios of q/Q, where q is the selected intake capacity. The calculation assumes that all the flows less than the

FIGURE 3.2
Non-dimensional flow duration curve



q/Q will be diverted and that diversion will be at the intake capacity q/Q when wadi discharges are higher than the diversion capacity. Diversion efficiencies calculated using these assumptions with the mean curve shown in Figure 3.2 are presented in Table 3.2. The table illustrates the predominance of lower flows in the annual runoff in spate rivers, that in this case do not include significant periods of seasonal base flow. More than half the annual discharge could be diverted with a canal intake capacity set at 10 percent of the mean annual flood discharge, while an intake with the capacity to divert 50 percent of the mean annual flood discharge would divert 96 percent of the annual runoff. Of course reductions to the theoretical diversion efficiency tabulated above are needed to account for the real situation, where canal and sluice gates at an intake have to be manually operated, often at night, in response to rapidly varying spate flows.

TABLE 3.2
Proportion of annual flows diverted

Diversion capacity ratio q/Q	Percent of annual flow diverted
0.1	54.3
0.2	76.8
0.3	86.6
0.4	92.2
0.5	95.6

If the regional data needed to prepare a non-dimensional flow duration relationship are not available, approximate estimates of the proportion of the wadi flows diverted to canals can be derived by using farmers' knowledge of the number and sizes of floods and the shape and duration of typical flood recessions. The procedure involves assembling a representative sequence of flood hydrographs and determining the proportion of the wadi flows that might be diverted for a range of intake capacities. If multiple intakes are to be used, bed seepage losses between the intake locations should also be taken into account.

It is also necessary to make an estimate of the likely variations between years. When data are not available, this can be achieved by assuming that the annual runoff volumes are approximately proportional to the numbers of floods that occur and using farmers' estimates of flood numbers for years with different return periods.

When the flow volumes diverted during the cropping season have been established, the area that could be irrigated can in theory be estimated by calculating the crop water requirements and conveyance and irrigation efficiencies. However, as indicated above, other factors will influence the area that can be irrigated. Farmers have their own views on the command areas that they are prepared to develop and these may not coincide with areas derived from rather simplistic calculations relying on assumed crop water requirements and diversion and conveyance efficiencies. In existing schemes estimates of potential cropped areas should at least be verified by comparison with currently cropped areas.

DESIGN FLOOD DISCHARGE

Estimates of extreme flood discharges for specified return periods are needed to design weirs and intakes. As spate floods are always characterized by a very rapid rising limb, they should not be represented using classic triangular hydrograph models which do not replicate well the rapid rise to peak, the rapid initial recession or the proportions of the flood volume occurring before and after the flood peak. Several methods can be used:

- analysis of long-term records of measured flood discharges;
- analysis of synthetic long-term runoff data derived from stochastic modelling;
- the rational methods based on a ‘design’ rainfall intensity, a time of concentration derived from catchment parameters and a runoff coefficient that depends on catchment conditions;
- regional flood frequency relationships;
- slope area calculations to estimate the size of the largest historical flood that has occurred, for which local informants can provide a reasonably reliable estimate of the flood water level.

In practice, the first method is virtually never feasible as long-term flow data only exist for a small number of wadis worldwide. The second would only be considered for large projects that have the resources to commission specialized hydrological modelling. Rational methods are used in some areas, for example Balochistan, in Pakistan, but require information on catchment characteristics for the selection of appropriate runoff coefficients and rainfall intensity, data that are not available in the regions where many spate irrigation systems are located.

Regional flood frequency relationships are widely used for flood estimation in un-gauged catchments. They are derived by pooling data from gauged catchments within hydrologically similar regions, to develop a dimensionless flood frequency relationship that can be applied to un-gauged catchments in the same region.

Care has to be exercised when transferring data from one catchment to another. Catchment elevation, shape and geology all play a significant part in the estimation of runoff characteristics. One of the mistakes in Sheeb in Eritrea was to approximate the flow results obtained for Wadi Laba to the smaller and more compact catchment of Wadi Mai Ule.

The mean annual flood discharge for the wadi being considered has to be known in order to use the method, and empirical methods can also be applied to estimate this from catchment properties. Table 3.3 proposes some empirical formulae. They need to be considered with caution as they are usually valid only in specific regional conditions.

TABLE 3.3
Methods for estimating mean annual flood peak discharge

Method	Equation	Note
Binnie (1988)	$MAF = 3.27 \,.\, A^{1.163} \,.\, MSL^{-0.935}$	Regional flood formula developed for wadis in Southern Yemen
Bullock (1993)	$MAF = 0.114 \,.\, A^{0.52} \,.\, MAP^{0.537}$	Developed using data from 43 semi-arid catchments in Botswana, Zimbabwe, South Africa and Namibia
Nouh (1988)	$MAF = 0.322 \,.\, A^{0.56} \,.\, ELEV^{0.44}$	Developed from regressions on data from 26 gauging stations
Farquharson et al. (1992)	$MAF = 0.172 \,.\, A^{0.57} \,.\, MAP^{0.42}$	Developed from 3 637 station years of data collected from arid zones worldwide.

In the table:

MAF = mean annual flood peak discharge (m^3/s)
A = catchment area (km^2)
ELEV = mean catchment elevation (m)
MSL = main stream length (km)
MAP = mean annual precipitation (mm)

Farquharson et al. (1992) also developed relationships for eight separate regions using catchment area only, as follows:

$$\mathbf{MAF = Constant\ .\ A^{\ Exponent}}$$

The following values for the constant and exponent and regression results are given in Table 3.4, where s is the standard error of the estimate of the exponent and r^2 is the regression coefficient.

TABLE 3.4

Regional values for constant and exponent and regression results *(Farquharson et al., 1992)*

Country or region	Constant	Exponent	s	r^2
Algeria/Morocco/Tunisia	0.489	0.801	0.07	0.92
Botswana/South Africa	8.75	0.388	0.06	0.49
Iran	0.145	0.866	0.15	0.60
Jordan	6.83	0.427	0.53	0.14
Queensland	1.31	0.597	0.07	0.71
Saudi Arabia/Yemen	0.991	0.701	0.16	0.43
USA (SW)	0.286	0.761	0.12	0.87
Caucasus/Central Asia (SW)	0.236	0.758	0.16	0.89
All arid region basins	**1.87**	**0.578**	**0.04**	**0.55**

If relationships for the specific local region are unavailable the *Farquharson et al. (1992)* mean relationship listed in the table can be used to estimate MAF. However, as estimates derived by using any of these equations may have a high standard error, it is recommended that estimates of MAF are at least verified by using estimates of the discharges of historical floods. This is discussed later.

Many regional flood frequency relationships are available. We suggest using the *Farquharson et al.* (1992) relationships that were developed from a large dataset of runoff stations in arid and semi-arid zones worldwide. The design flood for the required return period is calculated by multiplying the MAF by a growth factor for the 'design' return period selected from Table 3.5.

INCORPORATING LOCAL INFORMATION IN THE ESTIMATION OF FLOOD PEAK DISCHARGE

The reliability of estimates of MAF can be improved by making use of flood discharges calculated from historical water levels at or close to the location of new or improved intakes. The procedure involves obtaining information locally on the maximum wadi water level that occurred in the largest remembered historical flood and the number of years that the flood level was not exceeded (sometimes taken as the period since the historical event occurred). The flood water level is then used to derive an estimate of the peak discharge using a slope area calculation method (see next section). The approximate return period for the event can be estimated if it is assumed that the probability of a flood of the given magnitude occurring in n years is 0.5, when:

$$T = 1/(1-0.5^{1/n})$$

where:

T = Return period of the flood (years)
n = number of years over which the flood level was not exceeded.

TABLE 3.5
Flood growth factors

Country or region	Growth factor 50-year return period	Growth factor 100-year return period
Algeria/Morocco/Tunisia	4.30	5.83
Botswana/South Africa	4.70	6.51
Iran	3.70	4.81
Jordan	4.07	5.27
Queensland	4.82	6.53
Saudi Arabia/Yemen	4.84	6.66
USA (SW)	4.45	6.34
Caucasus/Central Asia (SW)	4.27	5.61
All arid and semi-arid regions (MAP < 600 mm)	**4.51**	**6.15**

By using the growth factors for the appropriate return period from Table 3.6 the ratio between the flood magnitude at the estimated return period and the MAF and hence an estimate for MAF can be obtained. The estimate for the MAF is then used to determine the design flood discharge for the appropriate design return period.

As an example, we assume that there is an estimate of the discharge of a historical flood available from a slope area calculation based on local information on the maximum water level observed in the last nine years. The flood discharge calculated from a slope area calculation is 250 m^3/s.

As the flood discharge was not exceeded for nine years, n = 9. From the above equation T = 13 years. From Table 3.6 the growth factor for 13 years is about 2.4. Hence, the MAF derived from the slope area flood discharge is:

$$MAF = 250/2.4 = 104\ m^3/s$$

The 100-year return period flood will therefore be 104 x 6.5 = 677 m^3/s.

ESTIMATES OF FLOOD DISCHARGE FROM WATER LEVELS

While information on runoff is often scarce or absent, fairly good estimates of water levels, sometimes dating back many years can be obtained from measurements or from consultation with local farmers. They can then be translated into runoff estimates and contribute to a better flood frequency analysis.

TABLE 3.6
Flood growth factors for Botswana and South Africa *(Farquharson et al., 1992)*

Flood return period (years)	Growth factor	Flood return period (years)	Growth factor
5.0	1.3	30.0	3.7
6.0	1.5	32.0	3.8
7.0	1.7	34.0	3.9
8.0	1.8	36.0	4.0
9.0	1.9	38.0	4.1
10.0	2.1	40.0	4.2
12.0	2.3	42.0	4.3
14.0	2.5	44.0	4.4
16.0	2.7	46.0	4.5
18.0	2.8	48.0	4.6
20.0	3.0	50.0	4.7
22.0	3.1	100.0	6.5
24.0	3.3	150.0	7.8
26.0	3.4	200.0	8.9
28.0	3.5	-	-

The Manning equation is usually used to compute discharges from water level, cross-section(s), the water surface slope, (often assumed to be the same as the bed slope) and an estimated Manning roughness coefficient which depends on the wadi bed conditions. Calculations are carried out for a reasonably uniform and straight wadi reach, located close to the actual or proposed intake. Measurement sites should be selected using the following criteria:

- Local information is used to make a reliable estimate of the water levels observed during a historical flood at the site.
- The length of reach should be greater than, or equal to, 75 times the mean depth of flow.
- The fall of the water surface should exceed 0.15 m from one end of the reach to the other.
- The flow should be confined to one channel at the flood level with no flow bypassing the reach as over-bank flow.
- Application of the flow resistance equation requires that the bed should be largely free of vegetation and that the banks should not be covered by a major growth of trees and bushes. Sites with bedrock outcrops should also be avoided.

It is difficult to satisfy all the above criteria and some compromise is usually necessary. The selected reach is surveyed to establish at least one cross-section and the bed slope. (Usually three cross-sections, at the start, middle and end of the reach are surveyed.)

The maximum flood water level is levelled to the same datum used for the cross-section surveys. Calculations using the Manning equation[1] are:

$$Q = (1/n) \,.\, A \,.\, R^{0.67} \,.\, S^{0.5}$$

where:

Q = discharge, in m^3/s
A = cross-sectional area of the flow in m^2
R = hydraulic radius, A/P, where P is the wetted perimeter of the cross-section, in m
S = the slope of the channel (no dimension)
n = Manning roughness coefficient. Manning's coefficient is tabulated for a range of channel conditions in most hydraulic textbooks. For wadis with coarse bed materials it is often taken as 0.035 or 0.04.

An alternative equation for wadis with coarse bed sediments *(Bathurst, 1985)* predicts the channel roughness coefficient from the size of the bed material and has been successfully applied to estimate flood peak discharges in Yemen wadis. The equation is:

$$Q = A \,.\, D^* \,.\, (g \,.\, R \,.\, S)^{0.5}$$

where:

Q, A, R and S are the same as above
D^* = (5.62 . log (d/D_{84}) + 4)
d = mean flow depth (approximately the same as the hydraulic radius, R).
D_{84} = the size of the bed material for which 84 percent of the material is finer (m)
g = acceleration due to gravity, 9.81 m/s^2.

The size grading of bed material and hence D_{84} can be determined by sieving large volumes of bed material taken from shoals of coarse sediments located within the slope-area reach, which are assumed to represent the bed material in high discharge flows (see section on sediment size data).

ESTIMATING SEDIMENT LOADS

Wadi morphology

The catchments of wadis are mostly located in mountainous regions that have a higher rainfall than the plains areas where the spate irrigation systems are located. The combination of poor cover, steep slopes and high-intensity rainfall results in high rates of soil erosion and a large supply of sediments to the wadi systems. The upper reaches of wadis typically have very steep slopes, coarse bed materials and a very high sediment-transporting capacity. Sediments ranging in size from boulders and cobbles to silts and clays are transported in large floods.

In the upper reaches, wadi channels are often contained within narrow valleys, and sometimes flow through gorge sections that act as natural hydraulic controls. In the larger wadis in Yemen and Eritrea, gorges located close to the mountain front are selected for stream-gauging sites (see Figure 3.3).

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[1] Calculations can be conveniently carried out using the 'irregular cross section' option in the DORC design tools section of HR Wallingford's 'SHARC' sediment management software. The software and manuals can be downloaded at http://www.dfid-kar-water.net/w5outputs/software.html.

FIGURE 3.3

Stream-gauging site, Wadi Tuban, Yemen

Wadi bed slopes reduce at the point where wadis emerge on to the plain and sediment deposition often results in the formation of alluvial fans. Bed widths increase the deposition zone downstream from the mountain front (see Figure 3.4). If not incised, extreme floods may cause a wadi to change its alignment and flow off in another direction down the slope of the fan. The wide main flood channel usually contains one or more meandering, shallow, low-flow channels, formed by the high flows of the preceding floods that carry the lower flood recession flows. Unless anchored by a bend or a rock outcrop, low-flow channels tend to be unstable and change their alignments from flood to another (see Figure 3.5).

The effects of bed seepage, channel storage and irrigation abstractions reduce flows as they pass downstream, the width of the main wadi channel also reduces in the downstream reaches. While the plains sections of wadis are accretion zones, rising wadi bed levels may be balanced to some extent by the general lowering of wadi beds caused by large floods. A general lowering of the bed by 0.5 m over a 50 km reach of a wadi in Saudi Arabia has been reported *(FAO, 1981)*. This was attributed to a flood with a return period estimated as only five years.

Relatively large bed level changes occur during floods, when wadi beds scour down and then reform during flood recessions. Measurements carried out using scour chains in Wadi Rima showed the wadi bed lowering locally by up to 1.5 m and then refilling to within a few centimetres of its original level during the passage of a large flood *(Lawrence, 1983)*. Repeated surveys of the dry wadi bed carried out over one flood season showed local changes in bed elevation of up to 1 m, with average fluctuations over the surveyed cross-sections of around 0.3 m. Careful attention is, therefore, needed when specifying existing natural wadi bed levels in the design of new wadi diversion structures.

The middle and lower reaches of wadis are usually contained within near vertical banks of alluvial sediment deposits that are vulnerable to attack from high flows. Bank cutting can result in significant changes in the wadi alignment and loss of irrigated land.

Sediment sizes

The transport and deposition of sediment in wadis, canals and fields of spate irrigation systems is strongly related to the size of the sediments being transported. At the

FIGURE 3.4

Wadi bed widening after emergence onto the coastal plain, Wadi Laba, Eritrea

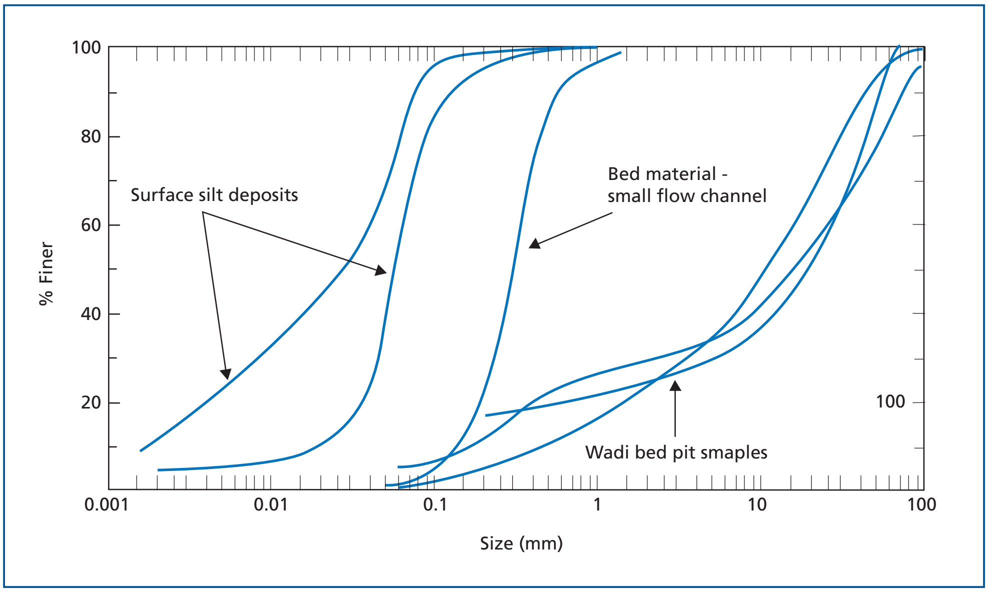
FIGURE 3.5

Unstable low-flow channels, Wadi Zabid, Yemen

mountain fronts, wadi beds usually contain a very wide range of sediments ranging from surface layers of fine sand, silts and clays deposited during the recession phase of floods, through coarse sand and gravels forming the beds of low-flow channels, to shoals of cobbles and boulders. The underlying alluvium typically contains all these materials, along with very large boulders that may only be exposed and transported by the largest floods.

The active beds and deposition layers from past floods can usually be observed in exposed banks or at the lowest points excavated in the wadi beds. The wide range of sediment sizes observed in the bed at a typical upstream wadi diversion site is illustrated in Figure 3.6. The sizes of wadi bed material reduce and become more uniform in the downstream direction. Wadis usually have sand beds in their lower reaches.

FIGURE 3.6
Wadi bed sediment sizes - Structure 1, Wadi Zabid, Yemen



Sediment transport

In most spate irrigation systems, only the largest floods are allowed to flow beyond the irrigated area. Smaller floods are either diverted to the fields, or seep into the wadi bed. Thus, although very large quantities of sediment are transported up to the first diversion point, usually very little sediment is transported beyond the irrigated area. Coarser sediments settle in the wadi channels and canals and finer sediments are deposited on the fields where farmers welcome sedimentation as a source of fertility. Figure 3.7 shows fine sediment deposit photographed twelve days after spate irrigation on a field in the Wadi Tuban system in Yemen.

Although management of sedimentation is a key factor in spate schemes, there is very little data to assist designers in assessing sediment transport and sedimentation rates or to design sediment management structures. The most reliable information has been derived from a small number of measurement programmes where pumped sampling

FIGURE 3.7
Sediment deposits, Wadi Tuban, Yemen

equipment has been used to collect sediment samples from fixed nozzles at various depths from flood flows *(Lawrence, 1986 and Mace, 1997).* The limited information that is available suggests that:

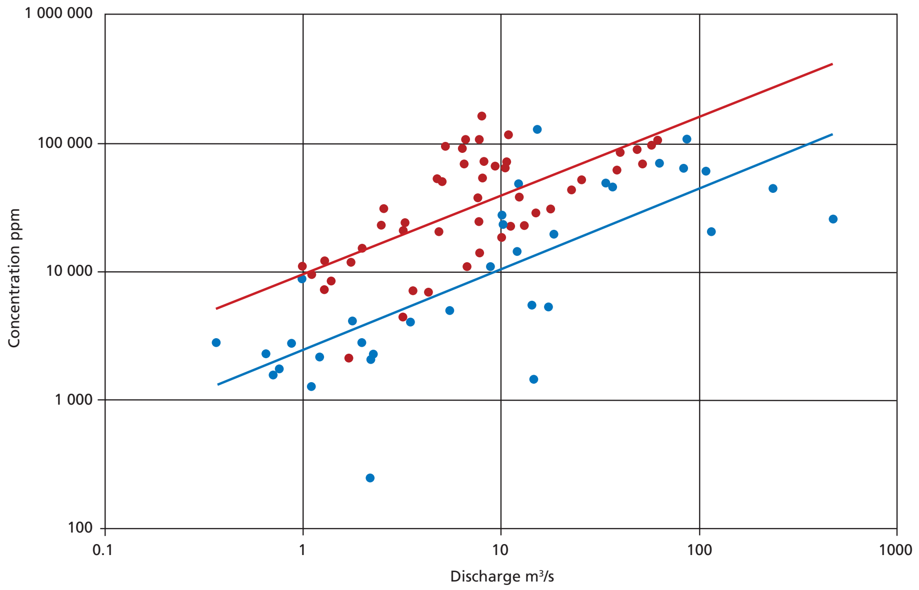
- Total load sediment concentrations rising to and exceeding 100 000 ppm, or 10 percent by weight can occur in floods in some wadis. Sediment concentrations up to 5 percent by weight in floods are common.
- Sediment transport is dominated by the finer sediment fractions. The proportion of silt and clay in the sediment load varies widely during and between floods and between catchments but typically ranges between 50 and 90 percent of the total annual sediment load. As they are 'supply controlled', fine sediment concentrations do not correlate well with wadi discharge (see Box 3.3 for fine sediment concentration in Balochistan and Eritrea).
- The sand load transported in suspension in wadi flows, which will be diverted to canals even at well designed intakes, is also relatively fine (generally between 0.1 and 1 mm) when compared with the parent bed material. Estimates of the sand load can be derived from empirical equations but should be supported, wherever possible, by measurements of the sand load variations during floods.
- Coarse sediments transported near the wadi bed by rolling and sliding represent only 5 percent or so of the total annual sediment load. Sediments of this size range from coarse sand, through gravel, to cobbles and in some cases boulders. They settle and block intakes and canals. Estimates of bed load sizes and concentrations are needed to design sediment control structures where these are included in larger major intakes. These are usually derived from empirical equations. However, their measurement is only feasible with the use of specialist equipment.

Measuring sediment size distribution

The need to control coarser sediments that settle in canals is discussed in Chapter 4. Sediment transport computations carried out to design sediment control structures are based on wadi bed sediment size distributions. They are too complex to be included in these guidelines, but the method of assessing sediment size distribution is described briefly below *(Lawrence, 2009).*

BOX 3.3

Wash load (fine sediment) concentrations for the Chakker River in Balochistan, and Wadi Laba (Pakistan)



The similarity of the gradients of the relationships between sediment concentration and discharge for the two wadis is fortuitous. Typically, the exponents in power law relationships for fine sediments transported as wash load can vary between $Q^{0.3}$ and $Q^{1.2}$.

Sampling of bed material in coarse-grained channels requires a very large sample size to represent the sediment distribution accurately. When the surface layers consist mostly of gravel cobbles and boulders, a randomized point-counting method of the bed material can be used as an alternative to sieving. This can be achieved by using a random walk to select stones for measurement:

- Starting at the centre of a shoal of coarse sediment, take one pace in a random direction and select the pebble/gravel/cobble lying directly at the end of your shoe.
- Pick up and measure the intermediate axis of this stone in millimetres.
- Repeat, changing direction after each pace so that sampling is random and taking care not to look at the wadi bed when pacing. Avoid the temptation to 'select' large gravels and cobbles. Ignore sediments smaller than 1 mm.

From these measurements a grading curve for the bed material can be produced by ranking the sizes of the intermediate axis in ascending order and plotting against a cumulative percent by number. The number of measurements needed depends on the range of sizes being sampled, but generally one hundred measurements will provide sufficient accuracy. Ideally this procedure should be repeated several times at different shoals and the representative D_{84} size taken as the mean of the individual D_{84} sizes.

For large canals with very coarse bed material, either of the methods listed above can be used to estimate discharges from water levels. For channels or canals with sand beds, an alluvial friction predictor is recommended to estimate channel roughness from bed material size and hydraulic conditions. One of the methods available in the design tools 'DORC' option of HR Wallingford's SHARC sediment management design software is recommended[2].

Estimating sedimentation rates on spate irrigated fields

Soils in spate areas are largely built up from wadi sediments. In some locations soil depths of 500 mm thickness have been developed over a period of 3–4 years, and alluvial sediment deposits many metres thick are observed in some of the older spate-irrigated areas. The rate that soil build up varies from location to location, depending on the sediment yield from catchments, and on the position within a scheme. Sedimentation rates are higher in the upstream fields, as they are irrigated more frequently and are also closer to the wadi, and there are fewer opportunities for fine sediments to settle out of the short, steep canals linking wadis to the fields.

The size range of the sediment deposits at different locations depends on the relative rates of sediment transport and deposition through the canal system. Some fine sands that are transported through the canals may settle in the upstream fields, while finer sediments, silts and clays tend to be transported further. Table 5.1, in Chapter 5, provides information on the annual rise rate for fields in spate-irrigated areas.

In existing schemes, past increases in field levels can therefore be assessed from the thickness of alluvial sediment deposits and the number of years that the scheme has been diverting water. This provides a guide to the expected future rates of rise of field levels that will need to be taken into account when the command levels for improved intakes and other hydraulic structures are being determined. For new schemes, particularly in regions that do not have nearby existing spate-irrigated areas, estimating future command changes is more difficult. However, approximate estimates can be made if information is available on catchment sediment yields, or the sediment concentrations in floods.

Catchment sediment yields, expressed in t/km^2.y, can be converted to a sediment concentration by weight in ppm by dividing the product of the catchment area and the sediment yield by the annual runoff volume in million m^3. Sediment concentrations in floods can be measured by taking frequent, regular, surface bottle samples in floods and, in the simplest form of analysis, by averaging the sediment concentrations in the bottles. Care should be taken to ensure that average samples are collected during flood flows.

The annual rise in the command levels of upstream fields can then be estimated from:

$$\Delta l \quad = n \,.\, d \,.\, \text{conc.} \,/\, (1.4\ 10^6)$$

where:

Δl = Annual rise in the level of the upstream fields (m)
n = Number of irrigations during a year
d = Depth of water applied per irrigation (m)
conc. = Sediment concentration by weight (ppm).

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[2] The software and manuals can be downloaded at http://www.dfid-kar-water.net/w5outputs/software.html

Chapter 4

Water diversion and control structures

SUMMARY

Experience shows that the most successful spate irrigation improvement projects do not significantly alter the way spate irrigation is practised. They combine the advantages of traditional systems with those of more permanent and less labour-intensive structures.

Improvements to spate systems must be designed so as to reduce the labour required to maintain intakes, improve the control of water within the distribution systems and minimize the capacity of large floods to damage canals and fields. They must guide and split flood flows, rather than constrain them, avoid excessive sediment load in spate systems and ensure that suspended sediments are deposited on the land and not in the canals. Their design must also ensure that they can cope with frequent and sometimes large changes in wadi bed conditions. At the same time, proposed improvements must recognize and respect the established system of water allocation arrangements, priorities and amounts, and avoid unintentional alteration of water distribution within the watershed between upstream and downstream water users.

The range of technically and economically viable design options must take into account the experience that the farmers have of the systems and of wadi flow. The role of engineers is primarily to assist farmers in selecting the most appropriate options that improve upon traditional schemes without introducing unnecessary changes. Farmers should therefore be consulted and involved in the planning, design, execution and operation of the rehabilitation and improvement works. Consultation is thus fully interactive and continuous, ensuring that the local situation is fully understood and reflected in the improvements. It is of paramount importance to understand farmers' irrigation practices, priorities and risk management strategies.

Engineering interventions involved in spate scheme improvement can be clustered into three groups: diversion structures (intakes), canals and water control/dividing structures and wadi training structures, including bank protection and embankments. In general, designs should be robust enough to take into account the uncertainty in prediction of flood sizes and patterns. Cost/benefit considerations will to a large extent dictate the alternatives selected, such as the use of fuse plugs to reduce the cost of permanent diversion weirs but still to maintain the design return period. Interventions need to be seen in a holistic manner and the engineers should give adequate and balanced consideration to both upstream and downstream water users and consider both overall water balance and allocation. Sedimentation problems linked to permanent structures must be manageable with the use of realistic levels of local resources, funds and skills so that sustainable levels of maintenance can be assured.

The following guiding remarks can be given for engineering interventions in the different types of spate systems described in Chapter 1:

- For traditional small schemes managed by farmers, options usually include the provision of more durable simple diversion structures, constructed from gabions, rubble masonry or concrete, with structures properly designed to resist erosion, scour and overturning and simple enough for farmers to maintain with indigenous skills and locally available materials.
- For new small schemes where spate irrigation is being introduced, the engineering options for traditional schemes may be applied, but the provision of a simple permanent structure and bed bars will often be a better option (compared to traditional structures) when farmers do not have experience of using traditional diversions.
- For medium-scale to large-scale traditional schemes, which are under farmer management and are treated as a number of small independent systems: this approach has the advantage that farmer user groups and arrangements for water distribution and maintenance remain unchanged. In some cases it may be prudent to work on the tail-end systems only. Many past modernization practices have tended to replace numerous small intakes by a limited number of major diversion structures, connecting the existing spate systems through a single main canal. While this may have advantages in terms of costs, the major disadvantage of the single new intake approach is that it reinforces the upstream users' control over diverted flows and reduces access to water for downstream users, who can no longer divert water directly from the wadi. This often leads to a substantial modification of established water distribution practices without farmer agreement. In cases where such an option is retained, discussions with all water user groups are needed to ensure that changes in traditional water allocation arrangements and water management practices are understood, equitable and accepted by all.
- In large wadis subjected to very high spate discharges, more experienced engineering expertise is needed to ensure that diversions are sufficiently robust to provide durability and less risk of failure or severe damage. However, these approaches, using more conventionally engineered structures, need to be balanced against costs (capital and recurrent) and the flexibility needed to meet the farmers' requirements and expectations and to adjust to the changing circumstances that are inherent in spate systems.
- For large schemes that have been improved in the past and provided with technically more complex infrastructure, such as more permanent diversion and water control structures, technical, social and environmental reviews will be needed. Experience has shown that operation and maintenance costs and negative impacts on existing water distribution practices and rights are systematically underestimated and that this leads to poor management, degradation of irrigation infrastructure and inequity in access to water. A careful assessment of all costs and benefits related to such schemes is therefore necessary to ensure that they are financially, socially and environmentally sustainable, that the improvements guarantee that adequate water is diverted to all farms (in comparison with traditional allocations) and that water allocation arrangements and water management practices are understood, equitable and accepted by all.

Diversion structures – traditional intakes can take one of two forms: spur-type deflection, and bund-type diversion. While they are simple structures, they have enabled spate irrigation to be sustained for many years with only local materials and indigenous skills. They are characterized by flexibility to changing wadi bed conditions, suitability for construction and maintenance by local farmers with local materials, a relatively high level of efficiency in water use and the ability to avoid excessive sediment transport in the canals. These advantages are obtained at the cost of regular destruction and reconstruction of intake structures after each large flood and environmental damage. The major disadvantage associated with traditional diversion structures lies therefore in the amount of labour needed to maintain and reconstruct intakes that are damaged or washed out by large floods and the continual use of new brushwood and tree material needed to reinforce the bunds.

There are several options for improving diversion structures, which depend on the site conditions, the available resources and farmers' preferences. These options essentially include:

- more durable diversion spurs with breach or overflow sections;
- improved diversion bunds (including the use of fuse plugs and bed bars);
- controlling the flows admitted to canals (natural orifice control or more formal gated intake structures);
- rejection spillways;
- a combination of the above.

Typically, improved diversion structures may include the following components:

- a bed stabilizer (bed bar) or a raised permanent weir, to control and fix the bed and hence the water levels at the division point. In most cases weirs are only needed to provide command to the immediately adjacent land, as both the land and wadi bed slopes are steep and most of the land is naturally commanded;
- a fuse plug, in earth or wadi bed material, to be used in conjunction with a permanent weir structure spanning only part of the wadi width, to increase the return period of the design and thereby reduce costs but still protect the intake and weir from exceptional floods;
- a scour or under-sluice, to exclude very coarse sediment material from the canal during periods of high flows. When gated, sluices can usually only be operated for the short periods when the wadi flows exceed the canal discharge and in agreement with water users,
- a breach bund made of local material, located just downstream from the intake structure and built over a bed bar that controls the location of the diversion bund and offtake. It will be breached during high flood flows and thereby return to the downstream river bed large amounts of coarse sediments transported by such floods and avoid heavy sedimentation of canals and blocking of intakes,
- a canal head regulator or intake, controlled by gates or orifice flow, to regulate the flows entering the canal and share water among several intakes. In large systems characterized by fixed intakes, gates are needed for sharing the water between the intakes. In these situations, a local experienced community operator assesses the arriving floods (timing, duration, size) and adjusts the openings in accordance with agreed schedules and water allocations; and
- guide or divide walls.

Canal design – the dimensioning of spate canals does not follow classical irrigation design. In spate irrigation systems the objective is to divert the maximum possible amount of water during the very limited duration period of the spate flood to reach as many of the fields as possible. Intakes and canals thus have a much larger discharge capacity per unit area served than would be the case in perennial irrigation schemes (10–100 times greater). Discharge capacities for intakes and canals are determined from an assessment of the distribution and size of flood flows within the annual hydrograph; the duration and variation of discharge during each flood event; and, as water is applied before crop planting, soil water-holding capacity in relation to assumed crop water needs, rather than to actual crop water requirements during the growing season. Actual canal discharge varies rapidly over the full range of flows from zero to the maximum discharge. Sediment loads in spate systems are very high and canal designers are not free to set the canal cross-section and slope to carry the required dominant discharge. Instead, they must make sure that flow velocities are maintained at relatively high levels to ensure an appropriately high sediment-transporting capacity.

This contrasts with conventional canal designs for irrigation systems, that are based on meeting actual crop water needs with supplied water relatively free of sediment and flow velocities determined by using a Froude number less than 0.7–0.8 (i.e. sub-critical flow + safety factor), for which a fairly narrow range of design discharges (0.7–2.0 l/s/ha), canal capacity and sections adopted are hydraulically efficient and cost-effective.

Traditional canals in spate schemes usually adopt prevailing land slopes without drop structures. Although these slopes are often much steeper than those adopted for canals used in perennial irrigation systems, head-cutting erosion is normally minimal as bed material is far coarser than in conventional earth canals. In addition, although local scours may occur, any corrosion will be filled by sediments as the spate flow recedes and the velocity in the canals drops. Typical canal structures in spate irrigation systems are flow-dividing structures, field offtakes and in-field check and drop structures. In improved spate systems, checks and drops are often included. Many of these water control structures introduced as part of scheme improvement interventions are similar to those used in conventional irrigation. However, the following points must be taken into consideration when improving (or extending) spate canal systems:

- Improving existing canal networks can give better water control and overcome some disadvantages of the field-to-field water distribution system but may require a change in the way that water is distributed. Any modifications could impact existing water rights and rules and thus need to be discussed and negotiated in advance with the farmers.
- Spate irrigation relies upon water application carried out as quickly as possible. The improved canal network must ensure that this continues and maximizes the areas irrigated in the short spate flow periods. This is particularly important to downstream farmers, whose time of exposure to irrigation flows is far less than that of upstream farmers, who access water from most floods in most years.
- Farmers' prior agreement to proposed changes and their full understanding of the implications for water allocation and distribution is essential for sustainable changes. In particular, the use of gated structures, either at the intake or in canals, must be determined with a clear understanding of operational implications for downstream users.
- As spate flows occur at short notice and are of short duration, choice of gate design and operating system must reflect the need for rapid opening and closing of the gates and be related to the peak time of the flood hydrograph. Manual systems are usually too slow even with a high gain mechanism; electrical

gates rely on the availability of power, which is often lacking at key moments; hydraulic gates are more expensive but are the most suitable, as they can be operated quickly and in response to rapid changes in the flood hydrograph.

- Where canals are performing reasonably satisfactorily, the design of improved or extended canals should be based on the prevailing slopes and cross-sections and supported by survey data. Canal design methods that simulate existing canal slopes and dimensions should be utilized both to check existing designs and extend designs to new canals.
- Velocities in the canal network should be maintained as close as is possible at a constant level throughout to ensure high sediment-transporting capacity and to minimize deposition in the canals (similar to the situation observed in traditional canals).
- In flatter areas with alluvial soils, scour damage should be avoided through adoption of regime theory, selection of appropriate canal dimensions and slope, division of flows and the provision of controlled intakes and embankments and associated bank protection works.

Sedimentation – wadi beds and banks are continually affected and eroded by large floods. This has implications for associated spate irrigation schemes. Wadi beds can be significantly lowered (both locally and permanently) during the passage of large floods and leave the invert of traditional intakes well above the new scoured wadi bed level, so that it is impossible to divert water into the canal system. Providing engineered structures (bed bars or low overflow weirs) to control wadi bed levels is a viable option, but can be difficult to justify in small spate schemes or where the wadi course is wide. In such cases, it has been found that providing farmers with access to bulldozers so that they can quickly reconstruct bunds across the wadi after major floods can be economically more attractive.

The ability to cope with changes in wadi beds and high sedimentation rates in the command areas and canals is critical to the success of spate irrigation. New intakes and canals have to be designed to cope with changes in wadi bed and/or field levels rising up to 50 mm/year. When new diversions are proposed, the following measures are recommended:

- Estimates of the rise in command levels expected over the design life of structures (>25 years) should be developed and used to design weirs, intakes and water control structures to maintain the irrigable command area. One option is to provide moveable stop logs that are progressively raised in line with the rising bed (an approach adopted in the Gash in Sudan). Alternatives at field level include increasing the gross irrigable area but maintaining the net irrigable area as some land goes out of command.
- Intakes associated with permanent raised weir structures should be provided with effective sediment sluices that are designed to be operated during the very short periods when flood flows exceed the diverted flows. Small settling basins designed to trap coarse sand, gravel, and larger sediments, before they can enter, settle and block canals, are also an option in these situations, provided that they are designed for easy, affordable and cost-effective removal of sediment by farmers' organizations immediately after floods.
- Where intakes are not associated with permanent raised weirs, the provision of bed bars and breachable bunds, built from local materials, on top of the bed bars provides an improved intake that works in a similar manner to sediment management in traditional systems.

River training – The scouring of wadi banks, undercutting at the outer curves of meanders and sedimentation at the inner curves during large floods erodes away valuable irrigated land and threatens villages and canals running parallel to the wadi banks. It is usually impossible to justify protection against such damage from large floods with conventional river-training works, because of the high costs involved when compared with the low value of the land and the crops that are grown. Often the best option is a combination of vegetative protection and mechanical control measures. All river training and bank improvements must form part of a complete plan to ensure that problems are not treated in isolation with the result that they are just moved to another location.

INTRODUCTION – LEARNING FROM PAST EXPERIENCE

The irrigation infrastructure, patterns of water distribution and arrangements for operating and maintaining traditional spate irrigation systems have evolved over time and adapted to the local conditions. Traditional spate irrigation systems divert water from spate wadis through the use of simple, locally developed and improved structures. Over many years, farmers have developed local knowledge of locating and constructing diversion structures, managing flood waters and organizing water distribution.

Traditional diversion and distribution structures enable water to be diverted from uncontrolled ephemeral rivers through the use of only local materials and indigenous skills. When multiple traditional diversion structures are used along a wadi, relatively high overall water diversion efficiency can be achieved. The principal disadvantage of traditional diversion methods is the excessive inputs of labour needed to rebuild the structures, which are frequently damaged or scoured out by flood flows, sometimes by design, and which annually require significant amounts of local timber and brushwood material for reconstruction.

Over the last three to four decades, relatively sophisticated and costly diversion structures, linked to new canal systems, have been introduced in some countries to modernize and improve the performance of traditional systems, e.g. Yemen, Pakistan, Morocco, and Tunisia. These well-intentioned interventions were designed to eliminate the need for the frequent reconstruction of traditional intakes which are regularly damaged by the larger spate floods, and in some cases to increase the volumes of water available for irrigation. While new engineered diversion and water control structures have mostly solved the durability problem, they have often failed to provide some of the other benefits that were anticipated, especially improved water availability for all. This disappointing performance has been variously attributed to:

- an increased inequity of water distribution, resulting from the construction of permanent diversion structures at the head of spate systems, which gave the upstream farmers control over a large proportion of the available flows, to the detriment of downstream irrigators (see example in Box 4.1);
- inadequate intake capacity, and hence water, in the spate networks through a failure to appreciate the link between exposure time to, and duration of, spate floods;
- problems due to high rates of sediment deposition in the fields and canals, resulting in the need for frequent desilting (see example in Box 4.2);
- the introduction of an operating authority who has the technical skills needed to operate and maintain modernized infrastructure but who has also reduced the farmers' role in diverting and distributing water and often ignores traditional practices;
- the unrealistic assumptions concerning levels and costs of operation and maintenance of spate systems (mostly canal and sediment basin desilting), required to keep conventionally designed irrigation canal networks running under spate conditions;
- failure to relate system design and operation to farmer management and likely levels of funding that they could raise for annual operation and maintenance; and
- failure to achieve an expected increase in irrigated area owing to over-optimistic assumptions about water resource availability (amounts, duration of floods and shape of the hydrograph) and the water diversion efficiency that can be achieved with rapidly varying spate flows and manually operated control gates.

These problems in many cases result from comparing the diversion efficiency, and hence intake capacity, of well designed permanent gated diversion structures with the much lower efficiency obtained from a traditional free intake and incorrect assumptions

BOX 4.1

How structural improvements modify the balance of power: the example of Wadi Mawr, Yemen

A new irrigation infrastructure in Wadi Mawr was commissioned in the mid 1980s. Located on the Tihama plain in Yemen, this was one of the last Tihama wadis to be modernized. The diversion structure was developed on the basis of lessons learned from earlier spate improvement projects. It includes what is probably the most sophisticated spate irrigation intake constructed anywhere in the world. A large proportion of the annual runoff in Tihama wadis consists of base and lower recession flows and high diversion efficiency can, in theory, be achieved with a single intake located at the head of the scheme which diverts only relatively low flows. The intake was thus designed to divert flows of up to 40 m^3/sec and was located on the north bank of the wadi at the head of the existing irrigated area. It was estimated that 88 percent of the mean annual wadi discharge would be diverted to new canals running down both banks of the wadi to supply water to the 39 existing primary canals (a siphon transfers water under the wadi to a supply canal located on the south bank).

The intake structure (see figure below) consists of a raised weir, a deep scour sluice with three gates and four head regulator gates feeding twin sediment-settling basins. The settling basins were designed to be flushed when sufficient water was available in floods, to flush coarse sediments trapped by basins back into the wadi. As up to 14 gates need to be operated during spates, electrically powered gates were provided.

This structure provides an example of a well engineered large-scale spate diversion system. Yet the operation of the intake, sluice and canals has been severely compromised by powerful landlords in the upstream part of the irrigation scheme, who have prevented the sluice and sediment-flushing facilities from working as planned so as not to ‘waste’ water. Flows have been diverted at the intake and commandeered for use mostly in the upstream part of the system, a new unauthorized canal has been constructed and water has been sold to farmers in another command area, outside the boundaries of the Wadi Mawr system. Farmers on the south bank and lower parts of the system have lost access to the water that they could have formerly diverted and have had to rely on the reduced water volumes available in the infrequent, very large floods that pass over the diversion weir. This case shows how an improved diversion system that should have benefited all farmers in a scheme was diverted from its intended role for the benefit of a few.

relating traditional seasonal irrigation with spate irrigation. Predicted diversion efficiency at a new formal intake needed to be compared with the combined diversion efficiency of the many independent traditional intakes that it replaced, including intakes outside the formal scheme area which utilized excess flood flows that do not occur every year. In other cases, over-optimistic assumptions of increases in cropped areas following modernization may have been influenced by the need to justify large investment projects with conventional cost/benefit criteria without an understanding of the farmers' concept of areas irrigated in below normal, normal and high runoff years.

BOX 4.2
Example of design problems in modernized systems

In Yemen, several large spate irrigation systems located on the Tihama coastal plain were modernized in the 1980s. They include Wadi Zabid, Wadi Rima and Wadi Mawr. The design of the modernized intakes became more sophisticated over time. The first scheme to be modernized, Wadi Zabid, consisted of five new permanent diversion weirs, most with canal intakes on both banks. The intakes immediately experienced diversion and sedimentation problems and, before its recent rehabilitation, the scheme was operated like a traditional system, with diversion essentially controlled by bunds built into the wadi bed by bulldozers, to guide flows towards the gated canal intakes (see figure below). Frequent canal de-silting was needed to maintain canal flow capacities.

Experience has shown that successful design of improved spate irrigation structures needs a sound understanding of the water-sharing and institutional arrangements that have underpinned the success of traditional systems for centuries, as well as the more obvious engineering, hydrological, agronomic and economic issues. For engineering interventions to be successful, they must:

- replicate as far as possible the way in which water has been traditionally diverted/abstracted and in many instances build on these traditional systems;

- recognize the unit flows for traditional spate systems that range from 10 l/s/ha (the Tihama average norm) to over 100 l/s/ha in some smaller wadis with short-duration spate flood flows;
- reflect the time commitments and technical knowledge of the farmers, thereby reducing labour commitments for routine and emergency maintenance and facilitating farmer operation;
- facilitate the control of large flood flows, to reduce damage to canals and field systems;
- as far as possible, replicate water distribution in line with accepted rules and rights, while providing flexibility to accommodate future changes in water distribution and cropping;
- ensure a right balance between the needs of different water uses and users (agriculture, drinking water, downstream users, etc);
- improve the capacity of the systems to function with high rates of sediment transport; and
- improve the ability to cope with the frequent big changes, resulting from large floods, in the levels and alignments of unstable river channels.

While many of these features were being promoted in spate improvement projects more than twenty years ago, providing them in medium-scale and large-scale spate schemes at an acceptable cost (both capital and recurrent) continues to challenge designers, irrigation engineers, aid agencies and donors. Improvements requested by farmers are usually aimed at reducing the excessive maintenance burden, through provision of more robust and more permanent diversion and water control structures. As spate systems are often diverting a substantial proportion of the annual flow volumes during relatively short periods to produce low-value subsistence crops, the economic returns from investments in new diversion and water control structures may be quite small. The challenge is thus to provide affordable improvements to the existing infrastructure that match as closely as possible the desired engineering interventions discussed above.

Often expected economic returns from improvements in spate irrigation are relatively marginal and can only warrant low-cost improvements. These low-cost improvements in spate infrastructure in most cases imply higher annual maintenance costs than more expensive structures, but they may also provide the added advantage of flexibility that is needed in the dynamics of spate irrigation to adjust to a rapidly changing physical environment. In some cases, where other factors come into play such as poverty reduction, groundwater recharge and improved reliability of water supplies in severely drought-affected areas, higher-cost engineering improvements may be justifiable, provided that the interventions proposed do actually meet these criteria and truly benefit the target groups. Where spate irrigation is being introduced into new areas, farmers will probably not have the traditional indigenous skills needed to divert and distribute spate flows through the use of traditional structures. In these cases again, simple but improved diversion structures, with permanent gated intakes and canal water control structures that are easily operated, may be needed.

The overriding principle is that there is no single approach to the design of improved spate systems. Specific requirements vary widely between, and in some cases within, schemes, but before proposals are finalized, it is essential that engineers fully understand the way in which the farmers' system has operated and farmers truly understand and comprehend what the engineers are proposing for them. It is important to keep a large repertoire: in some areas, permanent headworks will be useful, in other areas the use of gabion flow dividers/splitters or the engagement of bulldozers to construct earthen structures will be appropriate.

The engineering structures involved when spate schemes are improved can be described under three headings:

- diversion structures (intakes);
- spate canals and water control/dividing structures; and
- bank protection and wadi-training structures.

For each category, traditional structures are first described, followed by a discussion of improvement options.

DIVERSION STRUCTURES (INTAKES)

Intakes in spate systems have to divert large and varying levels of flood flows, delivering water to canals at a sufficiently high level to ensure command over the irrigated fields. They need to prevent large uncontrolled flows from entering canals, so as to minimize damage to channels and field systems and limit the entry of the very high concentrations of coarse sediments that are carried especially in the larger floods. These functions have to be achieved in unstable wadis, characterized by occasional lateral movements of low-flow channels within the wider wadi cross-sections, bank cutting and vertical movements of the wadi bed caused by scour and sediment deposition during floods. Intakes must also function over the longer term with rising irrigation command levels caused by sediment deposition on the irrigated fields and aggradation and degradation of wadi bed levels due to changing hydrological conditions, climate change and catchment deforestation.

Canals need to convey large volumes of water to fields quickly in the short periods when flood flows occur. The timing, duration and maximum discharge of spate flows are unpredictable and thus canal capacities have to cope with a wide range of design conditions. Water distribution systems developed for perennial irrigation are thus not appropriate for spate systems as canal capacities are determined for a relatively narrow and predictable range of design conditions. Traditional intakes and their modern replacements can be adapted to meet spate design conditions, although the design parameters will be very different, resulting in large differences in cost and maintenance requirements.

Traditional structures

Traditional intakes can take one of two forms. These are the spur-type deflector and the bund-type diversion.

Spur-type deflector

Deflecting spurs are mainly found in upstream wadi reaches, soon after the wadi leaves the foothills and begins to enter the flood plains. In these locations, longitudinal slopes are steep, bed materials coarse and water velocities during flood flows very fast. The structures consist of a spur, usually built from wadi bed material and reinforced with brushwood and other more durable materials brought down during floods. They are located within the main wadi bed and aim to divide or split the flood flows, with the larger part of the flow being encouraged to continue downstream. From the main deflector, a smaller bund is constructed across and extending up the wadi bed at a relatively sharp angle both to intercept low flow and divert it via the low-flow channel to an un-gated canal intake (see Figure 4.1). Three examples of traditional spur-type intakes from Ethiopia, Yemen and Pakistan are shown in Figures 4.2, 4.3 and 4.4.

FIGURE 4.1
Deflecting spur-type traditional intake

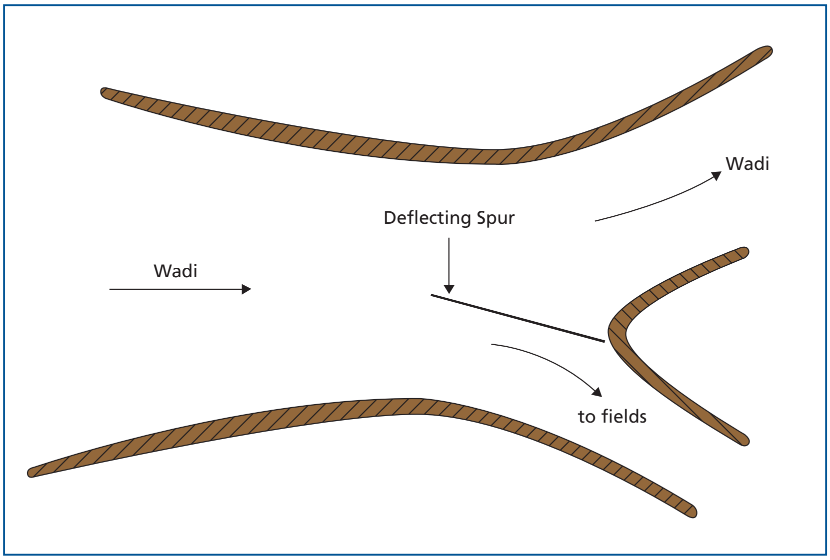


Figure 4.2 shows a spur intake in an upstream view from the head of a canal diverting water from a small sandy-bed spate river located in the south of Ethiopia. The spur, well located at the outside of a bend where it intercepts the low-flow channel, is constructed from tree trunks driven into the wadi bed, sealed woven branches, brushwood and sand from the river bed.

FIGURE 4.2
Traditional spate irrigation intake in Ethiopia

Figure 4.3 is taken from Wadi Rima in the Tihama Plain bordering the Red Sea in western Yemen. It shows the upstream end of a typical traditional spate intake constructed from cobbles and gravel, reinforced with brushwood, located at the outside (left bank) of the wadi bend. A new permanent diversion weir was constructed a few kilometres upstream from this intake in the 1980s but, as the intake capacity was insufficient to meet all of their water needs, farmers continued to use this and other traditional intakes to utilize excess flood flows from the larger floods that pass over the new diversion weir. This weir was one of the first in the programme of donor support to improving spate irrigation systems in the area and subsequent designers could have learned many lessons from these experiences.

Figure 4.4 shows a spur-type intake constructed from wadi bed material and pushed up by bulldozer at the outside of a river bend in a spate river in Pakistan. The wide, shallow cross-section of the diversion channel, typical of canals in spate systems, and the fine sediment deposits that have settled in the intake channel are well recognized. The photo also illustrates the intention of the farmers to take only a proportion of the peak wadi flood flow, at the same time abstracting as much of the lower and medium flows as possible. Although the examples shown above encompass intakes constructed in different ways, in wadis of differing sizes, catchment areas and flow characteristics and at widely separated geographical locations, they share many common features they:

FIGURE 4.3

Traditional spate irrigation intake in Yemen

FIGURE 4.4

Traditional spate irrigation intake in Pakistan

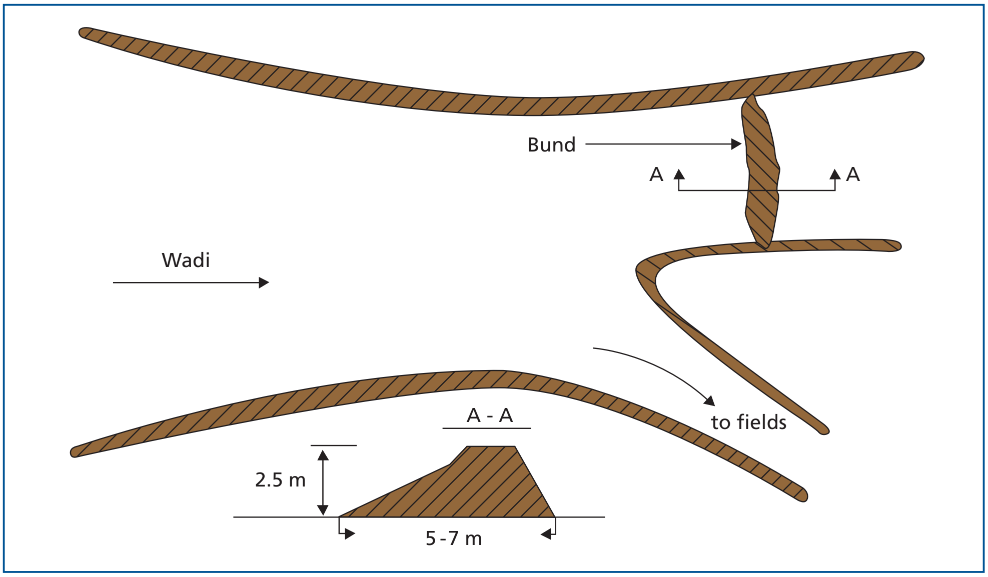
- are located at the outside of relatively mild wadi bends, where the deep water channel is scoured in floods, and where lower flows are channeled during flood recessions;
- consist of low spurs extending at a slight angle out into the wadi to intercept the low-flow channel and divert water to canals;

- are constructed from locally available materials and can be maintained and reconstructed by farmers without significant external support (in the last example, bulldozers are made available to farmers at subsidized rates);
- all take into account the force and damage that can be caused by large and very large flood flows and are designed to be breached or break when they occur, thereby reducing danger to the spate irrigation system;
- diversions are not ‘greedy’ and do not try to extract all the flow but are designed to ‘coax’ the flows into the intake and take as much as they dare without endangering the whole system; and
- while the different forms of construction result in varying degrees of durability, mainly depending on available labour and local materials, they are all likely to be damaged or completely swept away by larger floods.

Bund-type diversion

This type of diversion structure consists of a large bund constructed from wadi bed material that is built right across the wadi bed (see Figure 4.5). This diverts all the available wadi flow to canals at one or both banks. These structures are constructed in the lower reaches of wadis, where the bed slopes are flatter, available flows less frequent, water velocities are slower and the bed materials are finer than the sites where deflectors are used. All the wadi flow is diverted until the bund is overtopped and scoured out by a large flood or is deliberately cut by farmers. Box 4.3 shows an example of traditional diversion bunds in Eritrea.

FIGURE 4.5
Diversion bund intake



In Pakistan, some very substantial structures of this type of diversion bund are constructed in farmer-managed schemes to guide and divert flood water to irrigated areas. The dimensions of some diversion bunds constructed in DI Khan are shown in Table 4.1. In the Tokar system in Sudan, diversion and guide bunds are also in place but are supported by embankments whose main purpose is slightly different from those in Pakistan. They are used to restrict outflows to the sea and retain the flood flows within the middle delta, which is the most suitable land for irrigation. The Tomosay embankment is the biggest and most important. It extends for about 50 km along the western limit of the Tokar system and guides flow to the middle delta and away from the western delta. Only one main diversion bund exists, the Tomosay bund, and this is supported by smaller diversion bunds divided into three areas. No canal network exists, water being allowed to flow as a wide and shallow sheet over the area to be cultivated. This is a unique type of system that relies upon a high standard of land preparation and water management. In recent times, this has been lacking and thus the area irrigated is far less than the potential and historically irrigated areas.

TABLE 4.1

Dimensions of some diversion bunds in Di Khan in Pakistan

Location	Length (m)	Height (m)	Width (m)
Sad Swad	351	3.2	10.4
Sad Rabnawaz	754	7.0	12.0
Sad Dinga	330	1.9	15.1
Gandi Abdullah	178	8.0	14.0
Gandi Booki	1 350	3.0	8.0
Gandi Mullawali	87	1.9	4.5

BOX 4.3

Traditional bund intake under construction using draught animals in Eritrea

The figure below from the Red Sea plains in Eritrea shows a bund being constructed from wadi bed sediments dragged up by draught animals and scraperboards. Construction or reconstruction of bunds by using traditional methods obviously requires a very large input of labour and resources and a high degree of organization.

Several very subtle factors need to be considered in the design and construction of soil bunds:

- The location and height of the bund are chosen in such a way that they do not cause unwanted flooding of other areas.
- In case of a diversion bund across the wadi with a single offtake, the preference is for the bund to be constructed as an arc or at an angle to the direction of flow of the wadi, to dissipate the energy of the flood.
- In case of a cross-bund with offtakes at both banks, the bund will be constructed in a straight line; depending on the height of the bund and the slope of the land, the cross-bund may serve several upstream offtakes. Practical experience has shown that this is more suitable than constructing the bund as a V-shape, as during large flood flows the bund needs to be breached in the centre to reduce damage. The V-shaped bund will direct the large floods towards the intakes and eventually to the command area where they can cause significant erosion and gullies and hence the complete loss of large segments of irrigable fields. Also the cross slope would mean that the apex of the V could not be in the centre of the river if flows are to be delivered to both sides in proportion to the areas commanded.
- The preference is to construct the soil bund with loamy soil. Gravel and saline soils should be avoided. The latter would lead to cracking of the soil bund and early breaching before overtopping occurred.
- Preferably the soil bund should be developed in layers, with each layer being 1–1.5 m thick. Compaction can be achieved by bulldozer, animal action or by hand.
- The soil bund is reinforced by intermixing it with vegetation, by laying brushwood along the lower toe or by stone pitching. In some cases short wooden poles are driven into the most exposed and vulnerable sections to fix the bund to the river bed and to reinforce the bund.
- Generally care is taken to avoid animals trespassing and trampling on the structure, as this would weaken the soil bunds.

In Pakistan, large bunds are constructed at the downstream end of degrading river reaches to encourage siltation and reverse a general lowering of river bed levels that causes large areas to go out of command. In these systems, sedimentation is being actively managed by farmers to restore the upstream river bed levels to an elevation that allows traditional upstream intakes to continue to function.

A special variation is the so-called retention dam that is built in some of Morocco's wadis *(Oudra, 2008)*. With these retention dams, all floodwater flow is dammed and, as a result, the dam inundates the valley bottom of the flood plain. The water infiltrates the soil, and the wetted area can be used for agriculture (mainly for cereals such as barley) or for pasture improvement. Retention dams are found in large river beds with a very low gradient that have soils suitable for cereal cultivation.

Advantages and disadvantages of traditional intakes

Traditional diversion structures have been developed over many years and at some locations over centuries. While they may seem crude at first sight, they have been adjusted over time to the local wadi characteristics by the farmers and their ancestors and this has enabled irrigation to be sustained with the use of local materials only and indigenous skills. The advantages of traditional diversion structures can be summarized as having the following features:

- **Flexible**: the river bed topography, long section and the alignment of low-flow channels may change during medium or heavy floods, but the location and layout of traditional intakes can be easily adjusted to suit the changing wadi bed conditions. Diversion spurs can also be extended or moved upstream to retain command when sedimentation on the fields or in the canals starts to take fields out of command.
- **Based on locally available technology**: traditional intakes are constructed from local materials with the use of indigenous skills and can be maintained indefinitely by farmers without outside support. They are, however, associated with environmental problems resulting from unsustainable use of trees and brushwood and the difficulty over time in obtaining sufficient materials near to the diversion site.
- **Relatively efficient**: when a series of traditional intakes are used along wadis, high overall diversion water distribution efficiency can be achieved. Large floods may destroy diversion bunds supplying intakes at the head of large spate systems but, as the peak flood discharge passes down the wadi, the force of the flood peak is reduced, increasing the time of exposure to the flood flows so that significant flows can be diverted by the downstream intakes, once the upstream intakes have been destroyed. Although very high flood discharges occasionally occur, much of the annual runoff occurs in the medium to small wadi flood flows, that vary in duration and volume but can still be effectively diverted by traditional intakes without irreparable damage. These types of spate flows generally benefit the upstream spate systems that can use water from all spate events.
- **Limit diversion of high flows and high sediment loads**: the failure of deflecting spurs and diversion bunds and breach sections of the main intake canal at high wadi discharges abruptly lowers the water level at the canal intake. This reduces the discharges that are diverted, limits the damage to downstream canals and field systems and prevents the incursion of high concentrations of coarse bed material sediments, transported in the large floods, that would otherwise be deposited in the main canals and would not reach the fields.

However, there are some major disadvantages associated with traditional diversion structures. The most important is the enormous input of labour and resources needed to maintain and reconstruct intakes that are damaged, or washed out by the large floods (see Figure 4.6). In Eritrea, for instance, it is estimated that about 80 percent of the labour needed to operate and maintain a traditional spate irrigation system is devoted to maintaining and repairing intakes *(Haile, 1999).*

A second disadvantage associated with traditional diversion structures is that, although relatively high overall water diversion efficiency can be obtained with multiple intakes, it is not always possible to divert water where it is needed. When a large flood destroys upstream intakes, water from the following floods cannot be diverted until repairs have been completed. Conversely, if only small floods occur then these will either all be diverted at upstream intakes, or infiltrate into the wadi bed without reaching downstream diversion sites. In the Tihama plains in Yemen, losses within wadi beds have been estimated to represent about 2–3 percent of flood flows per km. In some cases, two floods can occur at an interval of a few days. Bund reconstruction thus requires the cooperation of large numbers of farmers and ready availability of replacement materials and equipment for the larger wadis. Even if these are at hand, vital floods can often be missed.

Over time, sediment deposition upstream from diversion bunds raises the upstream wadi bed and hence flood water levels – though the breaking of the bunds may locally reduce part of this effect. The sediment deposition may help in maintaining command when sedimentation results in rising field levels, but can cause local changes in wadi slope, head-cutting and bank erosion. It may also increase the probability that a bund will overtop and scour out earlier than intended and lead to the construction of larger bunds by the farmers to divert the same quantities of irrigation water. A closely related problem is the silting of the flood offtake channels due to lack of maintenance or other reasons. This causes pressure to build up on the river cross-bunds as the water cannot 'get away' and may lead to their early collapse.

FIGURE 4.6
A breach in a deflecting spur in Eritrea

In addition, there is a danger that bunds will not be breached when planned and very large flows will be diverted into the first reaches of canals. If this happens, the upper reaches of the main canal are transformed into a new course for the wadi and, in the worst cases, the whole canal can become a new permanent course for the wadi through the irrigated area. This creates enormous problems and damage to the spate systems and results in significant loss of land, damage to in-field systems and loss of command to secondary and other canals. The farmers appreciate this potential problem and thus bunds are often deliberately breached by them to prevent this from happening.

Low-cost improvement to traditional structures

Modest improvements to traditional intakes minimize changes to existing canal systems and water rights. The objective is to reduce the massive labour requirements involved in frequent rebuilding of intakes. Some improved traditional intakes developed by farmers in Yemen are described below. They contain many of the features needed to reduce maintenance requirements to an acceptable level.

In wide wadis in Hadramawt and Shabwa Governorates in Yemen, spur-type diversions similar to, but stronger than, the traditional types, are used (see Figure 4.7). A spur is constructed from interlocking stones set on a deep foundation, similar to traditional dry stone pitching. The height reduces from 1 to 1.5 m at the canal entrance down to only a few cm at the center of the wadi. The foundation is deep and wide and the spur is constructed with a trapezoidal or triangular cross-section.

In narrower wadis (<60 m), a weir spanning a wadi may be constructed from interlocking stones as an alternative to a diversion bund. The weir is set on a foundation (3–4 m wide) deep enough to rest on a suitable hard basis. The weir is formed from two walls of stones, with a sloping upstream face and a stepped downstream face (see Figure 4.8). The gap between the walls is filled with sand and small stones, the crest of the structure being closed with large stones or sometimes sealed with concrete. The stepped downstream face dissipates energy when the weir is overtopped, with large stones placed on the downstream wadi bed to control scour.

Canal entrances are formed by two stone structures (algamas). Algamas are conical stone structures, with a circular base of 3–4 m in diameter (see Figure 4.9). They are constructed by digging a circular foundation about 2 m deep and lining it with large stones and filling in the gaps with smaller stones. The rest of the structure is then built up, the centre being completely filled with small stones and cobbles. The height is usually 2-3 m above the wadi bed with side slopes that range between 35 and 40 percent.

Al Shaybani (2003) reports that in Wadi Beihan, in Yemen, the number of traditional structures has been decreasing as a result of the introduction of gabions. The farmers have become reliant on gabions supplied through an agency and ignore the traditional structures, even though they are claimed to be more effective than the gabion structures in some respects and can be cheaper to construct. Traditional structures can

FIGURE 4.7
Partially breached diversion spur in Wadi Beihan (viewed from the wadi towards the canal intake)

FIGURE 4.8
Diversion weir with stepped downstream face

FIGURE 4.9
Canal head with *algamas* on both sides of the canal entrance

FIGURE 4.10
Rehabilitated traditional weir in Wadi Hadramawt

continue to give good service following rehabilitation. Further improvements to the traditional weir have been made, including the addition of concrete facing, improved downstream scour protection and extending abutments with gabions. The Government has been providing gabions at no cost to the farmers and their use is widespread in Yemen for traditional intake improvement (see Figure 4.10).

The structures described above contain many of the elements needed to improve diversions of traditional systems, although these do not necessarily have to be constructed using traditional materials and methods. The 'hard' structures at the canal head play some role in limiting the flows admitted to the canal, but more importantly protect canal entrances from scour and provide a strong point to anchor a diversion spur or weir. The rejection spillways located along the canals are essential features in these systems for protecting the canals from excessive flood flows.

Many options for improvement exist, depending on the site conditions, available resources and farmers' preferences, but the underlying objectives remain: (i) to reduce the labour required to maintain intakes, (ii) to improve the control of water entering, and within, the distribution systems and limit the incursion of large flood flows, (iii) to reduce additional maintenance due to damage and siltation within the systems, and (iv) to retain as far as possible the traditional water diversion and management practices. In general improvements should:

- make it easier and less labour-intensive for farmers to operate and maintain;
- minimize the capacity of large and uncontrolled flood flows to damage canals and field systems;
- help maintain the distribution of water within the system in line with established
- rules and rights;
- avoid unintentional alteration of water distribution (including drinking water and water for animals) within the watershed between upstream and downstream water users;
- avoid excessive sediment load in spate systems and ensure that suspended sediments are deposited on the land and not in the canals; and
- cope with frequent and sometimes large changes in wadi bed conditions.

Options for improvement include:

- more durable diversion spurs;
- improved diversion bunds;
- controlling flows admitted to canals;
- provision of basic gated intakes; and
- provision of rejection spillways.

More durable diversion spurs

The direct replacement of traditional diversion spurs with more robust structures constructed from gabions, masonry or concrete has not always been successful. This is often because structures have not been sufficiently well designed to resist the scour or overturning forces generated in large spate flows. For example, simple rubble masonry walls constructed in wadi beds in northern Ethiopia to increase the durability of traditional division spurs were rapidly scoured out in large floods because of inadequate understanding of the depth of scour. More durable diversion spurs constructed on deep foundations and protected to a sufficient depth from scour have proved to be successful. Table 4.2 shows the relative durability of improved forms of traditional intake, in terms of damage suffered and the number of times they might be expected to be reconstructed in a 'normal' spate season, as reported by *Haile (1999)* for Eritrea.

TABLE 4.2
Durability of traditional and improved gabion diversion spurs in Eritrea

Type of diversion spur	Number of repetitions of reconstruction during normal spate season (average)
Traditional wadi bed material and brushwood	2–4
Stone	1
Gabion	Can last for up to 5 years

Successful examples of more durable diversion spurs constructed on deep foundations can be found in Yemen, when associated with measures to restrict flows entering canals and the provision of rejection weirs or sections along the first parts of the main canal. Both stone and gabion spurs seem to offer improved durability; however, both types of construction require suitable materials that will resist the high flow velocities and scouring action of sediment-laden waters. In most cases the natural small boulders, large stones and cobbles are only readily available in the wadi bed at upstream diversion sites.

Improved diversion bunds

Improved traditional bunds designed for breaching can be constructed with the use of bulldozers. The provision of bulldozers is the simplest means of reducing the labour required to construct more durable diversion spurs and more substantial and higher diversion bunds. As improved diversions will continue to function at higher wadi discharges than traditional structures, it will often be necessary to provide an intake control at the head of the main canal supplied by the bund to limit the maximum discharges that can enter the canals.

Pakistan is the main example of bulldozer programmes in support of spate irrigation. Bulldozers became readily available in the 1980s and 1990s under a number of aid-in-kind projects. In a short period, the bulldozer became the main means to build diversion and guide bunds. A system of building good relations with bulldozer operators established itself, which provided them with free meals and other support. In building soil bunds, the bulldozer operator is encouraged to select good loamy earthen soil and avoid gravel, coarse sand and cracking clay soils. In the case of these soils, it is better to excavate the foundation of the soils. In addition, the soil bund should be built in layers, each layer not exceeding 1.5 m, and compacted by driving the bulldozer across the newly-laid layer (see Figure 4.11).

Earthen diversion bunds can be improved by incorporating a low section in the centre of the bund that acts as a preferential overtopping section. This ensures that the first breach takes place away from vulnerable locations such as the hard structures, canal intakes and wadi banks. Farmers familiar with the concept will often assist in choosing a suitable breaching location to minimize damage and to reduce the possibility of the wadi's changing course during high flood flows and isolating the intake and main canal.

FIGURE 4.11

Diversion bunds under construction using a bulldozer in Pakistan

More permanent structures must be designed with spillway sections and appropriate energy dissipation arrangements. These structures need to be appropriately designed using standard weir formulae with stilling basin dimensions and lengths determined for the adopted return frequency of flood flows. The durability of the hard structures can be enhanced by the construction of breaching bunds that preferably break when flood flows that are higher than expected occur. Another option is for a breaching section to be built on top of a hard structure, so that when flood levels rise and threaten the intake to the command area, the earthen section is breached to ensure that the flood remains in the wadi river bed. An innovative approach for Spate diversion in a large wadi in Pakistan is described in Box 4.4.

The rebuilding of such breaching bunds does however present problems immediately after breaching as access within the wadi bed is difficult owing to the accumulation of silt around the upstream side of the breaching bund and the lack of sufficient suitable repair material close to the site of the breaching bund. The location of breaching bunds is also important: they should be built lower down the gravel fan. As experience from Eritrea has shown, if breaching bunds are located close to river gorges, they are likely to be breached too frequently owing to very high flood peaks and cause the loss of a number of important flood flows, thereby reducing the effectiveness of the bunds *(Anderson, 2006; Mehari, 2007)*.

Finally, reinforced flow ‘splitters’ (to divide spate flows into more manageable flows) that are well designed and provided with secure and deep foundations and scour protection works in the wadi bed are an effective means of reducing the impact of high flood flows and providing more controllable flows at canal intake sites. They can be improved by providing hard sections, either from gabions or pitched stones. The conical *algama* structures – developed in Wadi Hadramawt in Yemen (see above) – will provide a useful option in many instances.

Controlling the flows admitted to canals

Protecting canals from uncontrolled large flows becomes of greater importance when more durable diversion structures are introduced. This is achieved by providing some form of structure that permits flows up to the maximum capacity of the canal head reach to enter a main canal but that rejects higher flows. The most basic form of control is a head regulator structure without gates. In its simplest form, this can be a rectangular opening with two side walls constructed of suitable materials (masonry, concrete or gabions) that serve to ‘throttle’ the flows approaching the intake. Such a structure will be most effective where the maximum flood levels in the wadi are relatively low.

BOX 4.4

Coming to terms with diversion in large spate rivers: Sanghar (Pakistan)

In Sanghar, in the DG Khan spate irrigation scheme (Pakistan), the big challenge is to develop the command area using the diverted floods from a large river (there is enough water in the stream to expand the area under spate irrigation without any impact on downstream users). Improved diversion of water from large spate rivers has often been problematic and many improvement efforts have failed.

A design, based on the ideas of a sub-engineer residing in the area for a long time, has now been implemented. It consists of a very low crest weir spanning the 400 m width of the river. The foundations of the weir extend 4 m below the level of the river bed and the crest is only 60 cm above. On either side of the weir there is an open intake. In addition, the banks of the Sanghar River are reinforced in the vicinity of the weir. The design has a number of advantages:

- it stabilizes the river bed and makes it easy to catch the low flows;
- the flow over the crest can be regulated by farmers with very small bunds, either just in front of the weir (to divert more to the canals) or in the canal intake (to divert more to the main river), therefore reducing maintenance costs;
- large floods automatically pass over the crest and stay in the river bed – not causing damage to the command area; and
- the open intake sets a maximum to what can enter the command area.

The next development is to construct a head regulator structure without gates but with a top (breast) wall that acts as an orifice once the maximum design flow of the downstream canal is reached. The structure will initially operate as a free-flow structure but as the water level rises almost to the invert of the breast wall, the flow through the structure will change to orifice control. It is important in these cases to check that, even with the rise in upstream water levels, the flow passing through the structure can be contained within the downstream canal (including freeboard). This will give the desired elevation of the invert and the dimensions and height of the head structure. In some cases, where rising wadi bed levels are anticipated, or downstream irrigated land levels are expected to rise through sediment accumulations, the structure can be improved by providing concrete or steel stop logs for both the invert and soffit of the entrance, so that these can be removed or added to compensate for changing levels. Breast walls and high abutments are most needed when the wadi channel is confined and flood elevations are high. Gated intakes and rejection spillways located upstream from the head structure, in the case of approach channels to the intakes, and downstream, for gated weir intakes, provide further levels of protection.

Basic gated intakes

Gated intakes provide a capability to regulate the flow into a canal and can be considered where improved, more durable diversions such as weirs are used. The gates should be as wide as possible considering the intake requirements. The response time for the operation of the gates should be less than the time to flood peak (less than 10-30 minutes). Manual operation is usually too slow; electrical operation relies on power, which is often not available at key moments; hydraulically operated gates are the preferred option as they are quick and easy to operate. For this very reason, in Wadi Mawr, the manual operation is being replaced with hydraulic operation. If manual operation is the only available option, high-gain gears must be included to ensure adequately fast gate operation. In general, vertical lift gates wider than 2 m are not suitable for manual operation. All gates should be provided with large trash diverters/excluders that will trap the very large transported items such as trees, but not restrict flow to the intakes. These should be located upstream from the intakes, where possible, to guide large debris over the main diversion weir sections or around the diversion bunds or spurs, to ensure that no blockage of the intake or loss of water for the farmers occur. Easy access for machinery to these structures must be provided to assist with regular maintenance.

Openings for sluice gates should be as wide as possible to avoid accumulation of debris, since any blockage will cause a critical loss of water for the farmers. Gate design must be carefully considered, with the technical merits of radial and vertical gates balanced against ease of operation and capital costs. Vertical gates can normally be manufactured locally at lower costs than radial gates and are easier to install. However, they are constrained by the amount of lifting effort needed and must be provided with stop logs so that they can be sealed effectively in an emergency or for maintenance purposes.

As a safety feature, and on the assumption that gates may be left open when excessive floods occur, the gated opening must be designed to operate as an orifice as described for enhanced local intakes above. If the breast wall is set too low, it will reduce the actual flows that can enter the intake. For example, in the case of the Barquqa diversion weir and intake on the Wadi Siham in Yemen, the breast wall was set too low so that the stated design flow (5 m^3/s for 3 700 ha) could not be achieved. This resulted in the reduction of the command area served to 1 700 ha and an additional new weir (Dabaishia weir) and new main canal had to be built further downstream to supply some of the land omitted. It is essential therefore that intake flows are related to command areas and downstream main canal capacities and that resultant specific discharges (l/s/ha) are checked against design norms. Hydraulic calculations for free flow and submerged flow are also needed to cross-check the elevation of the breast wall and intake size.

Operational guidelines sometimes recommend that canal intake gates be closed during large flood peaks to prevent damage to the main canal and to exclude water carrying very high sediment loads. However, as this represents lost water to them, farmers are usually reluctant to accept any closure, especially on the rising flood limb, until the flood flows start passing over the diversion weir. In addition, operation of gates during high floods may be dangerous and impracticable. It is therefore unwise for designers to assume that gates will be closed during large floods and they should include assumptions for flow restriction using orifice control.

Gated intakes are obviously more expensive than un-gated structures and should have a long working life. A clear and effective maintenance programme must be worked out with the operating organization and designs must also comprehend any predicted changes in upstream or downstream elevations in both the canal and the wadi. Where necessary, downstream drop structures can be included on the main canal below the intake, although they are not normally necessary as spate canals are often characterized by relatively steep slopes. If drop structures are provided, it is important to consider 'stepped' drop structures, with the force of the water broken on a cascade of small steps. For spate systems in the flatter areas and in the upstream parts of spate systems, these may be needed to ensure that command levels over the land can be effectively maintained over time. As time passes, the drop will progressively reduce as the fields and the canal beds rise with increased siltation. Construction of these more permanent structures should use locally available materials and skills wherever possible. Preference should be given to equipment that is manufactured within the country and for which spare parts are available locally. This is particularly important for smaller works to be implemented by farmers and to ensure farmer-driven replication.

Walls of masonry, mass concrete (using selected and graded wadi bed material where suitable) or concrete blocks or stonework (ashlar) (if local block production capacity exists) may be preferable to reinforced concrete, as they are normally less expensive and require a lower level of setting out and construction skills. The most cost-effective construction materials will depend on site location, especially distance from the mountains and access to appropriate quarry sites. Masonry may prove to be the cheapest solution close to the foothills but mass concrete will be preferred where sand and gravel are easily available and larger stones are scarce. Such considerations and design/cost options must be carefully examined and discussed in detail with farmers during project preparation. Final designs need to consider that structures should resemble those that farmers consider suitable and successful.

Rejection spillways

With improved and more durable intakes, it is important to restrict flows diverted to canals to the design capacity of the downstream main canal, with allowances for freeboard. Rejection of excess flow either upstream or downstream from the head regulator/intake is an important safety measure that does not make significant increases to the overall costs. A rejection capacity is normally designed as a side spillway in the first part of the main canal system, where water can easily return to the wadi. The spillway needs to be designed as a lateral-flow weir capable of passing all the flow in excess of the downstream canal capacity. The spillway is more effective if a further flow control structure is provided on the canal just downstream of the spillway, so that water-level changes at the structure become more sensitive to excess flow than is the case in an open trapezoidal channel. An orifice control is the most effective means of increasing rejection, with the soffit of the orifice determined in relation to spillway crest level and deriving from the free-flow/orifice-flow hydraulic calculations. Rejection spillways and breach sections of canals are not new to farmers as this has been their means of flow control in traditional systems using indigenous resources and knowledge (see Figure 4.12).

FIGURE 4.12
Side spillway constructed by farmers in Wadi Rima in Yemen

New permanent diversion structures

A typical diversion structure includes a raised weir, with or without a fuse plug, a scour or under-sluice, a canal head regulator and a guide or divide wall. In the case of new permanent structures, an important decision relates to the choice between single or multiple intakes along the wadi to serve existing spate schemes and the location in the wadi. These different elements of design are discussed below.

Weirs

In perennial rivers, raised weirs are needed both to provide command and to divert the required amount of water into the intakes. In spate areas the land and wadi slopes are steep, and a high weir is not usually needed to achieve command. Moving an intake a short distance upstream, at the expense of a short additional length of canal, can provide the extra command needed more cheaply. The temptation to command 100 percent of the area when suitable weir sites are limited should be avoided, as the last 3–5 percent of command can often increase the costs by 20–30 percent. There are several reasons to use a weir: (i) to stabilize the supply water levels necessary in wadis where changes in bed levels in response to floods can be frequent, (ii) to control the longitudinal slope of the wadi, which can vary significantly owing to sediment deposition and scour resulting from wide variations in size and duration of flood flows, (iii) to control the direction of wadi flow and thereby reduce local stream bank erosion, and (iv) to provide the head difference needed to operate a scour sluice.

The weirs on some spate diversion structures are constructed with a mild cross fall along the crest towards the canal intake. This has been found to be effective in the spate irrigation systems in Yemen as they encourage the deep-water channel to flow adjacent to the canal intake. Some examples from the Yemen are given in Table 4.3.

TABLE 4.3
Weir cross fall – examples from Yemen

Site	Weir cross fall	Note
Wadi Bana	1 in 400	Proposed for diversion weirs
Wadi Mawr	1 in 120	One-quarter of weirs at the intake side has the sloping crest
Wadi Rima	1 in 70	Diversion weir
Wadi Rima	1 in 33	Gabion bed sill, set at natural wadi cross slope at a bend

In many countries, particularly in recent times in Eritrea, the thinking seems to be that spate irrigation is something very simple and easy, and that therefore supporting designs and calculations for structures such as weirs, spillways and stilling basins are not needed or can be estimated without detailed designs. This has resulted in many failures. It is important to reiterate that whether the new system is complicated or simple, sound designs and calculations are still required. In fact, given the unpredictable nature of floods, proper design of weirs is even more important in spate than in conventional irrigation systems. The following paragraphs discuss the most important design and construction considerations.

Stilling basins are provided downstream from weirs to dissipate energy and to reduce the scouring effect of high-velocity flows. Inadequate or poorly designed energy dissipation will cause hydraulic jumps to form outside the protected area of a structure and result in both longitudinal and lateral erosion and damage. Any weir structure, whether improved traditional or of modern design, requires supporting hydraulic and stability calculations that cover (i) seepage through and around the structure, (ii) length, elevations and widths of stilling basin and energy dissipation measures, (iii) stability calculations for sliding and overturning, and (iv) estimates of longitudinal energy loss down the canal system. Without these calculations, it is likely that the structure will fail and that the whole spate irrigation system will be put into jeopardy.

The cost of overall weir and related structures and associated energy dissipation arrangements increases with specific discharge (flow/unit width) and height over the weir and hence head loss across the structure. In many cases, the most critical design condition does not occur at maximum design flow when downstream water depths are high and hydraulic jumps are drowned out. The critical conditions occur between low and maximum flow before full downstream water depths are achieved. It is thus important that calculations are completed for a range of discharges. The general recommendation is: avoid high specific discharges and large head drops but adopt sufficient head to achieve effective sluicing and to maintain command over the area to be irrigated.

In designing and constructing weirs or bed bars, care has to be taken not to interfere with the subsurface flows in the gravel of the wadi bed. These are one of the main sources of recharge to wells for drinking water in the neighbouring areas and supplementary irrigation downstream from the weir site. There are several instances where the weir was built on the bedrock, which effectively blocked all subsurface flow downstream of the weir. This effect has been observed in several of the modernized systems in the Tihama, particularly Wadi Mawr and Wadi Siham, and has caused considerable hardship for those living downstream of this new infrastructure. Weepholes and pipe tunnels in these structures will avoid such unexpected outcomes.

One important aspect overlooked in the development of new or improved weirs for spate irrigation is the failure to establish means for measurement of each flood flow at the weir sites. Weir structures provide perfect control sections and sites for easy flow measurement and local operators can easily be trained in appropriate data collection. It is most important to gather more data on actual flood flows that pass the weir sites, to increase knowledge of flood sizes (volume of flow, peak flow), frequency and duration, to confirm design assumptions and to improve upon design concepts for other newer structures.

Fuse plugs

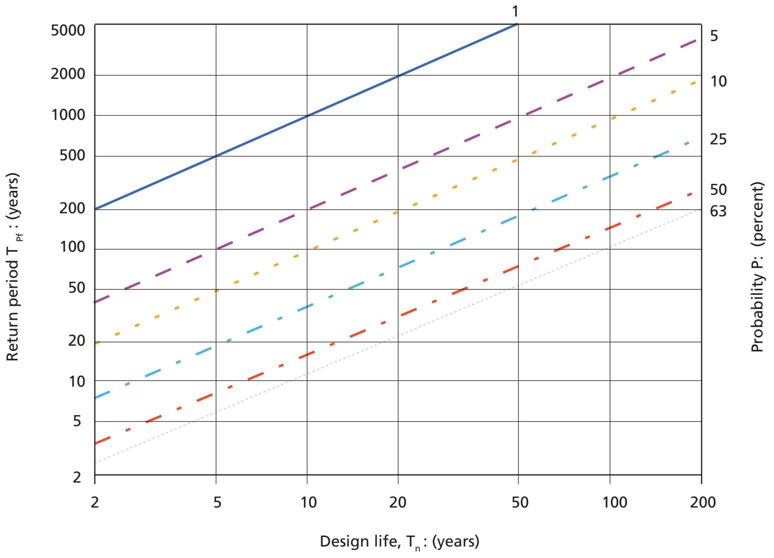
The integration of a breaching section, or fuse plug, in spate diversion structures has a long history and has been applied in Yemen, Tunisia, Eritrea and Pakistan. Flood frequency analyses are often based on limited hydrology data and are often little more than intelligent guesswork. In addition, flood frequency distribution in arid regions is usually highly skewed, with extremely high events occurring at a frequency of 4–5 years. Incorporating a fuse plug will protect permanent weir and intake structures in the event that a much larger flood than predicted occurs. It also enables the width and cost of a permanent weir to be reduced whilst design return periods are maintained. Farmers who are not familiar with the concept or have had bad experiences, for example in Sheeb in Eritrea, do not like the approach, particularly when they consider that the weir is breached too frequently, with the consequent loss of valuable irrigation water. In all spate systems, farmers want to extract as much of the wadi flows as possible as they are never sure when the next flow will come and how big it will be. What designers have to ensure is that after construction of the new weir and intake, farmers will still be able to divert at least the same amount of wadi floods onto their traditionally irrigated lands as before. The return period of breaking the fuse plug must be calculated carefully. It must be long enough to ensure farmers keep the benefits of the permanent structure it protects (i.e. no need for frequent reconstruction), but at the same time, the protective role played by the fuse plug in extreme floods should be maintained. A careful analysis of flood frequency distribution may help identify breaking points in return periods beyond which floods become much larger. In many places, this corresponds to a return period of 4 to 5 years.

If fuse plugs fail too frequently, farmers will take steps to reduce the labour needed for re-construction and increase the size of the breaching bund, thereby perhaps endangering all the improved structures at the site. In Chandia, Pakistan, for example, the fuse plug has been covered with concrete and, although this will certainly reduce the need for frequent re-construction, it will inevitably be breached in a more catastrophic manner, creating large scour holes and serious damage to the intake structure and weir, that is likely to have been overtopped and perhaps also to have failed.

The probability that one or more flood events with a specified return period will occur over the design life off a structure is shown in Figure 4.13.

FIGURE 4.13

Probability that floods with specified return periods will be encountered



For example, if a fuse plug is designed to fail at a discharge with a ten-year return period, then there is a 63 percent probability of one or more floods of this magnitude occurring over the design life. However, there is an appreciable probability that much larger floods will occur, for example, a 10 percent probability of a flood with a 1-in-100-year return period.

In the absence of reliable flow records, it may be necessary to adopt a flexible approach, choosing an initial conservative design (this may cause frequent breakings in the first year or two) and then adjusting the length and shape of the breaching section as experience is gained.

Scour sluice

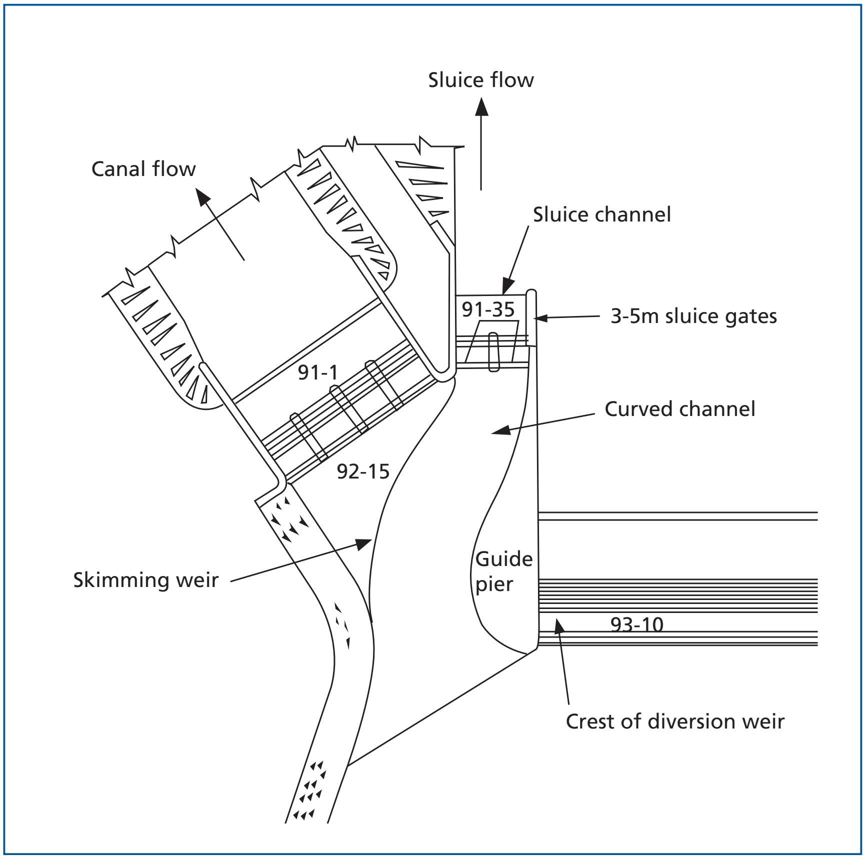
Wadis transport very large concentrations of fine sands, silts and clays. These cannot be excluded from canal networks at an intake and should therefore be kept in suspension and transported to the irrigated fields. However, the coarser sediments will settle in canal head reaches, eventually reducing the discharge capacity of the intake. The first step in minimizing such problems is to exclude as much of the coarser sediment as possible at the intake and then to ensure that any sediment that enters the canal system in suspension is not deposited until it reaches the irrigated field. This is achieved by diverting the bed load material transported in flood peaks past the canal intake, via a scour sluice, and by ensuring that the sill level of the sluiceway is set below the canal invert at its entrance. In addition, overshot structures on the canal systems need to be avoided and a constant and sufficiently high flow velocity maintained within the canal network.

The shape and discharge capacity of scour sluices have been the subject of numerous experiments. The curved channel sediment excluder (see Figure 4.14), has been used in several improved large spate irrigation intakes. This type of intake and sluice arrangement was developed to improve sediment exclusion in floods, by utilizing the beneficial effects mentioned earlier of a channel bend in excluding coarse sediment. An artificial bend is created in a short converging channel constructed upstream from the sluice gates. The canal intake is located on the outer side of the artificial bend, angled at about 30° with a small diversion angle. The sluicing capacity is set at around 30 percent of the canal design discharge. Providing an excessive sluicing capacity is self-defeating, as it will induce very high velocities in the flows approaching the intake, which will pick up additional coarse sediments, some of which will be thrown into suspension and diverted to the canal. In addition, farmers are unlikely to agree that an excessive volume of water be used for this purpose, as they will regard it as lost to their irrigation system (as discussed earlier).

The design and operation of scour sluices for spate schemes have important differences from the practices described in irrigation engineering textbooks and design guides based on perennial irrigation diversion practice. In particular the ‘still pond’ method of operation, frequently used at intakes in perennial rivers, is not applicable in wadis. Long divide walls, separating flows in the sluiceway from those passing over the weir, and projecting some distance upstream from the weir are not used in spate intakes, where the weir is usually sited upstream from the intake and sluice gates.

Operation of the sluice gate often poses problems. In practice, manual operation of sluice gates in rapidly varying spate flows, so as to follow idealized gate operation rules, has proved difficult or impossible. On the assumption that the structure is staffed when a flood arrives, the flood peak will often have passed the intake before the sluice gates can be fully opened. Apart from these practical difficulties, the first priority of farmers is to divert as much water as possible. They may be extremely reluctant to open sluice gates, except during the largest floods, when high flows diverted to a canal threaten to damage canals and water distribution structures. Thus, unless the water supplied via the sluice is needed for downstream diversions, frequent operation of sluices in farmer-managed systems cannot be assumed. Experience from large 'new' intakes in Yemen suggests that sluice gates should be constructed without a headwall, to improve the throughput of sediment and trash. The sluice gate in this case must be capable of being raised above the maximum expected high flood water level and designed to withstand the forces that would occur if the gate was left lowered and was overtopped in large floods.

FIGURE 4.14
Layout of a typical curved channel sediment excluder



Canal head regulators

Head regulators are designed to pass the canal full supply discharge when the water level in the wadi is at weir crest level. In spate intakes the width of the head regulator opening is usually kept approximately the same as the bed width of the downstream canal.

Head regulators in conventional river intakes are frequently aligned with the gates at 90° to the weir axis, but this requires flows entering the canal to turn through a large angle, which is far from ideal for sediment control. Much smaller diversion angles are recommended when sluicing during flood peaks is envisaged (see example in Figure 4.14).

The discharge capacity required at intakes (and for canals) in spate schemes is much larger per unit area served than would be the case for intakes in perennial rivers, as the objective is to divert the maximum possible amount of water to the fields during the short time periods when spate flows occur. Values based on intake design discharges and nominal command areas in existing improved systems range between 2 and 28 l/s/ha or more and depend on the discharge characteristics (hydrographs) of the wadis and the catchment areas rather than on crop water requirements. The low figure quoted above is for Wadi Rima in Yemen, where a large proportion of the annual discharge occurs as perennial base flows and low flood recession flows. The more typical higher figure is for an intake on the Wadi Mai Ule system in Eritrea, where most of the annual runoff occurs as very short spate flood events and where the catchment is compact. The latter intake capacity is regarded as low compared to the Eritrean MOA current practice and farmers complain that the intake is too small *(Anderson, 2006)*. The discharge capacity/unit area provided for intakes serving the three canal groups in Wadi Zabid in Yemen was 12.9, 15.5 and 40 l/s/ha, increasing down the wadi to reflect the reducing probabilities of receiving water. In Wadi Mawr in Yemen, a capacity of 21 l/s/ha was provided.

Discharge capacities obviously have to be selected taking account of the distribution of flows within the annual hydrograph, the duration of, and discharge variations during, flood events, and the soil characteristics (water-holding capacity) of the areas to be irrigated, rather than being based on crop water requirements. Simulation modelling, using representative flood sequences, has been used in larger schemes to ensure that a sufficient intake capacity is provided. In smaller modernization projects, where neither the data nor the expertise to carry out such studies may be available, the combined diversion capacity of existing traditional intakes can be used as a guide to the intake capacity that will be expected by farmers.

Single versus multiple intake

Diversion of spate flows in traditional systems is usually carried out at many locations along a wadi. Multiple intakes provide an effective solution when the cost of each diversion structure is low and each diversion supplies a relatively small canal system with manageable flows. When substantial improvements to diversion arrangements are envisaged, the practice in the past has been to provide a limited number of major diversion structures, often only one, serving large new canals that connect into and traverse the existing traditional canal network.

A major disadvantage of the single new intake approach is that it gives the upstream users control over diversion of a larger proportion of the annual flows, which in turn leads to an increase in the inequity between upstream and downstream users' access to water. This has often been a result of the way that systems are being operated in response to pressures from powerful local interests, rather than to inherent technical deficiencies in the water distribution arrangements. An equitable distribution of flows would have been possible in some of these upgraded systems if larger intake capacities had been provided. Although this might have required a change to water rights rules based on volumetric allocations and to operation by strong farmer groups or operating agencies that were able to enforce an equitable water distribution, these were not feasible in many of the systems modernized over the last 20–30 years. In Wadi Mawr in Yemen, for example, a sophisticated system was devised for dividing flows but was never used, as the farmers did not understand it and the water user associations (WUAs) were not properly involved from the start. The net result was that upstream users controlled all the water that could enter the system, and users in the middle and end parts of the command area did not receive sufficient water. Similarly, in some of the new spate systems in East Harrarghe in Ethiopia, downstream farmers have abandoned newly constructed systems and have reverted back to having independent downstream offtakes which give them more flexible control of water. There are many examples of farmers who own land commanded by the ‘improved’ systems but who do not receive enough water and have to reactivate their traditional intakes, in order to capture the flood flows that pass over the weirs of a new single permanent diversion.

In several spate irrigation intake and diversion improvement works, conventional economic analyses have been used to reach what are considered cost-effective designs and this has resulted in a diversion capacity for new intakes that is less than the combined capacity of the traditional intakes. This is the overriding problem in Wadi Siham in Yemen and Wadi Laba, Eritrea, where all such intakes are insufficient to meet the requirements of the previously commanded areas. It would appear that the designers did not comprehend the traditional means for sizing intakes or, if they did, it was not made clear to farmers and local authorities that only part of the previously commanded and irrigated area would continue to be irrigated under the new intake system. If a wadi approach had been used, relating existing and planned command areas, deficiencies in water supply would have been identified and some traditional intakes and canals retained to supply the omitted areas. Not only were some areas excluded, but the designs for the main canal cut off the traditional intakes and made them unusable. In Wadi Zabid, this constraint was recognized and the designs adopted comprise a number of separate intakes built from gabions and based on the traditional locations and design duties (15 l/s/ha to about 60 l/s/ha).

A close examination of spate systems that have numerous self-contained intakes and associated canals reveals that consolidation into a system supplied by one single diversion is not advantageous. Some rationalization may be essential if the number of independent diversion structures is to be reduced to provide better engineered and more durable replacements, and such an approach could then more closely replicate the traditional systems that they are to replace. Three examples of new permanent intakes with differing levels of sophistication and cost are described below.

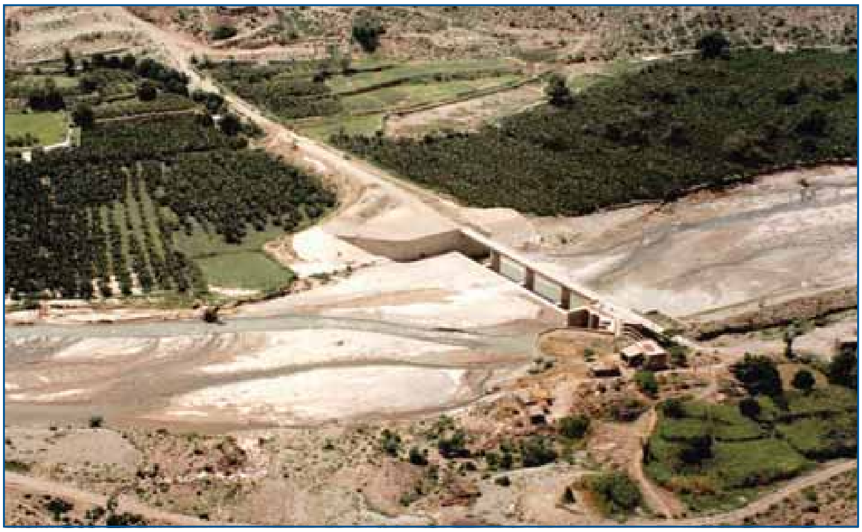
Example 1: New permanent intakes in Wadi Rima in Yemen
A new single diversion weir and intake was constructed on this wadi in the late 1980s at the upstream end of the spate-irrigated area close to the foothills and near to the site of the most upstream of the existing traditional intakes *(Oosterman, 1987)*. At the diversion site, the natural wadi width was constrained by rock outcrops and was fairly narrow, thereby providing a good site for a permanent weir structure. The intake consists of a raised weir, a single right bank canal intake and a low-level sluiceway located near to the intake (see Figure 4.15). The main canal supplied by the intake follows the high terrace on the north side of the wadi, passing water to the few traditional canals where it crosses them. Just before the start of the main flood plain and irrigated areas, the main canal divides into two, with the right branch designed to take one-third of the flow and the left branch the remainder by means of a siphon under the wadi.

The new system replaced a traditional spate system with many intakes along the wadi, with rotation between canals of base and low flood flows diverted at a single point at the head of the wadi. Its main technical features are (see Figure 4.16):

- ➢ A relatively high weir was provided to obtain the head needed for effective hydraulic sediment flushing. The 70 m long weir is constructed from mass concrete with a protective layer of stone to resist abrasion from the cobbles and boulders that pass over the weir in spates. The weir crest slopes down towards the canal intake, with a drop of 1 m across the weir crest, to encourage the low-flow channel to flow towards the canal. A short submerged bucket-type stilling basin was used.

- The gated under-sluice was designed to pass the lower, heavily sediment-laden layers of the approaching flows through the structure during floods. The sluiceway was originally intended to operate automatically in floods, but trash accumulations and deposits of fine sediments in the small openings that formed part of the hydraulic actuation system prevented the original system from functioning. The sluice gates are operated manually during floods. Initially trash blocked the intake, so a trash screen consisting of vertical steel pipes and horizontal steel cables has been constructed in front of the intake to divert trash over the weir.
- A gated canal intake is aligned with the approaching flow direction, supplying the main canal via a short settling basin designed to trap the coarse sediments before
- they enter the main canal. The settling basin can be flushed to return trapped coarse sediment to the wadi.
- The layout of the north side of the intake showing the under-sluice, canal intake, sediment-settling basin and sediment-flushing arrangements is shown below *(Oosterman, 1987)*.
- Soon after completion, disputes arose between the north and south bank canals over water allocations and this resulted in a high-level political decision that awarded equal allocations to both canals (intake design duty was 1.5 l/s/ha). Only two-thirds of the original design area of 10 000 ha could therefore be supplied with irrigation water from the new intake. The south canal thus receives far too little water for the command area and has made necessary the construction of two new intakes and the revival of the former traditional canal systems.

FIGURE 4.15
Wadi Rima spate irrigation intake, Yemen



Following problems with trash encountered during initial operation, a trash deflector was constructed from steel pipes and cables to deflect trash away from the canal intake and towards the sluiceway (see Figure 4.17). With this experience, the designers recommended that future similar structures should use a wide scour sluice, at least 5 m wide, built without a breast wall to allow large trash to pass through the sluice.

FIGURE 4.16
Plan of Wadi Rima intake and sediment-settling basin

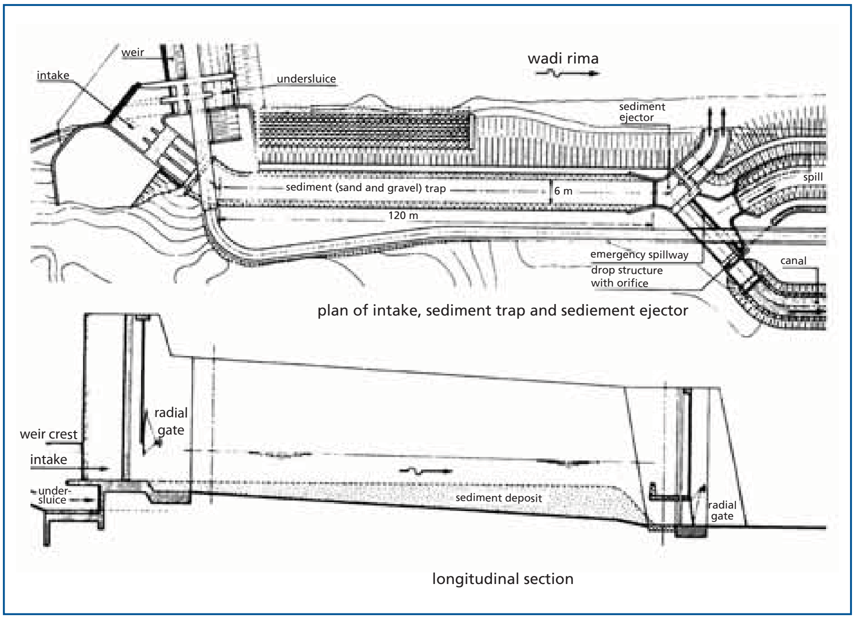


FIGURE 4.17
Trash deflector, Wadi Rima intake (2003)

Example 2: New permanent intake in Wadi Laba, Eritrea

A new intake was constructed to supply a traditional spate irrigation system in Wadi Laba located on the Eritrean Red Sea coastal plain. The design of the new intake profited from the experience gained in Yemen and from the earlier farmer-operated spate improvement projects in Pakistan. It was originally intended for farmer operation. The diversion structure viewed from upstream is shown in Figure 4.18.

FIGURE 4.18
Spate diversion structure constructed at Wadi Laba in Eritrea

The key features of the structure are: a) a canal intake incorporating a curved-channel sediment excluder; and b) a low-cost, short concrete weir, with a breaching section or fuse plug that connects the weir to the far bank. A short settling basin, designed to be excavated by bulldozer, was constructed in the canal head reach. This was intended to trap the gravels and coarse sands not excluded at the intake, particularly if it was operated in floods with sluice gates closed. A conduit near the canal head runs under the wadi to supply water from the main canal to the irrigated areas located on the opposite bank of the wadi.

In Figure 4.18, the canal intake gates and the gated curved-channel scour sluice are on the extreme left, the concrete weir is in the centre and the fuse plug extends from the end of the weir to the right-hand edge of the picture. The crest level of the fuse plug is higher than the design flood level at the weir end and reduces across the wadi, to ensure that the fuse plug washes out initially at the far bank.

The system was commissioned in the wet season in 2002, when a major flood, its peak discharge still being a matter of some dispute, washed out the fuse plug. This protected the weir and intake from serious damage, but as the fuse plug was not repaired for some months, water from the later floods could not be diverted and only a very small area was irrigated. Farmers regarded this as a serious failure of the new system, even though the fuse plug had functioned as its designers and project supervisors had intended.

An obvious lesson learned from this experience is that the implications of including a fuse plug in a diversion structure must be understood and, more importantly, agreed by the farmers or agency that will have to rebuild the plug when it fails. Robust arrangements must be in place to ensure that a fuse plug is rapidly reinstated following a breach. The fuse plug was repaired for the 2003 wet season and the new intake performed broadly as anticipated, stabilizing the wadi approach channels at the canal head, controlling the flows admitted to the canal and excluding large sediments from the canal head reach. The sluice was kept open as much as possible to provide water for downstream south-bank farmers, who were unhappy with the volumes of water supplied by the conduit. It did not prove to be possible to excavate the settling basin, as a bulldozer could not work on the wet unconsolidated sediments trapped in the basin, which rapidly silted up. Machines which can work from the bank are needed to excavate the settling basin mechanically. As a series of floods may occur within a few days, sediments often have to be removed when the canal is still flowing and before the sediment deposits can dry out.

While it is still a little early to draw firm conclusions from an intake and water distribution system requiring quite different operational skills to those needed for the traditional systems it replaces, *Haile (2003)* drew a number of useful conclusions based on the experience with the earlier traditional system and the first two years of operation of the new system. Many of these conclusions were concerned with institutional issues, particularly the need for more effective participation of farmers in the design and development of spate improvement projects. On the technical performance of the intake, *Haile et al. (2003)* reported that the operation of the intake structure, particularly the sluice gates, is problematical in very rapidly varying spate flows. This has been observed in many other spate schemes. Electrically powered gates can rarely be justified when conventional cost-benefit analysis is applied and are subject to power shortages. *Haile et al. (2003)* also reported that the diversion capacity provided at the new intake may be too small to irrigate the target command area, as the design area was not irrigated in 2003 although it was a year with very good floods

Example 3: Adurguyay intake in Gash Barka region in Eritrea

The Adurguyay intake is a basic permanent intake constructed on a small ephemeral sand-bed river in the Gash Barka region in Eritrea, a region where spate irrigation is being introduced to provide water in areas that have relied in the past on rainfed cropping. The river is much smaller than the wadis considered in the earlier examples. The structure, as shown in Figure 4.19, includes the elements found in conventionally designed river intakes, i.e. a raised weir, a gated scour/sediment sluice and a gated canal intake, but suffers from many of the problems already identified relating to intake capacity, silt exclusion and blocking of entrances to intake and sluices by transported debris. It should be noted that smaller command areas require higher unit flows, about 80–100 l/s/ha, to get enough flow through the intake whilst the flood lasts (10–20 min)

Local engineers report that this structure functioned reasonably well, from the engineering viewpoint, in the first year that it was operated by farmers but they do not record the impact on annual maintenance costs for silt removal and the ability of the system to meet all the water needs of the downstream farmers. They report that in this area masonry or concrete-type weirs offer advantages over the gabion weirs with un-gated canals that they have used at similar sites in the past and can be constructed at similar cost. The technical problems of diverting water from ephemeral spate rivers reduce as the wadis and their flood peak discharges become smaller.

Location of intake

The best location for a canal intake is on the outside of a relatively mild wadi bend, just downstream from the point of maximum curvature. At this location the deep-water channel is established at the outside of a bend during floods and this forms the low-flow channel during flood recessions. Locating an intake at the outside of a bend thus helps to ensure diversion of low flows. It also provides sediment control benefits at times of medium to large flood flows when a wadi is flowing at a reasonable depth over its full width. Secondary currents generated at a bend sweep coarse sediments that are transported on or near the channel bed towards the inside of the bend and away from the canal intake. This principle is also used at intakes with curved-channel sluiceways.

FIGURE 4.19
Adurguyay intake, Eritrea

The disadvantage of locating an intake at the outside of a bend is that trash picked up by floods tends to concentrate at the outside of a bend and interferes with the intake. The problem is worst at very sharp bends. There are three basic options that can be combined for managing trash:

- ➢ encourage the trash to pass down the wadi through careful design;
- ➢ detain the trash upstream of the intake, e.g. with a floating boom, where it will not significantly obstruct the flow; and
- ➢ design the canal intake so that (smaller) trash can pass through and into the canal.

The third option is usually the most attractive in cost terms although this requires effective and attentive system management. However, there is an upper limit to the size of trash that can be passed into a canal and, once something becomes trapped, then it will obstruct the passage of smaller trash so that a blockage follows.

Although adopted in some large spate systems, double-sided intakes, i.e. structures with canal intakes on both banks are not usually recommended. Ensuring that water flows to both sides of wide wadis, when the diversion weirs are silted to crest levels, usually requires active intervention in the wadi bed to construct channels or bunds. However where intakes exist on the left and right banks, these have often derived from traditional practice and systems and have allowed adequate flows to both sides through the presence of small islands or physical barriers that split the flows. In smaller wadis, basic diversion structures may have an essential role, particularly in areas where spate irrigation is being introduced to formerly rainfed areas and farmers do not have indigenous skills in diverting and distributing spate flows.

SPATE CANALS AND WATER CONTROL/DIVIDING STRUCTURES

Traditional canals and water control structures

In traditional spate systems, flows are diverted to short, steep canals. Large canals may split into two or more branches to reduce flood discharges to manageable flow rates, but there are usually no secondary or tertiary distribution systems. All the flow in a canal is diverted to a group of bunded fields by an earthen bund that blocks the canal. Water is passed from field to field until all the fields in command have been irrigated. The canal bund is then broken, and the process is repeated at a bund constructed further down the canal at the next diversion point. Once the bund is breached, the canal water level drops below the level of the field offtake, preventing further diversion until the bund can be rebuilt. The order in which fields are irrigated and the number and depths of irrigation are usually controlled by established water rights agreements (see Chapter 7 for details).

The objective is to divert the maximum possible amount of water to the fields in the shortest time periods, sometimes less than an hour. By avoiding constrictions in the system, this approach can also ensure that minimum deposition of silt occurs in the canal systems with most of it ending up on the fields. Canals in spate schemes thus need much larger capacities per unit area served than canals in perennial irrigation schemes.

The upstream reaches often resemble wide and shallow natural wadi channels, with beds formed from coarse sediments. The size of the bed sediments reduces rapidly in the downstream direction, and middle and lower reaches typically have sand beds. The lower reaches of established canals may have stable armoured beds and flow between well established banks that are protected from high water velocities by natural vegetation.

Traditional canals in spate schemes are often constructed without drop structures and are far steeper than conventional canals used in perennial irrigation systems (see Box 4.5). Gates are not used and control of flows is carried out through proportional dividers and farmer management. Particularly where the area is flat, ‘soft’ and sandy – as in the DI Khan, DG Khan and Kacchi in Pakistan – care is taken to guide the water over a large area, to avoid the erosive effect that comes with too steep slopes. However, some traditional canals feature different types of water control structures, ranging from the simple earthen bunds used to head up and divert water from a canal to a group of fields or divide flows, to drops and side spillways used to protect a downstream canal network against excessive flows or too high and erosive velocities.

Examples of traditional canal water control structures are described below. Figure 4.20 shows a traditional canal diversion bund in Wadi Zabid in Yemen in 1980 that has been breached to pass water further downstream. The bund diverts all the canal flow until the fields under command have been irrigated, with water usually being passed directly from field to field. The bund is then breached and water passed downstream to the next diversion point. Figure 4.21 shows a stepped drop structure that was developed by farmers and copied in large numbers in the Wadi Zabid system. The drop structures avoid uncontrolled flows that may otherwise lead to gullies and loss of soil moisture or may make it difficult to divert water downstream.

Improved traditional canals and water control structures

Improving traditional canals may include changes in canal design and the installation of new or improved water control structures. Such structures can be clustered in five groups: check and drop structures, flow-splitting structures, flow spreaders, field offtakes and in-field structures. Many of the water control structures used in improved spate systems are similar to those used in conventional perennial irrigation practice.

FIGURE 4.20

Traditional canal diversion bund, Wadi Zabid, Yemen

FIGURE 4.21

Stepped drop structure, Wadi Zabid, Yemen

BOX 4.5

Traditional canal slopes: the example of Wadi Zabid, Yemen

Traditional canals usually follow the prevailing land slope and rarely incorporate the drop structures used in conventional canal systems to reduce flow velocities. High slopes provide the high velocities needed to convey very high sediment loads, and traditional canals rarely suffer from the excessive sedimentation problems observed in the canals of some modernized spate systems. This is because the velocities are maintained high throughout the system, a situation of torrential flow where the inertial forces dominate over gravity forces (Froude number >1). Abrupt changes in direction are avoided as are sudden reductions in velocity of flow at closed structures. Although quite high flow velocities are generated, canals do not seem to suffer from widespread scour problems. This is probably because bed materials are much coarser and erosion-resistant and the high rates of scour are balanced by the very large incoming sediment loads.

Bed slopes of traditional canals in the original (before modernization) Wadi Zabid system in Yemen are reported by FAO/UNDP (1987) and presented below:

Canal	Maximum capacity (m^3/s)	Average bed slope (m/km)
Mansury	40	3.8
Rayyan	60	3.7
Bagr	40	3.7
Gerhazi	50	3.9
Mawi	60	4.8

The canal slopes are about half of the slope of the Wadi Zabid bed at the upstream diversion site, and are much steeper than the canals in the modernized system, which were designed with a slope of around 1 m per km or less. The modernized canals rapidly silted up and needed frequent desilting to maintain discharge capacities. They were designed based on conventional thinking on maximum permissible velocity in earth canals which is too low for spate irrigation canals.

There are, however, important additional features that have to be considered in spate schemes:

- A canal network will already be in place when existing spate schemes are being improved. Improved canal networks, supplying water to controlled field outlets, can give better control and overcome some of the other disadvantages of the field-to-field water distribution system, but will probably also require a change in the way that water is distributed. This could have a great impact on existing water rights and rules and needs to be negotiated with farmers in the design phase.
- Any improved system must ensure that irrigation can be carried out quickly, in the short periods when spate flows occur. Experience suggests that major modifications to canal systems of farmer-managed schemes should not be considered unless there is significant siltation, scour or canal-breaching problems, or farmers request improvements. Improvements should be developed with the farmers to ensure that they understand and agree with any implied changes to

water distribution. The unpredictability and speed of spate flows call for simple water control rules that avoid any complex canal operation. In particular, the use of gated structures, either at the intake or in canals, must be decided with clear understanding of management implications, as spate flows usually occur at short notice and often do not give farmers sufficient time to operate the gates.

- In existing schemes, where canals are performing reasonably satisfactorily, the design of new or extended canals should be based on the slopes and cross-sections of existing traditional canals, derived from surveys. If the discharge capacity is to be changed, then the survey data can be used to select a canal design method that best mimics the existing canal slopes and dimensions. The selected method can then be applied to design the new canals. Any modifications must ensure that the high sediment-transporting capacity is maintained through the canal network.
- It is important to note that conventional 'regime' canal design methods were developed for canals in perennial irrigation systems that are operated within a fairly narrow range of discharges and have a small sediment input. This contrasts with the situation in spate canals, where discharge varies rapidly over the full range of flows from zero to the maximum discharge. Sediment inputs are very large and canal designers are not free to set the canal cross-section and slope to carry the required discharge without also providing an appropriately high sediment-transporting capacity. This rules out the use of most conventional canal design procedures.

Canal design

The Simons, Albertson and Chang canal design equations and methods are adapted to situations of high sediment loads seen in traditional spate canals *(Lawrence, 2009).* These methods have been successfully used to design new canals in spate systems. Computations with these methods can be carried out using HR Wallingford's SHARC sediment management software that can be found at: http://www.dfid-kar-waki.net/w5outputs/software.html.

In conventional irrigation, the peak or design discharge is used to determine the canal bed slopes and cross-sections. Following this approach for spate canals will result in serious siltation problems at lower flows. This is because spate canals flow at their full design discharge for very short periods of time. Most of the time the canal flow is much lower than the peak discharge and a steeper canal bed slope than that set by the maximum flow is required to avoid sediment deposition. As a rule of thumb, about 70 percent of the peak discharge could be used to determine the slope and width of spate canals when one of the canal design methods mentioned above is used. The capacity to convey the maximum discharge is then provided by increasing the depth and freeboard. There may be some erosion of the canal bed and banks when the flow in the canal is large but, as very high flows are maintained for short periods and will be carrying very high sediment loads, there is little chance of serious scour problems occurring.

Check and drop structures

While diversion from canals by a series of earth embankments (bunds) is a simple system, bund reconstruction is difficult while there is water in a canal and the recurrent effort of rebuilding the embankments is labour-intensive. Farmers often request better control structures when schemes are being improved.

One option is to provide an intermediate design of combined check/drop structure. This comprises a basic drop structure, combined with an earthen embankment for heading up the flow to redirect it onto a series of fields. This type of structure is often observed in the more mature traditional systems, when there are substantial drops between fields. The earth embankment should not be constructed within the structure, where there is a significant risk of seepage failure at the interface, but should be built upstream. The use of an earth embankment keeps the operation similar to the situation of an embankment without a structure. Provision of gates makes operation simpler and eliminates the need to reconstruct bunds after each flood but runs the risk of sediment deposits.

The primary function of this type of structure is to limit the scour hole that forms when an embankment is breached. This scour hole, unless excessively large, will generally fill up with sediment when flows into the canal decline and finish. Drops usually have simple stilling basins protected by placed stones and broad crests that can be raised to reflect progressive changes in command levels within the overall system.

When more conventional gated or combined drop/check structures are adopted for spate schemes, the following issues need to be considered:

- If the traditional water distribution practice is unchanged, then each structure along the canal will, in turn, receive the full canal flow (except for losses). All structures have to be designed for the maximum canal discharge.
- Gates are relatively expensive and generally not preferred as they permit abuse of water rights and can encourage siltation if not operated effectively. Stop logs are much cheaper, but are not recommended as they are difficult – usually impossible – to remove during spate flows and provide overflow rather than undershot control. Perhaps a better alternative is proportional flow division, which is the traditional approach in most systems with open or undershot flow.
- It is necessary to ensure that the upstream water level is below any offtakes when a structure is open to allow one-directional flow down the canal.
- It is important to know whether the structure is required to raise the upstream water level in the canal to achieve adequate command of the land.
- Where gated controls are provided, additional measures for passing excess flows must be considered, in the (likely) event that spate flows in the canal arrive when the structure is closed. (Can excess water safely spill over the upstream banks or does the structure need to include spill capacity?)

An upstream view of a combined gated check and drop structure designed and constructed by local Yemeni experts is shown in Figure 4.22. This is a good structure from the design point of view but the figure shows lack of operational understanding. The structure is meant to be an on-off system, which implies that both gates should not be closed at the same time, as they are shown to be in the figure.

There will be a need for downstream energy dissipation measures when a structure incorporates a drop to raise upstream water levels to gain command of the land. This is also true when excess flow is allowed to spill over the structure or jet flow is allowed to occur under a partly open gate. In conventional systems, a depressed stilling basin is used to dissipate this energy safely. Conventional stilling basins can add another third to the capital cost of structures but will reduce the annual maintenance needs and expenditures. This cost can be reduced by accepting some scour downstream of the structure, providing a shorter but depressed stilling basin, or no protection, but with side wall foundations deep enough to avoid undermining, and accepting temporary scour during periods of high flow.

Flow-splitting structures

Flow-splitting structures are provided on main or secondary canals where flows were traditionally divided proportionally between groups of farms or where it is necessary to reduce flood flows in canals to smaller, more manageable discharges. Division structures are important and may be one of the most justifiable investments in spate scheme improvement projects. They are best if built from local materials, with the use of gabions or dry stone pitching, and designed in close consultation with farmers.

FIGURE 4.22
Gated combined check/drop structure in Yemen

An example of improved flow splitting is the Mochiwal flow distribution structure built on Daraban Zam in DI Khan in Pakistan. At Mochiwal, the channel is split into two directions. The north channel feeds a lower-lying area of 500 ha, whereas the west channel feeds 3 000 ha. Before the intervention, the problem was that all the flood tended to go to the north area where it would create havoc and wash out all diversion structures while the west channel did not receive any water. The construction of a gated structure on the north channel made it possible to regulate the water distribution to the benefit of both sub-command areas.

One approach for splitting flow used in Eritrea was to provide a hardened flow division structure, constructed from gabions, that splits high flows into two channels and provides a durable hard point that farmers can use to anchor temporary diversion bunds, that can be adjusted from spate to spate to manage the distribution of lower flows. An example of such a structure constructed in Eritrea is shown in Figure 4.23.

Flow spreaders

Flow spreaders are not very common but have been applied in Morocco at the tail of lined sections of flood channels. They are large triangular structures meant to spread flood water over a wide section at the end of the flood channel and avoid scour at a single point.

FIGURE 4.23
Gabion flow bifurcation structure in Eritrea

Field offtakes

While some spate schemes have a recognizable canal system serving each field, field-to-field irrigation is usually practised. Under this system, the uppermost field receives the water first and it is allowed to pond to a pre-determined depth. When that depth is reached, the field bund is breached and the ponded water is released to the next field. Meanwhile, any incoming flow passes through the first field to the next one. This process is progressively repeated.

The main advantage of this system is that water is applied quickly at high flow rates, during the short time that spate flows occur. There is also no investment in, or land lost to, a separate canal system. Crops in upstream fields may be damaged if there is a flood when the downstream land is still entitled to water. Further, the lack of separate channels means that more water will percolate en route and less water will reach the downstream areas (an advantage for the upstream fields).

The normal upstream-first hierarchy for spate irrigation means that the flow capacity of field offtakes has to be sufficient to take the full incoming canal flow. Properly engineered large capacity offtakes are expensive. Open channel offtakes are less expensive than gated culverts. Whether offtakes need gates or other means of closing them will depend on the canal water level when any check structures on the canal are open.

In more conventional water distribution systems, where water is supplied to a number of field offtakes at the same time, there is still a requirement to provide large offtake capacities. Very substantial irrigation duties are required in spate schemes to supply water at the flow rates wanted by the farmers.

In-field structures

Fields naturally form into a series of level terraces. There is, therefore, a difference in level between each field and the next one downstream. This difference increases over time as the upstream fields receive more water and sediment than the lower fields.

Water flowing from one field to the next causes erosion, the extent of which depends on the drop, the flow and soil conditions. In many cases, farmers place boulders where excessive erosion occurs, and more permanent drop structures between fields may be needed. An example of a gated field water distribution structure used in a modernizedspate system in Yemen is shown in Figure 4.24.

FIGURE 4.24
Gated field water distribution structure in a modernized spate system in Yemen

The importance of such field-to-field systems should not be underestimated and they represent a major improvement in water productivity. The reduction of downstream erosion avoids in-field gullying, which could lead to a dramatic depletion of soil moisture apart from the loss of irrigation to the downstream fields, since water moves without control from field to field.

A related structure is the field-inlet structure that has become popular in several areas in Pakistan where in many areas the field sizes are very large and surrounded by high bunds. The system is usually based on irrigation by a single flood event and water is applied sometimes at a depth of close to 1 m. This poses a problem not so much of letting water into the large bunded field but of preventing it from flowing out once the irrigation is over. To prevent this from happening, simple intake structures have been introduced with stoplogs which have gained popularity fast (see Chapter 5 for further details).

WADI BED RETROGRESSION AND WADI TRAINING

Wadi beds can be significantly lowered during the passage of large floods and it is not unusual for traditional intakes to be left stranded above the new scoured bed level, making it impossible to divert water into the canal system. The usual response is to relocate the intake or to extend a diversion spur further upstream to regain command. Where this is not possible, it is necessary to install one or more low check structures to trap sediments and raise the bed levels. It would usually be beyond the capacity of farmers to construct structures that span a wadi and are robust enough to survive spate flows.

Providing structures to control bed levels is an option but it is often difficult to justify in small spate schemes. The preferred material for bed sills is mass concrete, which can be cast into excavated trenches. Gabion bed sills have also been used, with mixed success: even when protected by a surface skin of concrete, they may have a very short life at upstream sites where boulders and cobbles are transported in floods *(Lawrence, 1982)*. Bed stabilizers should be designed so as not to cut off all subsurface flow in the river bed and thus deprive downstream well-owners.

In Pakistan, where bulldozers are available to farmers at subsidized rates, some very large bunds have been constructed to regain command in degrading wadi sections. While the bunds may sometimes fail, this approach is often the most cost-effective option.

BANK PROTECTION

High flow velocities during spates often erode wadi banks, particularly in the meandering middle and lower reaches. The sinuous flow alignments within the wider wadi channel result in scouring and undercutting of wadi banks at the outer curves and sedimentation at the inner curves. This causes meander patterns to develop and migrate downstream. Bank erosion scours out valuable irrigated land and can threaten canals running parallel to the wadi banks. Both these processes can be seen in Figure 4.25 which shows the Wadi Rima in Yemen shortly after it emerges from the foothills into the flood plain.

FIGURE 4.25

Bank cutting and the development of a meander, Wadi Rima, Yemen

FIGURE 4.26
Bank protection using brushwood and boulders, Wadi Laba, Eritrea

Farmers regard their irrigated land as a priceless asset and they give bank protection work a high priority. Brushwood and stone are used to protect vulnerable sections of wadi banks and in some cases low spurs are created by planting lines of shrubs out into the wadi, which trap sediments and eventually reclaim the land that has been eroded. Bank protection using boulders and brushwood in Eritrea is shown in Figure 4.26. This form of construction, used for both bank protection and diversion spurs, is unsustainable due to the overexploitation of trees and shrubs. Farmers have to travel increasingly large distances to collect the material they need.

The most important problems faced in isolated river training are bank protection works that cause damage by deflecting the flow elsewhere. River training and bank protection must be approached in a holistic manner, not just by treating the effect in one place. However, it is usually impossible to justify protection against damage from large floods with conventional river-training works because of the high costs involved when compared with the low value of the land and the crops grown. Some localized civil works may be justified where villages, bridges or roads need to be protected, but even then localized works may soon become outflanked or compromised by changes in the channel alignments in the untrained upstream sections of a wadi.

Nevertheless, something has to be done to check erosion and reclaim irrigated land that has been scoured out. Where canals run parallel to a wadi, protection is often needed to safeguard the water distribution system. ‘Low-cost’ river training and bank erosion control schemes using boulders or gabions are shown in many river engineering handbooks. For wadis, substantial and expensive structures are needed owing to the very high flow velocities and deep scour depths that will occur.

Camacho (2000) suggests the use of natural vegetation for bank protection as a more sustainable and lower-cost option than more conventional river-training works in spate-irrigated areas. Vegetation reduces local flow velocities, causing sediment to be deposited in front of and behind a vegetative barrier. The coarse sediments and silt transported during high and medium flows, mixed with vegetative debris (trash), can build up to form natural protective structures. When established, vegetation can withstand normal floods and if damaged by a large flood will sprout again and regenerate. The difficulty is in establishing vegetation where it is needed, as natural vegetation occurs where the flow velocities are low and seeds are deposited and covered with enough sediment to cause germination. Unfortunately, these locations are not always where bank protection or wadi-training spurs are required.

Vegetation can be established at high flow velocity locations by planting cuttings deep and giving them some initial protection against scour and washout. Some suggestions of how this might be achieved are given in *Camacho (2000)*. Vegetation would be planted in good wet soil at the bottom of a ditch, backfilled with graded material, ranging from sand immediately above the soil through gravel and shingle to large boulders on top. Bank protection could be achieved by armouring the most exposed parts of the outer curves where erosion is taking place with dense vegetative cover grown under the protection of a provisional retaining wall constructed from wadi boulders. Wadi training would be achieved using short vegetative spurs. Figures 4.27 to 4.29 show preliminary designs for bank protection quoted in *Camacho (2000)*. It may be necessary to improve the level of scour protection indicated in these sketches.

FIGURE 4.27
Bank protection using natural vegetation

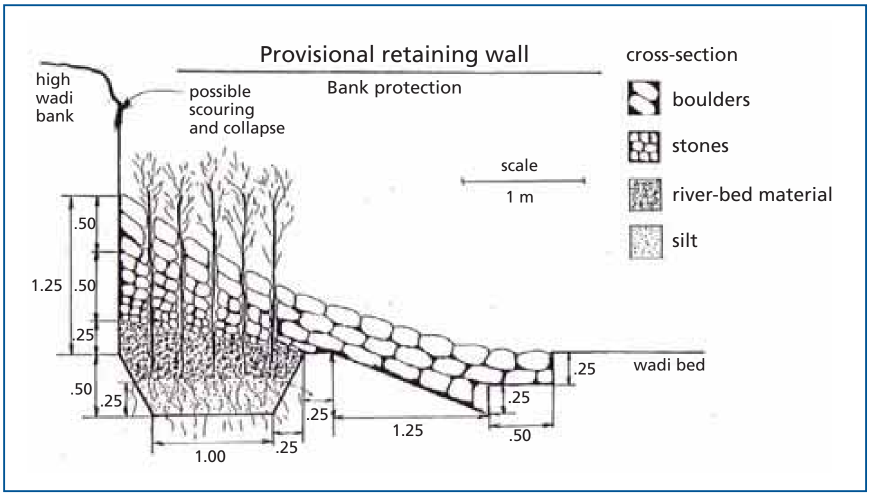


FIGURE 4.28
Spur using natural vegetation

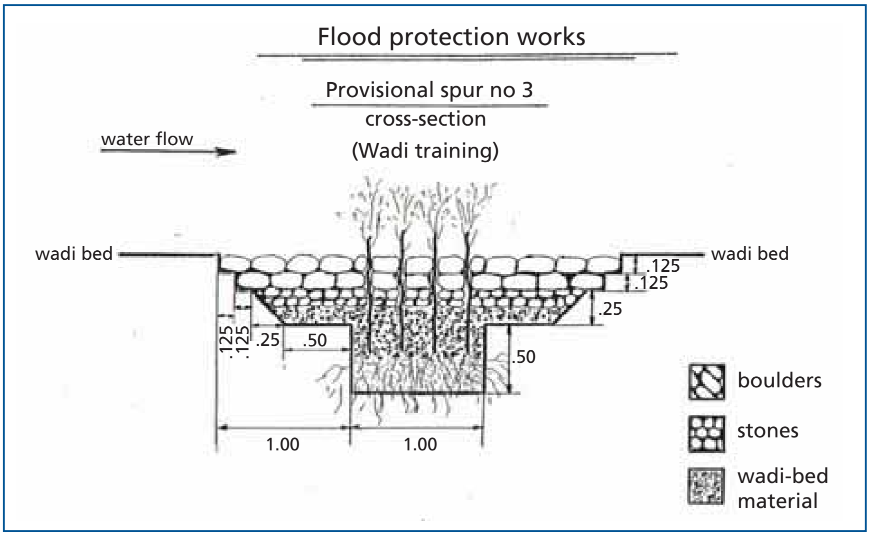
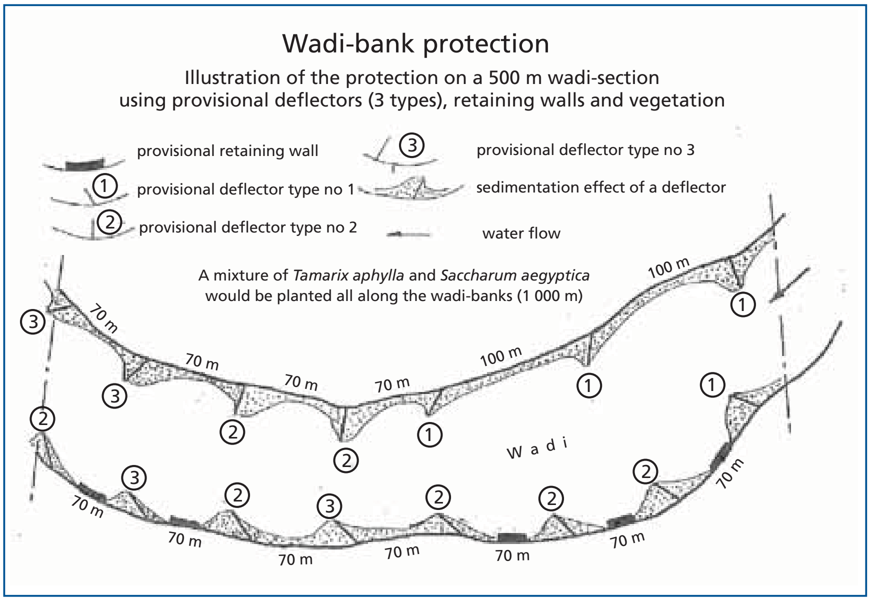


FIGURE 4.29

Proposed bank protection using retaining wall and spurs with shrubs



Chapter 5

Soil and field water management

SUMMARY

Interventions in spate irrigation have mostly concentrated on improving the diversion of spate flows and much less on improving the productivity of irrigation water. In spite of potentially substantial gains, often little attention is given to soil fertility management, improved field water distribution or better moisture conservation. These components may have as large an impact on crop production as improvement in water supply and should therefore be considered an integral part of spate improvement projects.

Spate soils are largely built up from the heavy sedimentation loads of spate water and thus their textures vary within the spate systems as a result of the sediment transport and depositing pattern. Sediments are important for soil profile development capable of high soil moisture conservation (up to 350 mm/m) and they are also major sources of soil fertility replenishment. However, the high level of sedimentation of spate systems can also represent a problem when field levels rise and go out of command. In designing spate improvement interventions, it is important to consider mitigation measures that farmers apply to cope with their local situations and ensure that proposed interventions will accommodate land rise issues.

Spate soils generally have good water-holding capacities with relatively moderate infiltration rates that vary with soil texture, density and soil management practices. The most common problems with soil are the low organic matter content and the low availability of nitrates and some micro-nutrients. This situation can be improved by incorporating crop residues into the soil, by growing leguminous crops, by practising crop rotation and by growing fodder crops that attract animals and thus providing a larger supply of organic fertilizer through animal dung.

Field water management in spate irrigation systems is as important as effective water diversion. Owing to the great temporal and special variation of its floods, the nature of spate irrigation does not allow farmers to follow a predetermined irrigation schedule where water quantities are applied to a crop when it is needed. This does not mean that water distribution within the command area is either haphazard or unplanned. Water distribution is regulated by prevailing water rights and rules and generally follows a number of principles that includes: a) rapidly spreading the available flows so as to prevent spate water rapidly disappearing in low-lying areas; b) dividing the floods into manageable quantities so as to avoid erosive flows and gully formation; and c) ensuring that large enough water volumes to irrigate the downstream areas are conveyed in the short time that spate flows are available.

One important issue in field water management is the choice between field-to-field irrigation and distribution through canals and individual field outlets. In many spate systems, a rudimentary canal network with field-to-field irrigation is in place. While improved canal networks, supplying water to field outlets, can

give better control of water and overcome some of the disadvantages of the field-to-field water system, changing to controlled field outlets may have unforeseen implications. Any improved water distribution system should:

- ensure that irrigation can be carried out quickly, in the short periods that spate flows occur. This requires canal and water control structures that have a much larger discharge capacity in relation to the area served than would be used normally in perennial irrigation systems.
- support the stability and manageability of the distribution network by introducing structures that stabilize the bed of the flood channels and reinforce field-to-field overflow structures and by making sure that gullies are quickly plugged.
- ensure that farmers understand and agree with the implications of any implied changes to water distribution and, where new canals are needed, agree to provide the additional land that will be needed to construct the canals. Additional land that will be needed to construct canals will almost certainly be taken from previously irrigated land.
- ensure that interventions be developed with the farmers, as they are generally the ones most able to identify the opportunities and possibilities for improvement in water distribution.

The design of the command area also plays an important role in field water management. Keeping the command area compact may increase the possibility of making a second irrigation and there are indications that the water productivity of the second irrigation turn is higher than the first. Smaller command areas encourage more investment in pre-irrigation land preparation and bund maintenance, because the predictability of the system is higher and makes it easier to cooperate.

Field bunds play an important role in field water application. There is a relationship between soil water-holding capacity, the likelihood of receiving one or several irrigations, field size and the height of field bunds. Field bunds are typically higher in areas where water supply is less reliable, while they remain relatively low where water supply is frequent and abundant, typically in the upper part of spate schemes. The maintenance of field bunds has a profound impact on water productivity in spate irrigation. Maintaining field bunds is an individual responsibility with a collective impact because, if bunds in one field are neglected, the water will move across the command area in an uncontrolled fashion, not serving large parts of it and causing field erosion at the same time.

A number of techniques are available to improve the control of field water application and distribution. They include better levelling of field bunds so that water overflows over a relatively large stretch, digging a shallow ditch downstream of the bund to spread overflowing water over the entire breadth of the field, the reinforcement of overflow structures, and improved field gates.

Moisture conservation in spate irrigation is at least as important as water supply, especially since in many systems floods arrive well ahead of the sowing season and hence spate irrigation is characterized as ‘pre-planting irrigation’. Several techniques to conserve soil moisture can be applied in spate systems, including ploughing before and after irrigation, conservation tillage, soil mulching, breaking soil crusts and encouraging the burrowing action of insects and crustaceans.

INTRODUCTION

Soil and water management in spate irrigation systems is vital for two reasons. The first is that in spate systems the soils are largely induced by human activity. They are built up from the sediments transported with the spate flows that settle when water is ponded on bunded fields. The water-holding capacity, infiltration and fertility of these soils are usually good, but soil management is required to counter land rise, maintain fertility and in some areas to avoid soil crusting and compaction, as well as to reduce bare soil evaporation and deep percolation losses.

The second reason is the importance of moisture conservation in crop production. In spate systems, irrigation before planting provides the main source of crop moisture. Conserving this moisture is essential to crop production. Good moisture conservation can have an impact on production often greater than improvements to the water diversion systems.

This chapter discusses the development of spate soils and the management of soil quality, water distribution and management at field level and moisture conservation and its techniques.

SOIL MANAGEMENT

Development of spate soils

Soils in spate areas are largely built up from sedimentation in the early years of development of a spate system. They are further affected by the continuing sedimentation that is inherent in spate irrigation. A relatively flat stony area can be developed over a few years by irrigating it with sediment-laden spate flows. Farmers in spate schemes often divert water to collect alluvial silt and silt loam sediments to develop soils or provide fertility even when crops do not need water.

The rate that soil builds up varies from one location to another, depending on the sediment yield from catchments, and on the position within a scheme. Sedimentation rates are higher in the upstream fields, as they are irrigated more frequently and are closer to the wadi, while they are relatively lower in downstream areas that rarely receive water. Average siltation rates on spate-irrigated fields in systems in Eritrea, Sudan, Pakistan and Yemen are summarized in Table 5.1.

TABLE 5.1
Field rise rates in spate-irrigated areas

Scheme	Annual rise rate (cm/year)
Wadi Laba, Eritrea (measured 2003/2004)	Upstream fields: 1.0–3.5 Middle fields: 0.8–2.0 Downstream fields: 0.5–1.2
Wadi Laba, Eritrea (long term estimate)	3.0 (IFAD data)
Eastern Sudan	1–3.9
Balochistan mountain systems	> 5.0
Wadi Zabid, Yemen	Upstream fields: 2–5

Source: Mehari (2007), IFAD (1995), Ratsey (2004), Kahlown & Hamilton (1996)

The constant sedimentation of spate systems is a blessing, as it brings much needed fertility to the fields, but it can turn into a curse when over the longer term it causes field levels to rise above command level. In traditional systems, this can be compensated for over the medium term by moving intakes further upstream and by constructing higher bunds in flood canals to raise water levels. However, in many long-established spate systems one finds areas that are abandoned as they have gone out of command and can no longer be irrigated.

To mitigate land rise, farmers move soil to the field bunds while levelling their fields (see Figure 5.1). In Pakistan, material is scooped from the inner side of the bund, leaving a depression of typically 6–8 m wide on the inner side of a bund. This depression holds the first thrust of water, helps control sedimentation and also prevents in-field gullying by reducing the speed of water entering the field. In Eritrea, it has been reported that the need for large quantities of soil to reconstruct and maintain traditional earthen field bunds and command area structures frequently damaged by floods significantly reduced the number of fields that fell outside the irrigable command area *(Mehari, 2007)*.

FIGURE 5.1
Field bund being strengthened with soil scraped up from irrigated land

Sedimentation within the bunded fields tends to form a series of approximately level terraces (see Figure 5.2), with drops in level between the fields, which help the field-to-field irrigation system to function *(Williams, 1979)*.

Large sediment particles tend to settle out in the canals near the wadi intakes. However sand may be transported to, and be deposited on, fields close to wadi intakes to form coarse sandy soils. Finer sediments, with lower settling velocities, are transported in suspension and can travel with the water to more remote locations. Finer sediments, silts and clays, are mostly transported through the canal systems and are deposited on the fields. As a result soil textures and water retention capacity vary within the spate systems, with soils in the middle part of the wadi normally having the best water retention capacity. For Wadi Abyan in Yemen, water retention capacities for different soil texture classes were compared. Table 5.2 highlights the relatively low water retention capacity of the sandy soils in the upstream areas.

FIGURE 5.2
Spate-irrigated fields in Wadi Zabid, Yemen

In Wadi Laba in Eritrea, the soil profiles are 2.5–3 m deep and are predominantly of silt loam texture. They can retain up to 350 mm/m of water. This implies that the soils could conserve a maximum of 1 050 mm of water within the 3 m deep soil profile and 700 mm within the 2 m deep effective root zone of sorghum and maize (the major spate-irrigated crops) respectively and therefore contribute substantially to satisfying crop water requirements.

TABLE 5.2
Available water in different soils in Abyan delta in Yemen

Soil textural class	Available water in 1 m depth of soil (mm)
Loamy sand	39
Sandy loam	83
Silt loam	163
Clay loam	170
Silty clay loam	202

Source: Mu'Allem (1987)

Land levelling

Under the field-to-field water distribution system, sedimentation helps in levelling the land and only coarse land levelling is usually carried out by farmers. Farmers often assume that the floodwater will level the land by depositing more sediment in the low spots but this is not always the case *(Tesfai, 2001)*. Too large variations in the levels within fields lead to over-watering and leaching of plant nutrients at lower levels, and under-watering at higher levels. This results in poor water use efficiency and typically uneven crop growth and yields within the same field *(Goldsworthy, 1975; Williams, 1979; Atkins and Partners, 1984; Mu'Allem, 1987)*. Crops in the low-lying flood-irrigated fields do not grow well and suffer from nitrogen deficiency *(Mu'Allem, 1987).*

It is common practice for fields to be maintained at a slight slope. In Balochistan (Pakistan), this is done to ensure that rainfall will be collected at one edge of the field, making cultivation possible in the lowest part of the field in years when there are no significant floods *(van Steenbergen, 1997)*. Individual fields may also retain a slight slope to enable water to flow easily from one field to the other *(Makin, 1977).*

FIGURE 5.3
Boundary between irrigated and non-irrigated land, Wadi Zabid, Yemen

The difference between the levels and structure of irrigated and non-irrigated soil areas is very clear. Figure 5.3 shows the western boundary of the irrigated area, with relatively deep alluvial soils, and the contrasting lower, sandy, desert scrub land at the western edge of the irrigated area in Wadi Zabid in Yemen.

Soil fertility management in spate systems

Soils in spate systems have generally good water-holding capacities: loams, silty loams, sandy loams and sandy clays are common. In some areas, such as the Wadi Abyan in Yemen, wind erosion has had a negative impact on soils as it has caused fine particles on well-established loamy areas to be blown away. This problem is more severe in areas that are only cultivated infrequently, in particular the tails of the spate systems.

Infiltration rates in irrigated soils vary with soil texture, density and soil management practices *(Williams, 1979)*. Infiltration rates range from 7.5 to 20 mm/hour in highland systems in Balochistan *(Kahlown and Hamilton, 1996)*, from 15 to 23 mm/hour in Wadi Laba and Mai Ule systems in Eritrea *(Mehari, 2007)*, and from 40 to 60 mm/hour in Wadi Rima in Yemen *(Makin, 1977a)*. They are reported as moderately rapid to rapid in Wadi Bana and the Abyan Delta in Yemen *(Atkins, 1984).*

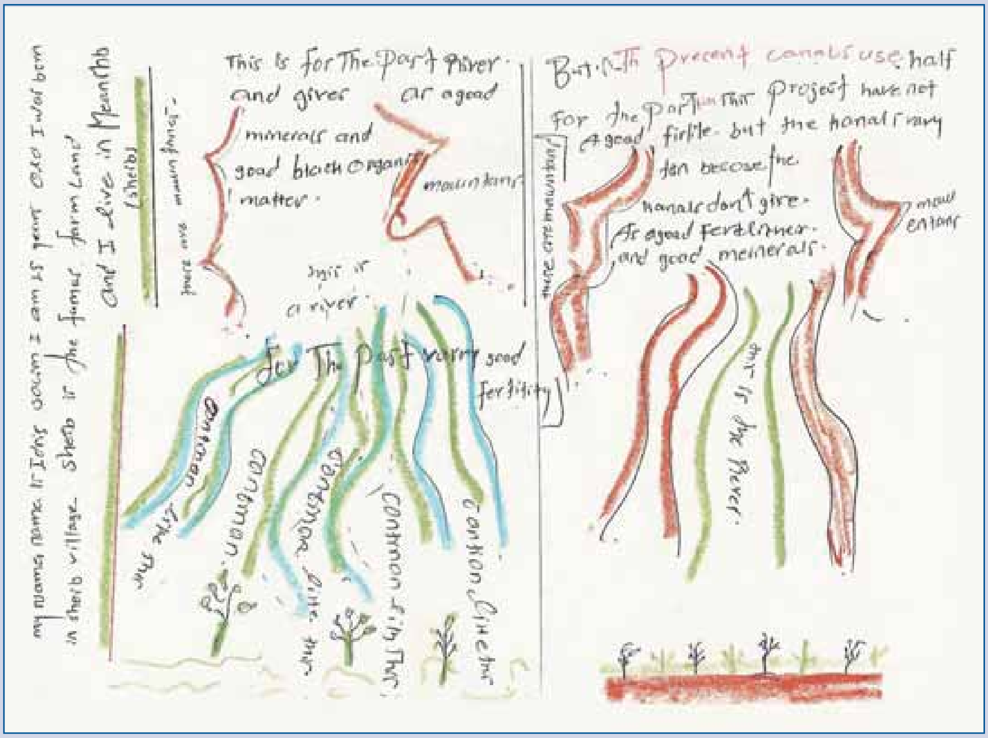
In many spate areas, soil fertility is not generally an issue. Fertility is ensured by the regular replenishment of fine silts, carrying organic material eroded from the catchments. Farmers in spate systems are often able to correlate the sediment contents of the flood with the part of the catchment where the flood originates. In some exceptional cases farmers even apply a policy of closing the system for spate flows that are known to carry large quantities of salt. Farmers' perception of regular replacement of fertilizing silts should, thus, always be considered when improvement in spate systems are introduced; otherwise, misunderstanding and conflict may arise between farmers and the engineers responsible for improving the system. An example is given in Box 5.1 for Wadi Laba in Eritrea.

BOX 5.1

Farmers' perception of silt replacement, contrasting with an engineering option for improvement in Wadi Laba, Eritrea

In Wadi Laba in Eritrea, there was concern among farmers that a small gravel trap, constructed as part of the modernization of the system, would also intercept the fertilizing silts. In reality only a tiny fraction of the fine sediment load entering the canal network could have been trapped in the settling basin. These concerns were reflected in a school children's assessment of the system carried out as part of a project appraisal process.

Schoolchildren's assessment of the fertilizing role of sediments in spate irrigation



The most common soil fertility problems are the low availability of nitrates and the unavailability of some micro-nutrients *(Atkins, 1984; Tesfai, 2001; and Mehari, 2007).* As the floodwater deposits sediments with each irrigation, there is no time for weathering and pedogenetic processes to take place *(Tesfai, 2001; Tesfai and Sterk, 2001).* Some deep soils may restrict root growth because of stratification caused by frequent textural changes in the soil profile *(Mu'Allem, 1987).* In Wadi Laba in Eritrea, after decades when spate-irrigated fields have relied entirely on the sediment brought along by floodwater for fertility replenishment, evidence shows that the fields were deficient by about 50 percent of the 103 kg/ha/year nitrogen fertilizers required for an optimum sorghum yield of 4.5 t/ha/year *(Mehari et al., 2005b).*

Organic matter is one of the major sources of soil fertility, particularly of nitrogen and phosphorus, and improves the soil infiltration and water retention capacity. Soils in spate systems are often relatively low in organic matter content. With actual field measurements in Wadi Laba in Eritrea, *Mehari (2007)* found that the topsoil of the upstream, midstream and downstream fields have on average 2.5, 1.7 and 0.9 percent of organic matter respectively. The corresponding subsoil samples have slightly lower contents at 1.8, 1.5 and 0.6 percent. The lowest and highest percentages of organic matter in soils are 1 and 5 *(Randall and Sharon, 2005)*. Hence, the upstream fields had (in 2006) slightly below average, and the midstream and downstream fields had low and very low percentages of organic matter respectively. Owing to the field-to-field water distribution practice, the upstream fields might have received more flood water in the past years, which might have given them the edge in the build up of organic matter. Content of less than 1 percent organic matter was also reported in Wadi Rima and elsewhere in Yemen *(Girgirah et al., 1987)*. The low organic matter content of the soils is often related to the sparse natural vegetation in the catchments. The small amount of organic material available decomposes rapidly in the high temperatures that prevail in many areas.

Soil organic matter and fertility can be improved by incorporating crop residues into the soil (but crop residues are often used as fodder), by growing leguminous crops and by practising crop rotation. The practice of planting fodder trees has been promoted in the flood water spreading systems in Iran *(Kowsar, 2005)*. Trees such as *Atriplex lentiformis, Acacia salicina, Acacia cyanophylla and Acacia victoriae* attracted a population of sheep and cattle, providing a larger supply of organic fertilizer through animal manure. This, in turn, has attracted the dung beetle, whose burrowing action has loosened the soil and increased the infiltration rates of flood water. The introduction of the sowbug (*Hemilepistus shirazi Schuttz*) has had the same beneficial effect.

FIELD WATER MANAGEMENT

Interventions in spate irrigation usually concentrate on improving the diversion of spate flows. Water management within the command area has often been treated as a ‘black box’. In spite of substantial potential gains, there has been little attention to field water application and improved water distribution at field level. Yet, field water management in spate irrigation systems is as important as effective water diversion.

Field water distribution methods

Because of the special and temporal variations of its floods, farmers are unable to follow a particular irrigation schedule for spate irrigation; they cannot apply water to a crop as needed. In spite of this, water distribution within the command area is neither haphazard nor unplanned. Water distribution is regulated by water rights and rules in force at the time and follows the following principles:

- spate water flows must be spread quickly to prevent its disappearance in low lying areas;
- flood quantities must be divided manageably to prevent erosive flows and the formation of gullies; and
- large enough water volumes should be ensured for downstream irrigation in the brief time spate flows are available.

Beyond these general principles, water distribution within the command area is determined by:

- the prevailing local custom, sometimes derived from Islamic water law (upstream users have priority);
- whether water is distributed field-to-field, or each field has its own inlet from a canal; and
- whether the flood flows are concentrated in a small area or spread over an extensive area.

There are four methods which are commonly known for distributing water at field level in spate irrigation. These methods are grouped into two practices:

- practices in command area water distribution: field-to-field distribution or individual field distribution;
- sizing of command area: extensive distribution or intensive distribution.

Field-to-field water distribution or individual field offtakes

In field-to-field irrigation, there are no tertiary canals and in most cases no secondary canal. In general, all the flow in a canal is diverted to a group of bunded fields by an earthen bund that blocks the canal. When the upstream field of the group commanded by the canal bund is irrigated, water is released by making a cut in the downstream field bund to release water to the next field. This process is repeated until all the fields in command have been irrigated. If the spate continues after all fields have been irrigated, the canal bund is then broken and the process is repeated at a bund constructed further down the canal, at the next diversion point (see Figure 5.4, see also Box 5.2 for field-to-field water distribution in Eritrea).

FIGURE 5.4
Field-to-field water distribution

The alternative to field-to-field water distribution system is to supply fields from individual field inlets on secondary canals. In Yemen and in the eastern lowlands in Eritrea, field-to-field systems are common, whereas in Pakistan individual field intakes are the norm (see Figure 5.5). The dividing line is not absolute and both systems can exist in the same spate irrigation scheme.

In spate irrigation projects, individual field inlets are often preferred to field-to-field inlets because they offer higher control of water distribution. This view, however, needs

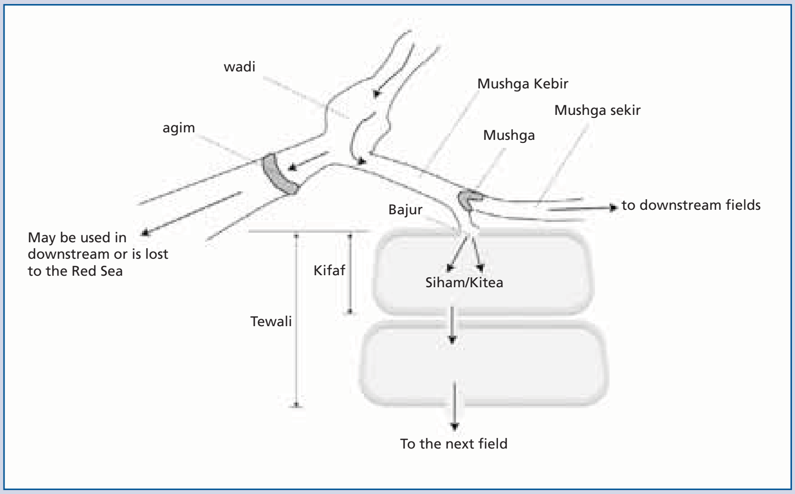
BOX 5.2

Field-to-field water distribution system in Eritrea

In field-to-field irrigation systems in Eritrea, the main canal, *musgha-kebir,* delivers water to the secondary canal, *musgha-sekir*. This in turn conveys the water to a block of 20–30 fields, which have one common inlet, locally known as the *bajur*. The water first enters the most upstream field and, when it is completely flooded, usually to a level of 50 cm, water is conveyed to the immediate downstream field by breaching one of the bunds. This process continues until water stops flowing. Sometimes, when there are no farmers around, the water overtops the bunds to make its way to the next field, but this in most cases severely erodes the field bunds. *(Mehari et al., 2005c)*

The fields are locally named as *siham/kitea* and have a roughly rectangular shape and a size of 1–2 ha. They are surrounded by earthen bunds. The height and width of the bunds range from 0.3 m to 1 m, and from 1 to 4 m respectively. The bunds that border only a single field are called *kifafs* (singular: *kifaf*) and the bunds that enclose two or more fields are called *tewalis* (singular: *tewali*).

Sketch of field-to-field water distribution system in Eritrea



Severly eroded field bund in Wadi Laba, Eritrea *(Mehari et al., 2005b)*

to be qualified. Field-to-field irrigation is well adapted to spate irrigation: it allows large volumes of water to be applied to fields rapidly in the short time periods that spate floods flow, helps to control sediments and level the land, is well established and based on existing water rights and management rules and requires minor initial investment.

On the other hand, well designed individual field distribution systems can provide substantial improvement in field water distribution and therefore increase overall water productivity. They help to reduce scours in field offtakes, increase the flexibility of water distribution, allow for irrigation of downstream fields without damaging upstream fields and require less maintenance. However, they need to be adapted to the specific conditions of spate irrigation. Conventional water distribution systems based on perennial irrigation practice, with many small field outlets open at the same time, cannot achieve the same results in spate systems, where water has to be supplied at high flow rates to large areas.

FIGURE 5.5
Individual field distribution system in Pakistan

Some controlled systems use secondary canals to supply very large plots at high flow rates. However, large fields can introduce new inefficiencies. In their study on field water application efficiency in large (5 ha) fields in Balochistan, *Kahlown and Hamilton (1996)* estimated that 1 m of water would need to be applied to achieve 200 mm moisture storage, while the rest went into deep percolation. Internal bunds dividing the fields into smaller areas (0.5–1 ha) could help improve distribution uniformity.

The relative advantages and disadvantages of field-to-field and individual controlled systems are compared in Table 5.3. The choice of the water distribution system to be adopted will depend on local conditions and needs to be negotiated with the farmers. Table 5.3 can be used to assess the positive and negative aspects of both systems and their relative importance in a given context. If water distribution rules are well established, and farmers do not consider that the existing field-to-field system represents a major constraint, such a system can be maintained, possibly with some improvements to field offtakes, as described in a later section in this chapter. Instead, if farmers identify major shortcomings in the existing system, options for improvement, and implications in terms of operation, maintenance and distribution rules may be analysed and used as a basis for the design of an improved field water management system. The design of the system itself, including the layout of the canals, the selection of groups of farmers to be served by a canal, as well as the possible need for land redistribution need to be carefully negotiated between the farmers and the engineers in charge of the spate improvement works.

There is a third, more rudimentary way of field water distribution which involves the use of guide bunds that spread floodwater over a large area. Spate systems with guide bunds are found in the western lowlands in Eritrea where most of the spate irrigation is very recent, much of the irrigation is on land that was rainfed earlier, where soils are already well developed, though not deep enough to ensure a pre-planting system. Guide bunds are also used in the still very rudimentary Tokar system in Sudan. The guide bund system does not favour soil development and, as fields are not bunded, they do not allow the water to be impounded and infiltrate slowly. This approach often does not lead to sufficient retention of residual soil moisture. It is therefore not recommended when spate flow is the major source of irrigation but could be applied at a lower cost in situations where spate flow is used as a supplementary water supply.

TABLE 5.3
Comparison between field-to-field and individual water offtakes

Field-to-field irrigation systems	Individual water offtakes
No land is required for secondary canals.	Land required for secondary and tertiary canals is estimated to be within the range of 10–25 percent of total area, though at the end of season canal beds are sometimes cultivated *(Mehari, 2007).*
Water distribution usually well regulated by local rules, although timing of breaching can be a source of conflict.	Gated control structures make it possible to divert water at any time and in contravention of established water rights. Gated control structures imply new water distribution practices which may differ substantially from established water rights.
Compulsory maintenance of system often regulated by local rules.	Farmers need to adapt to new operation and maintenance rules.
The breaching of the field bunds helps to remove large quantities of sediment from the command area and reduce the risk of rising command areas getting out of command.	Less scope to remove sediments from the command areas naturally – as signified by very high field bunds. In flat areas this can be a significant problem.
Help to level land in irrigation fields.	When plots are large, the lack of levelling will create uneven irrigation.
No problem of canal sedimentation.	Sedimentation in canals affects their ability to provide water to the downstream fields.
Damage of upstream field bunds may jeopardize flows to lower areas.	Group water supply is not vulnerable to breaking of individual field bunds.
Smaller floods do not reach tail-end plots. Smaller floods later in season are not diverted because upstream plots are cultivated. Possible damage to growing crops during second or third irrigations.	Individual offtakes allow for more flexibility and the possibility of irrigating downstream fields even later in the season without damage to upstream crops
Minor investment but high, labour- intensive maintenance costs.	Require expensive investment in gated flow control and division structures and field offtakes with a high flow capacity.
In-field scour on lands result from the breaching of downstream bund. Abrupt changes in elevation from field to field, with scour problems and impossibility of regulating the depth of water application correctly.	Gated structures reduce risk of scour and improve water application regulation.

Extensive or intensive water distribution

Another factor distinguishing methods of water distribution at field level is whether irrigation is spread widely or concentrated in a small area. Whereas in extensive systems a single irrigation is common, fields may be irrigated twice or three times before cultivation when floods are concentrated on a small area. Local crop varieties are well adjusted to soil moisture stress, but even so, there is evidence that for the sorghum crop in Yemen *(Makin, 1977* and *Williams, 1979)* and sorghum and maize crops in Eritrea *(Mehari, 2007)*, the yield produced from two or three irrigations would be more than two or three times the yield from a larger area irrigated once.

Both types of water distribution pattern can exist in the same system and depend in part on the moisture-holding capacity of the soil. *Makin (1977)* describes the use of base flows and small floods to provide several irrigations near the mountain front in Wadi Rima in Yemen and the contrasting pattern of a single large irrigation at the tail of the same system. In some other cases, farmers avoid irrigating their land for a second time, particularly if a crop is established on the land. In Las Bela District in Balochistan (Pakistan), sorghum may be irrigated twice, but if it is mixed with pulses or sesame, farmers say that crops are damaged by a second flooding and more subject to disease. Once the crops come up, farmers are hesitant to put floodwater on the land, as it would damage the young plants. Similarly, later in the season when the crop stands are higher, there is the fear that additional irrigation would invite pests and floods that come late in the season may be diverted to other areas.

The design of the command area therefore plays an important role in field water management. Keeping the command area compact may increase the possibility of making a second irrigation, and there are indications that the water productivity of the second irrigation turn is higher than the first. Smaller command areas also encourage more investment in pre-irrigation land preparation and bund maintenance, because the predictability of the system is higher and makes it easier to co-operate.

The choice of an intensive or extensive system is related more to the flood pattern and to the agreed water rights than to considerations of crop response to water. Concentrating spate supplies on a small area will make it easier to decide where to plough prior to the spate season with the aim of improving infiltration rates on those fields where irrigation is possible. However, some systems are not amenable to intensification. The spate systems in the Suleiman plains and Kacchi plains in Pakistan depend on a single soil bund that is supposed to be broken when the irrigation is over. As long as the bund stands, land can be irrigated, but after it is breached there may not be a second chance. Moreover, some of the smaller rivers may carry only one substantial flood in a year.

Improvements can be introduced through tests and demonstrations of different options for intensification of water application and subsequent results in terms of crop yield for different crops. Care must be taken, in this case, of considering the inter-annual variability of supply and assessing the implication of possible changes in the water distribution pattern for water rights.

Field water application and the importance of field bunds

In spate irrigation, it is generally assumed that irrigation application should result in an average of 400 mm net stored in the soil *(Camacho, 1987)*. It is also reported that the application of 600–1 000 mm of water in a single pre-planting irrigation is sufficient to raise all spate-irrigated crops, provided that the moisture-holding capacity of the soil is satisfactory *(Mu'Allem, 1987)*. In the spate systems in Sudan, 500 mm is used as the norm, with a single watering per season. In other areas, the preference is for several irrigations. In Eritrea, arable fields are flooded three to four times, with an irrigation gift of about 50 cm each time, giving a wetting depth of about 2–2.4 m in the soil profile.

There is a relationship between the height of field bunds and the availability of water both in terms of frequency and volume of irrigation. In Wadi Rima in Yemen, in locations where crops can expect to receive only a single irrigation, the bunds are high and the depth of the water application averages 400 mm. In locations closer to the wadi, which can expect two or more irrigations per crop, bunds are lower and the amount of water absorbed for each irrigation averages 300 mm *(Makin, 1977)*. In Yanda-Faro in South Ethiopia, field bunds are 20 cm high, not different from field bunds in perennial systems. In Daraban Zam in Pakistan, they can be up to 3 m. In systems with large plots, bund heights may easily reach 2–3 m.

The depth of water that can be impounded in a bunded field during particular irrigations often affects the choice of crop grown. Box 5.3 illustrates different scenarios for water impounded in bunded fields in Balochistan (Pakistan), Yemen and Eritrea.

BOX 5.3

Different scenarios for water impounded in fields and choice of crops grown in Pakistan, Yemen and Eritrea

- In Las Bela District in Balochistan, if 300 mm are impounded, then guar (cluster bean) alone is sown, mainly as a fodder; if 750 to 900 mm are stored, then castor is sown; otherwise a mix of sorghum, mung and sesamum/guar is sown. Farmers generally do not aim to achieve depths of over 900 mm. Mustard is only planted when two or more floods can be impounded on the same plot prior to cultivation.
- In Kacchi District in Balochistan, when there is little floodwater, the land is inspected after the water has receded. If the depth of wetting is insufficient, crops are only sown in depressions or adjacent to unbreached bunds.
- In Nal Dat in Balochistan and where the depths of water applied are insufficient to meet the crop water requirements for all crops, rainfall is relied upon for meeting the deficit.
- In parts of Bateis command in Wadi Bana in Yemen, farmers apply more than 750 mm of water to cotton, 250 mm more than is required by the crop. Not all this water may be absorbed by the soil – the balance recharges the aquifers.
- In Eritrea, if the farmers irrigate their fields three times (1 500 mm), they plant maize as a second crop. When the total irrigation supply is less than 1 000 mm, the more drought-resistant sorghum ratoon of the hijeri local variety is preferred.

Sources: MacDonald (1987a), Halcrow (1993b), and Mehari (2007).

The maintenance of field bunds has a profound impact on water productivity in spate irrigation. Maintaining field bunds is an individual responsibility with a collective impact, because, if bunds in one field are neglected, the water will move across the command area in an uncontrolled fashion, not serving large parts of it and causing field erosion at the same time. The importance of maintenance can be derived from its central place in some of the management arrangements in spate systems. In the rules and regulations for spate systems in Wadi Laba in Eritrea and Wadi Tuban in Yemen, there were explicit penalties for farmers who did not take sufficient care in maintaining the field bunds, that could go as far as compensating for the crop loss of the disadvantaged neighbour. A step further is the hereditary tenancy arrangements that are common in

Pakistan's spate irrigation systems, under which the tenant is the *de facto* co-owner of the land but his entitlement is conditional on his continued upkeep of field bunds. High field bunds pose a great challenge for timely reconstruction and maintenance, particularly when heavy machinery is not at hand and traditional labour and oxen are the only available resources. While 2–3 m high field bunds are common in many large (5 ha or more) spate-irrigated fields in Pakistan and Yemen, having a field bund of more than 1 m is usually not necessary. The security of irrigation is also very much a function of the strength of the field bunds. To make strong bunds, moist soil is compacted and rat-proofed. Overflow structures and gates may be used to control the inflows and outflows and to minimize the chance of unplanned breaches. In several spate systems, penalties are in place for farmers who do not maintain the field bunds, as this affects the supply of water to downstream users.

Apart from proper maintenance of field bunds and giving them a minimum strength, a number of other techniques are in place to control field water application and distribution:

- keeping the bunds at the same level so that water overflows over a relatively large stretch;
- digging a shallow ditch immediately downstream of the field bund to spread water over the entire breadth of the downstream field. This is done in Pakistan, where field bunds are very high;
- reinforced overflow structures, usually with local stone pitching, to make sure water starts to overflow gradually without unpredictable breaking of the field bund (Figure 5.6);
- improved field gates. In Pakistan, the Water Resource Research Institute developed a field inlet gate that consists of an orifice with a round lid to close it (Figure 5.7). Downstream a small stilling basin ensures the energy of the overflow is dissipated and water spreads generally over the downstream field. This innovation gained quick popularity in the area where it was introduced. It cost US$700–900 in 2006.

FIGURE 5.6
Stone reinforced field-to-field intake structure in Pakistan

FIGURE 5.7
Improved field intake, orifice with a stilling basin in Pakistan

MOISTURE CONSERVATION

Moisture conservation in spate irrigation is as important as water supply, as crop yields can be severely depressed by soil moisture deficit. Farmers in the coastal eastern lowlands in Eritrea, for example, estimate that a person who has his own bullocks would have a yield 30–100 percent higher than another who does not own bullocks. The reason for this difference is that, with draught animals of one's own, one could plough fields and repair bunds after every irrigation, thus vastly increasing soil moisture retention. Research in Yemen suggests that, if land is not ploughed within two weeks after irrigation, up to 30–40 percent of the moisture may be lost. Several techniques to conserve soil moisture are applied in spate systems:

- ploughing prior to and after irrigation;
- conservation tillage and soil mulching;
- breaking soil crusts.

Ploughing prior to and after irrigation

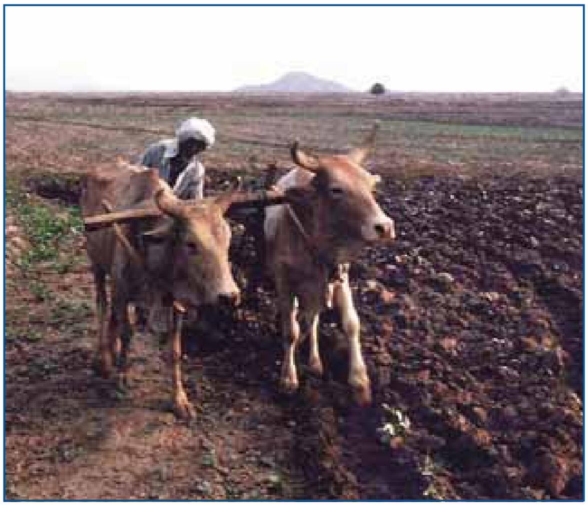
Breaking the topsoil through ploughing land prior to irrigation greatly increases infiltration rates (see Figure 5.8). *Makin (1977)* reported that initial infiltration rates for Wadi Rima in Yemen increased from 40 to 60 mm/hour. Pre-irrigation ploughing also makes cultivation much easier and quicker to carry out once the floodwaters arrive, which is important, as a great deal of labour is required to cultivate the land after irrigation *(Williams, 1979)*.

FIGURE 5.8
Ploughing prior to irrigation to break topsoil

There is a close link between the practice of pre-ploughing irrigation and the likelihood of water supplies. In areas where the probability of irrigation is low, for example in intensive systems, it is unlikely that farmers will invest time and effort in soil preparation.

The topsoil should be ploughed loosely after irrigation or rainfall (see Figure 5.9) to conserve water *(Williams, 1979)*. However, as the soil is wet, it may not be possible to plough the land for 8–12 days after irrigation, and some water will inevitably evaporate *(Makin, 1977)*. The common recommendation is not to delay ploughing for more than two to three weeks, to avoid water loss through evaporation or deep percolation. Extending the post-irrigation period beyond that time may cause a moisture loss in the range of 40 percent. In the Kacchi District in Balochistan, where soils are relatively clayey, fields tend to dry out at the surface. It then becomes important to drill seed deep into the soil. Farmers can only plough fields once and the seedbed is often too cloddy for good, even germination and establishment *(MacDonald, 1987a)*.

FIGURE 5.9
Ploughing after irrigation/rainfall for moisture conservation, Sheeb, Eritrea



Smallscale farmers in coastal south Yemen reportedly ‘bury the irrigation’ when the floods come out of season. They plough the land and ensure the topsoil is loose. In some instances they even cover the land with sorghum stalks to reduce evaporation losses further.

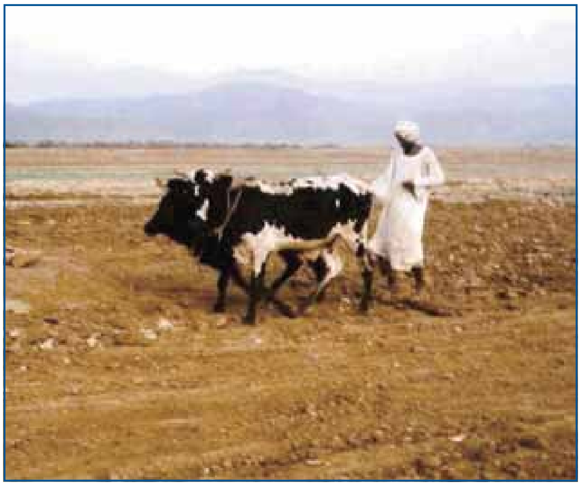
FIGURE 5.10
Simultaneous ploughing and sowing using the *jeleb* in Wadi Laba, Eritrea

In Eritrea, combining ploughing and sowing minimizes the degree of compaction of the subsoil and thereby enhances the soil’s hydraulic conductivity and infiltration rate. Farmers use the *jeleb*, which is a hollow plastic tube into which the plough operator drops two or more seeds every few seconds while tilling the land (see Figure 5.10). The reduction of the degree of compaction through simultaneous ploughing and sowing is considered to be the main reason behind the low soil bulk density of the Wadi Laba fields, which has been maintained at about 1–1.3 kg/m^3. A bulk density of 1 600 kg/m^3 affects root growth, one of 1 800 kg/m^3 severely restricts it *(Mehari, 2007)*.

Conservation tillage and soil mulching

Conservation tillage in Sheeb in Eritrea is called *mekemet*, a term derived from the local *Tigre* word *kememnaha*, which literally means: “we have sealed it”. This technique is practised in the approximately ten-day period between the last flooding and the sowing of seeds. It can also be done earlier if the field is not expected to get any additional irrigation. Farmers plough the fields about 0.15 m deep to create a tilth, which conserves the soil moisture by reducing the evaporation losses from the soil surface. At sowing time, the tilth layer is broken down by shallow tillage followed by sowing *(Tesfai, 2001)*. Soil moisture measurement in twelve selected Wadi Laba fields has shown that *mekemet* can conserve as much as 20 percent of the soil moisture that would have otherwise been lost to evaporation *(Mehari, 2007)*. During operation, the farmer (operator) stands on the oxen-drawn wooden plate and scoops up a thin layer of soil, mulching surface soil pores (see Figure 5.11). The same practice is reported from Ethiopia, Pakistan and Yemen, where farmers try throughout the growing season to keep the topsoil loose to reduce evapotranspiration.

FIGURE 5.11
Soil mulching, *mekemet* in Wadi Laba, Eritrea



Breaking soil crusts

In areas with silt soils or calcareous soils, soil crusting can affect water use efficiency. Such soils may form surface crusting, which can reduce the infiltration rate by 20–40 percent *(Mehari, 2007)* and thereby affect the amount of residual soil moisture. Therefore, special measures are required to keep the topsoil loose to avoid frequent field trampling. In the piedmont plains of the Sulaiman Range in Pakistan, clayey soils, including silty clays, clays and silty clay loams, form a major part of the Rod Kohi land *(Khan and Rafiq, 1990)*. They are generally more difficult to till and are prone to surface cracking. The soil crust that develops reduces the infiltration rate, increases runoff, restricts seedling emergence and reduces crop yield *(Nizami and Akhtar, 1990)*. Appropriate management and agronomic techniques include tillage, surface mulching, increase in soil organic material (by applying manure and incorporating crop residues where possible), seeding at appropriate (15–20 cm) depth, planting on ridges and use of mechanical crust breakers *(Nizami and Akhtar 1990; Tesfai, 2001)*.

Silt soils are prone to compaction if machines are used on wet soils. Soil compaction slows down root penetration. Soil water and nutrients become less accessible to the plant and crops grown on compacted soils will show the effects of drought stress first. Continuous flood irrigation may lead to a hard compact layer at a depth of 30–40 cm. Clay particles carried in the floodwater are washed down the profile and make it difficult for the plant roots to reach the water, which leads to a reduction in productivity. One option to address this problem would be to break the hard pan every two to three years by chiselling, using a heavy power unit.

Chapter 6

Agricultural practices and extension services

SUMMARY

The high risk of crop failure associated with spate irrigation and consequent risk mitigation strategies adopted by farmers do not leave much space for the classical improvements in agricultural practices that are justified in intensive agriculture. There are, however, some niches of possible production gains that can be obtained through carefully designed changes in cropping practices.

Farmers in spate systems have developed various cropping strategies to cope with the risks inherent in spate irrigation. These include:

- growing local varieties that are adapted to the local agroclimatic conditions and have a high tolerance to drought;
- growing crops that produce some fodder even if the floods fail and grains cannot be grown;
- practising intercropping, so that, in bad years, one of the planted crops can be harvested;
- selecting crops in relation to the timing and volume of the first irrigation and, where possible, of subsequent irrigations; and
- selecting crops in relation to the soil moisture available after irrigation.

Sorghum, millet, wheat, maize and pulses are the main subsistence crops in spate-irrigated areas. Cash crops like cotton or sesame are usually grown only after a staple crop has been harvested and the subsistence needs of farmers have been met. The selection of the crop and varieties that are grown in spate areas depends on a number of factors:

- location of the field within the system;
- timing and volume of irrigation water that is likely to be received;
- resistance to drought, pests and disease;
- alternative use in drought periods when grains cannot be grown, e.g. as fodder;
- suitability for storage;
- possibility of ratooning; and
- market and, where relevant, support prices.

Research for the development of improved varieties in spate irrigation is practically non-existent and when some varieties exist they are difficult to obtain. Local cultivars fare well in terms of drought resistance, labour inputs, market values, food values and storage but these factors are usually not taken into account in plant breeding. Efforts need to be made to develop varieties that are adapted to spate conditions. Exchanges of local varieties between spate systems should be considered more systematically.

The yields of most spate-irrigated crops are highly variable. In bad years, parts of the scheme may not produce any crop, while the crops on other fields may only receive enough irrigation to produce some fodder. The wide ranges in yields observed in spate schemes can be attributed to:

- the unreliability of irrigation;
- the degree of control that farmers can exercise over spate flows;
- the farming skills in soil moisture conservation practices; and
- the priority that farmers give to spate irrigation, considering that many of them work in other sectors because of the low return to labour in spate.

In most spate-irrigated areas, there is minimal use of chemical or organic fertilizers such as manure. While yields could be increased through a combination of greater investment in fertilizers, pest control and labour, it is important to note that the traditional cultivars used in most schemes do not always respond well to increased use of fertilizers. Other factors that contribute to the limited use of chemical fertilizers are the cost and extent of availability of chemical fertilizers, access to credit, the lack of information on the use of fertilizers, and the high level of risk that fertilizers will be washed off by uncontrolled irrigation.

The large difference in cropping practices between areas and countries explain in part the range of observed yields and indicates that there are opportunities to improve crop yields through the adoption of better agricultural practices. Research suggests that there is scope for production increases with relatively simple adjustments to farming practices, such as early planting, mulching and deep ploughing, well-targeted use of fertilizer, etc. Areas for improvement include:

- the introduction of an integrated farming systems approach, including livestock and agroforestry;
- the use of improved seed varieties – for instance, by more exchange of varieties between areas;
- a better understanding of the balance of nutrients, including those brought by spate floods, and better guidance on fertilizer application;
- cultivating more minor crops and wild plants – such as truffle mushrooms or vegetables; and
- a better control of post-harvest losses, which can be reduced by simple improvements in storage.

Although there is considerable scope for crop productivity improvement through extension and research, these services are usually poor and ill-adapted to the specific concerns of spate-irrigated areas, and the bulk of investment in agricultural research usually goes into perennial irrigated agriculture. Spate irrigation is rarely part of the agriculture or engineering curriculum in formal educational institutions. Yet research into a wide range of topics is needed to address specifically the needs of spate irrigation agriculture. Research needs to be systematically carried out in consultation with farmers through farmer-led trials and experiments and through farmer-to-farmer extension activities.

The picture is different in areas where conjunctive use of groundwater and spate irrigation is possible. In such circumstances more intensive agriculture with high-value cash crops is possible under spate irrigation (Chapter 10 provides more details).

INTRODUCTION

Spate irrigation generally supports a low-input, risk-averse type of farming owing to the recurrent uncertainties in the timing, number and size of floods that occur and the potential damage to crops and irrigation infrastructure caused by large floods. At some locations, in any one year, few if any significant floods occur, which makes cropping impossible.

While the risks of crop failure in spate-irrigated agriculture are quite high, the probability of receiving irrigation is not equally distributed throughout the command areas. Within an area served by a wadi or within an area supplied from one offtake, there will be lands that have widely varying probabilities of receiving irrigation. This typically would range from very high for fields close to the wadi and when the wadi has some seasonal base flow, to very low, possibly only once in every five years, at the downstream end of schemes. The crops grown and the agronomic practices adopted reflect these variations.

Drought-resistant crops such as sorghum, millet, wheat, pulses, oilseeds and cotton dominate the cropping patterns. The production of fodder is also a priority in most spate-irrigated areas in order to support livestock. Livestock provide traction for ploughing and bund building, and act as a form of saving, as animals can be sold to generate cash in bad years. In addition, farmyard manure can be an important source of income.

This chapter summarizes the agronomic aspects of spate irrigation, including the choice of crop varieties, cropping pattern, and associated agricultural practices, and explores possibilities for improvement.

CROPS GROWN IN SPATE IRRIGATION

Farmers have developed various cropping strategies to cope with the precarious circumstances that are part of spate irrigation:

- they generally grow local varieties that are adapted to the local agroclimatic conditions and have a high tolerance to drought;
- they grow crops that produce some fodder even if the floods fail and grains cannot be grown;
- they may practise intercropping, whereby two or three different crops with different water requirements and harvesting times are planted in the same field, so that, in bad years, one of the planted crops can be harvested;
- at some locations, their crop choice is determined by the timing and volume of the first irrigation and, where possible, subsequent irrigations. For example, in Pakistan sorghum is grown in fields with early irrigations, oilseeds and pulses are irrigated later and the last summer floods are reserved for the cultivation of wheat during the winter months; and
- at other locations, their selection of crops depends on the soil moisture that is available after irrigation.

Varieties

The selection of the crops and varieties that are grown in spate areas is affected by a number of factors, amongst which are the: (a) location within the system; (b) timing and volume of irrigation water that is likely to be received; (b) resistance to drought, pests and disease; (c) alternative use in drought periods when grains cannot be grown, e.g. as fodder; (e) suitability for storage; (d) possibility of ratooning; and (e) market and, where relevant, support prices *(Pratt, 1977; Atkins and Partners, 1984; Camacho, 1987; Wadud and Ahmad, 1989; Michael, 2000b*; and *van Steenbergen, 1997).*

Rooting depth is an important factor in spate irrigation, where the crops need to be able to exploit all the available moisture stored in the soil profile. Sorghum and millet can root to about 3 m and cotton to over 3.5 m and are therefore well suited to spate irrigation *(Williams, 1979)*. Maize is less suited to spate irrigation when only one irrigation can be applied, as roots rarely grow more than 1 m and cannot reach soil moisture stored deeper in the soil profile.

Sorghum, millet, wheat, maize (Figure 6.1) and pulses are the main subsistence crops. Farmers usually consider growing cash crops, e.g. cotton or sesame, only after a food crop has been harvested and their subsistence needs have been met *(Goldsworthy, 1975; Makin, 1977a*; and *Camacho, 1987)*.

FIGURE 6.1
Spate-irrigated maize, Eritrea

The range of crops grown under spate irrigation in Eritrea, Ethiopia, Yemen, Pakistan and Tunisia are listed in Table 6.1. What is striking is the differences between and within countries. In Pakistan, oilseeds and pulses are very common in spate areas. In the Horn of Africa, they are absent, which indicates that there are more opportunities in this region for trying crop diversification.

There are also many wild herbs, vegetables and shrubs in spate-irrigated areas that have useful local economic values. Spate irrigation by nature collects seeds from a large catchment and deposits them in the moist soil of the common area. In the spate-irrigated areas along the Kohi-Suleiman in Pakistan, drub grass is common (*Desmostychia bipinnata*), serving as an important source of fodder as well as a land stabilizer. The short-lived *blue moola* flower is important for livestock as well, fed to sheep and cattle to improve the quality and fragrance of their milk. The wild *teenda* and *chunga* vegetables are important supplements to human diets. Another common sight is the small *ak* plant (*Calotropis procera*), which has a range of medicinal purposes, including anti-inflammatory treatment. Another interesting plant is the *lana* shrub (*Salsola bariosma*), which is slowly burned and its ashes used as a detergent. Some of

TABLE 6.1

Crops grown in spate areas in Eritrea, Ethiopia, Pakistan Yemen and Tunisia

Country/region	Range of crops grown	Reference
Eritrea		
Eastern lowlands	Sorghum: most preferred and is widely grown in the northern part of the eastern lowlands. Maize: ranks second and is widely grown in the southern part of the eastern lowlands. Others: pearl millet, cotton, sesame, groundnut, tomato, pepper, okra, kerkede, and watermelon.	*Ogba-Michael (2004)*
Sheeb area	Main crops: sorghum (hijera variety) and maize. Minor crops: pearl millet, sesame, groundnut and, vegetables.	*Tesfai (2001)*
Ethiopia	Sorghum, maize, millet, cowpea and horse bean (mainly local varieties that are drought-resistant).	*Michael (2000a)*
Pakistan		
Kachhi District, Balochistan.	Sorghum, mung bean, moth bean, melon, rapeseed.	*MacDonald (1987a)*
Lasbela District, Balochistan.	Sorghum, mung bean, sesame, guar, castor, mustard or rape.	*MacDonald (1987b)*
D.I. Khan, Balochistan	Wheat, gram and mustard (sarsoon) in rabi. Sorghum and millet (joiwar and bajra) in kharif.	*Khan, A.B. (1990)*
Rod-kohi area in D.I. Khan, Balochistan	Sorghum, millet and sweet melon (spring). Sorghum, millet (summer), local mustard (summer). Wheat, gram (chickpea), rape/mustard (winter).	*Khan, M. (1990)*
Piedmont Plains (Sulaiman Range)	Wheat, sorghum, millet.	*Khan and Rafiq (1990)*
D.I. Khan	Gram, wheat, barley (rabi). Bajra, jowar (cherry), mung bean (kharif).	*Wadud and Ahmad (1990)*
Chandia, Balochistan	Basic crops: fodder sorghum and livestock, pulses, oilseed and wheat. Minor crops: coriander, radish and melon.	*Halcrow (1993a)*
Nal Dat, Balochistan	Sorghum, fodder guar, pulses (masoor or mash) (kharif). Wheat, some oilseed (rabi).	*Halcrow (1993b)*
Kharan, Balochistan	Wheat, sorghum, melon.	*BMIADP (1994)*
Toiwar, Balochistan	Wheat, barley (rabi season). Mash and maize (kharif season).	*Halcrow (1998)*
	Maize, melon, sorghum, cumin, pulses (kharif season).	*Rehan (2002)*
Yemen		
Wadi Rima	Sorghum, bulrush millet, lentil, cowpea, beans and watermelon.	*Goldsworthy (1975)*
	Sorghum, bulrush millet, cotton, sesame, maize and cowpea.	*Makin (1977a); Pratt (1977)*
Wadi Mawr	Sorghum, cotton (main crops).	*Tipton and Kalmbach (1978)*
Abyan Delta	Cotton, sesame, sorghum, watermelon, millet, groundnut. Bulrush, millet and groundnut are grown unofficially.	*Atkins and Partners (1984)*
Wadi Ahwar	Long staple cotton, sorghum, millet, vegetables, and melon.	*Girgirah et al. (1987)*
Wadi Rabwa	Sorghum, maize, millet, sesame, pulses, and medium staple cotton.	*Girgirah et al. (1987)*
Tunisia	Wheat, olive, and almond.	*Nouael II Project*

these wild species could have larger market opportunities. The most spectacular crop in this regard is the underground truffle mushroom, which is found in some spate-irrigated areas in Pakistan and Iran, that could fetch very high export prices.

Yields

The yields of most spate-irrigated crops are highly variable. In bad years, parts of the scheme may not produce any crop, while the crops on other fields may only receive enough irrigation to produce some fodder.

The wide ranges in yields observed in spate schemes are variously attributed to the unpredictability of water supply, degree of control that farmers can exercise over spate flows, farming skills and soil moisture practices and the priority that farmers give to spate irrigation, considering that many of them work in other sectors because of the low return to labour in spate *(Goldsworthy, 1975; Makin, 1977a; Tipton and Kalmbach, 1978; Atkins and Partners, 1984; Mu'Allem, 1987; Shah, 1990; Tesfai, 2001;* and *Rehan, 2002).* Figure 6.2 shows a contrast between a poor, under-irrigated sorghum field and a good one in Eritrea. Table 6.2 gives an indication of the range of yields achieved in spate irrigated areas in Eritrea, Iran, Yemen, Tunisia, Morocco and Pakistan.

FIGURE 6.2
Poor, under-irrigated sorghum field and a good one in Eritrea

Yields also vary substantially from one year to another. In the areas of the Shabwah Governorate in Yemen, the average yields are 1 500 to 2 000 kg/ha for sorghum and 1 000 to 1 500 kg/ha for millet. However, the yields of sorghum and millet may rise to 2 500 kg/ha and 2 000 kg/ha respectively in years with good rains and floods or reduce to 800 kg/ha and 600 kg/ha respectively in dry years *(KIT, 2002).* There are, however, large differences in cropping practices between areas and between countries that cause the range of crop yields to fluctuate. This indicates that there are important opportunities to improve crop yields through the adoption of better crop and moisture management practices. The average yields of main crops under spate irrigation in different parts of Yemen are given in Table 6.3.

TABLE 6.2
Crop yield in spate-irrigated areas (kg/ha)

Country	Crops grown under spate irrigation	Yields (kg/ha)
Eritrea	Sorghum	800 – 3 800
	Maize	500 – 2 000
	Pearl millet	200 – 900
	Cotton	200 – 1 000
	Sesame	100 – 800
	Groundnut	700 – 2 500
	Tomato	500 – 2 000
	Pepper	900 – 4 000
	Okra	500 – 1 500
	Watermelon	1 000 – 3 500
Iran	Sorghum	2 000 – 6 500
	Wheat	2 500 – 6 000
	Barley	600 – 2 500
	Watermelon	10 000 – 13 000
	Date Palms	400 – 700
	Mungbeans	800 – 1 100
Morocco	Wheat	1 200 – 1 500
	Barley	1 500
	Maize	900
Pakistan	Sorghum	360 – 550
	Sorghum fodder	1 500 – 4 800
	Oilseeds	150 – 350
	Pulses	200 – 500
	Cotton	360 – 620
	Castor	395 – 988
	Mung bean	270 – 550
	Mustard	760
	Gram (Chickpea)	789
	Wheat	450 – 1 706
	Barley	905
	Millet	564
	Mash	480
	Chickpea	470
Yemen	Sorghum (Grain)	600 – 3 500
	Sorghum (Fodder)	810 – 11 500
	Millet	600 – 1 200
	Maize	1 000 – 1 500
	Sesame	350 – 700
	Melon	5 000 – 14 100
	Cotton	350 – 8 500
	Qaira (for grain)	900 – 1 500
	Groundnuts	1 200

Source: van Steenbergen et al., 2008

Yields also vary reflecting the adequacy of irrigation and the effort made by farmers in moisture conservation and husbandry. Table 6.4 shows yields in the traditional Wadi Rima system (before modernization) for areas with different probabilities of irrigation.

TABLE 6.3
Crop yields in spate-irrigated areas of Yemen (kg/ha)

Crop	Coastal area (Red Sea)	Coastal area (Aden Gulf)	Coastal area (southern Yemen)	Wadi Rima (Tihama)	Wadi Mawr (Tihama)
Sorghum	2 000 – 3 500	700–1 200	900	–	–
White	–	–	–	1 100	1 000
White ratoon	–	–	–	600	–
Red	–	–	–	–	600
Millet	–	700–1 200	900	800	600
Cotton	650–1 350	–	–	1 100	1 000
Extra long staple		850–950	900	–	–
Medium staple		1 000–1 600	1 500	–	–
Sesame	700	350–650	500	700	700
Maize	1 100–1 500	–	–	1 400	1 000
Melon	–	7 900–14 100	10 000	–	5 000–5 500
Groundnut	–	1 200	1 200	–	–

Source: Al-Shaybani (2003), Mu'Allem (1987), DHV (1979), and Shahin (1990)

TABLE 6.4
Crop yields in areas with different probabilities of irrigation in Yemen (kg/ha)

Crop	Perennially spate – irrigated area	Regularly spate – irrigated area	Irregularly spate – irrigated area
Maize	1 200 – 1 300	1 200	–
Sayf Sorghum			
Grain	1 000	800 – 1 000	600
Fodder	3 200	1 900 – 2 300	2 000
Sorghum			
Grain	1 400	400 – 1 100	–
Fodder	3 500	1 000 – 2 800	2 200
Sorghum			
Grain	2 500	1 000 – 2 500	1 100
Ratoon	800	300 – 800	200
Cotton	8 500	850 – 3 500	350
Millet	–	500 – 1 000	500
Sesame	–	200 – 500	200

Source: Makin (1977)

The perennially irrigated area here refers to lands close to the mountain front that were irrigated with reliable seasonal base flows that could be rotated between fields.

As shown in Table 6.2, relatively high yields are also obtained in the eastern lowlands of Eritrea. The water management practice there is to divert as many spate flows as possible to a relatively small area; ideally, farmers hope to achieve two or three irrigations before planting. The result of this approach is that in a good year harvests in Sheeb can be larger than in most spate system elsewhere in the world – up to 3 500 kg of sorghum on the first cutting and half of that again as a ratoon crop *(van Steenbergen, 2003)*.

Compared with the yields of spate-irrigated crops in Yemen and Eritrea, yields in Balochistan (Pakistan) are significantly lower (see Table 6.2). The reason is that most spate-irrigated crops in Balochistan receive one flood irrigation and are then dependent on 'unreliable' rainfall for addition moisture. In Yemen, in contrast, supplementary irrigation from groundwater is common, while in Eritrea there are often two or three floods before seeding, with soil moisture being conserved every time.

Changes in cropping patterns

In several areas, there is a decline in the cultivation of traditional spate-irrigated crops. In Pakistan and Yemen, traditional cereal crops, such as sorghum and millet, cannot compete with imported wheat, which is sold at low subsidized prices in the local markets. With increasing prosperity and urbanization, changing taste may lead to deterioration in the position of the local producer compared with that of the importer. Rising standards of living and changing habits can reduce the market for traditional grains, such as sorghum, allowing imported wheat and other cereals to take their place *(Makin, 1977)*. Consumers in Yemen prefer wheat, as the consumption of traditional food grains indicates a low socio-economic status.

Furthermore, research, extension and credit services have been directed to high-value crops, at the expense of traditional spate-irrigated crops, and promoting the use of groundwater for irrigation. The cropping patterns in Wadi Tuban and Wadi Zabid in Yemen have changed dramatically, owing to the remarkable increase in shallow wells since the 1980s. As a result, the area under banana has increased from 20 ha in 1980 to more than 3 500 ha in 2000 in Wadi Zabid (see Figure 6.3), while about 2 300 ha are under vegetables in Wadi Tuban. This shift in cropping pattern has improved the living standard of farmers, but it has mainly focused on the upstream region of the scheme and has led to reduced spate flows to the downstream area and thus has deprived the tail-end farmers of their livelihood. Examples of the cropping patterns adopted in spate-irrigated areas in Eritrea, Ethiopia, Pakistan and are shown in Table 6.5.

FIGURE 6.3
Bananas irrigated by spate flows and shallow groundwater Wadi Zabid, Yemen

TABLE 6.5

Cropping patterns in spate-irrigated areas in Eritrea, Ethiopia, Pakistan and Yemen

Country/region	Cropping patterns/additional information	Reference
Eritrea	Crops usually sown from mid-September after flooding of fields has subsided, and harvested after 90–120 days.	*Tesfai (2001)*
Ethiopia	Two cropping seasons, locally known as hagaya (September – January) and ketena or sorora (April-August). Normally plots are double-cropped under mixed cropping and ratooning system. Usually up to three types of crops (if not varieties) are intermixed in one cropping season.	*Michael (2000a)*
Pakistan		
Kachhi District, Balochistan.	Mixed crop of sorghum, mung bean and moth bean (sown after summer rains in July, August and September). Spring plantings of sorghum and melon made whenever possible. Rapeseed sown after late summer rains, important in some areas. Melon grown on one February-March flooding. Wheat only sown when there are late floods, particularly in late August and September. Main crop of sorghum sown as soon as possible after first summer floods. Rare for these crops to receive a second watering; farmers prefer to expand acreage with subsequent storm water. Irrigation priorities: sorghum, pulses, mustard, wheat.	*MacDonald (1987a)*
Lasbela District, Balochistan.	Sorghum, mung bean, sesame and sometimes guar sown on early floodwater (July-August). Castor sown on floodwater that arrives August-September. Late water stored to grow rape in December (mustard rarely grown due to insufficient moisture). Spring sowings of mixed mung and sorghum or guar as monocrop made if sufficient water (usually grown as fodders). Irrigation priorities: castor, sorghum + guar, mustard.	*MacDonald (1987b)*
Rod-kohi area in D I Khan, Balochistan	Long planting season (February-August) for spring and summer crops; October-December for winter crops.	*Khan M. (1990)*
Chandia, Balochistan	Basic farm system of area fodder, sorghum and livestock is combined with pulses, oilseed and wheat. Sorghum – high value when grown for fodder, often interplanted with pulses, mainly mung. Sorghum ratooned – high return on investment. Wheat grown on finer-textured land (wheat riskiest crop).	*Halcrow (1993a)*
Nal Dat, Balochistan	Planting time for kharif crop June-early July. Crop harvested September-October. Rabi crop sown in October, harvested in April-May.	*Halcrow (1993b)*
Kharan, Balochistan	Wheat sown October-December; no wheat grown unless there are floods. Wheat harvested April-May. In drier years, wheat and sorghum used for fodder.	*BMIADP (1994)*
Balochistan	Early monsoon floods used to grow sorghum; subsequent floods used for oilseeds. If monsoon arrives late, moisture stored and a wheat crop grown.	*van Steenbergen (1997)*
Toiwar, Balochistan	In the kharif season cropped area is restricted owing to shortage of water.	*Halcrow (1998)*
	Melon and pulses more drought-resistant; maize sensitive to water stress.	*Rehan (2002)*
Yemen		
Wadi Rima	Lentil, cowpea, bean and sometimes watermelon sown in the rows between the millet, if farmer thinks soil moisture sufficient. Sorghum most widespread and profitable crop (75 percent of total value of crop production in an average year). Bulrush millet has superior drought-tolerance. Maize locally important. Cannot be reliably grown under single-spate irrigation, but popular under more regular wadi irrigation. Cowpea undercropped beneath both sorghum and maize. Cotton main cash crop. Usually several floods in March-May, which allows production in most years of early subsistence crop of sorghum or millet. Sesame less important, but is apparently expanding under spate and pump irrigation.	*Makin (1977a); Pratt (1977)*

Country/region	Cropping patterns/additional information	Reference
Coastal areas of the Yemen	Two distinct flood periods – seif (March-May) and kharif (July-September).Seif floods permit the cultivation of a few field crops on a limited area. Crops include melon and sorghum, either as grain-cum-fodder if left till harvest, or green fodder if harvested 50–60 days after planting. Kharif floods permit the cultivation of several field crops on a larger area. These crops include the main cash crop (long and medium staple cotton), sorghum, millet, sesame, melon and, more recently, groundnut (on a limited area).	*Mu'Allem (1987)*

Another trend is that state-organized cultivation is declining and with it the cultivation of cash crops such as cotton and castor. Both in south Yemen and in Sudan, cotton was common in the spate systems until the 1960s and processing and marketing facilities were in place. In the Gash system, government-organized cultivation of castor replaced it but in the end in all areas state monopolies ceased to exist and farmers were given the freedom to choose their own crops.

Cropping patterns in farmer-based, spate-irrigated areas are strongly influenced by the priority given to subsistence crops, the need to grow forage to support livestock and the strategies that farmers adopt if there is insufficient water. In Balochistan, farmers at the head of the system, who normally receive a more reliable supply, can follow a cropping pattern of mixed sorghum, mung beans and wheat. As water becomes less reliable at the middle and tail-end sections of the system, the cropping pattern changes. If the flood season arrives late, moisture is stored in the soil and wheat is grown. If the flood season is early, sorghum is grown and later floods are used for oilseed *(van Steenbergen, 1997).*

OPTIONS TO IMPROVE AGRICULTURAL PRACTICES

The high risk of crop failure associated with spate irrigation does not leave much space for the classical improvements that are justified in intensive agriculture. There is, however, a possibility that production gains can be obtained through carefully designed changes in agricultural practices.

Traditional versus improved varieties

Farmers mainly use local varieties. Local cultivars are well adapted to their environment, having developed over long periods. Where water supply is limited, a local cultivar can produce both grain and fodder and, if additional rainfall or floodwater becomes available, the yield increases *(Williams 1979).*

In Yemen, local varieties of sorghum and millet have less growth above ground than improved varieties and can tolerate extremely dry conditions by regulating their water use through surface area. There is evidence to suggest that local cultivars have slightly faster, deeper-growing root systems than improved cultivars so that they can exploit moisture held deep in the soil profile *(Williams, 1979).*

In traditional systems, seed is normally retained from one year to the next. The practice of using self-produced seed, however, can lead to diseases. Yet there are very few substitutes for the traditional varieties as agricultural research in most countries has been concentrated on improving the yields of perennially irrigated crops. Seed may be purchased in some instances when self-produced seed becomes liable to disease *(Halcrow, 1993a and b; Goldsworthy, 1975;* and *MacDonald 1987a and b)* and the use of improved seed varieties through exchange between spate areas should be considered more systematically.

Practically no improved varieties have been developed for the purpose of spate irrigation, and when some varieties exist they are difficult to obtain *(Halcrow, 1993a).* In Kachhi District in Balochistan, improved varieties have been shown to have no advantage over local cultivars *(MacDonald, 1987a).* In DI Khan in Pakistan and Sheeb, Eritrea, however, some efforts have been made:

- early-maturing sorghum varieties have been made available to farmers and these give higher yields than local varieties;
- higher-yielding varieties of bajra have been developed, which are not damaged by birds and which grow better in hot and dry conditions;
- a gram variety has been developed which is blight-tolerant, *(Khan, 1990)*; and
- tetron sorghum variety, introduced in Eritrea, has shown better resistance to drought and pest infection.

Finally, although the main focus of research is often on improving crop yield per unit area, the availability and sustainability of a variety is also crucial *(Michael, 2000b)*. Local cultivars still fare well in terms of drought resistance, labour inputs, market values, food values and storage, and these factors need to be given more consideration in research.

Cropping intensities

The extent, size and number of floods affect the cropping intensity and these change from one year to the next *(MacDonald, 1987a)*. Cropping intensities vary widely between and within countries and schemes. The range of copping intensities in Eritrea, Pakistan and Yemen is illustrated in Table 6.6. Clearly, as for yields, fertile land situated close to the wadi and receiving a reliable supply of water will have higher cropping intensities than areas where there is a shortage of water.

Planting density

The amount of water that plants use depends on the quantity of soil moisture that is available, the root growth rate and the extent of root development. The farmer can influence the relationship between these factors by adjusting the planting density on the plot of land according to whether or not further rain or floodwater in the growing season is likely to occur *(Williams, 1979).*

A very dense plant population creates a high competition among the plants for moisture, nutrients and light. As a result of this competition, plants, especially sorghum, grow very thin and tall and the yield is low. Young crop stands of high plant density are more affected by drought than equal stands of lower density. *Williams (1979)* suggests that, in order to use water more efficiently, it may be more suitable to grow cultivars that yield more grain per plant and grow them at a lower plant density. In spate irrigation systems, however, as is the case in Eritrea *(Ogba-Michael, 2004)*, planting at high density may be preferred by farmers for the following reasons:

- a densely grown crop can be thinned and used to feed their animals, which do not have any other source of feed;
- Waterlogging and infestations of insects such as locusts and heavy attacks by birds can kill young plants. These problems reduce the plant population as well as the yield. To cope with such problems high-density planting is preferred; and
- Densely grown plants suppress weeds and the majority of the farmers do not practice weeding.

TABLE 6.6
Cropping intensities in spate-irrigated areas of Eritrea, Pakistan, and Yemen

Country/region	Cropping intensity (%)	Notes	Reference
Eritrea			
Sheeb area	165		*Tesfai (2001)*
Pakistan			
Kachhi District, Balochistan	30–40	Typical overall cropping intensity	*MacDonald (1987a)*
	90–120	Cropping intensity for irrigated areas – depending on the small amount of sequential cropping of wheat and April-planted fodder.	
	150–180	On land that is well and regularly watered, when a sorghum-mung-moth crop and an early sorghum crop are grown back to back.	
Lasbela District, Balochistan	30–60	Typical values in sailaba areas can rise to 120 percent overall in exceptional circumstances with very reliable flooding. Individual bundats may have cropping intensities of 200 percent at a time. In rainfed areas, cropping intensity can be as low as 20 percent.	*MacDonald (1987b)*
Yemen			
Wadi Rima	150	Spate irrigation has a high water use efficiency – though land at the end of most canals receives spate on such an irregular basis that it is basically rainfed.	*Makin (1977)*
	230	Areas receiving regular spate irrigation (significant area of sorghum ratoons).	
	130	Areas receiving irregular spate irrigation (11 percent of area lies fallow in any one year) – success in cropping depends to some extent on timely rainfall.	
Wadi Mawr	'High'	Cropping intensities in main spate irrigation areas lying close to wadi are generally good because of the concentration of good arable lands and the more reliable water supply.	*Tipton and Kalmbach (1978)*
Wadi Bana and Abyan Delta	33–143	Reflects uncertainty of water supply – increases from north to south.	*Atkins and Partners (1984)*

Fertilizers

In most spate-irrigated areas, there is minimal use of chemical fertilizers *(Goldsworthy 1975; Tipton and Kalmbach, 1978; Atkins and Partners, 1984; Shah, 1990; Halcrow, 1993b; Michael, 2000a; and Tesfai* and *Stroosnijder, 2001)*, or organic fertilizers such as manure *(MacDonald, 1987a; Halcrow, 1998; Michael, 2000a;* and *Tesfai and Stroosnijder, 2001).* Farmyard manure is used in some areas of Balochistan (Pakistan) where soils are sandy and recognized as being relatively infertile *(MacDonald, 1987b).* Incorporating crop residues in the soil is also generally not practised, as they are often used as fodder.

It is usually taken for granted that yields could be increased with greater investment in fertilizers, combined with improved cultural practices and adequate irrigation *(Tipton and Kalmbach, 1978; Mu'Allem, 1987; Khan, 1990;* and *Shah, 1990).* While this was true in the case of improved high yielding varieties in the coastal plains in Yemen (Table 6.7), the yield of local varieties in the same region did not respond to the input of fertilizers *(Goldsworthy, 1975).*

Most spate farmers believe that their soils are naturally fertilized by the fine sediments that are deposited during flood irrigation. Floods often carry around 10 percent in weight of fine silts that are deposited on the fields. *Gilani (1990)* reported that the floodwater in DI Khan in Pakistan contain up to 35–40 percent silt. Silts are usually rich in plant nutrients and possibly nitrate *(Atkins and Partners, 1984; Shah, 1990; Tesfai, 2001). Mu'Allem (1987)* reported that a 1 m depth of irrigation with heavily silted water spread over 1 ha, contains 0.92 kg nitrogen, 0.01 kg phosphate and 11.02 kg potash. However, the origin of floodwater affects its nutrient value. In the Sheeb area in Eritrea and when spate flows come from nearby hills and mountains, which have little vegetation cover, the sediment is poor in nutrients. Runoff from the highlands, where land is used for agriculture, contains organic matter and plant nutrients. Although soils in Sheeb receive inputs of total N, P and K from spate flows, soils are in fact low in N and organic matter. The application of organic fertilizers would thus increase the organic matter content of the soil and improve the water storage and nutrient retention capacity of the soils *(Tesfai, 2001).* These questions and possible improvement options are discussed in detail in Chapter 5.

TABLE 6.7

Yield responses of spate crops to nitrogen fertilizer and improved cultural practices in the coastal region of Yemen

Crop	Long staple cotton	Medium staple cotton	Sorghum/ millet	Sesame	Melon	Groundnut shelled seed
Treatment	**Yield (kg/ha)**					
Nitrogen at (9.3 kg/ha) and improved agricultural practices	221	339	212	121	2482	263
Control yield	147	226	151	81	1711	202
Increased yield over control	74	113	61	40	770	61
Increased yield over control	50%	50%	40%	49%	45%	30%

Source: Mu'Allem, 1987

In the Sheeb area in Eritrea, farmers believe that mineral fertilizers and manure burn the crops *(Tesfai, 2001)*. However, if manure is applied after irrigation has finished and before the seeds are sown, fertilizers will be retained in the soil, and manure will decompose and dissolve so that germinating seeds do not get burned *(Tesfai, 2001).*

There are, however, other factors that contribute to the limited use of chemical fertilizers. These are:

- the cost, as the use of chemical fertilizers depends on the availability of credit to farmers;
- the lack of experience of farmers in the use of fertilizers and pesticides;
- the availability of chemical fertilizers; and
- the high level of risks that fertilizers will be washed off by uncontrolled irrigation.

It is, however, to be noted that much of the literature on fertilizers comes from the 1970s and 1980s, when large investments in spate irrigation were being made in Yemen and Pakistan and tended to be biased towards the larger spate systems where there was some agricultural extension support to farmers. More site-specific studies, carried out in small farmer systems rather than in the controlled environments found on research farms, are needed to develop clear guidance on cost, benefits and attractiveness to farmers of the use of increased inputs in spate cropping.

Pest and disease control

As the cropping pattern in many spate irrigation systems is dominated by monocultures and large areas are planted at the same time, the impact of pests and diseases can be dramatic. The use of pesticides and insecticides is rare as most farmers lack the financial resources to apply these products. Following a number of insect attacks, which affected the quality and quantity of the crops, several types of crops were not cultivated in the Sheeb area in Eritrea during the 2000–2001 cropping season *(Kahsaye, 2002).* In Eritrea and Ethiopia, crop damage by birds is widespread, especially of sorghum.

The traditional cropping system is designed to be flexible enough to cope to a certain extent with inevitable crop failures induced by pests and diseases. At the beginning of a cropping season, a late-maturing, high-yielding crop is planted. If this crop fails because of over-flooding or shortage of water or pest and insect attack, it is replaced by an early-maturing and drought-, pest-and disease-tolerant variety, which is usually a low-yield variety.

Some adaptive research has been conducted by local agricultural institutions in spate-irrigated areas to introduce crop varieties that are high-yielding and at the same time resistant to drought, pest and bird damage. Examples include Bajar and Hijeri sorghum varieties in Pakistan and Eritrea respectively, which were tested and found to be less affected (as compared to other local varieties) by drought, pest and bird damage *(Khan, 1990* and *Mehari, 2007).* Such adaptive research on crop varieties should be promoted as an integral component of crop productivity improvement projects and endeavours.

Crop rotation

In many areas, crop rotation is not practised and in most cases farmers are not aware of its benefits. In Wadi Rima in Yemen, for example, no crop rotation is practised. As a result of continued monoculture, soil fertility is declining, yields are decreasing and plant pests and diseases are multiplying. In contrast to the situation in Pakistan, there is no leguminous crop in the rotation in Yemen which by nitrogen fixation could build up fertility for the succeeding crop *(Goldsworthy, 1975).* Where practised, crop rotations may be relatively simple. In Chandia in Balochistan, for example, the crop rotation is sorghum, fallow and oilseed. However, in most areas, and with increasing population pressure and the pressing need to grow subsistence crops, improving rotational practice is not seen as a priority by farmers *(Makin, 1977; Halcrow, 1993a;* and *Shah, 1990).*

FIGURE 6.4
Sorghum ratooning

Ratooning

Sorghum ratooning (see Figure 6.4) provides a high return on investment. In the Sheeb area in Eritrea and when there is sufficient floodwater, sorghum can produce a main crop, a first ratoon crop with grain yield and a second ratoon crop of forage only, without the application of any fertilizers *(Tesfai, 2001)*. When the main crop has matured, the remaining moisture in the soil profile is deep and, unlike new seedlings, a ratoon crop is able to extract this moisture. Ratooning also saves on material and labour, as land does not require preparation or sowing and there are no seedlings to tend. The length of time between sprouting and harvesting is always shorter 70–80 days) in a ratoon crop than in a seeded crop *(Halcrow, 1993a;* and *Tesfai, 2001).*

GRAIN STORAGE

In Eritrea traditional grain storage causes 4–14 percent crop loss *(Haile et al., 2003)*. Investigations by an NGO working in the spate-irrigated area of Daraban Zam in Dera Ismail Khan in Pakistan, found that grain storage losses averaged 7 percent for a several reasons: the work of insects and pests; the storing of grains before they were completely dried and the high moisture in storage spaces. Grains were typically stored in 50 kg plastic bags or earthen containers that were usually not tightly closed. Storage spaces were in most cases multi-functional and shared with residential or animal husbandry functions. A number of low-cost changes were introduced that brought down storage losses to less than 1 percent:

- cleaning of grain prior to storage;
- construction of special storage place;
- fumigation of seeds affected by pests and diseases;
- improved storage containers:
  - earthen containers of (150 x 90 x 120) cm, containing 1 200 kg of grain, separated from the walls and floors, containing an opening closed with a wooden plug;
  - large polyethylene bags (binda), containing 2 000 kg of grain, placed on an elevated platform and tightly closed with plastic sheeting on top;

THE ROLE OF LIVESTOCK

Because livestock is an integral and important component of the livelihoods of households in most spate-irrigated areas, livestock support programmes – ranging from restocking after drought and providing para-veterinary services to improvement of fodder availability within the irrigation command area – can make substantial contributions to livestock production (see Table 6.8).

TABLE 6.8
Examples of improvements in livestock production

Improvement	Description	Likely impact	Remarks
Livestock restocking	Making draught animals available after drought or other services on credit or on rotational system	Availability of draught animals will contribute to land preparation	
Veterinary or para-veterinary services	Training of local animal health workers	Most appropriate basic animal health care, especially for transhumant groups or livestock owners	In some cultures it may be best to train women health workers especially for care of small ruminants
Rangeland improvement	Selective closure and floodwater spreading	Rangeland regeneration can be remarkably fast	In many areas there are informal rules for insider and outsider groups, including monetary compensation for using local rangelands

The main source of animal feed is usually crop residues and rainfed grazing lands. A second source is the cultivation of spate-irrigated fodder crops, such as (green)

FIGURE 6.5
Marketing green sorghum as fodder, Yemen

sorghum (see Figure 6.5). In Eritrea and Sudan, ratooning sorghum is an important feed for livestock as well. The cutting of weeds in the fields and along the canals is another source of forage and leaves from trees in and around the spate-irrigated fields are also used to feed animals. For instance, households in the Sheeb area in Eritrea practise 'zero-grazing' from October to May, whereby the animals are fed with cut grass from the fields, to prevent livestock from causing damage to standing crops and to economize on the scarce animal feed. Farmers in the northern part of Amhara State in Ethiopia have moreover indicated that spate irrigation has boosted the availability of animal feed through a significant increase in biomass production. The improved availability of animal feed has improved household income generated from livestock products.

A less common but potentially important practice is irrigation of grazing land. In the Gash flood plains in Sudan, large areas are covered with a variety of annual and perennial grasses through seasonal flooding with excess floodwater from the Gash River. According to traditional water governance practices, the first flood in the river is diverted to the extremes of the scheme in order to stock drinking-water for livestock and to irrigate the grazing lands, so that animals will be kept away from the planted crops. However, increased mechanized farming activities on traditional grazing lands, as well as the migration of additional livestock herds from other areas, have increased the pressure on the remaining rangelands, which are gradually deteriorating.

Under the Artificial Groundwater Recharge Project on the Gareh Bygone Plain in Iran, the average yield of indigenous vegetation on spate-irrigated rangeland was 11 times higher (445 kg/ha) than for rainfed land (42 kg/ha), whereas the average crown cover was 31 percent for spate-irrigated rangeland against 16 percent for rainfed grazing land. If the yield of the planted quail bush is also added, the overall yield for spate-irrigated rangeland is 23 times higher, which is enough to graze four sheep on one hectare for an entire year *(Kowsar, 1999)*.

Spate irrigation aimed at producing fodder for pastoral communities was tried in Turkana district (Kenya) in the late 1980s. This was done with large temporary brushwood diversion weirs with graded canals to facilitate the overtopping and uniform spread of the water on the land. Although they were quite productive, these structures were not sustainable since they had been constructed through food-for-work programmes with little concern for community ownership.

AGROFORESTRY

An important element in spate agriculture is agroforestry. Spate irrigated trees are often planted on field bunds and in outwash areas. In the Shabwah Governorate in Yemen, each household has between 25 and 50 species of zizyphus trees in and around their spate-irrigated fields for beekeeping, fodder, fruits, timber, fuelwood and medicinal uses, whereas spate-irrigating farmers in the Tihama region earn an additional income from the sale of fuelwood and/or charcoal. In the Konso spate irrigation system in Ethiopia, many trees can be found and many beehives have been installed. In the spate-irrigated areas of Pakistan, trees are also common and are used for many purposes. For instance, trees with large spines, such as the acacia species, are used for constructing fences around fields, in order protect standing crops from roaming animals and to build corrals for safeguarding livestock at night. Women use dwarf palms for the production of mats, ropes and sandals. Trees also provide vital shade for livestock during the hot season.

In DI Khan in Pakistan, tree plantations were laid out in specially designated land with a relatively low probability of irrigation. Fields were prepared in diamond shape in order to concentrate runoff and spate releases on the tree plantations. In the Gash in Sudan, there are trees that depend on the excess flooding of vast areas of the plains outside the Gash spate irrigation scheme.

In the floodwater-spreading areas of the Gareh Bygone Plan in Iran, eucalyptus and acacia species were planted in a sedimentation basin of about 3.6 ha and the average yield after eight years was 60 m^3/ha of stem wood and 18 m^3/ha of fuelwood. In a less flooded area of 6 ha, the average yields for stem wood and fuelwood were 39 m^3/ha and 11.7 m^3/ha respectively. The annual carbon sequestration potential of spate-irrigated eucalyptus is 3 699 t/ha, and 3 392 t/ha for acacia. It is estimated that the annual income from stem wood, fuelwood and fresh leaves could be US$290, which is substantial, considering the low risk and very low capital investment. Other noticeable incomes could also be derived from forest by-products, such as forage, food products, pharmaceuticals, honey and beeswax.

In the Tihama region in Yemen, tree coverage has increased with many important multifunctional indigenous trees. The most important ones are *Zizyphus spina-christi*, for high-quality honey, forage, timber wood, fruit, detergent (from the dry leaves) and camel fodder; *Salvadora persica*, used to produce toothbrushes (from the roots) and food condiments (fruits) and also used to stabilize sand dunes; *Balanites aegyptiaca* for shelter, camel feed and fruits; and *Acacia ehrenbergiana*, providing prime-quality honey, forage, goat fodder and charcoal wood. The moisture captured from the acacia charcoal (*keteran*) is used for skin treatment of livestock *(Haile and Al-Jeffri, 2007).*

Agroforestry offers multiple advantages and trees are well adapted to the uncertainty associated with spate irrigation. In particular, growing nitrogen-fixing trees like acacia species can help to improve soil fertility. The wood can be used as fuel as there is a high demand for fuelwood in the area to replace cow dung, that can then be used as a fertilizer, leading to better yields. Trees can be used as a source of fodder and provide crops with some shelter. *Iqbal (1990)* and *Kowsar (2005)* have proposed an alternative mixed system of raising trees, agricultural crops and livestock simultaneously in spate-irrigated areas in Pakistan and *Tesfai (2001)* refers to the potential for growing trees along field bunds. Box 6.1 shows the value of trees for bee-keeping in Yemen, Ethiopia and Pakistan and Table 6.9 gives examples of possible improvements in agroforestry practices.

AGRICULTURAL EXTENSION, TRAINING AND RESEARCH

Although there is considerable scope for crop productivity improvement through extension and research, these services are usually poor and ill-adapted to the specific concern of spate-irrigated areas. Many regions lack a resident extension service supporting spate irrigators, and when this is available, agricultural research and extension services do not meet spate farmers' development needs *(Khan A B, 1990; DHV, 1988)*. In Pakistan, the spate-irrigated areas lie in the most marginalized and socially low-ranking districts *(Van Steenbergen, 2003)*. This is reflected in the decision making and resource allocation for the irrigation sector at the national level. The bulk of investment in agricultural research and physical development has gone into perennial-canal-irrigated agriculture. Spate irrigation is not part of the agriculture or engineering curriculum in any formal educational institution of the country. The lack of academic knowledge and the lack of empathy among decision makers for the marginalized communities that practice spate irrigation have negatively affected state support for extension, training and research. Yet, the spate-irrigated sector accounts for more than 1.5 million ha and has potential to reconcile food security with natural resource management in a very fragile environment *(ICARDA, 1998).*

BOX 6.1

Use of trees by spate farmers in Yemen, Ethiopia and Pakistan

In Yemen, the honey from *Ziziphus spina-christi* and *Acacia ehrenbergiana* is fetching the highest prices for honey anywhere in the world. Each household in Shabwah Governorate has between 25 to 50 ziziphus trees in and around their spate-irrigated fields for beekeeping, fodder, fruits, timber, fuelwood and medicinal uses. In the Tihama area in Yemen, trees are cut and sold directly as fuel or used to produce charcoal for sale. The smouldering wood of *Acacia ehrenbergiana (ketaran)* is carefully collected and used to treat skin diseases of goats, donkeys and camels. In Ethiopia, a large number of trees, such as acacia, are found in the command areas of spate irrigation systems in Konso, where many beehives have been placed. In Pakistan, trees such as tamarisk are common in the spate-irrigated areas in Balochistan and Dera Ghazi Khan and Punjab. They are used for many purposes, including their use and sale as fuel, either as wood or charcoal. Women use the dwarf palm for making mats, ropes and sandals. Trees with large spines, such as the acacia, are used to construct fences to protect crops from animals and to corral livestock.

Source: Verheijen (2003)

TABLE 6.9

Examples of improvements in agroforestry practices

Improvement	Description	Likely impact	Remarks
Spate-irrigated trees	Combination of local water harvesting and planting high-value (grafted) tree crops.	High-value use of 'outwash areas' – that may otherwise have little value.	
Uprooting of invasive species	Uprooting of mesquite manually or mechanically; processing into charcoal	If not controlled, mesquite will invade spate fields and channels.	Mesquite is a problem in spate areas in Sudan and Yemen (Tihama).
Improved marketing of non-wood forestry products	Improvement of marketing of high-value, non-wood products, such as honey and medicinal products.	Can add significant farm incomes.	Range of products such as detergents, traditional medicines and fodder. Zizyphus and acacia honey fetch US$30/kg in Yemen.
Local tree cutting bans	Bans on using trees for external sales of charcoal production.	Will protect trees in common lands.	Effectively enforced in Sheeb in Eritrea.

Research into a wide range of topics is needed to increase yields and the returns from spate irrigated agriculture. These topics are listed in Table 6.10 *(Goldsworthy, 1975; Makin, 1977a; Williams, 1979; Atkins and Partners, 1984; MacDonald, 1987a and b; DHV, 1988; Khan A B, 1990; Michael, 2000b; Rehan, 2002).* Furthermore, it is important to improve the link between research and extension *(Michael, 2000b)*. Research needs to be systematically carried out in consultation with farmers, in farmer-led trials and experiments on working spate systems and through farmer-to-farmer demonstration activities and get away from the 'research farm' approach. Of particular relevance to research in spate irrigation is the integration of indigenous technical knowledge with scientific knowledge to increase productivity and ensure sustainability *(Tesfai, 2001)*.

Of these research topics, possibly the most important is the development or the dissemination of higher-yielding but drought-resistant varieties and of improved water management and soil moisture conservation practices.

TABLE 6.10
Research topics needed in spate irrigation

Seeds and cropping pattern
Drought-resistant crops
Propagation of seedlings
Establishment of seed banks
Potential for high-value crops (e.g. mushrooms, wild vegetables)
Improvement of existing mixed/intercropping systems
Land preparation
Land preparation before flooding
Land levelling
Farm tools and mechanization
Time of sowing
Crop spacing and plant density
Crop management
On-farm water management (including depth of water retained)
Moisture conservation through mulching or deep tillage
Soil conservation
Fertilizer applications
Weed and pest control (including documentation of indigenous pest management practices)
Harvesting and crop storage
Harvesting methods
Post-harvest methods
Improvement of crop storage
Other
Use of tree crops
Improving animal nutrition
Improvement of sharecropping arrangements
Land distribution practices

Chapter 7

Water rights and water distribution rules

SUMMARY

Water distribution rules and rights have evolved over time in traditional systems to help mitigate the unpredictability that is inherent in spate irrigation and reduce the risk of conflict by regulating relations between land users that have access to floodwaters. The way rights are defined in spate systems is different from the way they are defined in perennial systems. In spate irrigation, water rights describe acceptable practices in a given situation, rather than quantifiable entitlements to a resource. Water distribution rules make it easier to predict which land will be irrigated. They define the likelihood of irrigation for different areas and hence serve as the key to the collective maintenance and rebuilding of diversion infrastructure. The rules and rights are therefore also at the core of the arrangements for maintenance, the landowners who contribute to the labour-intensive maintenance being rewarded with access to the inherently unpredictable spate flows.

A clear understanding of existing water rights and rules in a given spate irrigation system and a good comprehension of the possible impact of external interventions on existing water distribution and system maintenance rules and practices are essential. They will help set up water distribution rules in new systems, identify opportunities for improvement in enforcement and modification of water rights, take into account new circumstances and the way they affect distribution rules and avoid unintended drawbacks of the proposed changes.

Demarcation rules define the area entitled to irrigation. They often protect the prior rights of downstream landowners, by prohibiting new land development upstream, which could result in the diversion of floodwater to new lands. Closely related to the demarcation rules are those concerning the **breaking of diversion** structures, or the timing of a water right. The rules on breaking bunds are usually in place in areas where the entire wadi bed is blocked by earthen bunds, as in the lowland systems in Pakistan. The **rules on flow division** between irrigation channels arrange the distribution of water between the different flood channels. A fourth category of rules is the **pre-arranged sequence** in which fields are irrigated within the irrigation system. A fifth type of rules concerns the **depth of irrigation** and is expressed in agreements on the height of the field bunds, which determines the amount of floodwater that can be stored in the fields. A sixth category of rules is the **right to a second water turn**. In many systems, floods come and go and a season may bring a series of spates, posing the problem of distribution of a sequence of floods. Two options are possible, either the option of upstream landowners to take a second turn, or the obligation to restart irrigation from the place where it stopped the previous time. Finally, there are rules that take into account the possible changes in the wadi bed and in land elevation inherent in arid land hydrology and concern the location of diversion and other structures and compensation for lost land.

All the above rules impose a certain predictability and equity while ensuring efficiency in the use of the resource. The first three rules prevent the water from being monopolized in the head reaches of the flood irrigation system. The sequence rules, in turn, identify priority areas, and equity issues are significant in the fifth and seventh rules. The sixth rule shows how spate systems attempt to balance efficiency with equity in water distribution.

Maintenance is as important as water distribution in spate irrigation, and water distribution rules dictate the way maintenance is organized. In many systems, the right to irrigation by spate flows is in proportion to one's contribution to repairs to the headwork or flood channels. If one abstains from public duty, one is simply not allowed to open the intake to one's field. Water distribution rules often serve to create a reasonably coherent group of land users who are dependent on the spate system and jointly undertake the maintenance of the structures.

Of crucial importance to maintenance is the critical mass required in undertaking repairs. This is particularly relevant when repairs depend on human labour and draught animals and a large force is required to rebuild structures and make repairs. When tail-end users are systematically deprived of flood water supplies, they may no longer want to contribute to the maintenance. The critical mass factor hence works as a way of avoiding too large inequity in water distribution. However, the importance of critical mass may be expected to diminish when maintenance becomes mechanized or directly undertaken by government organizations.

An important requirement of the maintenance rules in place is their robustness, i.e. the degree to which they will ensure the constant rebuilding of the common works. This is particularly challenging when there is substantial work to be done and it is highly probable that years will pass without irrigation for much of the command area. In these circumstances, contributions based on land shares usually have a greater resilience than those based on benefit, capacity or contract (see details in the text).

The extent to which water rights and rules in spate irrigation are enforced depends mainly on the social structure within the community and the level of the overall governance in the area. Spate systems need a far greater degree of discipline than other resource management systems and the rules must be observed by the majority of the farmers. This can be achieved only when there are local organizations that are accountable to most farmers and that apply well accepted enforcement approaches that take into account the social structure of the communities concerned.

Enforcement of water rights and rules in spate irrigation is closely related to the authority of local organizations and government institutions and to the level of codification of water distribution rules. Traditional spate systems usually have well established local governance. In larger systems enforcement of rules is usually done through a mixture of user organization and local government. The role of local government is in such cases to regulate local water distribution arrangements, organize maintenance by water users and solve disputes. In some spate systems, the rules are codified. Codifying water distribution rules clarifies and completes local water management arrangements and introduces a neutral factor in resolving disputes.

Water rights in spate systems are not static. They change in accordance with new situations created by various factors. Amongst those factors are the increase in population and the pressure for new land development, changes in cropping patterns and new market opportunities, the introduction of more permanent spate diversion structures, the shift in power relations, and the changing levels of enforcement. One of the main challenges faced by users of spate irrigation is the decline in the authority of the organizations charged with spate governance. It is particularly striking – as one might expect the opposite – that enforcement has declined as water has become scarcer. There are different reasons for this:

- competition with more labour-rewarding opportunities;
- increased use of groundwater in the spate command areas, leading to reduced need for collective action;
- confusion of responsibilities following public intervention and investment in the system; and
- reduced importance of collective action with the introduction of mechanized power.

Structural improvements in spate systems have implications for distribution and maintenance rules, which need to be considered carefully in the design phase. The construction of new permanent and more robust headworks often result in better upstream control, integration of previously independent systems, more controlled flow and changes in the maintenance requirements. Usually systems are integrated to obtain economies of scale that can justify the large investment required in civil works. Such changes bring together in one single system communities of farmers that may have little interaction between them. If not considered carefully at the outset, such a situation can lead to intractable social problems or even prevent improvement projects from materializing.

Interpretation of rules and their implication for the design and operation of new infrastructure is best done directly by farmers, with discussions facilitated to help them understand the proposed arrangements and the actions to be taken to respond to changes in the system. For existing spate irrigation systems, water rights and actual practices need to be investigated, shared, agreed and, where possible, even codified. For new schemes, a basic set of water distribution rules needs to be agreed with farmers when the schemes are designed. They should be widely shared and arrangements for supervision and enforcement agreed upon. It is desirable that any water distribution arrangements have a high level of flexibility to adjust to unforeseen circumstances. Robust arrangements on management and agreement are more important than detailed specifications on how water is distributed.

Changes in spate irrigation systems usually affect existing rules and local organizations. They are often accompanied by changes in the legislation. This legislation is vital for providing farmers' organizations with the legal recognition and the authority they need to collect and manage water fees, run independent bank accounts, make direct contacts with funding agencies and own or hire machinery and other necessary assets for water management. Ensuring financial and organizational autonomy, however, requires more than legislation. It calls for support of the organizations through capacity-building programmes that include financial accountability, and a technical package with clear operation and maintenance guidelines.

MANAGING UNPREDICTABILITY

Water distribution rules and rights help to mitigate the unpredictability inherent in spate irrigation. Rules and rights impose a pattern and reduce the risk of conflict, by regulating relations between land users that have access to floodwaters. Rights are defined in a different way in spate systems from the way they are defined in perennial systems. In essence water rights in spate systems are reactive. They deal with agreed claims in a changing and variable environment. They describe acceptable practices in a given situation, rather than quantifiable entitlements to a resource, as in perennial systems.

Water rights and water distribution rules in spate irrigation regulate access to water and hence minimize conflict. Water distribution rules make it easier to predict which land will be irrigated. As such, they encourage land preparation by pre-flooding, which is important for adequate water storage and moisture conservation (see also Chapter 5). Water rights and water distribution rules also define the likelihood of irrigation for different areas and hence serve as the key to the collective maintenance and rebuilding of diversion infrastructure. In particular, where floodwater users depend on one another for maintaining flood canals and reconstructing diversion structures and if this work is substantial, agreement on how water is distributed is a precondition for cooperation. However, water distribution rules are not necessarily finely detailed. *Serjeant (1980)* makes this point for instance for Wadi Rima, Yemen, noting that “many of the disputes seem to lie dormant, though not forgotten, … they can spring to vigorous life with some new turn of circumstances”. *Al-Maktari (1983)* makes a similar observation for the unwritten customary rules in Wadi Surdud.

Water distribution rules also have to be placed in the context of medium- and long-term changes in flood irrigation systems. Increases in land levels and changes in wadi courses and flood canals are almost unavoidable. Spate irrigation systems are morphologically far more dynamic than perennial irrigation systems. Water distribution rules deal both with reducing and mitigating the risk of such dramatic long-term changes, as well as coping with them when they come along. In the end water distribution rules tend to be packages describing the distribution of floodwater, the way maintenance is organized, the practices for avoiding breaches and changes to the command areas and the arrangements and penalties associated with operating the rules. Table 7.1 summarizes one such set of rules for the Kanwah spate river (Rod-e-Kanwah) in Dera Ghazi Khan District in Pakistan. The rules were recorded during a land settlement of 1918/1919 and are still used.

The remainder of this chapter describes the most common types of water distribution rules, including the rules on protecting command area boundaries and on maintenance. It describes how the rules are enforced. There is a strong relation between the overall governance in an area and the local organization for spate irrigation and the codification of the water distribution rules in particular. The final section describes how changes in water distribution are caused and how they take effect. Several recent engineered interventions in large spate schemes have unwittingly altered water distribution rules by creating new opportunities for different players. The reactive nature of water distribution rules in spate systems has often led to a gradual accommodation of these new opportunities. The purpose of this chapter is to increase awareness and understanding of water rights and the changes therein, so as to:

- support the development of water distribution rules in new systems;
- understand the process of codifying and enforcing water rules and rights and identify opportunities for improvement in enforcement and modification of water rights; and
- understand the impact of interventions on existing water distribution rules and practices and avoid the worst pitfalls.

TABLE 7.1
Water management rules in Rod-e-Kanwah (Kot Qaisrani, DG Khan, Pakistan)

Water distribution	Command area protection
• Water distribution starts from the head and goes to the tail. • When, after a first irrigation the upstream fields are watered but the downstream fields are not irrigated sufficiently, then the upstream field can still take precedence in using the second flow. • There is no limit on depth of irrigation of an upstream field (though this rule exists, it is not always practised and is conditioned by the crop sowing, maturity time, etc.) • Nobody can sell or donate his share of water. In land transactions, water is transferred as well. • A field cannot be supplied by more than one diversion structure. • If a bund in a flood channel irrigates two fields, water will first be applied to the higher land. • When a diversion structure has been washed away during irrigation, it is permitted to construct a new diversion even if water is already reaching other fields.	• Even if fields remain barren for long periods, the right to irrigation remains valid. • The location of a diversion structure, channel intake or division structure can be changed with the mutual consent of landowners. • If, after filling his own field, a landowner delays breaching his diversion structure and a nearby field is destroyed, then the losses will be met by the person who did not breach the diversion structure in time. • No person has a right to construct a new branch/flood canal that deviates from the prevailing situation. However, when the channel has changed naturally, then a new flood canal can be constructed, provided the earlier flood canal is completely damaged. • When a person intentionally destroys the water course/diversion, then loss is recovered both for the loss of water and the destruction of the adjacent field(s). • On the reappearance of eroded land, (through siltation), the rights are vested with the original owner.

Maintenance	Others
• Common maintenance work is performed on the basis of area of land. • To maintain the flood embankments close to a main bund is the responsibility of all users of the *ghannda* (diversion bund). • Strengthening the banks of flood canals is the responsibility of the owner of the land facing the wadi bank. • Landowners whose fields are irrigated through overflow *(chal)* and not through bunds and embankments do not take part in the common maintenance work.	• Ownership of the flood channel – including trees within the channel – is based on ownership of the adjacent fields. • A diversion structure can be constructed on one's own land as well as on others' land, wherever it is most suitable. • Nobody can expand his land by encroaching upon the river bed. • When a shareholder does not contribute his labour during the specific period, he will not have a right to water in the current year. If he wants to contribute in future, then he will have to compensate for the previous year's costs of common labour and provide eight days' labour as a fine.

RULES AND RIGHTS

There are several types of rules that regulate the distribution of the varying quantities of floodwater. Not all rules apply in every system, but it is usual to find that several rules are used simultaneously. The most common and widely applied rights and rules relate to the following:

- demarcation of land entitled to irrigation;
- breaking diversion bunds;
- proportion of the flow going to different flood channels;
- sequence in which the different fields along a flood channel are irrigated;
- depth of irrigation that each field is entitled to receive;
- access to second and third water turns; and
- distribution of large and small floods.

In addition there are rules that regulate changes in the command area and system morphology. These are related to:

- maintenance of bunds and boundaries;
- adjusting the location of intakes and other structures;
- manipulating wadi bed and flood canal scour and siltation processes; and
- compensation for lost land.

WATER DISTRIBUTION RULES

Rules on land demarcation

Demarcation rules define the area entitled to irrigation. As such, these rules precede all other water distribution rules. They define the command area and within it the land users who have access to the spate flows. Demarcation rules often protect the prior rights of downstream landowners, by prohibiting new land development upstream which could result in the diversion of floodwater to new lands, formation of a new group of stakeholders and the loss of farming systems and other established water uses downstream. This can result in violent conflicts, particularly in areas where irrigation development is relatively new. There is a long history of disputes on water rights in Wadi Rima, Yemen, related to the construction of 'illegal' upstream canals. In some cases, expansion into new areas is possible within the rules, though they do not explicitly include such a use in origin. Usually this is possible in downstream areas but examples have occurred in upstream regions too. Thus land demarcation may sometimes not be a strict rule in such situations. In some other cases, common lands can also be brought under irrigation, although the original rules do not give them a clear entitlement to irrigation.

The demarcation of the outer boundaries of a spate irrigation scheme also ensures that overspill from breaches in flood channels does not develop into an established practice *(van Steenbergen, 1997).* The consequences of such demarcation rules are the penalties for negligence in the maintenance of bunds and channels. In the spate systems of the Suleiman range in Pakistan, explicit agreements exist, obliging landowners to plug gullies that have developed after severe floods. This is to prevent new drainage patterns developing in these soft alluvial plains. Similarly, in Eritrea and South Yemen farmers are penalized for not maintaining field bunds, which could cause water to escape to new areas. Such rules, however, are not in force everywhere.

In some systems, there are 'sanctioned' overspill areas. Though they do not have a recognized claim to the spate flows, the custom is that these areas receive water during unusually high floods. Water is then allowed to escape at certain prearranged points to avoid damaging the canal network downstream.

Like most of the other distribution procedures, demarcation rules are in place when water is scarce. They are more common in lowland systems, where land is abundant, than in highland systems.

Rules on the breaking of bunds and timing of water rights

A category of rules closely related to the rules on the boundary of the spate area concerns the breaking of diversion structures, or the timing of a water right. The rules on breaking bunds are usually in place in areas where the entire wadi bed is blocked by earthen bunds, as in the lowland systems in Pakistan. The earthen bunds are generally made in such a way that they scour out in high floods. This works as a safety valve (see also Chapter 10). It avoids substantial damage to the canal network, as very large floods flow down the river rather than damaging canals and fields. In several systems, there are also rules on when farmers can break bunds, for example once the designated area served by an upstream bund has been irrigated or when a certain time slot of the flood season has elapsed. An example of such time slots are the rules for breaking *ganndas* (a local term in Pakistan for an earthern bund that diverts spate flow from a wadi to a main canal) in the Nari spate system in Kachhi, Pakistan and is outlined in Box 7.1. The rules were formalized in 1917 and are still observed, although there is considerable tension concerning the actual breaking of bunds.

BOX 7.1

Rules on Nari system in Balochistan, Pakistan

- From 10 May to 15 August the landowners of the Upper Nari are allowed to make *ganndas* in the Nari River.
- When the land served by one *gannda* in Upper Nari is fully irrigated, the landowners in that *gannda* must allow landowners of the next *gannda* to break it.
- After 15 August the landowners of Lower Nari are allowed to make *ganndas* in the Nari River course.
- Landowners in Upper Nari are not allowed to irrigate their land during this period or let the water go to waste.
- Water is not allowed to go to waste to the low-lying areas east and west of the Nari River. Guide bunds will prevent water flowing to these areas – all landowners will contribute towards these bunds with farmers in Lower Nari paying twice the amount per hectare in case bunds on the Upper Nari are broken.
- If any dispute arises, judges appointed by Kalat State will inspect the area and are authorized to decide whether a downstream party should be allowed to break the *gannda* at an appropriate time or whether a guide bund should be repaired within 5–10 days. If repairs to guide bunds are not made, the main bund of the area concerned may be broken.
- In case a landowner refuses to contribute *gham* (the contribution for maintenance), his land may be confiscated.

The reluctance of upstream land users to have their bund broken is not only because it allows more water to be diverted to the upstream area, but also because it saves the effort of rebuilding the bund in a subsequent year. An example of such a case in the Chakkar River in Balochistan (Pakistan) is given in Box 7.2. Rules based on the time slots when water diversion is allowed in different parts of the system are also found in Yemen. An example from Wadi Zabid is shown in Box 7.3.

Rules on flow division between irrigation channels

This category of rules arranges the distribution of water between the different flood channels (Figure 7.1). Where an area is served by several flood channels, there may be an agreement on the proportion of floodwater going into the different channels. In the Tafilalet Plain in Morocco, for instance, the distribution of spate water between different areas is based on proportions of the flow from Oued Ziz *(Oudra, 2008).* All diversion structures have been designed on the basis of this agreement and a consensus exists to avoid any new construction or change of the existing structures.

In practice, flow division is often achieved by using rather crude hydraulic structures, for example the head sections of flood canals may be of different widths and obstructions may be placed in front of some of the channels to achieve the required division. Flow division may also be practised along a flood channel, with the width of the field intakes determining the proportion of flow that each field receives.

BOX 7.2

Disputes over bund breaking in the Chakkar River in Balochistan, Pakistan

This is a fairly typical example of a dispute on the breaking of a soil bund and concerns the Chakkar Bund on the Chakkar River in Balochistan. In the past, this earthen bund – spanning some 50 m across the river – was constructed using bullocks and tractors. It collapsed every year, as the water seeping through its base undermined the structure. In 1990, the landowners of Chakkar were given a generous allocation of bulldozer time by the government. They used this by making a very strong bund and the bund did not fail that year. It irrigated all the demarcated land of Chakkar and then the Chakkar landowners allowed the water to escape through a breach in their flood channel to an area that was not entitled to floodwater. The same pattern repeated itself in the subsequent year. The Chakkar landowners were not keen on breaking their bund, as they wanted to spare themselves the effort of rebuilding it. This led to fierce protest from downstream landowners, who approached the head of the district administration and argued that he should break the controversial soil bund. However, the verdict of the head of the district administration was only partly a success for the complainants. He reasoned that he could not break the bund since there was no earlier agreement on breaking bunds in the Chakkar River. However, he did maintain the demarcation rules and ordered the Chakkar farmers to repair the breach in the flood channel to prevent water from going to unauthorized channels

FIGURE 7.1

Flow division in a flood canal, Yanda-Faro, Konso, Ethiopia

BOX 7.3

Water distribution in Wadi Zabid

The traditional canals in the Wadi Zabid system are split into three groups, with water rights at different times of the year. These rules were retained when the system was modernized in the 1980s. The canal groups and the periods when they have water rights are:

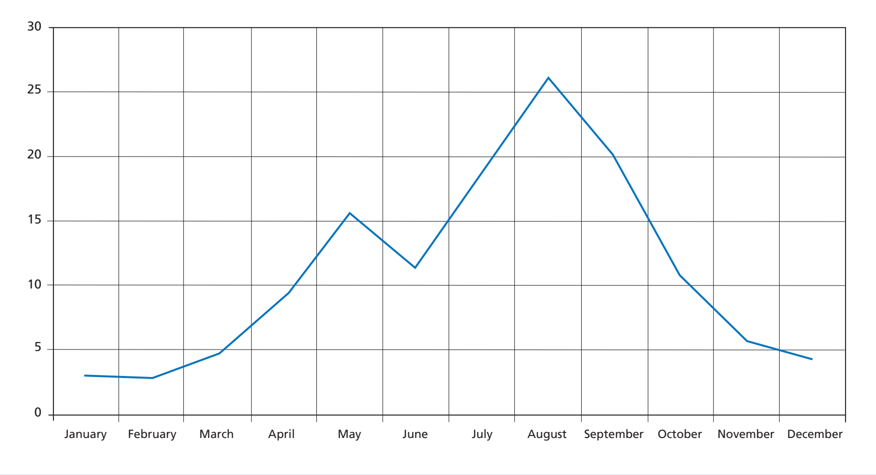
Group	Nominal command area (ha)	Dates
Group 1 (upstream canals)	4 325	29 March–2 August
Group 2 (middle canals)	9 165	3 August–13 September
Group 3 (downstream canals)	1 305	14 September–18 October

Canals within the groups also have water rights at different periods within the group turns.

This allocation gives the upstream canals access to base flows and the first part of the main flood season. The middle reach canals (group 2) have about six weeks during the period when the main flood season occurs to irrigate the largest area. The downstream canals have a shorter period at the end of the main flood season.

Mean monthly flows measured upstream some distance from the first canal offtake are shown below. Some water is lost in minor abstractions and bed seepage between the measuring location and the first canal offtake and little flow reaches the first diversion structure outside the period of the water rights.

Mean monthly flows at Wadi Zabid (million m^3)



Flow divisions within the flood channels may be fixed, but it is more common that there is a large degree of flexibility to adjust to changing bed levels of river and flood canals and to variations in the flow. An example of a flexible flow division is the traditional main division in the flood canal of Wadi Laba in Eritrea, which used to be adjusted by moving brushwood around. During a spate, the water masters of the five main flood channels stood on top of the structure and adjusted it to ensure that the flows to each area were fair, taking into account earlier irrigation. In the same system, a series of gabion command area flow division structures were constructed to distribute water between major command area channels and to stabilize the canal beds. The first designs were conventional, but later, a more flexible structure was developed at the instigation of farmer leaders.

In Balochistan (Pakistan), flow divisions are affected by the canal bed and water levels and slopes and it is unusual to find rules in this area. Conflicts due to changing canal-bed levels, after fertile fine sediment deposits were taken from the channels, are reported in *Ahmad et al. (1998).*

Farmers have also worked out automatic flow division systems: when the quantity of water is small it is diverted to one part of the command area only and the other canals are blocked, usually with a small earthen bund. When flood flows are larger, water breaks the small bunds and flows to several channels simultaneously.

Rules on sequence of irrigation

A fourth category of rules is the prearranged sequence in which fields are irrigated. Where it applies, the route water follows within the area entitled to irrigation is described in detail, in terms of the branch channel that will receive water first and the priorities of the different fields near the branch channels. Irrigation in many cases moves from the head of the channel to the tail *(Maktari, 1971).* In Yemen, the fundamental rule governing the use of spate water for irrigation grants upstream users priority rights to irrigate their fields but downstream users may not be denied the right to surplus water after the upstream users have exercised their rights to divert a quantity of water sufficient to satisfy their needs. Sequence rules are called *numberwar* or *saroba paina* in Pakistan or *ala ala fala ala* or *rada ah* in Yemen.

The sequence is adjusted according to the level the flood reaches. If the flood is low, water will only flow in one or two of the priority branch channels and the sequence rules will apply to those channels only. But, if the flood brings large quantities of water, it will find its way through a large number of channels simultaneously. Moreover, during high floods the force of the water is greater and, instead of being controlled and regulated, it will flow into a large number of fields at the same time.

In some cases, the ‘head reach first’ principles do not apply. One example is the Chandia system in Balochistan (Pakistan), where the upstream area is only supplied at high water levels or after the downstream area has been irrigated. In other systems there are rules to send larger floods downstream on a priority basis.

Rules on depth of irrigation

All the four rules discussed above impose a certain predictability and equity, while ensuring efficiency in the use of the resource. The demarcation of command areas, the rules on breaking of bunds and timing of water rights and the rules on flow division, with the limitations on the width of field intakes, prevent the water from being monopolized in the head reaches of the flood irrigation system. The sequence rules, in turn, identify priority areas. Equity issues are also significant in the fifth type of the water distribution rules, which concerns the depth of irrigation and is expressed in agreements on the height of the field bunds. These field bunds are usually built up from the sediments deposited within the fields. The height of the bunds determines the amount of floodwater that can be stored in the fields.

Rules on the height of the bunds, and hence irrigation depth, are standard practice in Yemen and appear to be based on a ruling of the Prophet Muhammad. The amount of flood flow to be applied to a field with palm trees shall be the depth of two ankles or an amount sufficient to reach the tree trunk. According to the eleventh-century Islamic jurist Al-Mawardi, the underlying principle of this ruling is that the amount of water applied shall be sufficient to water the crop and that it is easy to measure *(Varisco, 1983).* The prevalence of irrigation depth rules in Yemen is probably related to the practice of field-to-field irrigation. In this system, a farmer gets his turn as soon as his neighbour has completed irrigating his land. This is done by cutting the bund surrounding the field of the upstream farmer. Competition between neighbours can be fierce and rules on water depth may have evolved to mitigate this. Moreover, if the bund in the neighbouring field is very high and too much water is impounded, uncontrolled breaching could cause severe damage to the neighbouring fields. These rules, however, are not common in spate areas in Pakistan. It is only in some of the small mountain systems in Balochistan that they are in place, prescribing that the soil for repairing these field boundaries shall be taken from the lower plot (Ahmad *et al.*, 1998).

In contrast, when each field is fed by its own separate intake, as is usual in the spate irrigation systems in Pakistan, such conflicts are rare and rules on the depth of inundation are unusual. The amount of water applied depends on the height of the field bund and the levelling (or the lack of it). Yet in most systems there is no limitation in this respect. Field bunds are seen as a way of disposing of the excess silt that accumulates with the floodwater and can reach any height.

In general, it appears that the height of the field bunds is influenced by two factors: the size of the field and the number of irrigations that are expected. When fields are only approximately levelled, a large field needs high field bunds to ensure that all parts of the fields impound a reasonable depth of water. Fields of 1–2 ha in area with field bunds higher than 1 m are found in Yemen and fields of up to 4–5 ha in area with very high field bunds are found in Pakistan. The field bunds need to be high enough for sufficient water to infiltrate the soil for the intended crop if only one irrigation is likely to occur. When two or more irrigations are probable then less water needs to be impounded and lower bunds are used.

The probability of receiving irrigation is also a factor that influences the height of the field bunds. In the Wadi Rima traditional system in Yemen, low bunds are found near the mountain front where two or more irrigations are almost assured, and the largest bunds, over 1 m in height, are found at the downstream margins of the system where only one large irrigation is possible in years when large floods reach the downstream sections of the wadi or the flood canals *(Makin, 1977).* Figure 7.2 shows high field bunds in Wadi Tuban in Yemen.

Figure 7.3 shows small bunded plots in a spate system at Yanda-Faro in Konso, Ethiopia. The Yandefero system is characterized by a large number of relatively mild floods, allowing a distribution of water not very different from a perennial system, with secondary canals and fields with low bunds.

Rules on second turns

A final category of rules is the right to a second water turn. Several crops, though they may survive on one water application, give significantly higher returns when they are irrigated more than once. Sorghum, wheat and cotton are examples. Sorghum, in fact, is often grown as a ratoon crop to catch an off-season flood. For other crops, like pulses, one watering is sufficient.

FIGURE 7.2
Spate-irrigated fields in Wadi Tuban, Yemen

FIGURE 7.3
Small bunded plots in a spate system at Yanda-Faro, Konso, Ethiopia

In many systems, floods come and go and a season may bring a series of spates. This poses a dilemma: is the water that comes with a second flood to be applied on the land that is already under cultivation? Or, is priority given to those cultivators whose lands are still dry? Both variations exist, either the option of upstream landowners taking a second turn, or the obligation to restart irrigation from the place where it stopped the previous time and irrigate all downstream land before upstream owners can use the water again. Where restrictions are imposed on upstream owners, they usually apply in the planting season. In Morocco it is common that within the same *seguia* the priority of the upstream part is paramount, yet with some exceptions: during the sowing period the irrigation turns will restart from where they were interrupted during the last flood. After this period, generally lasting three months, the rule is to irrigate only those lands that have already been sown *(Oudra, 2008)*. There are exceptional, inter-seasonal cases of downstream water rights, such as those regarding the Jama Bund in Kharan, Balochistan, or Wadi Laba in Eritrea. Here irrigation in the next season starts where it stopped the previous season.

Closely related to the rules on second turns is the size of the command area. Having a relatively small command area makes it possible to irrigate a field more than once – which can have a considerable impact on crop yields, as the second irrigation often 'lifts' the crop out of the stress zone. In Morocco, for instance, the traditional water management system aimed to secure on average two irrigation turns at the earliest time of the flood/irrigation season *(Oudra, 2008).* The farmers believed that a two-irrigation turn was sufficient to secure cereal production (mainly barley); whereas three irrigation turns would cause a bumper harvest.

Rules on large and small floods

Finally, the water distribution may differ according to the size of the floods. One example discussed above is the automatic flow division when floods are large and able to break the bunds in the various flood channels. In other systems there are explicit rules on how to accommodate small and larger floods. Small floods tend to be diverted to the upper sections of the command area, if only because small floods are not likely to travel that far. A rare example of explicit rules dealing with floods of different sizes concerns the Irrigation Plan for Wadi Tuban in Yemen (see Box 7.4).

BOX 7.4

Water allocation rules for Wadi Tuban, Yemen

The principle of *rada'ah* (upstream land first) is applied in Wadi Tuban. It gives precedence to upstream users, who have the right to a single full irrigation of their fields before their downstream neighbours, both between and along the main canal systems. Furthermore, the rule has been established that spate water will not be diverted into fields that have already received either base flow or earlier spates. To ensure the efficient use of spate water, the allocation is based on the following Irrigation Plan:

- When the spate flow is small (5–15 m^3/s), priority is given to the canals in the upper reach of the wadi.
- When the spate flow is of medium size (15–25 m^3/s), priority is given to canals in the middle reach of the wadi.
- When the spate flow is large (25–40 m^3/s), the flow is directed either to Wadi Kabir or Wadi Saghir in the lower reach of the delta, depending on which one has the right to receive the spate water.
- When the spate flow exceeds 40 m^3/s, the flow is divided equally between Wadi Kabir and Wadi Saghir.

RULES ON MAINTENANCE

Maintenance rules are as important as water distribution rules in spate irrigation and, in turn, water distribution rules dictate the way maintenance is organized. Because the area of irrigated land fluctuates widely from year to another, it is difficult to match farmers' contribution to maintenance to actual irrigation, as is the case in perennial irrigation. In maintenance of spate irrigation systems, there is often an inevitable degree of unfairness, summarized in the Yemeni saying that "he who pays is the laughing-stock of the man who has the right to water first". Box 7.5 describes the maintenance rules of the Korakan Spate Irrigation Systems in Balochistan (Pakistan).

There are several types of contribution to maintenance work by farmers. Amongst these are: a contribution according to land shares, graded contributions, a contribution according to capacity, a contribution according to benefits and a contribution by contract.

- A typical example of a contribution according to shares is the *jorra* system practised in many spate irrigation systems in Pakistan. A *jorra* stands for a pair of bullocks – the unit of work in the repair programmes. Agricultural fields are also measured in terms of *jorra*; the amount of land that can be cultivated with one pair of oxen. The shareholder has to participate with his oxen in accordance with his land share, irrespective of whether it was irrigated or not.
- Graded contributions are particularly common in the larger spate systems of the Kachhi Plains of Balochistan or in some of the now disused spate systems in Saudi Arabia *(Wildenhahn, 1985).* Different villages have to contribute different maintenance levies – with areas in less privileged places contributing proportionally less to the collective effort.
- Contribution according to capacity is a variation on the two systems above. In accordance with their land shares, farmers are expected to bring bullocks to the common maintenance work. Farmers who do not own draught animals, however, are expected to contribute their own labour. As ownership of draught animals is a fair reflection of the returns from spate irrigation in the previous years, this system is largely fair.
- An example of contribution according to benefit comes from Dameer Bakar in Tareem District in Hadramawt in Yemen. One-fifth of the crop is set aside to pay for the maintenance. This type of rule works well in systems where the benefits are guaranteed. It would, however, be ineffective in systems where there is a genuine risk that a number of years go by without irrigation.
- With contribution by contract, only those who want to be entitled to water contribute, while others are expected to close their field inlets. The rules can only be practical in relatively small systems, where it is easy to check on earlier contributions, and cannot be used in field-to-field systems, where opting out is not an option. An example of this practice is in the Toi War system in Balochistan.

An important requirement of the maintenance rules in place is their robustness, i.e. the degree to which they will ensure the constant rebuilding of the common works. This is particularly challenging when the work that needs to be done is substantial and there is a good probability that there will be years without irrigation for a large part of the command area. Contributions based on land shares often work better in these situations than those based on benefit, capacity or contract. Mitigating rules that spread spate water in a relatively egalitarian way include the demarcation of the command area and restrictions on the depth of irrigation and second water turns. The scale of the flood irrigation system is an important factor in applying mitigating rules. Mitigating rules are more feasible in small systems than in large systems.

BOX 7.5

Maintenance rules in Korakan spate irrigation systems in Balochistan, Pakistan

The different soil bunds along the deeply incised Korakan River in Kharan, Balochistan, are fully farmer-managed. The existing operation and maintenance practices for a number of larger bunds illustrate the capacity of farming communities to manage their spate irrigation systems without substantial government support.

The *Jama Bund,* with a command area of more than 2 000 ha, is normally breached four to five times during the flood season. Farmers are able to rebuild the bund within five days with the help of tractors, whereas it took one month to undertake this work with the help of bullocks in the past. Each farmer has to contribute labour and cash in accordance with the size of his irrigated land. If a farmer does not contribute his share, he loses automatically his right to use spate water for irrigation purposes. In 1992, the farmers spent PKR 15 000 for renting tractors. The operation and maintenance of the entire spate irrigation system is carried out without the employment of a canal master.

The *Shah Bund*, which is made of sand, is breached partially with every flood and 20–25 farmers are able to rebuild the breached portion within one to two days with the help of their own oxen. Each farmer has to contribute labour for the repair of the bund according to the size of his irrigated fields, even if he has already irrigated his land. The reconstruction of the bund and the distribution of spate water are undertaken without the supervision of a canal master.

The *Nothani Bund* is normally breached once every 3 to 4 years. If the bund is breached, the community of about 100 farmers is able to reconstruct the bund within a few days with the help of their bullocks. A canal master (*miriaab*) is in charge to organize the reconstruction work and to mobilize the farmers, who are supposed to contribute labour in accordance with the size of their irrigated lands. If a farmer does not contribute his labour share, he is fined PKR 50 for each missed working day.

The *Madagan Bund* is breached by every large flood as it is made of sand. Until 1992, about 80 farmers rebuilt the breached bund with their bullocks within a couple of days. If the damage to the bund was very large and the farmers were not able to undertake the reconstruction works before the next expected flood, they could call on the help of other farmers from other areas on the basis of mutual assistance (*asher*). In 1993, the bund was rebuilt with bulldozers, when 200 bulldozer hours were provided by a local politician and an additional 100 hours were paid by the farmers.

The *Karkhi Bund* commands an area of more than 1 200 ha and farmers from 12 different communities have to contribute labour and cash for the maintenance of the bund and the canal system according to their respective land shares. In case the bund has been washed away by a large flood, bulldozers are rented and the necessary cash contributions are collected by the village leaders in each community.

As seen above, there is a strong link between the rules on distributing spate water and the organization of maintenance. In principle, it is a two-way link. In many systems the right to irrigation by spate flows is proportionate to one’s contribution to repairs to the headwork or flood channels. If a farmer stops contributing labour to the public good, he will not be allowed to open the intake to his field (especially where the field network is supplied by individual intakes). The link works the other way around; water distribution rules often serve to create a coherent group of land users who are dependent on the spate system and will jointly undertake the maintenance of the structures. In particular, the demarcation of the irrigated perimeter is important as this defines who has an entitlement to the floodwater. Without this, it is difficult to form a group of partners and the organization of the recurrent repair work becomes problematic, as well as the formulation of rules on cost sharing. A second issue is the critical mass required in undertaking repairs. This is particularly relevant when repair is dependent on human labour and draught animals and a large force is required to rebuild structures and make repairs. When tail-end users are systematically deprived of floodwater supplies, they may no longer want to contribute to the maintenance. The critical mass factor hence works as a check on too large an inequity in water distribution. However, the importance of critical mass may be expected to diminish when maintenance is mechanized or undertaken by government organizations instead.

RULES ON ADAPTATION TO CHANGES IN WADI MORPHOLOGY

The nature of flood systems implies changes in land elevation and in the form and elevation of the wadi bed. In many instances, there are special sets of rules to account for these morphological changes. These rules concern the location of diversion and other structures; the alteration of the ephemeral river bed level and the direction of flood canals through scour and siltation processes; and compensation for lost land.

An example is the Sheikh Hyder Zam system in DI Khan (Pakistan). A number of local rules are in place to accommodate these constant changes to the system. First, major diversion bunds may have to be reallocated. As bad-quality soil (cracking clays or saline layers) gets deposited in an ephemeral river or intake sections silt up, the location of an earthen bund may have to be changed every now and then. The common practice is for all land owners to go to the site and identify the location from which water can feed all or most of the land. Arguments that some land may now no longer be commanded are usually not given weight. The new location of the diversion bund should however not interfere with the benefits accruing to riparians lower down.

In case a suitable location is not available for the construction of new diversion bund in the village territory then, with the permission of the local District Officer, a new bund can be constructed in the land of another village. In case a particular bund is heavily damaged and there is no time to reconstruct it or make a new bund in another location, then downstream people may join upstream landowners to work on the upstream bund and get water from the upstream bund. The upstream landowners cannot stop the downstream landowners from participating in earthwork on their bund and are bound to release water to them.

In Sheikh Hyder Zam in Pakistan, there are also rules on the reallocation of flood channels. For instance, if a section of a flood channel becomes too deep and needs to be changed, it can be changed provided the next diversion structure in the flood channel is not damaged. To test this, a modest amount of water may be released from the new section to the downstream structure by making a small hole in the upper *wakra* (an earthen bund that diverts spate flow from a secondary canal to a field) to find out if it can stand the pressure. If a flood channel become unserviceable for irrigation through erosion or gullying, all the stakeholders, with mutual consultation, can construct a new flood channel that can easily and conveniently feed all the fields in the area. The landowners are not paid compensation for the land that comes under the new flood channel.

ENFORCEMENT

The extent to which water rights and rules in spate irrigation are enforced depends mainly on the social structure within the community and the level of the overall governance in the area. In the spate irrigation systems in the eastern lowlands of Eritrea, farmers have comparable access to land and there is no great contrast between large and small landowners. Local government is active and there is a well established organization of farmer leaders. As a corollary, disputes on water distribution are unusual. This may be contrasted to frequent disputes in Tihama systems in Yemen, where powerful parties stand accused of using their power to their own advantage and tail-end areas are increasingly marginalized.

Spate systems need a far greater degree of discipline than other resource management systems, yet the returns are sometimes small. Enforcement of water rights and rules in spate irrigation is related to three factors:

- local water users' organizations;
- actions of government organizations; and
- codification of water distribution rules.

Social enforcement through user-based organizations

In smaller systems, enforcement of rules is done through self-motivated local organizations. It is important to understand these organizations and the role they play and take them into account in spate improvement strategies.

Local governance is often the prerogative of a small group of well respected members of the community. The system in Belilo scheme in East Harrarghe in Ethiopia is quite typical. The allocation of water is supervised by a water master, called a *malaaka*. Water distribution rules are established by consensus among the members of the community. The *malaaka* supervises water distribution and ensures that basic maintenance tasks are performed. There is no honorarium but the appointment as *malaaka* is considered an honour and a service to the community. The appointment is for an indefinite period, as long as the performance is satisfactory. In Belilo there was a change of guard when the system was upgraded and it was felt that a younger and more dynamic water master should take over. The lack of democracy and transparency in the appointment of the leader may, however, lead to inequity in access to water, corruption and overall under-performance of the system.

Often the move to formalize water management is part of external investment in a system. In improved spate systems, the maintenance requirements change – often with a cash component – and organizations need to adjust to this. There are many successful examples of the building of local organizations on traditional organizations. An example of well performing farmers' organizations in managing improved spate irrigation systems is the case of the Sheeb Farmers' Association in Eritrea (see Box 7.6). In Tunisia, the traditional water use groups have been formalized as AICs (associations of collective interest), endowed with a legal personality and formally recognized by the administration. A management contract of 3 years' duration is signed between the administration and every AIC. AIC expenses cover running and maintenance expenses of facilities.

However, externally induced changes in governance may negatively affect the performances of spate systems when they do not take existing local governance into account. In Yemen, until the 1950s, allocation of spate and base flows in Wadi Tuban, as well as water distribution, including the length of diversion structures, was the responsibility of the *Sheikh al-Wadi*, who was appointed by the local Sultan. If upstream users took water without the permission of the Sheikh al-Wadi, the latter had the power to impose a crop ban on the violator's land. Alternatively, downstream farmers had the right to grow crops on the irrigated fields of their upstream neighbours. If crops were already cultivated, the yields had to be given to the immediate downstream farmers after the harvest. With government intervention through the collectivization of agriculture, the responsibility for operation of the spate irrigation systems was taken over by government employees and staff in the agricultural cooperatives. The role of traditional organizations declined, in particular after the reunification of South and North Yemen in 1990, and left a vacuum in terms of local institutions. This situation resulted in increased conflicts between upstream and downstream users, as the traditional rules concerning the distribution of spate and base flows were no longer observed *(Al-Eryani and Haddas, 1998).*

BOX 7.6
Sheeb Farmers' Association, Eritrea

The Sheeb Farmers' Association is an example of a well performing farmers' organization, managing an improved medium-sized spate irrigation system. The Sheeb Farmers' Association is based on the traditional well established local organization of *ternafi* (sub-command leader) and *teshkil* (heads of sub-unit). What has been added is an executive committee (consisting of a chairperson, secretary, treasurer, four members and an invited representative of the local administration) and the tasks of managing the 'modernized' headworks in an efficient way and undertaking fee collection in support of this.

The Association came into force in January 2004, following a general election. It has a formal constitution recognized by the local government and it received training in financial assessment, the use of bulldozers and frontloaders, the design and operation of the system, general organization and computer skills.

Membership is compulsory. In the year 2006, it was expected to raise Nfk1 500 000 (US$100 000), based on annual fee contribution of US$400/ha for all land, irrespective of its irrigation status. Default was generally low (8–11 percent) and late payments were recovered in the subsequent season with a fine. The fee collection is well organized, with all members having individual passbooks in which their payments are recorded.

The Sheeb Farmers' Association had several other achievements to its credit in the period 2004–2007. It coordinated the traditional maintenance of soil bunds and flood channels, with as great a value added as in the work on the modern parts of the system. It was also involved in solving a number of water distribution issues and coordinated successful adjustments to the water distribution system that arose from the new civil works. In general, it is a well recognized and appreciated association.

Enforcement through government organizations

In larger systems, enforcement of rules is usually done through a mixture of user organization and local government. The role of local government is in such cases to regulate local water distribution arrangements, organize maintenance by water users and solve disputes. In many instances, however, the authority with which the government enforces rules has declined. The recent history of the spate systems and the slow institutional erosion in DG Khan and DI Khan in Pakistan is illustrative of this type of problem (see Box 7.7).

BOX 7.7

Evolution of governance in DG Khan and DI Khan systems, Pakistan

Up to 1973, the Government nominated one of the biggest and most well respected landowners of a village as *numberdar*. The *numberdar* had a dual function. First, he was in charge of organizing other landowners and farmers for the construction of the flood diversion works and overseeing the distribution of floodwater in line with the codified practices. In addition he was attesting local applications and documents. The *numberdar* was also responsible for collection of the land tax, based on crop yields, from other landowners and for depositing it with the government treasury and he was allowed to retain an agreed percentage as compensation for his services. Every landowner had to maintain a certain number of bullocks according to the size of his land, and make them available for the construction of diversion bunds. The construction of the main diversion bunds was directly supervised by a government employee (*darogha*), who had the authority to call upon all the landowners to take part in the work. The distance between each diversion structure was fixed to allow floodwater to travel with sufficient velocity to avoid silting of channels and river sections.

In 1973, the Government introduced several changes.The first was the termination of the *numberdari* system. The responsibility for collecting land tax was assigned to the local revenue officials (*patwari*) in the respective villages. Another change was the introduction of free or heavily subsidized bulldozer time. With these changes the institutionalized system of collectively constructing diversion structures ended. The construction of diversion works was undertaken with heavy mechanical equipment, under the supervision of the Assistant Commissioner, Rod-Kohi region in DG Khan. The rule on the distance between the diversion points was no longer observed. With distances often shortened, the velocity of floodwater was reduced and this caused silting of the flood channels.

After 2001, the situation worsened. The general neglect of the system had resulted in siltation in parts of the system and gully formation elsewhere. At this time the Agriculture Engineering Department was abolished and, with it, access to subsidized bulldozer services ended. The legal powers of the revenue staff were removed, making it impossible for them to summon water users to perform collective work.

Of special relevance in the administration of spate irrigation is the interface between hydrological and administrative boundaries. Governance of spate systems has traditionally integrated the interconnectedness between water users in a wadi. With modern administration, such integration is not always preserved, in particular when spate systems have their catchment area in one province and their command area in another province. For instance, in Pakistan, all spate irrigation rivers originate in Balochistan Province and irrigate in Punjab Province. The case may be worst when wadis cross national borders. In 1997, Afghan farmers stopped the Pishin River flowing into Pakistan. As a result, farmers in Pakistan were not getting water any longer. It was the Sharia Laws, under which no one is allowed to block the water permanently in such a situation, that helped to resolve the problem in this case.

Government alone or local organizations alone are sometimes not adequate to enforce these laws. Unfortunately local laws in many cases do not cover such uncommon aspects of resources management.

Codification

In some spate systems, the water rights and water distribution rules are codified. The oldest example is Wadi Zabid in Yemen, where the rules for distributing base and spate flows between the different diversion structures were first recorded 625 years ago by the renowned Islamic scholar Sheikh Bin Ibrahim Al-Gabarty. The scholar is still revered and his grave visited by a large number of followers on the occasion of an annual festival.

Similarly, rules on spate rights in the large systems in the Suleiman range in Pakistan (DI Khan and DG Khan) have been documented in a register, the Kulyat Rodwar, which was prepared by the Revenue Administration during the British colonial period. The register contains a list of all villages responsible for the labour on each bund. A special functionary was responsible for the enforcement of these rules, exhorting farmers to plug gullies and rebuild their bunds. The spate-irrigated areas were an important grain basket at the time and an important source of tax, hence the interest by the Revenue Administration. As they were recorded, the water distribution rules also provided the opportunity to resolve a number of long-standing disputes *(Bolton, 1908).*

In the main spate-irrigated area of Balochistan, in Pakistan, the long and extensive Nari system in the Kacchi Plains, detailed rules have been written down concerning the breaking of the different bunds in the spate course. These rules were enforced by the *teshildar ghandahat*, an official put in place by the then native ruler of the area, the Khan of Kalat, whose land was located at the tail-end of the system. After Kalat State joined Pakistan in 1948, this functionary became an employee of the new administration.

FIGURE 7.4
Pakistan: Revenue Official using the 1872 record of rights

Codifying water distribution rules clarifies and completes local water management arrangements and introduces a neutral factor in resolving disputes. Testimony of the importance of codifying water distribution rules is the continued use made of water registers, prepared as long ago as 1872, in the spate-irrigated area of DG Khan (see Figure 7.4). Yet, recording water rights as such is not sufficient to mitigate conflict or ensure that water rights are observed. The vehement conflicts on Wadi Rima in Yemen in spite of codified water rights stretching back over the centuries clearly illustrates this point *(Makin, 1977).*

It is more common for water distribution rules not to be formally registered, even in relatively large systems. In some systems this is because there is little competition for the floods as the distance between the mountains (where the spate flows arise) to the sea or the main river (where they discharge) is short. Even when there are no formal rules, local district officials are often requested to intervene in conflicts in spate systems – particularly where it concerns water rights between different areas.

A related subject is the registration of land titles. In some systems, particularly in Sub-Saharan Africa, there are no individual land titles. This is the case in the Gash system in Sudan. An annual lottery determines who will have access to the land. This system discourages any land improvement, such as field bunding, the key to moisture retention (see Chapter 5). Recent efforts of land titling have been initiated under the ongoing Gash Sustainable Livelihoods Improvement Project, by establishing clear entry and exit rules for the leaseholds, screening and clearing the tenancy registry books, fixing leaseholds in conjunction with increased control of floodwaters and, finally, devolving enforcement of the exit and entry rules to farmers' organizations and water users' associations *(Cleveringa et al., 2006)*.

CHANGING WATER DISTRIBUTION RULES

External factors affecting water rights

Water rights in spate systems are not static. They change in accordance with new situations created by various factors. Among these are the increase in population and the pressure for new land development, changes in cropping patterns and new market opportunities, the introduction of more permanent spate diversion structures, the shift in power relations and the changing levels of enforcement.

One example of such adjustments in rules took place in Wadi Laba in Eritrea, where they occurred in response to the increase in the number of inhabitants. Land under spate irrigation increased from about 1 400 ha in 1999 to nearly 2 600 ha in 1990. As a result, the existing rules increasingly failed to guarantee that all the fields received water at least once a year. In the mid-1980s, to deal with this with new reality, the farmers modified the rules to indicate that fields which did not get a single irrigation in the previous flood season would have priority in the next season.

It is also evident that there is a strong link between enforcement and overall governance. There are several examples where new water rights have been created by power play and intimidation. The development of water rights in Wadi Rima in Yemen during the last few centuries illustrates well the factors operating in the allocation and distribution of base and spate flows (see Box 7.8). The skewed local power distribution, the weak nature of local government and the absence of an effective countervailing power created the setting for the 'capture' of spate water rights by strong players – literally bulldozing their way through. In Wadis Zabid, Siham and Mawr there have been examples of major upstream land development and water diversion by powerful parties in contravention of existing traditional rights or legal injunctions. This has been propelled by the possibilities of highly profitable banana cultivation based on the conjunctive use of groundwater and spate flows. The situation is quite different in Eritrea and South Yemen, where the social structure has been more egalitarian and the role of local government has remained strong.

Changes induced by new infrastructure

The construction of new permanent and more robust headworks has often resulted in better upstream control, integration of previously independent systems, more controlled flow and changes in the maintenance requirements. The impact of these changes is summarized in Table 7.2. They all result in greater control by upstream water users.

Provision of better control of water at the upstream end of a system often disturbs the delicate balance that exists between upstream and downstream diversions – as reported from many places, for instance Morocco *(Oudra, 2008)*. It is not uncommon for new structures to create a new water management situation, which over time changes *de facto* the water distribution rules. An illustration of this is the change in water distribution in Wadi Rima in Yemen after the construction of the headworks. In the past, the tail-end area was served by independent intakes. The common headworks allowed better upstream control of the spate flows, but over time the volumes of water passed on to the tail area were reduced *(Al-Eryani* and *Al-Amrani, 1998).*

In the past, water was diverted by earthen or brushwood diversion structures, that were usually destroyed during high floods, allowing water to go downstream. Now, with a permanent structure, in principle only the peak flow crosses the weir, but the lower flows remain upstream because of the way the system is operated.

BOX 7.8

Changing water rights in Wadi Rima, Yemen

At the end of the seventeenth century, four main canals were irrigating fields in the middle reach of Wadi Rima, which were constructed by the first settlers. During the last three centuries, the allocation and distribution of base and spate flows along Wadi Rima were affected by the following developments:

- In 1703, the right of abstraction was extended to downstream farmers, who were granted the right to take water for 20 days in November, 10 days in June and 10 days in August. The resulting abstraction restrictions were confined to the upper four canals and not to additional canals further upstream, probably because they only took small amounts of water.
- In 1809, the customary water allocation rights were established for six different *shaykhdoms* and they continued to function without any major change for about 100 years. These water allocation rights only apply to low flows, i.e. base and flood recession flows, and not to flood flows.
- Owing to the development of two upstream canals around 1900, farmers from the middle reach felt it necessary to take action through the courts to establish their prior rights to the low flows. They succeeded in obtaining an injunction to block the two new canals until their four canals had taken all the low flows to which they were formally entitled, without any restrictions either on the cropping intensity or the number of irrigations per crop.
- Following a civil war between the Imam and the Zaraniq people in 1928–1929, a tract of land was expropriated by the Imam and the Al Hudayd canal was constructed from the point where the wadi emerged onto a coastal plain to irrigate this tract of land. Although this new upstream canal initially took a small quantity of water, it took water throughout the year, thereby violating the principle that new lands should not be irrigated with low flows. The precedent created was used by landowners on the south bank to abstract the low flow as well. As their canals were much larger, they took the entire low flow at the expense of the downstream users.
- The people who had lost their traditional access to the dry season flow, protested vehemently and they ultimately took the law into their own hands by breaking the main canal on the south bank. However, the influential canal owner succeeded in jailing the culprits and eventually forced them to repair the canal.
- The irrigation expansion continued on the north bank, despite the ruling in 1931 that the Al Hudayd canal, commanding the land of the Imam, should be closed.
- In 1952, major works were authorized by the Imam to enlarge the Al Hudayd canal to expand the irrigated area. Simultaneously, the Government sold water to people without original water rights at the expense of users with traditional rights to use the water of the Wadi Rima.
- Following the revolution in 1962, a committee consisting of the Minister of Justice, local magistrates and the secretary of the former Imam, ultimately decided that the claims of the people of the south bank should be respected and that the Al Hudayd canal, now supplying government land, should be closed. Until the mid-1970s, however, the Governor of Hudeidah did not implement this decision, possibly fearing the reaction of the people on the north bank *(Makin, 1977).*
- The new modernized irrigation system commissioned in the late 1980s recognized at least some of the claims of the water users of the middle reach on the south bank. A division structure was designed to provide one-third of the flow to the north bank and two-thirds to the south However the majority of the water is still being used on the north bank – the powerful north bank water users have vandalized the control gates at the flow division structure and the operating agency does not have the power to impose the water distribution envisaged when the scheme was modernized.

TABLE 7.2
Effect of engineered headworks on water distribution

Larger upstream control	Puts upstream land users in a position to control flows that would have destroyed their intakes in the past. Decreases downstream access to flood flows and larger flood recession flows.
Combining independent intakes	Creates dependency and creates new tail-enders, as water is distributed sequentially, whereas earlier each area diverted part of the floods.
Controlled flows	Reduce the risk of scour and gullying, but the attenuated flows may no longer reach the extreme ends of the command area.
Changed maintenance burden	Generally reduces the dependence of upstream land users on the labour of downstream land users.

In Wadi Laba in Eritrea, the modernization which was completed in 2001 replaced the main earth bund with a permanent weir and many other secondary earthen distribution structures with gabions. The modern structures required a different type of maintenance, replacing labour and the collection of brushwood with earth-moving machinery such as loaders, bulldozers and trucks which, in turn, called for new technical and financial arrangements. In the past, the critical mass of labour needed for collective maintenance was the key to the enforcement of water rules. The new maintenance requirements have changed the way that water distribution is organized. Instances were witnessed where upstream farmers used large floods and irrigated their fields two to three times before downstream fields got a single turn, which caused many conflicts. The rule of sequential water distribution was not applied any more, partly also because the new infrastructure effectively reduced the number of the largest floods which in the past were serving the tail-end fields.

Another example of the inevitable impact of larger upstream control on water distribution is the Rehanzai Bund in Pakistan (Box 7.9). The Rehanzai Bund case shows that it is hard to make enforceable agreements in the absence of an effective authority and in a situation where people have considerable differences in power. Ultimately this technically successful change in diversion bund increased inequity in the system. In other cases, the change in water distribution creates severe conflict. One of the most spectacular examples is the flood diversion weir, built on the Anambar Plains in Balochistan (Pakistan). The weir was meant to divert spate flows to the upstream land but also cut off the base flow to the downstream area. Tensions ran high between both communities and were ultimately resolved when by mutual consent part of the weir was blown up (see Figure 7.5).

Another change sometimes brought about by engineering interventions is the integration of previously independent systems, extensively discussed in Chapter 4. A variation of this occurs when a system with a free intake is replaced by a common controlled diversion. Usually systems are integrated to obtain economies of scale that can justify the large investment required in civil works. Such changes bring people (sometimes entire communities) together in one single system. In the past such communities may have had little affinity with one another and there may have been little interaction between them, but they are forced to work together to distribute scarce water. In some cases this has led to intractable social problems and in others it has prevented integrated systems from materializing.

BOX 7.9

The Rehanzai Bund, Balochistan, Pakistan

The massive earthen Rehanzai Bund – stretching over 2 km – was constructed at the confluence of the Bolan Rover and an offshoot of the Nari River on the Kacchi Plains of Balochistan. The construction of the bund allowed the control of spate flows in the Bagh area, where previously the spate flow had been too fast to capture. After the Rehanzai Bund was completed, a number of well-placed landlords constructed a series of permanent diversion bunds immediately downstream of the new bund. This obstructed the water rights of the tail-end Choor-Nasirabad area. The district administration supported the case of the downstream farmers and instructed the upstream landlords to break the bund after their area had been served. The landlords, who had considerable power and influence, refused to do so. As time passed, more and more people had to leave the Choor Nasirabad area for lack of farm income. The remaining group was too weak to exert any influence and the upstream landlords prevailed

FIGURE 7.5

Diversion weir blown up by farmers as it interfered with the base flows, Pakistan

Implications for spate governance

Interpretation of rules and their implication for the design and operation of new infrastructure is best done directly by farmers, with discussions facilitated to help them understand the proposed arrangements and the actions to be taken to respond to changes in the system. For existing spate irrigation systems, water rights and actual practices need to be investigated, shared, agreed and where possible, codified. For new schemes, a basic set of water distribution rules needs to be agreed with farmers in the design phase. They should be widely shared and arrangements for supervision and enforcement agreed upon. When possible, it is desirable that any water distribution arrangements have a high level of flexibility to adjust to unforeseen circumstances. Robust arrangements on management and agreement are more important than detailed specifications on how water is distributed.

The water rights and rules need to be drafted and implemented in a way that meets the floodwater management needs in a given situation. They should be adjusted to, and tested in, new situations that arise, for instance, when traditional systems are modernized and permanent concrete weirs replace earthen diversion spurs. If the water rights and rules are not compatible with the new situations, they can end up being frequently violated and become a source of inequity in water distribution and of conflict, which may in turn contribute to:

- paving the way for disintegration of the long established local farmers' organizations; and causing the creation of a gap between the poor and the rich in what were rather homogenous societies as regards wealth;

- accelerating the downfall of downstream farmers, leaving them unprotected against the excessive capture of the floodwater by the upstream farmers; and
- deliberate destruction of investments.

When structural changes affect water distribution and scheme maintenance to the extent that traditional rules become obsolete, a new set of rules is needed that must be consistent with national legislation. Modern laws and legislation are vital to providing farmers' organizations with the legal recognition and authority they need to collect and manage water fees, run independent bank accounts, make direct contacts with funding agencies and own or hire machinery and other necessary assets for water management. These activities contribute to making the farmers' organizations financially and organizationally autonomous and provide farmers with the security they need to operate and invest in their scheme. Of particular importance to farmers are the following questions:

- What kind of land and water user rights do spate irrigation communities and individual farmers have?
- What decision-making power do these user rights confer on the farmers' organization regarding the cropping system, the water rights and rules, and other important land and water utilization activities? and
- What obligations, if any, do the farmers' organization and the communities as a whole need to fulfil to retain the said rights?

However, ensuring financial and organizational autonomy requires more than legislation. It also needs sincere efforts to graft farmers' organizations on earlier local organizations and avoid creating dual structures (traditional and formal). It further calls for supporting the organizations through capacity building programmes that, among other things, entail financial accountability as well as through a technical package with clear guidelines on how to operate and maintain the different components of the new scheme. Such activities are needed to guarantee an active participation of the farmers and their organization in the development and management of the spate irrigation system.

Chapter 8

Management arrangements

SUMMARY

The viability of spate systems is mostly determined by the strength of the organizations involved in their operation and maintenance. Large, integrated systems can require relatively elaborate organizations, whereas small runoff diversions can be operated more simply. The larger the system, the more difficult it becomes to organize common maintenance activities, not least because some areas will always have a larger likelihood of receiving otherwise unpredictable flood supplies.

While farmer management exists at some level in all spate systems, there are essentially three types of management arrangement:

- predominantly farmer-managed;
- farmer-managed with involvement from local government or other external support; and
- managed by a specialized irrigation agency, in which case farmers may become passive recipients of water delivered.

For farmer-managed schemes, development projects should not attempt to formalize agreements for water distribution and scheme maintenance unnecessarily. These agreements have to be made by, and left to, farmers on the basis of prevailing practices, unless they themselves request assistance from a higher-level authority. Projects should, however, ensure that:

- there is clear leadership by locally appointed caretakers and/or by committees accountable to a wide constituency of land users and not to a limited interest group;
- there are clear and specific arrangements for maintenance. Maintenance arrangements must be able to cater for prolonged periods of crop failure;
- overhead and transaction costs are kept low – effectiveness, simplicity and ability to react quickly are most important; and
- larger schemes are divided into sub-groups that can effectively mobilize contributions to maintenance and enforce rules on water management at a local level.

Large, agency-managed schemes in general struggle to reach financial sustainability and are vulnerable if long-term routines can no longer be guaranteed. A series of criteria need to be fulfilled to ensure successful agency-managed spate irrigation schemes. They include the principles of transparency, accountability and subsidiarity, the acknowledgement and integration of existing traditional arrangements, effective communication and guarantees of financial sustainability.

Of particular relevance is the introduction of bulldozers to assist farmers in maintaining diversion weirs. While bulldozers respond to a real need, and provide much required assistance, in reducing the burden of maintenance work on farmers, they should be managed in a way that does not modify unduly the balance of power between users.

INTRODUCTION

Most spate irrigation systems have a long history of farmer management – some of the world's largest farmer-managed irrigation systems are spate schemes. The reconstruction of diversion structures across spate watercourses and the operation and maintenance of a network of flood canals requires strong and effective organizations. The viability of spate systems is often determined by the strength of the organizations involved in their construction and maintenance. A historic example is the ancient Ma'rib dam in Yemen, which is believed to be built around the third millennium BC and was intended to divert water from spate floods rather than to store water over long periods. The dam was sustained by a strong state organization, so that its eventual failure has been linked to the diminishing capacity of the state to manage the system (Chapter 1 provides more details).

There are essentially three types of management arrangement:

- predominantly farmer-managed;
- combination of management by local government and farmer management; and
- combination of specialized agency management and farmer management.

There is a link between the management arrangement and the scale of the systems, as shown in the rather simplified overview given in Table 8.1. Full farmer management is common in smaller systems, on tributaries and small streams. Such systems are often relatively simple to operate. There may be no diversion structures and a simple, almost automatic system of water distribution may be in place. Some small schemes obtain limited support from NGOs. In larger systems, the role of the local government becomes more important to mediate in disputes and oversee operation and maintenance (O&M). Agency management has often followed in the wake of public investment in very large systems.

TABLE 8.1
Overview of management arrangements

Mode of management	Farmer management	Farmer management with support of local government	Management by local government in partnership with farmers' agency management
Typical size	*Less than 1 000 ha*	*1 000-5 000 ha*	*More than 5 000 ha*
Examples	Upland systems, Balochistan Hadramawt systems Eastern and western lowlands system, Eritrea Spate systems, Ethiopia	Rod Kohi systems, DI Khan and DG Khan (Pakistan) Kacchi and Las Bela systems (Pakistan) South Yemen systems in the past	Tihama and South Yemen Systems Gash System (Sudan)

Management arrangements of spate irrigation systems evolve with time. The past 20 years has witnessed a clear movement in development policy towards strengthening the role of farmers in management and their increased participation in operation and maintenance. In some cases, the operation and management responsibility of medium to large systems has been handed over to farmers' organizations. At the same time, many countries have seen a drastic reduction in the role of government in the operation of spate irrigation schemes. Pakistan is a case in point.

FARMER MANAGEMENT

Farmer management is common in all spate irrigation systems, but the level of involvement of farmers varies from one scheme to another. It may range from the management of an entire system to management of secondary flood canals or to on-farm water management only. Maintenance in spate systems includes the reconstruction of soil bunds or brushwood diversion structures in mobile wadi beds, or the repeated restoration of field bunds and canal banks. The local organizations operating these labour-intensive and unpredictable systems are often intricate.

Although there are many examples of long-lasting, traditional, farmer-managed systems, farmer management is not without problems. Rules are rarely codified and not always comprehensive. Leadership may be contested. Powerful landowners may take advantage of the weakness of local farmer and government organizations and divert water upstream of the schemes and create new *de facto* water entitlements for themselves. Existing arrangements may not be able to adapt to changes or unpredicted situations, such as the introduction of heavy machinery or new infrastructure, changes in the spate course or the introduction of groundwater-based agriculture.

In describing the arrangements for farmer management, there are three main factors:

- internal organization;
- external support mechanisms; and
- activities beyond spate management.

Internal organization

In most traditional farmer-managed systems, transaction costs are kept to a minimum. It is common to have a committee of experienced farmers supervising the works on an honorary basis. The committee may meet regularly and invite all farmers, depending on the strength of the local organization (Box 8.1). Other committees come together less frequently and invite office holders only.

BOX 8.1

Committee meetings in Bada, Eritrea

The first meeting of the committee and group leaders is usually held after the harvest to discuss the reconstruction of the diversion structure (*agim*). The second meeting takes place after the reconstruction to evaluate the work on the *agim*. The third meeting is held before the start of the planting season to discuss whether diversion structures require additional maintenance and whether measures to avoid crop damage by pests and livestock are necessary. During this meeting the committee usually decides on the fields to be irrigated with the water from late floods. The fourth meeting takes place after the planting period to organize crop protection, and to discuss measures to control damage by floods, especially in the field-to-field system. Meetings should be attended by at least two-thirds of all farmers. Farmers absent during a meeting have to accept the decisions made.

Source: Haile and Van Steenbergen (2006)

Maintenance is usually organized as common labour. It is usual for a series of days to be planned, during which all farmers take their earth-moving equipment and draught animals and provide free labour for the execution of the maintenance works. This simplifies work arrangements and makes it easy for all to see who is present to make his contribution and who is not. In some of the larger spate irrigation systems in the Kacchi Plains in Pakistan, a water tax, called *gham*, is still collected through a network of local leaders.

The number of paid functionaries is usually small and seasonal. Remuneration is, in most cases, in kind (dispensation from maintenance labour, share in the crop). This contrasts with government staff working on spate systems who are usually paid in cash and on a full-time basis. Many small systems are run with little formal organization. In some of the small systems in Hadramawt in Yemen, for instance, spate water follows a set route through the canal system and excess water is channelled back to the wadi. Farmers divert water when needed and no one supervises the water distribution.

Larger farmer–managed systems may have paid employees. In the Kacchi Plains and Rod Kohi areas of DI Khan and DG Khan, local engineers (*raakha*) are appointed to supervise the construction of the large earthen bunds and to check the safety of the bunds during the flood season. In a few spate irrigation systems in the Las Bela region in Balochistan (Pakistan), *sepoys* are engaged. Their main role is to mobilize farmers to contribute to the reconstruction of the diversion structures. This position was established at a time when native rulers organized the construction of the diversion structures with forced labour. After the dissolution of the princely state and the formation of the State of Pakistan, farmers continued with the employment of the *sepoys*, as they valued their role. The most common function however is that of water master, called *rais* or *arbab* in various areas in Pakistan, *sheikh-al-obar* or *sheikh-al-shareej* in Yemen, *ternafi* or *tashkil* in Eritrea and *malaaka* in Ethiopia. The water master coordinates the water supply to the flood channel and sees that water is distributed along the channel or sections as per established rules, assesses the repair works and mobilizes the contributions for maintenance. An overview of typical farmer-employed functionaries and their scope of work is described in Box 8.2.

Not all functions are remunerated. In the Wadi Laba system in Sheeb in Eritrea (see Figure 8.1) there is a well articulated system in place of unpaid water masters both at the level of main groups, served by primary flood canals, and at the level of sub-groups or blocks. All in all, there are five main group leaders and 77 sub-group leaders *(Haile et al., 2003)*, some of the latter being women. The area served is 2 800 ha and so the management responsibility of the five group leaders is extensive. The group and sub-group leaders also take on board other tasks, particularly distributing agricultural inputs. The main group leaders are part of an Irrigation Committee that decides on the water distribution in the main command areas.

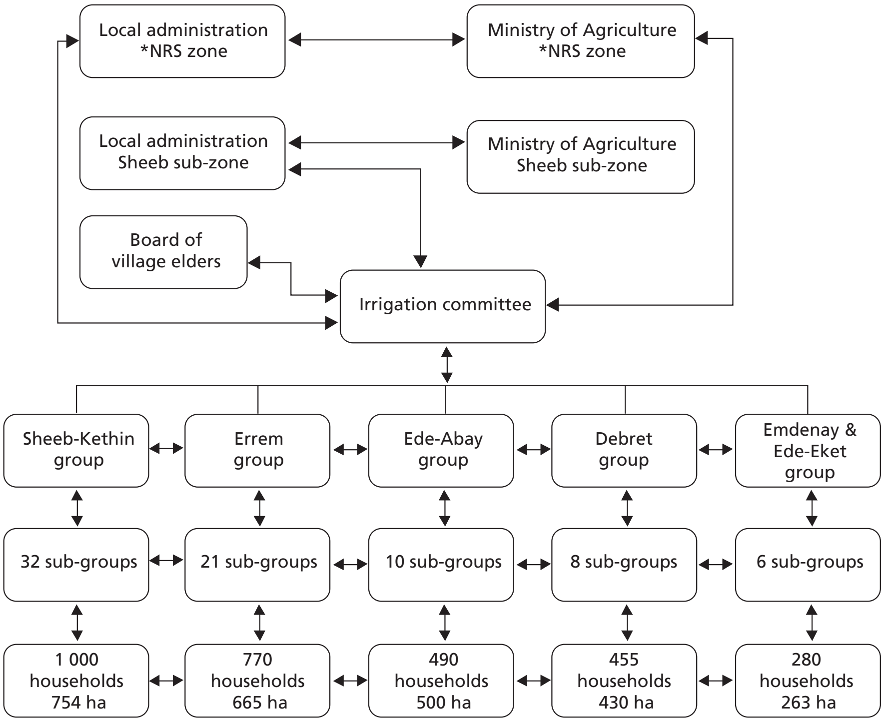
The existence of sub-groups makes it easy to mobilize labour for maintenance at the level of the block and group/flood channel. It also facilitates the implementation of rules on the maintenance of field bunds, etc. The sub-group leader (called *tashkil*) ensures linkage between individual farmers and the water master. He conveys the instructions of the group leader to the individual farmers and submits messages and requests of individual farmers to the group leader. Traditionally, the sub-group leaders have been elected directly by the individual farmers of each farmers' sub-group; although the Ministry of Agriculture is sometimes involved. In order to be elected as a sub-group leader, a candidate should be physically fit, having authority to mobilize the farmers for collective labour, and preferably be literate. It is also crucial that a sub-group leader does not move from the area. The sub-group leaders are not remunerated for their efforts.

BOX 8.2

Examples of traditional water management functions

Main system (main diversion)	
Sheikh al-wadeyen (master of two wadis) *Wadi Tuban, Yemen*	*Raakha (engineer/guard on earthen bund)* *DI Khan, Pakistan*
• Determines the water share of each main canal following consultation with each *Sheikh al-obar* (canal leader) • Decides the number of days that water is allocated to each main canal. • Decides the works required to divert spate water into the main canals.	• Supervises the layout and position of the earthen bund, when it is constructed. • Before the rainy season, inspects the structure and points out the weaker sections. • Keeps watch during the spate season and communicates with individual field owners, water users' associations, downstream farmers and the revenue department. • Witnesses the breaching of the *sad/ghandi.* • Keeps in contact with the *raakha* of the next downstream structure(s)
Sub-system (flood canal)	
Ternafi (sub-command leader), *Sheeb, Eritrea*	*Sheikh al-shareej, Wadi Zabid, Yemen* *Sheikh al-obar, Wadi Tuban, Yemen*
• Assesses the amount of labour required to carry out specific works. • Mobilizes labour for maintenance of irrigation structures. • Supervises the works undertaken by farmers of his group. • Checks if all fields in his group receive irrigation water • Conveys information and directives from the local administration/Ministry of Agriculture to the sub-group leaders. • Investigates reasons when a farmer has not contributed labour during collective works. • Transfers messages and requests from to the local administration. • Prepares written reports about the works undertaken by his group.	• Assesses the quantity of water going into the primary flood canal so as to avoid erosion. • Enforces water distribution rules and supervises water distribution. • Decides which particular plot of land has the first right to receive water when the next flood comes. • Calculates the operation and maintenance costs and charges each farmer in proportion to his irrigated area. • Mobilizes farmers for the reconstruction of the diversion and control structures and the cleaning of the canals. • Settles any dispute among water users and reports violations.
Block (part of flood canal or branch channel)	
Tashkil (block leader), Sheeb, Eritrea	
• Monitors the progress of field bunding. • Organizes and supervises large teams of farmers to work on the main structures. • Implements community rules for the management of floodwater. • Ensures water delivery to the branch canal where his sub-group is located. • Imposes fines on those who waste or steal water from adjacent fields. • Collects land tax among the individual farmers in his sub-group.	

FIGURE 8.1.
Farmers' organizational structure in Wadi Laba, Eritrea



**NRS refers to the Northern Red Sea: an average household has 7 members*

Source: Haile et al., 2003.

External support – the use of bulldozers

In addition to the resources mobilized internally, farmer organizations often benefit from external support. Particularly since the 1970s, bulldozers have become popular for rebuilding soil bunds, plugging gullies in the command area and making field bunds (see Figure 8.2). In many spate areas, the availability of bulldozers has revitalized farmer-managed spate irrigation.

Balochistan Province in Pakistan has probably had the largest infusion of mechanical equipment. In 1948, the Department of Mechanized Cultivation was created, equipped with seven bulldozers. These bulldozers were used to develop agricultural lands and raise earthen field embankments to retain more soil moisture. From the 1960s onwards, the fleet of earth-moving machines expanded rapidly, much of it tied to aid programmes from Russia, Italy and Japan. By 1975, the Department possessed 231 bulldozers, and this number further increased to 321 in 2002. There has, however, been a large fallout, because of heavy use and insufficient maintenance, and it is estimated that only 70 percent of them were still operational in 2005.

Bulldozers are often made available to farmers at substantially subsidized rates. In Balochistan, Pakistan, rental prices to farmers have been as low as US$1–5/hour,

FIGURE 8.2
Bulldozer repairing a traditional diversion spur during a flood recession. Wadi Rima, Yemen.

covering less than 10 percent of the operational cost, and have been widely used for political purposes. The usual practice has been for farmers to take care of the bulldozer operator and encourage him to work effectively by providing a gratuity, paying for assistants and, at times, paying for fuel and small repair costs. From 1985, political office holders were privileged to distribute 'bulldozer hours' to farmers. Testimony of the importance of bulldozers in spate management, this programme turned into one of the most popular programmes of political patronage in the Province. Common practice was to give the bulldozer hour allocation to a village leader who was instrumental in collecting votes. During the 1990s, the bulldozer time allotment was more than the working capacity of the bulldozer fleet in the province. Bulldozers are used for a variety of purposes, but in spate irrigation areas they have been particularly popular because they allow the timely reconstruction of the massive earthen diversion bunds.

It can be argued that if it had not been for the availability of bulldozers, spate irrigation would have been in decline in Balochistan. The social organization required to mobilize human and animal power for construction of diversion structures and flood channels has been difficult to sustain in places. The same applies to other areas. In the Sheeb systems in Eritrea, bulldozers were employed to plug gullies, created throughout the irrigated areas after uncontrolled flooding, thus vastly improving local soil moisture retention.

The intensive use of bulldozers can have drawbacks. Research in DG Khan in Pakistan has pointed out the inexperience of some of the bulldozer operators, resulting in inappropriate structures. Training of bulldozer operators, and making them work under the guidance of local farmer leaders, was recommended. Another drawback is in the use of bulldozers to construct higher and stronger soil bunds that do not break and jeopardize downstream water allocations. Long-term sustainability is also at risk. This can be witnessed in several areas in Pakistan, where bulldozers and frontloaders are far beyond farmers' economic standard. The largest drawback of the bulldozer programmes is their success – and the vacuum that is created when they gradually go out of service and are not replaced.

COMBINED MANAGEMENT OF USER ORGANIZATIONS AND LOCAL GOVERNMENT

Where systems become larger, the role of local government in management becomes more important and complements that of local farmer organizations. There are several examples where local government has played a constructive and supplementary role in supervising water distribution and organizing maintenance. Particularly because of the 'reactive' nature of water rights in spate systems, a strong and legitimized authority is crucial in the management of large spate systems. In the Sheeb system in

Eritrea, different rules and regulations were formulated and applied by farmers to fine individual farmers who did not contribute labour as required, or who were breaching a main canal, field bunds or a field gate without permission. Livestock owners could also be fined if their animals caused damage to standing crops in the fields. As many groups in the eastern lowlands had problems with the enforcement of these rules and regulations, they had to request the local administration to use its power to collect the fines. In 1995, the three local irrigation committees were requested to draft uniform rules and regulations in consultation with the local administration. Subsequently, the newly drafted rules and regulations were issued by the local administration as its official rules for its entire area of jurisdiction.

Another example of the constructive role of local government in spate irrigation comes from DI Khan and DG Khan in Pakistan. From 1872, the colonial Revenue Administration recorded the rights and rules in the spate irrigation systems, after endorsement by local leaders. To date these documents remain an important reference for any arbitration and conflict resolution. Apart from the settlement of rights, revenue staff oversaw on a day-to-day basis the distribution of spate water, urging repairs and the plugging of breaches. Traditionally, local user associations took care of the maintenance, providing labour, traction animals and material. The role of the colonial administration was to ‘organize’ these activities during peak periods and emergencies. Farmers who did not take part in the *kamara* (collective maintenance activities) were fined. In addition, labour was at times brought in from neighbouring areas. This engagement had a number of positive side-effects. Grain production increased, bringing stability and creating goodwill among the local tribal populations. New areas were brought under cultivation and this resulted in settlement and an increase in land revenues. Within the revenue department of the local administration, Rod Kohi departments were established and continued to exist after independence. They come under the Deputy District Officer, who until recently had the powers of a magistrate and could fine, penalize and have defaulters or violators arrested. The Rod Kohi departments are made up mainly of regulatory staff, engaged in conflict resolution and safeguarding the application of floodwater rights. The local engineering was left to the farmers.

Given the magnitude of the area under spate irrigation, the staffing levels are very modest (see Table 8.2 for the staff composition of Rod Kohi departments in Pakistan). The explanation is that a strategy of encouraging governance at the community level is in force. Contrary to the practice in perennial canal systems, the policy has been to follow local decisions for disputes occurring in spate-related issues. Local elders and community members are expected to reach consensus on sensitive issues. The administration facilitates the process and intervenes only when necessary. One of the most important points has been to avoid bringing cases related to spate irrigation to courts of law, but instead to give the final authority on arbitration and adjudication to the deputy commissioner at the district level.

These arrangements changed with the decentralization of 2001. Before 2001, the District Government had the authority to check on illegal actions of farmers under the Minor Canals Act. The Naib Tehsildar could punish and fine accordingly in cases of violation of the indigenous rules agreed upon by all members of water users’ associations/ sharecroppers/farmers. It was very common for the Naib Teshildars to issue no-bail warrants to farmers failing to contribute to the collective labour. After the devolution of administration in Pakistan, these powers and authorities of Naib Teshildars have been withdrawn from the Revenue Department and direct involvement of officials is, in theory, not possible any more. More recently, the Government has been working to make the new local government more compatible with local situations. Under the new system, the political, elected person called the district Nazim is head of administration.

TABLE 8.2

Staff composition, Rod Kohi departments, Pakistan

	NWFP		Punjab		
Staff Position	**DI Khan and Kulachi Teshils**	**Tank District**	**DG Khan Districts**	**Rajanpur District**	**Remarks**
Spate Command Area	*224 000 ha*	*118 000 ha*			
Deputy District Officer, Revenue/Rod Kohi	1	1	1	1	General administration of district; general supervision; power of magistrate; final authority in conflict resolution.
Tehsildar	1	1	1	1	Daily supervision; power of magistrate; contact with farmers.
Naib Tehsildar	2	1	2	2	Assistant teshildar
Qanoongo/ Darowgha	2	5	7	2	Supervision, daily contact with farmers.
Patwari/ Naib Qasid	8	6	10	2	Maintains records of rights.
Muhafiz (reader)	1	3	2	2	Watchman/reader of flood measurement.
Temporary Muhafiz		8			
Auxiliary staff	8		33		
Facilities	Office facilities, jeep,telephone for DDO	Office facilities, no jeep, no wireless	Office facilities, no jeep, no wireless	Office facilities, no jeep, no wireless	

A third example of joint management by farmer groups and local government – with local government in a steering and facilitating role – comes from south Yemen. Until 1950, the Sheikh al-Wadi (Master of the Wadi) was responsible for the management of the entire Wadi Tuban on behalf of the Sultan of Lahej. The main responsibilities of the Sheikh al-Wadi were to monitor the allocation and distribution of spate water in accordance with existing rules and regulations; to decide on the length of each *uqma* (traditional diversion spur); to decide on the allocation of small and medium spate flows that cannot reach the tail of the spate river; and to impose and enforce sanctions for taking water without prior permission.

From 1950 to 1967, the role of the Sheikh al-Wadi was taken over by the Agricultural Council that was established following the issue of a decree by the Sultan. The Agricultural Council reported to the Sultan and the Director of the Agriculture Department acted as Chairperson and 17–25 representatives of landowners and sharecroppers were selected as members on the basis of their experience and knowledge. In 1954, the Agricultural Development Board was established to introduce the cultivation of cotton in the spate irrigation systems of Wadi Tuban. The Board took over the O&M services, whose costs were covered through the collection of irrigation fees based on irrigated area.

The basis for the management of the system was an elaborate set of rules, including the governance arrangements (composition, function and meeting) of the Council and rules for water distribution. These covered compensatory water allocations, cost contributions, the funds managed by the Council, arbitration procedures through the Agricultural Court, agricultural transactions, standard lease and tenancy arrangements, penalties for unauthorized use of floodwater or base flow, penalties for negligence of canal banks (causing water to escape to another area), penalties for failing to contribute to maintenance and penalties for failing to pay fines. The governance arrangements linked to these rules, explaining the scope of activities of the Agricultural Council, are given in Box 8.3.

This system ended with the creation of an independent South Yemen in 1967. The Agricultural Council was replaced by an Irrigation Council. Members of the Irrigation Council were directors of state farms and farmer representatives from state farms and cooperatives, as well as political leaders and representatives from the Agricultural Cooperative Union. The Agricultural Development Board was replaced by the Public Corporation for Agricultural Development for Tuban Delta, which became responsible for the O&M services but without the authority to recover any costs from the farmers or their cooperatives. From the early 1980s, the responsibility for the O&M of the spate irrigation systems was transferred to the irrigation section of the Ministry of Agriculture. After the unification of South and North Yemen in 1990, the Regional Irrigation Department of the Ministry of Agriculture and Irrigation (MAI) also made no attempt to recover the O&M expenditures on the modernized spate irrigation systems. In 1996, the Governor of Lahej and the MAI issued Resolution 14/1996 and Decree 7/1996, which reestablished the Irrigation Council, which has a consultative and advisory role only. The role of the Irrigation Council is to discuss and approve the irrigation plan as proposed by the Director of the Regional Agricultural Office; decide on how floods can best be used; and assist in the management and maintenance of the irrigation structures. Management of the spate system irrigation in Wadi Tuban has, however, become confused, as it is no longer clear who is in charge. As a result the Local Council, the Irrigation Council and the Irrigation Department of the MAI all order instructions on the distribution of water. Figure 8.3 shows farmers attempting to control water flows in Wadi Tuban.

FIGURE 8.3
Farmers using brushwood to head up the flow in a canal. Wadi Tuban, Yemen

BOX 8.3

Governance arrangements in the Agricultural Council in Tuban, Yemen

Composition

- Director of Agriculture (Chairperson), Permanent Secretary of the Department of Agriculture (Deputy Chairperson) and 17–25 members, representing the landlords and cultivators.
- *Mashayikh al-A'bar* (supervisors of channels) from the two wadis may be invited to attend meetings but their opinions shall be advisory in nature.
- The Director of Agriculture shall submit to the Sultan a list of the names of those whom he nominates for the membership of the Agricultural Council. The Sultan shall select from among them the required number.
- The term of membership of the Council shall be two years as from the date of appointment.

Functions

- Rationalization of the irrigation problems.
- Protection of the aqna (the right proportions of water established by custom for the irrigation of individual parcels of land) and the *raddyi'* (the sequence of allotting irrigation water to channels and parcels of land established by custom) and the allotting to each channel, barrage, sub-channel and 'marginal' channel the amount of water to which it is entitled according to the established system, i.e. the custom.
- Rationalizing [the rules of] *ijdrah* (tenancy) and *sharak/shirk* (sharecropping).
- Distribution of land among small and large cultivators.
- Division of water between the wadis.
- Maintenance of channels and barrages.
- Devising a system for dealing with the irrigation of lands which are forced to pay *furuq* (contributions for the maintenance of channels) and *masarih*, (contributions for the building of barrages in the *wadi*) each year notwithstanding the fact that they remained unwatered.
- Regulation of maintenance charges on channels and wadis and assigning a special fund for them.
- Introduction of a special system for the irrigation of land, which is planted with red sorghum and provision for its second watering so that the local food security is ensured.
- Scrutinizing agricultural land sales and purchases.
- Review of penalties applied to offenders and transgressors.
- Issuance of an annual report of revenues and expenditure, submitting to the Sultan and then have it published for the information of the public.
- Issuance of bye-laws and putting them into execution after obtaining the assent of the Sultan.

Conduct of Transactions

- The Council shall be convened twice each month and during the spate season at least twice weekly or at any time desired by the Sultan.
- If a member fails to attend four consecutive sessions, without permission or adequate excuse, such a member shall be regarded as having resigned.
- The Chairperson shall preside over the meetings and the Permanent Secretary shall act as deputy in his absence. If both are absent a Chairperson shall be elected for the Council from among those present.
- All decisions of the Council shall be taken by simple majority vote but, when the votes are equal, the Chairperson shall have a casting vote; and a quorum shall be considered to be established only when more than half the number of Council members are assembled.

Source: Maktari, 1971

AGENCY MANAGEMENT

Experience from existing large spate systems

Where specialized agencies have taken responsibility for the management of spate systems, it has usually been as a result of massive public investment in spate irrigation. Not all government investments have, however, translated into the creation of agencies for spate management. For example, the role of the Irrigation and Power Department in the management of the government-constructed spate irrigation systems in Balochistan has been limited to the appointment of O&M staff and guards and the execution of repair works on an ad hoc basis. The Irrigation and Power Departments did not have a routine maintenance programme and the already inadequate budgets for maintenance were further curtailed during the 1990s. In other areas also – DG Khan, DI Khan (Pakistan), Hadramawt (Yemen) or Eritrea, for instance – public investments in spate systems have not resulted in agency management, though in some cases government has assumed responsibility for larger repairs.

The two main examples of agency management to date are the modernized systems in the Tihama (Yemen), managed by the Tihama Development Authority and the Gash System in Sudan. Agency management has suffered from:

- an inability to ensure basic maintenance as a result of under-funding;
- an inability to manage and distribute water in a moderately fair manner because of poor links to farmer organizations or local government; and
- high expectations on continuous support from the agency

The first example of agency management is the Tihama Development Authority (TDA) in Yemen. From the 1970s onwards, the TDA became responsible for the operation and maintenance of the large spate irrigation systems, modernized under a large externally funded programme. TDA's responsibility formally extended down to the level of field turnouts. In the modernized scheme, farmers' responsibility was formally reduced from managing large complex traditional systems to diverting water through field ditches to their fields. Farmers in the Tihama were required to pay two percent of their agricultural production from spate- irrigated fields as an irrigation fee but this system was never implemented. As a result, the TDA often lacked the funds to undertake the O&M necessary in modernized spate irrigation systems.

Data on the O&M budgets for four agency-managed schemes in the Tihama are presented in Chapter 9 and illustrate this trend. The O&M budget received for Wadi Zabid and Wadi Rima, both managed by TDA, cover only a fraction of the costs. The same applies for Wadi Tuban and Wadi Bana in south Yemen. These systems had the additional problem of an inflated payroll, a legacy of past governments.

Earlier, the O&M of the spate irrigation systems in the Tihama were organized by traditional water masters. In the past, the Sultans charged certain families with the responsibility of canal masters, a position that was inherited. The strong control also prevented farmers from violating traditional rules regarding the distribution of spate water, despite the tradition of resolving disputes through conflict. When TDA first asserted its authority, it was able to resolve a large number of disputes.

However, the enforcement of these traditional rules has weakened with time, as the TDA staff were not adequately supported by the authorities concerned to prevent large landowners operating gates without permission. TDA tried to engage the local council to induce farmers but with little success. From the mid-1980s, the number of water conflicts between upstream and downstream farmers increased significantly.

These were intensified by the rapid expansion of banana cultivation, causing many upstream farmers to divert as much water as possible to their banana fields. In several of the main wadis in the area (Zabid, Mawr and Siham), powerful farmers have literally bulldozed new upstream offtakes through. Owing to its growing inability to ensure equitable water distribution in accordance with the existing rules, the TDA gradually abandoned its supervisory role in this field. At the same time, an increasing number of canal masters saw their power eroding due to influence exerted on them by large landowners in the upstream areas (See Box 8.4).

BOX 8.4
Irrigation committees without power – the example of Wadi Zabid, Yemen

In 1988, the Ministry of Agriculture and Irrigation issued Decree No.361/1988, establishing Irrigation Committees consisting of seven members, of which only two are selected farmers' representatives. The main tasks of the Irrigation Committee were defined as:

- to document traditional water rights and customs, as well as land having irrigation rights from base and spate flows;
- to resolve conflicts regarding water allocation and distribution;
- to define the relationship with farmers and outline their duties and responsibilities with regard to the distribution of water;
- to make proposals concerning the role of farmers in the O&M of the spate irrigation systems; and
- to provide advice regarding the optimal use of water and assist in the implementation of irrigation plans.

In 1990, the Tihama Development Authority (TDA) issued Decree No.6/1990 to facilitate the formation of the Irrigation Committee for Wadi Zabid, with five government members and two farmers' representatives. According to the decree, the Irrigation Committee only had the right to formulate recommendations, which needed the approval of the TDA Chairperson and the Governor. The newly formed Irrigation Committee never became effective. Farmers were insufficiently represented, the mandate was too narrow to generate interest and neither decree was fully implemented.

In response to the limited role of the agencies and the limited number of active canal masters, farmers have increasingly taken the initiative to organize the O&M of their irrigation systems themselves without waiting for assistance from outside. To organize and coordinate the O&M, farmers have formed informal groups at village level. Due to the spontaneous, autonomous organization of farmers, who are taking action to ensure that the canal system and diversion weirs are operational, the utilization of base and spate flows are still effective. Most of the maintenance works are executed with the help of their own oxen, while machinery is hired when needed. According to a baseline survey conducted in 2001, farmers receiving water from modernized systems paid an average amount of YR4 000-7 000 (about US$25-47) per year for the O&M, whereas farmers in traditional spate irrigation systems paid about YR20 000 (US$135) per year, as they have to reconstruct their traditional diversion structures every year *(World Bank 1999, 2000a, 2000b).*

A similar experience was seen in the Gash System in Sudan, where the Farmers' Union is supposed to be elected by the farmers. Given that the constituency was not clearly defined in the scheme, and many farmers do not have ready access to irrigated areas, they lost interest in its administration. The Farmers' Union thus tended to represent the interests of the local tribal hierarchy, tribal sheikhs and elites in the project area.

Under-funding was an important obstacle for the now abolished Gash Development Authority (1992–2002). Lacking financial and technical resources, the scheme's irrigation infrastructure deteriorated seriously and the Gash system experienced a decline in income – from a cotton export zone it became a marginal subsistence crop area. In 2002, the Gash Agricultural Scheme (GAS) was incorporated by decree to undertake the management of the Gash irrigation scheme. It has a board of directors chaired by the Federal Minister of Agriculture and co-chaired by the State Governor, to whom the Chairperson delegated his powers. GAS activities are focused on the repair and maintenance of canal offtakes. However, it is still constrained in its ability to plan for development because of inadequate funding, lack of revenues and lack of technical capacity.

Conditions for successful agency-based management

Based on these and other experiences, the following principles need to be respected to improve the likelihood of success and ensure the sustainability of large, agency-managed spate irrigation systems:

- Clarifying and strengthening the roles of both farmers and local government and reducing the role of specialized agencies will be appropriate in most cases.
- Local government can be the repository of agreements on water distribution and maintenance arrangements and make use of its normal powers to solve conflicts between farmer groups. Its authority will be acknowledged by farmers if it operates on a basis of transparency, accountability and fairness.
- Maintenance has to remain a specialized activity. It should be done primarily by farmers, whenever possible. Contracting private companies is also an option and, in any case, the employment of a large full-time staff in the agency for maintenance should be avoided. This will avoid a situation when everyone is responsible, but no one does the hard work of maintenance.
- Public financial support is better directed at recovery from unusual damage and investment in extension and farmer support rather than routine maintenance, which should be transferred, or left, to farmers.
- Effective communication mechanisms are important to avoid a gap in perception between agency staff and farmers.
- Farmer representatives elected from a wide constituency should play an important role in the management of agency schemes. Marginalizing farmer representatives or undue influence by powerful interest groups has to be resisted. Councils of user representatives, local government representatives and service organizations may be the most appropriate method of management.

Chapter 9

Economics of spate irrigation

SUMMARY

Returns to agriculture in terms of spate irrigation are often low and the scope for deriving significant additional economic benefits from investment is constrained because of:

- variations in cropped area and crop production from year-to-year and season-to-season;
- inherent risk of total crop failure in certain years with no or damaging floods;
- domination of staple crops with limited market value; and
- limited potential gain in water productivity resulting from the relatively high diversion and conveyance efficiency of existing spate systems.

Evidence shows there is no scale economy for spate irrigation. Unit costs tend to increase as systems become larger because of the technical complexity related to such systems, and the much larger flows that need to be taken into account in the design of civil engineering works. Smaller spate systems are less complicated and can avoid expensive and complex infrastructure such as cross-river siphons, sedimentation ponds and lengthy flood channels. In this respect the trend in spate irrigation is opposite to that in perennial irrigation investments. Investment in smaller spate systems may have a better return than those in large spate systems. The picture may, however, change if spate irrigation is combined with shallow groundwater use or adequate local rainfall, or when care is taken in soil moisture management.

In designing spate irrigation improvement projects, the trade-offs between investment costs, maintenance costs and the level of service deserve more attention than in the past. In particular, the very nature of arid zone hydrology requires a different approach towards risk management than for perennial irrigation infrastructure. Provision for rebuilding parts of the system, after major floods, are often a more cost-effective option than designing permanent structures. Similarly, designing simple un-gated headworks may, in many cases, be more cost-effective than sophisticated structures, and present less operational constraints, while ensuring satisfactory distribution of water to the fields.

Economic analysis of development options should include investigation of links between initial costs and subsequent maintenance costs, using realistic valuations of farmers' input. A low-cost approach may have significant sustainability and 'ownership' advantages:

- a simple technology that can be easily maintained;
- less dependent on heavy machinery and imported materials and supplies;
- most of the construction works can be carried out by farmers themselves;
- repairs are less costly and can be executed faster as only locally available materials and/or skills are required; and
- the impact of failure is partial as diversion structures have smaller command areas.

The benefits of spate irrigation cannot be assessed only on a foreseen increase in crop production. Investments in spate irrigation often have significant social and environmental benefits. The assessment must take into account the recognition that farmers in spate areas often have no viable alternative means of support. The impact of sustaining and supporting these systems, thus, differs from investments where the main target group has access to alternative livelihood opportunities. Social and environmental benefits of spate irrigation should be included in an economic analysis, as a minimum, scores should be allotted in accordance with the importance. A list of such benefits is provided in this chapter.

INTRODUCTION

Returns on investment in spate irrigation is generally low and often does not justify large capital outlays. This, however, has not prevented large investments being made in spate-improvement projects in the past, often with doubtful results. Yet, cost-effective improvements are possible in spate-irrigation systems that can contribute substantially to poverty alleviation, improvement of rural livelihoods and local food security. Some investments – examples are given in this chapter – can be returned within a year. Moreover, spate irrigation can significantly contribute to wider basin resource management and improved sustainability of fragile arid environments. These externalities should be taken into account when assessing the benefits of spate irrigation development.

This chapter discusses the economics of spate irrigation, focusing on the costs of improvement options. Benefits are assessed looking at different planning horizons and the broader livelihood and environmental impacts.

ECONOMIC ANALYSIS OF SPATE SCHEMES

Any investment in improving or modernizing traditional spate irrigation systems can only be economically feasible if the net economic benefits are significantly higher than the economic returns of the traditional spate-irrigated agriculture. The scope for deriving significant additional economic benefits from investments in spate irrigation is limited by the following factors:

- the cropped area and crop production vary considerably over the years because of variations in the size and frequency of floods;
- there is an inherent risk of total crop failure in years with no floods or very large floods that wash away the diversion structures before any land can be irrigated;
- cropping patterns that, in most areas, are dominated by the cultivation of traditional crops having limited market value and are grown mainly for home consumption; and
- the diversion and conveyance efficiency of most spate-irrigation systems, which is already relatively high as most surface water is used for irrigation, finds its way to groundwater recharge, or is used for the flooding of forests or grazing areas.

In many cases, substantial economic benefits may, however, come from higher water productivity through the conjunctive use of groundwater and spate water, improved soil moisture management, better flow distribution and improvements in agronomy (see Box 9.1)

As the scope of potential economic benefits from investments in spate irrigation is relatively limited, and to ensure that the improvement of spate irrigation systems make sense in economic terms, development costs must be proportional to expected benefits. A robust, low-cost approach has the following significant advantages:

- simple technology is used that is easily adopted by local farmer-engineers, ensuring that both construction and maintenance can be undertaken at the local level, using locally available materials;
- most of the construction works can be carried out by the farmers themselves;
- repairs are less costly, and can be executed faster, as only locally available materials and/or skills are required; and
- the impact of failure is partial as low-cost diversion structures have smaller command areas than larger, permanent diversion structures.

BOX 9.1

The ingenuity of the Mochiwal division structure in Pakistan

Mochiwal Division on the Darabam Zam in Dera Ismael Khan (Pakistan) is probably one of the most cost-effective spate irrigation investments. The Mochiwal division structure consists of three-gated divisions, operated with hoisting gear. The function of the structure is to distribute the flow between two spate irrigation channels – the North and the West Channel. The cost of the structure including the short guide bund sections was US$2 000.

Prior to the Mochiwal Structure, the flow of the Darabam could not be controlled. It disappeared in its entirety to the low lying North Channel areas, every time causing considerable damage to this flood channel (see picture). The water could not be controlled in the North Channel as the spate flow washed away all earthen diversion structures in its path. At the same time the West Canal was left high and dry in most years.

The Mochiwal Structure now controls the inflow into the North Channel and keeps the flood to a manageable quantity. At the same time, it diverts the water from Darabam to the West Canal command area, where there is substantial land. An investment of US$2 000 restored and safeguarded farming on 3 500 ha.

In fact, some of the most expensive investments, e.g. Wadi Siham diversion structures, have been amongst the least successful. While low-cost options are attractive when considering economics and sustainability, it is also important to consider the level of service that can be provided. There are very few examples of farmers wishing to dispense with even poorly designed permanent diversion structures (although they may often wish to modify them) and return to their labour-intensive traditional diversion arrangements. Finally, the feasibility of investment in spate irrigation depends upon the probability of receiving water. Areas with a more reliable supply of spate water justify higher levels of investment than areas with a less reliable supply of spate water. In areas where the flood probability is once every ten years, it is hard to justify extensive investment.

COST OF SPATE IRRIGATION DEVELOPMENT

As discussed elsewhere in this report, several types of programmes have supported the improvement or modernization of spate irrigation. These programmes have had varying degrees of success. It is obvious that investment in civil engineering to provide permanent gated headworks and new canals in large systems has attracted most visibility. Nevertheless, it has also drawn criticism because of the high development costs, and the often disappointing and sometimes even negative impacts.

Table 9.1 gives an overview of investment costs per hectare for different types of interventions in different countries. It is evident that unit costs very much depend on the nature and size of the system and the type of intervention. In general, very high costs were incurred in systems that involved the construction of permanent headworks and new canals on large systems.

Contrary to what may be expected, economies of scale do not apply in spate irrigation. One reason is that development or improvement costs are very much concentrated in headworks, while the command area may vary substantially in relation to availability of land and water. In addition, unit costs tend to increase as systems become larger because of the technical complexity of larger systems, and the much larger flows that have to be taken into account when designing civil engineering works.

In large systems, a diversion structure has to span a wide wadi, and stand up to very large design floods. Permanent structures cannot be allowed to fail in large floods, as in traditional systems. Often, because of the costs involved, a single headwork is constructed supplying water to canals that were formally supplied from their own individual intakes. This requires the development of lengthy new supply canals and extensive bank protection. When there are irrigated areas on both sides of a wadi, a siphon or conduit under the wadi bed is needed to pass irrigation flows to the other bank, which adds to the costs (double-sided intakes are generally not used because of the difficulty of managing water distribution between both banks).

The cost per hectare for a system with civil headworks on a large project (1 500 ha and above) are between US$1 350–2 000/ha (with some exceptional peaks above this amount). While the cost for permanent headworks on small systems is considerably less: US$180–450/ha. The cost for systems with non–permanent headworks, essentially soil bunds, is far less again (mainly below US$125/ha). These soil bunds, though not permanent, are not necessarily rebuilt every year. The Rehanzai Bund in Pakistan, for instance, has been in operation for more than 20 years.

In general, permanent headworks on small systems and investments in soil bunds provide high returns and defeat the notion that investment in spate irrigation is unrewarding. Such programmes may achieve costs of water storage (in the soil profile) that are highly favourable compared to investments in other water control structures in arid areas, especially dams. The same argument extends to supporting improved soil moisture conservation, command area programmes (such as gully plugging) and investing in conjunctive use of groundwater and spate flows. In many cases, investment in such activities, as well as complementary programmes in improved agronomic practises, show the highest dividend.

This is exemplified by the study of the economic rate of return (ERR) of spate irrigation projects. An FAO study on investment costs in irrigation *(Salman et al, unpublished)* included information on the economic rate of return, looking at the different types of irrigation: spate, localized, sprinkler and surface irrigation. The comparison between the four categories is given in Table 9.2 and shows that spate irrigation systems in the study managed an acceptable rate of return.

The analysis shows that the economic rate of return (ERR) for surveyed spate irrigation projects correlates negatively with the size of project and the unit cost, proposing that the ERR tends to be higher for smaller projects (see Figure 9.1). As smaller spate irrigation systems are less complicated, expensive and complex infrastructure can be left aside, they do not need cross-river siphons, sedimentation ponds and lengthy flood channels, which means they may tend to be better off economically than are larger systems.

TABLE 9.1
Development costs of different types of spate irrigation projects

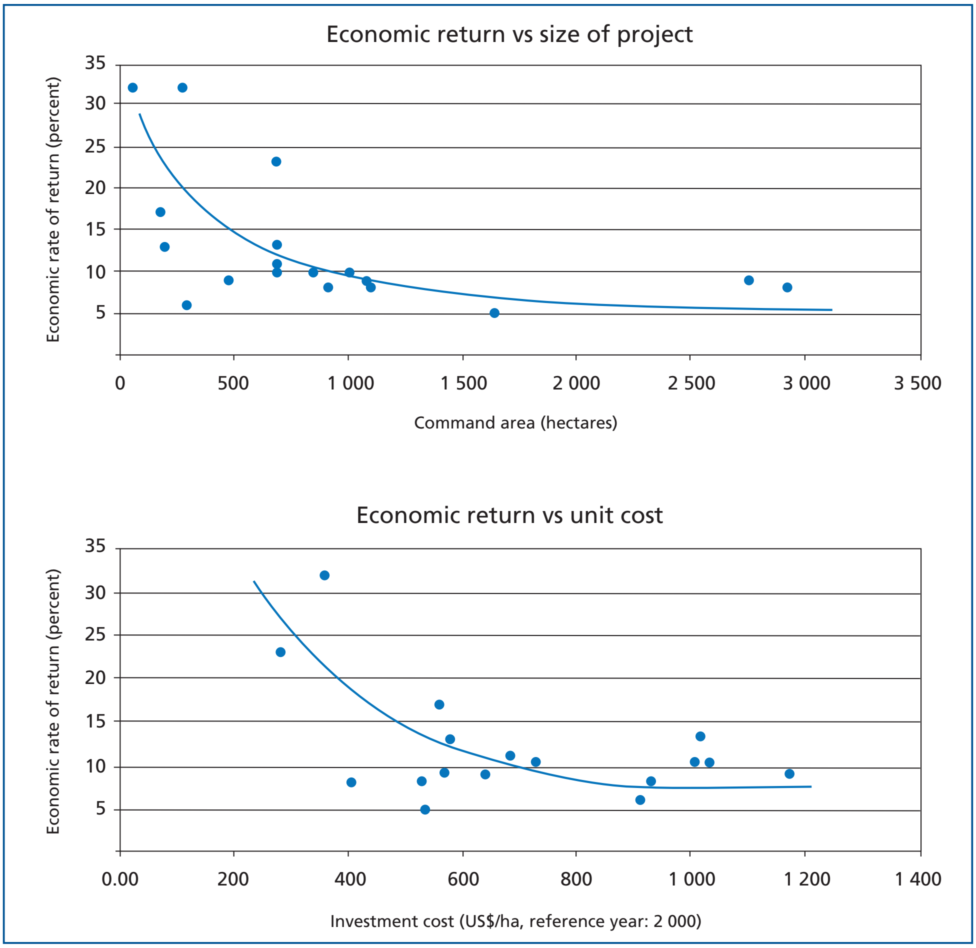
Intervention	Unit Cost (US$/ha)	Description
Non permanent headworks		
Rehanzai Bund, Pakistan	5	Large soil bund and embankments with gabion core, diversion channels – irrigating 12 000 ha (1984)
Gathelay, Eritrea	51	Soil bunds, gabion structures (2002)
Karkhi Bund, Kharan, Pakistan	70	Bulldozer built soil bund–irrigating 20 ha, but larger potential (1993)
Wadi Labka, Eritrea	110	Gabion reinforced guide bunds to flood channels
Miscellenous systems in Omomyya	170–220	Soil bund, gabion structures
Grasha, Eritrea	123	Soil bund and diversion channel
Garen Bygone, Iran	160	Flood water spreading
Permanent headworks, small systems		
Mochiwal, Pakistan	1	Flow splitting structure at critical point
Alebu, Eritrea	181	Diversion weir and guide bund
Mogole, Eritrea	341	Diversion weir and guide bund
Bultubyay, Eritrea	444	Diversion weir, guide bund, and flood channel
Rehabilitation		
Dameers Hadramawt, Yemen	90	Small systems
Dameers Hadramawt, Yemen	151	Small systems
Command area works (Irrigation Improvement Project), Yemen	150–300	
Sidi Bouzi, Tunisia	252	Small system
Oum Aghanim, Morocco	620	Diversion weir, canal, distribution structures
Tambardoute, Morocco	699	Diversion weir, canal, distribution structures
Touizgui, Morocco	628	Diversion weir, canal, distribution structures
Afra, Morocco	895	Diversion weir, protection bund, distribution structures
Permanent headwork, large systems		
Koloba, Ethiopia	250–350	Diversion weir, breaching bund, siphon
Nal Dat, Pakistan	646	Not built
Marufzai, Pakistan	1 346	
Wadi Laba, Eritrea	1 420	Diversion weir, breaching bund, siphon (2000)
Barag, Pakistan	1 478	
Sidi Bouzi, Tunisia	1 480–2 500	
Mai Ule, Eritrea	2 420	Diversion weir, breaching bund and diversion channel (2000)
Wadi Labka, Eritrea	3 517	Diversion weir, breaching bund, embankments (not built)
Wadi Siham, Yemen	11 000	Diversion structure, sedimentation pond, flood channel – later replaced by system of flood protection and re-enforced independent intakes

TABLE 9.2
Economic rate of return comparison between different irrigation technologies

Type of irrigation	Average size of projects	Average unit cost	Average rate of return (%)
Spate	6 636	919	12.9
Localized	26 395	1 446	20.0
Sprinkler	21 351	3 196	21.5
Surface	39 490	3 519	20.5

Source: Salman, et al. (unpublished)

FIGURE 9.1
Economic rate of return for spate irrigation projects against project size and unit cost



BALANCING INVESTMENT COSTS, MAINTENANCE COSTS AND THE LEVEL OF SERVICE

There is an element of 'management of expectations' in new infrastructure-oriented schemes. In traditional systems, a degree of unpredictability and a very high maintenance burden is expected. In externally funded infrastructure-oriented projects the standards for water diversion efficiency, and keeping maintenance costs to a minimum, are often given greater consideration; while intermediate options may be more cost-effective. Investment costs must, therefore, be linked to the level of service provided by the different engineering approaches.

Simple soil bunds or spur type diversions, in spite of the cost-effectiveness of their construction with a bulldozer, require frequent repair in the critical sections, often every 1 or 2 years and, in extreme cases, may need to be replaced more than once every year. These systems require more effort from farmers in their operation and maintenance, as uncontrolled flows are admitted to canals work then needs to be done on reconstructing canal diversions, repairing scour damage and, in some cases, removing sediment deposits.

In the right circumstances, a simple permanent intake, provided with effective sediment control facilities, may provide a much higher level of service, and dramatically reduce operating and maintenance requirements over an engineering life of 20 or 30 years. Box 9.2 illustrates this point and gives an example of a high cost concept being substituted by a more cost-effective solution, where the difference in level of service was balanced against overall cost.

BOX 9.2

Gabion guide bunds rather than permanent diversion structures in Wadi Labka, Eritrea

In Eritrea, 1 200 m long gabion-reinforced guide bunds were constructed by the Ministry of Agriculture in Wadi Labka at a cost of US$430 000. In the original project proposal, permanent headworks were proposed for Wadi Labka and a diversion structure was foreseen in the gorge of the ephemeral stream. Wadi Labka is extremely wide and the technical and financial feasibility of this option could never be justified. Instead, a series of gabion-reinforced guide bunds were constructed, combining manual labour and bulldozer work. The gabions served to divide the flood and reduce the likelihood of early washouts in the head section of the flood channels on either side of the Wadi Labka stream. The cost of the gabion river engineering options (US$110/ha) compares favourably with the earlier proposed civil engineering option of US$3 500/ha.

The trade-off between initial investment costs and subsequent operating and maintenance costs in spate systems deserves more attention than has been given to date. Data on the operation and maintenance budgets for four agency-managed schemes with permanent headworks and canal systems in the Tihama of Yemen are shown in Table 9.3. These indicate an average ‘optimal’ O&M cost of around US$33/ha in 1998.

The O&M costs of the Wadi Laba and Mai Ule systems in Eritrea are comparable. These costs are estimated at US$40/ha including the cost of replacing the frequently failing breaching bund. The cost for maintenance in the Gash system in Sudan was estimated at US$14/ha (mainly for de-silting), which is also comparable. Recent data from four spate systems in Morocco put the O&M cost higher at US$54–88/ha. In Yemen and the Sudan, the required budget was far more than the actual budget received, which was mostly spent on maintaining a large permanent agency staff, offices, vehicles and other support services. Very little was spent on actual scheme maintenance. In contrast, in Wadi Laba and Mai Ule, the funds were collected by the Sheeb Farmers’ Association and spent only on system maintenance, thanks to the high productivity of the Sheeb systems which made this possible.

TABLE 9.3

Actual and optimal O&M in four agency-managed systems, Yemen

Intervention	Wadi Zabid	Wadi Rima	Wadi Tuban	Wadi Bana
Area covered (ha)	17 000	8 000	6 606	12 400
Actual situation				
Staff employed	97		486	395
Staff costs (US$)	37 704	25 111	474 074	218 519
O&M budget requested (US$)	76 296	23 704	328 889	222 963
O&M budget received (US$)	14 815	14 074	13 333	26 667
Optimal situation				
Staff number	95	59	84	116
Salary costs (US$)	67 407	45 185	55 556	81 481
Operational budgets (US$)	54 815	32 593	33 333	76 296
Maintenance budgets (US$)	13 333	11 111	11 111	17 037
Depreciation (machinery/vehicles) (US$)	242 222	147 407	145 185	351 852
Total (including 15% miscellaneous) (US$)	434 815	271 852	281 481	606 667
O&M cost (US$/ha)	29	34	35	32
Average cost (US$/ha)	32.8			

Adapted from: Al-Eryani, M. Mohamed Al-Hebshi and Anwar Girgirah (1998)

At the other extreme, the costs of O&M for traditional systems are mostly farmers' direct labour, and their investment in draught animals. These costs vary enormously from scheme to scheme and from year to year, and are not known with any precision. It is reported that in most of the traditional spate irrigation schemes in Eritrea, about 80 percent of the farmers' effort is spent on repair and reconstruction work of diversion structures, field embankments and canals *(Haile, 1999)*. Some estimates of initial and subsequent maintenance costs for a range of types of traditional spate diversion spurs in Eritrea are given in Table 9.4.

TABLE 9.4

Comparison of initial and maintenance costs for traditional diversion spurs in Eritrea

Type of diversion spur	**Initial cost (US$)**	Estimated damage as percent of initial cost during normal spate season	Number of repetitions of construction during normal spate season	**Maintenance cost (US$)**
Stone	88	50	1	44.5
Soil	31	100	2–4	63.5–126
Brush wood	40	60	2–4	48.6–97.2
Mixed	60	40	2–4	48–96
Gabion	325	20	–	65

Source: Haile (1999), and Haile and van Steenbergen (2006)

Excluding the gabion option, maintenance costs for traditional diversion spurs average around 1.8 times their initial cost. This figure can be compared with a range of options for other engineering interventions (see Table 9.5). While these approximate figures tell almost nothing about the level of service delivered by the various options, or their long-term sustainability, the trade-off between initial investment cost and the subsequent maintenance burden is very clear.

TABLE 9.5

Relation between initial investment cost and maintenance costs – comparison between traditional and other engineering interventions for spate diversion in Eritrea

Type of engineering	Annual cost of maintenance/initial cost)
Traditional diversion spur, excluding the gabion option (Average from Table 9.4)	1.8
Soil bund (bulldozer)[1]	0.33
Gabion diversion (Table 9.3)	0.2
Permanent headworks and new canals in large agency-managed schemes[2]	0.025

1. Assuming that the bund needs to be reconstructed every 3 years.
2. For an initial development cost of US$1 400/ha and 'optimum' maintenance cost of US$35/ha

For farmer-managed schemes that do not carry the costs imposed by full-time agency management, comparisons of initial investment costs, with best estimates of the lifetime O&M costs, provide valuable guidance as to the most economic development approach to be adopted when spate improvement projects are being planned.

ASSESSING THE BENEFITS OF SPATE IRRIGATION DEVELOPMENT

Integrating risk management in the design of spate systems

Part of the explanation of the high cost of some spate-irrigation projects has been an approach of developing fail-safe, even if costly, and sometimes not very efficient options. Instead, in comparing costs and benefits of spate irrigation, it may be useful to use a different planning horizon, rather than the 20–30 year period common to water infrastructure projects. Water users may have a different planning horizon, and may be willing to accommodate more risks in line with the uncertain, variable and dynamic nature of spate irrigation.

In spate irrigation, the concept of infrastructure and the associated notions of permanency over the relatively long engineering life of hydraulic structures need to be reconsidered. A mixture of improved soil and water management, and low-cost investment in diversions with a short, useful life may be preferable to the high-cost approach, provided they translate into a reduction in terms of the farmers' labour involved in the frequent rebuilding of intakes. This approach is closer to the traditional system of managing spate irrigation, and links better with existing water allocation rules, the disruption of which affects the degree of solidarity among the water users.

Another justification, calling for a better assessment of the relation between risk, costs and benefits, lies with the hydrology of arid areas where spate irrigation takes place. Typically, as discussed in Chapter 3, arid zone hydrology is characterized by very large variations in the number and intensity of floods. While the statistical distribution of floods varies from one place to another, it is not infrequent to experience major floods with a 4 to 5 year return period. A careful study of the return period of major floods, and an analysis of the costs and benefits associated with different levels of security, may show there is no scope in seeking to control a 50 or 100 year flood. Rather, the design of improvement interventions should follow the philosophy of spate systems and seek an intermediate level of control that offers best cost-effectiveness. The combination of permanent headworks with a fuse bund that needs to be reconstructed every 4–5 years is an example of such trade-off.

Taking into account broader livelihood and environmental impacts

Investments in spate irrigation often have significant social and/or environmental benefits, including:

- **Poverty alleviation** for a large number of households, who cultivate relatively small spate-irrigated areas as owner-operators and/or sharecroppers, derived from improved agricultural production and/or livestock activities.
- **Improvement of food security** for the number of months that farming households can satisfy their food consumption in normal years.
- **A multiplier effect** because more money enters the local economy as a result of the involvement of the local labour force, artisans and contractors in the execution of the construction works as well as an increase in the marketing and processing of agricultural and livestock produce.
- **Creation of temporary labour opportunities** during the execution of construction works as well as more permanent labour opportunities in the agricultural sector because of the increased cropped area and/or cropping intensity, especially for landless households and farming households with small plots.
- **Reduction in seasonal migration** as the need to migrate to areas in search of labour is reduced because of higher incomes from spate-irrigated agriculture and/or livestock keeping.
- **Reduction in the cutting of trees** as the need to earn an additional income from the sale of fuelwood or charcoal decreases, because of higher incomes from spate-irrigated agriculture and/or rearing livestock.
- **Reduction in the cutting of trees and shrubs** as fewer are required for the frequent reconstruction of the traditional diversion structures and any other irrigation infrastructure; and
- **Maintenance of the integrity of the land alongside ephemeral streams** that, if not managed under spate irrigation, would easily be subject to braiding and river erosion.

Spate irrigation always takes place in precarious environments – arid and remote. There are often very few options for generating income. The most common livelihood strategy is the diversification of the household economy. In addition to a highly variable income from spate-irrigated agriculture, households may have one or more source of income from keeping livestock and wage labour and, to a lesser extent, from the sale of handicraft products. The assessment of the feasibility of investments in spate irrigation, thus, should not be based only on the direct economic benefits derived from agricultural production, but also on the social and environmental benefits that may be obtained. As it is not always easy to quantify the potential social and environmental benefits of various options, they should, as a baseline, be given scores in accordance with the probability that these benefits would be achieved, and project assessments should use this ranking in selecting the preferred options. In addition, it may be useful to explore different ways of valuing capital in investments that have an explicit poverty alleviation objective.

The functioning of spate systems in many areas is a matter of survival. When the spate system fails, the only option for spate framers is migration, and with it the unravelling of a livelihood system. In assessing the benefits of spate irrigation, the fact that needs to be taken into account is that farmers and livestock keepers in these areas often have no viable alternative means of support. Hence the impact of sustaining and supporting such natural resource systems differs from investments, where the main target group has access to alternative livelihood opportunities. To illustrate this point, and the broad impacts on livelihoods of the failure of traditional spate systems, which might often correspond to a ‘no project scenario’, a social assessment of two years of drought in Balochistan 1998–2000, is summarized in Box 9.3.

BOX 9.3

Social assessment of two-year drought in Balochistan (1998–2000)

- A sharp decline occurred in the consumption of nutritious items as well as staple food intake. In many instances, the people substituted their normal food items with inferior items. For instance, 33 percent of villages reported a reduction in staple food quantity, 57 percent villages reported reduction in nutritious items such as meat, milk and ghee, and 66 percent of the villages reported substitution of normal food items such as sugar with inferior items such as raw sugar (*gurr*) during 2000.
- There were many instances medical treatment was postponed because of cost. During 2000, 47 percent of the villages reported switching over to herbal medicine; up from 9 percent in 1999.
- Purchase of new clothes and footwear declined from 52 percent in 1998 to 36 percent in 1999 and fell to 11 percent during 2000.
- A sizeable dropout rate was noted from educational institutions in the villages surveyed. The main reasons were the increased demand for domestic and productive labour and the cost of education. In 2000, the dropout rate of 71 percent was related to the increased demand for labour and 29 percent stated inadequate means of support. Both these conditions were a direct outcome of acute water scarcity during this period.
- There was a sharp decline of the area under annual crops such as wheat, millet, sorghum, vegetable and alfalfa. This occurred in 90 percent of the surveyed villages in 1998 while 10 percent of the villages reported no annual crops in this year. During 1999, respondents from 28 percent of the villages reported a further decline in the cropped area and 72 percent reported no crop at all. All the villages reported no annual crop in 2000 because of failure of rainfall.
- Reduction/de-stocking of livestock occurred in 33 percent of villages during 1998, in 90 percent of villages in 1999, and in 48 percent of villages in 2000.
- During 1999, people in 24 percent of the villages in the study area took production loans, while in 2000 the ratio of villages where such loans were taken, was 14 percent. Consumptive loans were taken in 43 percent of villages in 1998, 95 percent of villages in 1999 and 76 percent of villages in 2000. In about 14 percent of the villages, people were refused loans by the lenders because of defaults on the previous borrowing. At the community level, wealth redistribution mechanisms such as religious and voluntary charity ceased to function.
- In Qila Saifullah District, migration occurred in 90 percent of the villages ranging between 5 and 54 percent of total village households. This phenomenon occurred in 80 percent of the villages ranging between 11 and 48 percent of total village households in Mastung. Emigration seriously affected village decision-making mechanisms.
- Finally, large-scale changes in primary economic activities: dependence on agriculture as a main source of subsistence decreased from 80 percent of the surveyed population to 38 percent in Qila Saifullah, and from 80 percent to 6 percent in Mastung. Similarly, the percentage of people depending on labour as their main economic activity increased from 7 to 32 percent in Qila Saifullah and from 9 to 42 percent in Mastung.

Chapter 10

Spate irrigation in the context of river basin resource management

SUMMARY

It is important to place the development of spate irrigation in the context of river basin management. If it is well designed and managed, spate irrigation systems can fulfil several important functions in basin management, beyond providing water for agriculture, rangeland and local forestry. They include:

- preserving biodiversity;
- mitigating flood peaks;
- stabilizing river systems; and
- recharging groundwater.

On the other hand, ecosystems in arid and semi-arid regions are generally precarious. Careful consideration must be given to the possible effects and impacts of the development of spate irrigation systems on natural resources as well as on water quality and quantity.

Spate irrigation is closely linked to biodiversity and natural vegetation. Spate systems are depositories of local biodiversity – collecting seeds from a large catchment and depositing them in moist soils – and may feed ephemeral wetlands that are rich in species. Natural species of vegetation are often of considerable value and may provide an additional source of income to local communities. Grasses and shrubs, for instance, sustain livestock populations, while trees are used for various purposes. In some places, the introduction of alien species, such as mesquite, can negatively effect spate-irrigated land and represent a major problem.

The clearing of land of trees and shrubs close to spate-irrigated areas is primarily associated with the traditional construction of diversion bunds and the collection of wood for fuel. Thus, options to reduce the unsustainable use of local trees and shrubs, through the construction of more permanent diversion structures, should be highly promoted.

Much effort in spate irrigation is placed on stabilizing wadi reaches to ensure the continuous supply of water to fields. The viability of spate irrigation systems, as a means to help stabilize river systems, should be acknowledged and promoted. In particular, the use of natural vegetation, specifically planted for river training, should be encouraged because of its lower costs and the advantage of its being environmentally acceptable.

In spate-irrigated areas, the risk of sand dune formation is ever present. Dune formation particularly threatens the fringes of spate systems. The formation of sand dunes surrounding spate-irrigated areas can be exacerbated when agriculture stretches into marginal areas or when unsustainable agricultural practices in

rainfed farming include systematic clearing of land of roots and natural vegetation. The rehabilitation of sand dune areas requires the engagement of farmers to plant native trees and dwarf shrubs and to reduce agricultural encroachment on fragile land.

To a certain extent, the development of spate irrigation can contribute to flood mitigation by reducing the likelihood of large floods. There is an upper limit to this, however: spate systems intercept moderate to medium flows while peak floods are usually passed on down the wadi and may still create havoc downstream. Through their effect on the stabilization of ephemeral streams, spate systems can help avoid unexpected downstream breaches. Some interesting experiences of flood spreading have been tested and can help mitigate the damage caused by major floods while contributing to groundwater recharge locally.

The relation between spate irrigation and groundwater is complex. Spate irrigation offers opportunity for *in situ* groundwater recharge but, at the same time, reduces possible recharge downstream. The balance of opportunities and costs is site-specific, and a careful assessment of potential and constraints of groundwater use and recharge needs to be done to understand the implications of proposed spate-related interventions. In particular, most of the water diverted onto the land by spate irrigation is accounted for by evapotranspiration, and the proportion of groundwater recharge is less. When designing spate irrigation systems, a careful assessment of the changes in water balance must therefore be performed at the level of the river basin to understand the implications on the overall hydrology of the wadi.

Of particular relevance is the potential impact of spate diversion on the recharge of major aquifers in alluvial fans and in downstream plains where water productivity, through groundwater-based irrigated agriculture is, in most cases, much higher than in spate irrigation. This raises the issue of the relationship between upstream and downstream water users. Conditions, where downstream users would take greater advantage of water used by upstream spate farmers, could be the foundation for negotiations based on the concept of payment for ecosystem services, where part of the gains obtained from additional recharge downstream could be used to compensate upstream farmers for losses incurred related to reduced water supply.

On the other hard, groundwater development in spate systems has the potential to considerably modify agricultural practices and can sustain highly productive farming. Where groundwater is available, the unpredictability associated with spate irrigation disappears, and farmers can rely on a safe supply of water for their production. Wherever groundwater development has been possible, farmers have taken advantage of it and harnessed water in a more productive way than that expected from traditional spate systems. Some estimates show that groundwater-based irrigation is six times more productive than spate irrigation. Where recharge is possible, according to local aquifer and terrain conditions, it should therefore be considered as an integral part of the design of spate projects.

The reliability of spate irrigation would be greatly increased if water from flood peaks could be stored in reservoirs and then released when needed for irrigation. A conventional response to the unpredictability associated with spate irrigation would be to store floodwater in dams upstream of irrigation schemes. However, in arid environments dominated by extreme flood events and high sediment load, such an option is, in most cases, not feasible. Reasons include rapid siltation of reservoirs, the negative affect groundwater recharge and water users downstream and a high rate of unproductive evaporation from the reservoir. Wherever possible, options that effectively enhance aquifers' recharge should be preferred, as they score better both from the viewpoint of cost as well as effectiveness.

LINKING SPATE IRRIGATION AND NATURAL RESOURCE MANAGEMENT

This chapter describes the linkages between spate irrigation and natural resource management in the river basins of which spate systems are part. Ecosystems in arid and semi-arid river basins are generally fragile, and they have limited capacity to adjust to changes. If the usage of natural resources, such as land and water, is changed, the environmental consequences are often greater than foreseen. Consideration should be given to the possible effects and impacts of the development of spate irrigation systems on the available natural resources as well as water quality and quantity. Spate irrigation systems are very much part of these natural resource systems and are themselves affected by changes in the land and water resources in the river basins.

It is important to place the development of spate irrigation in the context of river basin management. Spate irrigation systems, when they are well managed, fulfil several important functions, beyond the spate irrigation per se: preserving biodiversity, mitigating flood peaks, stabilizing river systems and recharging groundwater. These spate irrigation system functions of are often influenced by other development activities elsewhere in a basin. The complexity of interaction between spate irrigation and other development activities on the one hand and the river ecosystem on the other is well illustrated in the case of the Manchar Lake in Sindh province of Pakistan. The lake is formed by spate flows maintaining several extra functions beyond the spate irrigation. It used to be an excellent example of flood management and surplus floodwater. Moreover, it served biodiversity, drinking-water, fisheries and was an abode of indigenous communities. The lake, however, witnessed a downturn after contaminated agricultural drainage water, from a perennial irrigation system in the upper reach of the basin, was routed to the water body.

Linkages between spate irrigation and natural resource management in the river basins, the effects that river basin management have on spate irrigation and the impacts of spate irrigation on river basin, management are summarized in Table 10.1.

NATURAL VEGETATION AND BIODIVERSITY

Ephemeral rivers are often unexpectedly rich depositories of vegetation. Spates collect seeds from a large part of catchments and deposit them in the river bed and flood irrigated fields. The moist, and often organic-rich layers of silt forming spate irrigated fields, provide a favourable environment for wild trees, plants and mushrooms to germinate and develop. Logs and branches, often carried over considerable distance by spate flows, may add to this process by lodging against trees growing in or along the river channel, creating small blockages, trapping organic material, and further supporting vegetative growth *(Jacobson et al., 1995).* Spate irrigated areas have ecosystems with a great biodiversity of plants and animals, in particular birds. In Balochistan (Pakistan), spate flows have contributed to the development of wetlands, which are an excellent refuge for migratory birds *(Nawaz, 2002).*

Temporary wetlands in dry areas, such as ephemeral ponds, often have a considerably high biodiversity, especially freshwater wetlands *(Brendonck and Williams, 2000).* Biodiversity is very much related to the duration of the aquatic phase, especially amongst crustaceans. The species richness in arid-area, temporary wetlands can be higher than in permanent temperate or humid-zone wetlands. Wetlands in arid areas contain considerable ‘hidden’ biodiversity in the shape of egg banks of multiple species, that often make it possible for species to survive weather variability or the early drying of ephemeral pools. The spate fields, lakes and ponds are an excellent abode for these highly important species. Moreover, birds favour spate fields where organic agriculture is practised and where they are least disturbed.

TABLE 10.1
Linkages between spate irrigation and natural resource management

Issue	Impact of spate irrigation	Impact on spate irrigation
Biodiversity and natural vegetation	• Spate systems are depositories of local biodiversity.	• Wild plants and trees are often additional sources of income. • Mesquite infestation has a negative affect on use of the command area.
Catchment degradation	• Cutting of trees for traditional diversion structures may contribute to the degradation the catchment area.	• Catchment degradation changes runoff patterns and increases sediment loads.
River morphology	• Spate systems tend to stabilize river morphology. • Encroachment on river banks creates vulnerable areas.	• Catchment degradation and cutting of riverine forest and bank vegetation causes changes in runoff regime and may trigger scouring and widening of wadi beds.
Dune formation		• Dune formation particularly threatens the fringes of spate systems.
Flood management	• Spate systems usually intercept moderate to medium flows, only large floods are passed on down a wadi.	• Major floods change river morphology and affect viability of spate systems.
Groundwater recharge	• May be either positive or negative. May increase recharge by slowing down flood flows. May decrease recharge by extracting water from the wadi and increase evaporation • Cutoff structures may obstruct subsurface flows that are the major source of groundwater recharge.	• In areas where groundwater is available, conjunctive use of groundwater and spate flows can sustain highly productive agriculture.
Upstream and downstream water use	• Spate irrigation may reduce water availability for downstream use.	• Intensification of upstream water use may change water availability for spate irrigation

Natural species of vegetation are often of considerable value. A sample of native species occurring in the spate-irrigated area of DG Khan in Pakistan and their productive uses is given in Table 10.2. Grasses and shrubs, for instance, sustain livestock populations, while trees are used for various purposes. Tamarix trees are used for fuel, utensils and tanning, while acacia is used as timber, fuelwood and for the construction of protective fences. Ziziphus is a typical multi-purpose tree as it provides fodder, fuelwood, timber and fruits, while it is also used for medicinal purposes and beekeeping. In many countries, such as in Pakistan, the dwarf palm is used for the production of mats, ropes and sandals. In the spate-irrigated areas of Pakistan, the harvesting of various types of mushroom is a lucrative activity, with truffles fetching particularly good prices. The spates also carry wild vegetables and cucurbits to the fields. During years when the harvest is poor, natural vegetation can help families survive these adverse periods.

There is considerable variation between spate systems with respect to the degree of natural vegetation that occurs. The spate systems in the Tihama in Yemen are largely devoid of natural vegetation, while there is a great diversity of wild vegetation in those of Ethiopia, Pakistan and Sudan. In extreme cases, there are spate irrigation systems where natural vegetation grows out of control. In the spate irrigation systems of the Gash and Tokar in the Sudan, there has been a severe invasion of mesquite (P*rosopis jutiaflora and*

Prosopis chilensis) since the 1990s *(FAO, 2000)*. The species were introduced as part of dune stabilization programmes, but soon got out of hand. The aggressive spread of the mesquite in the Gash and Tokar spate systems in the Sudan is largely the result of poor field and marginal land management arrangements, related to the absence of permanent land ownership in these systems. The mesquite is a prime source of income for landless families, who use it to produce charcoal.

Under the new Gash Livelihoods Project, the eradication of mesquite is now foreseen in combination with land titling. This will need due consideration of mesquite's economic importance as the primary source of cash income, particularly for the landless, and its river bank stabilization effects. The project will identify suitable alternative non-invasive tree species for establishment on public lands and women's group woodlots in the area. Such tree species will include nitrogen-fixing trees as well other trees with extensive root systems.

TABLE 10.2
Native tree species and economic uses in Suleiman spate-irrigated area (Pakistan)

Botanical name	Common name	Economic uses
Acacia kacquemonti	Kikri	Leaves browsed
Acacia nilotica	Kikar	Timber, leaves browsed
Aerva javanica	Bui	
Alhaji camelorum	Jawan	Weed
Aristada depressa	Lumb	Grass (poor quality)
Calligonum polygonoides	Phog	Sand stabilizer
Capparis deciduas	Karir	Firewood, browse
Carex sp.		Palatable grass
Cenchrus biflorus	Lidder	Weed
Cenchrus ciliaris	Dhaman	Palatable grass
Cenchrus pennisetiformis	Lidder	Low-quality grass
Crotalaria burhia	Chag	
Cymbopogon jawarancusa	Khavi	Medicinal value
Cymbopogon schoenanthus	Khavi	Low quality grass
Cynodon dactylon	Khabbal	Palatable grass
Desmostachya bipinnata	Dab	Low quality grass
Dichantium annulatum		Palatable grass
Diptergium glaucum	Fehl	Palatable grass (camels)
Eleusine flagellifera	Chimber	Low quality grass
Euphorbia spp.		Browsed
Haloxylon recurvum	Khar	Browsed (camels)

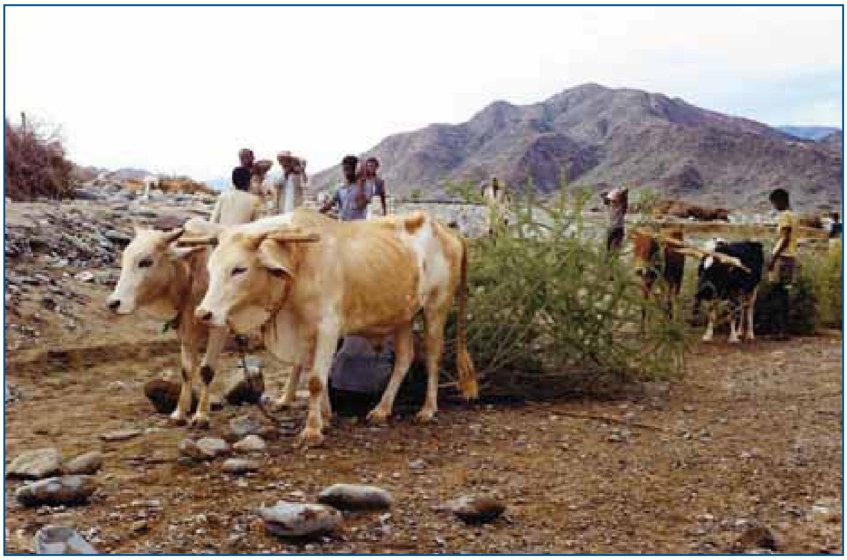
Botanical name	Common name	Economic uses
Haloxylon salicornicum	Lana	Browsed (camels)
Indigofera oblongifolia	Jhil	
Kochia indica	Bui	Low quality shrub
Lasiurus sindicus	Ghorka	Palatable grass
Leptadenia pyrotechnica	Khip	
Panicum antidotale	Murat	Palatable grass
Panicum turgidum	Murat	Low quality grass
Peganum harmala	Harmal	Medicinal value
Phoenix dactylifera	Khajoor	Fruit tree
Poa spp.		Palatable grass
Prosopis cineria	Jand	Timber, browse
Prosopis juliflora	Mesquite	Firewood, browse
Rhazya stricta	Senhwar	Medicinal value
Saccharum munja	Sarkanda	
Salsola foetida	Lani	Browsed (camels)
Salvadora oleodis	Wan	Browsed
Suaeda fruticosa	Lana	Browsed
Tamarix aphylla	Frash	Sand stabilizer, utensils
Tribulis terrestris	Bhakara	Weed
Withania coagulans	Paneer	
Zizyphys Mauritania	Ber	Timber, browse, honey forage
Zizyphys nummularia	Mallah	Browsed

Source: PARC/UNEP/NESCAP 1994

CATCHMENT DEGRADATION

The construction of brushwood spurs and weirs in traditional spate irrigation requires large numbers of trees and branches. Because of its multiple properties, acacia branches are preferred. The intensive use of acacia trees seriously threatens the long-term sustainability of spate irrigation in the Eastern Lowlands. For example, it has been reported that more than 28 000 trees are required annually in the 3 000 ha system of Sheeb in Eritrea (see Figure 10.1 for shrubs collection in Eritrea). Farmers estimate that it now takes ten times longer to gather the acacia shrubs needed to maintain their system than in the past. Similarly, in the border area of the Sudan with Eritrea, brushwood flood-spreading structures were traditionally built from branch palm (*Hyphaene thebaica) (Niemeijer, 1993).* This tree has now largely disappeared from the area and the steep decline in water spreading is associated with its loss. In several parts of Ethiopia natural vegetation has become scarce and the sorghum roots are excavated and used in place of brushwood for flood diversions, with further negative consequences on soil fertility and erosion.

FIGURE 10.1
Collection of shrubs for the repair of flood diversion spurs in Eritrea



Desertification of the areas close to irrigated areas is associated with the construction of diversion bunds and the collection of wood for fuel and construction. Many other factors cause deforestation and land degradation in the upper catchment areas where spates flows are mostly generated. These include the expansion of agriculture and overgrazing driven by rising populations, and the breakdown of indigenous terracing and other erosion control measures *(Scholte et al., 1991)*.

RIVER MORPHOLOGY

Spate irrigation occurs either in mountain valleys, or in the plains close to the mountain front often at the end of a gravel fan. Particularly in the latter areas, wadis tend to be unstable. Spate farmers attempt to stabilize these sections of the wadi to ensure a continuing supply of water to their spate irrigation schemes. Changes in the river morphology may originate in the lack of protection of local vegetation, i.e. the cutting of riverine forests or of riverbank vegetation. Changes are triggered by historic floods that usually result in a general lowering of river bed levels. The construction of flood canals at unsuitable sites may also increase the degradation process, as the river may change its course during a large flood.

There is usually a gradual transition in the vegetation along spate wadis. The upper reaches experience more frequent floods, and the physical disturbance that comes with them removes the vegetation. In the lower reaches, discharge decreases as a result of upstream abstractions and infiltration to the wadi beds. Infrequent floods result in harsh environments where only hardy drought-resistant plants can survive *(Jacobson et al., 1995)*. Vegetation can be used as an indicator to assess the pattern and reliability of flooding.

The vegetation that develops in ephemeral river beds also plays an important role in their stabilization. This is particularly true in spate wadis in alluvial plains, which do not have beds armoured with gravel and cobbles, and are prone to scour. While the degradation of the ephemeral river bed is often a natural phenomenon, its speed and intensity can be increased by human action, such as the cutting of trees and bushes in and along the river bed as well as the degradation of wadi catchments.

Degradation of an ephemeral river bed may advance to such an extent that canal intakes are left far above the wadi bed and that diversion becomes impossible. An example is the Yanda-Faro River in Konso in Ethiopia. It was reported that the historic *El niño* floods that occurred in 1998 resulted in a rapid degradation of the river beds in the region and the erosion of the riverbanks *(Farm Africa, 2003)*. The cutting of vegetation and free cattle grazing in a downstream riverain forest was among the factors that caused the Yandefero River to change course and discharge into a lower section of the main river. The result was a continuous degradation of the river bed over a length of 10 km, which rendered many existing upstream intakes unserviceable (Figure 10.2).

FIGURE 10.2

Lowered river bed and eroded river banks causing the abandonment of the canal head, Ethiopia

Wadi beds move up and down in response to the flood pattern experienced. Abandoned intakes and canals, that can no longer be used, are often seen in the older spate-irrigated areas. Farmers in Barag in the south of Balochistan, Pakistan, for instance, had to abandon their existing diversion structure in the 1980s because of the degradation of the river bed *(Halcrow, 1993)*. The recent history of the Korakan River in Balochistan, Pakistan illustrates the impact of the degradation of the river bed on the livelihoods of many households. Until the early 1970s, about 2 000 households living in 30–40 communities depended on 11 collective diversion bunds and a large number of individual structures for the irrigation of their fields on both riverbanks. As a result of the cutting of trees and overgrazing of vegetation in and along the river bed, the degradation process started in the downstream reach of the river at the beginning of the 1970s. Between 1976 and 1989, 7 of the 11 bunds could not be rebuilt by the farmers as the level of the river bed was too low and the river too wide. As a result, many fields could not be irrigated for many years and their owners migrated to other areas *(Halcrow, 1994).*

Vegetation sometimes helps in raising the river beds. When trees, such as tamarix, colonize the bed of spate rivers, flows are slowed down, sediment settles and bed levels rise. In many rivers prone to degradation, as in wadi Tuban and wadi Siham in Yemen, as well as in Korakan River in Balochistan, a ban on cutting vegetation along the wadi bed has been put in place by the spate irrigation farmers. In other areas, farmers have actively planted tamarix saplings. In Balochistan several projects have planted different trees and shrubs including tamarix along the banks and inside the rivers for multipurpose functions. This was done on a participatory basis on the request of local farmers and villagers.

Not only does vegetation withstand normal floods, but regeneration is possible from regrowth when damage occurs during exceptional floods. Sediments deposit in front, over and behind the vegetative barrier. Sedimentation of coarse material, during high and medium floods and of silt mixed with vegetative debris at low flows, eventually forms a solid natural protective structure.

The distribution of natural vegetation in wadis is, however, limited to sites of low-speed flow, where seeds are deposited and covered with enough sediment to obtain germination. In sites characterized by swift currents, vegetation establishment can only be obtained by planting cuttings deep and offering protection against scouring.

WIND EROSION AND SAND DUNE FORMATION

In many spate irrigation systems, the risk of sand dune formation is ever present. A study by FAO using aerial photography dating from 1976 and 1987 for Wadi Zabid in Yemen suggests that 5 percent of the productive area was lost to sand movement in that period. One reason why spate irrigation faces the threat of sand dune formation is that agricultural land stretches increasingly into marginal areas, with little accessibility to spate flows and poor (sandy) soil textures. Another explanation may be related to the practice of rainfed agriculture in the sand dune areas. In some places, when there is adequate rainfall for rainfed agriculture, farmers tend to uproot natural vegetation and crop marginal, sandy land. Animals graze the area after the harvesting of millet and, as a result, the sand dunes are stripped of natural vegetation and regeneration becomes slow and difficult *(Scholte et al., 1991).*

The rehabilitation of sand dune areas requires the engagement of farmers in planting native trees and dwarf shrubs. In the Tihama (Yemen), a dwarf shrub (*Dipterygium glaucum*) and two tuft grasses (*Pannicum turdidum and Odysseum mucronatum*) form the vegetation cover that will eventually stabilize the sand dunes *(El-Hassan, 1999).* Management of the rehabilitated land is crucial and cultivation and grazing should be limited, if not prevented. This can only be done with the full participation of local populations.

Another closely related problem is wind erosion. In dry plains, wind erosion tends to remove the finer particles of soils, causing loss of soil fertility. Watering of soil through the continued use of the spate systems is the best strategy to minimize these impacts.

FLOOD MANAGEMENT

The role that spate irrigation can have in flood mitigation is often overstated. In Pakistan, for example, the development of spate irrigation systems has been advocated because it would help reduce damage to the large perennial canals on the western side of the

Indus irrigation system. The hill or mountain torrents have at times caused considerable damage to the large-scale perennial irrigation systems. Studies commissioned by the Federal Flood Commission in Pakistan explicitly envisage the dual objective of spate-irrigated agricultural development in the piedmont plains and the protection of perennial irrigation infrastructure such as the Chasma Right Bank Canal, the Dera Ghazi Khan Canal, the Flood Protection Bund Complex and the Pat Feeder Canal *(NESPAK, 1998).*

Yet, the contribution that development of spate irrigation can make to flood mitigation is limited and, in general, there is little experience in managing spate irrigation systems for flood mitigation. The extreme floods are those that cause the most damage and they are only marginally mitigated by spate irrigation systems since spate irrigation makes prevailing use of low and medium floods. Still, widespread development of spate irrigation in the catchments and tributaries or the larger wadi systems can reduce the chance of large floods building up. Simple hydrological models, based on the flood assessment methods described in Chapter 3, can provide rough estimates of possible impacts of spate irrigation on floods. Spate irrigation systems also tend to stabilize ephemeral streams, which avoids unexpected breaches downstream.

A related technique for flood mitigation is that of flood spreading. Experimental work has been done in Iran by the Soil Conservation and Watershed Management Research Institute. Starting with a pilot project at the Gareh Baygon Plain, a number of measures were implemented on 60 000 ha of land. The main purpose was the spreading of floodwater for recharge on alluvial fans, reviving the vertical well systems (*qanats*) and encouraging the development of new wells. Part of the water was used for spate irrigation. In flood spreading, water is diverted from the bed of an ephemeral river, channelled through a desilting basin and spread over a number of bunded fields. The bunds run along the contours, and channels collect the excess water and pass it down to the next contour bunds. Eucalyptus and acacia trees are planted in the water spreading area. At the bottom of the spreading area, water is collected and diverted back into the river. Good results are claimed with this technique, both for recharge and flood control. It was estimated that the damage produced by a large flood in Gareh Baygon spreading area represented only 2.5 percent of the cost that would have been incurred downstream had the flood flows not been captured by the flood spreading system.

In Balochistan, when floodwater is in surplus, it is diverted to specific locations for collection into ponds used for domestic and animal drinking-water. These sites are preferential groundwater recharge areas. Upon drying of ponds, villagers dig shallow wells inside and around ponds to collect water.

INTERACTION BETWEEN SPATE IRRIGATION AND GROUNDWATER

The relation between spate irrigation and groundwater is complex. Spate irrigation provides the possibilty of in situ groundwater recharge, but also reduces the chance of recharge downstream. On the other hard, groundwater development in spate systems may considerably modify agricultural practices and can sustain highly productive farming. The balance of opportunities and costs is site-specific, and a careful assessment of potential and constraints of groundwater use and recharge should be done to understand the implications of proposed spate-related interventions.

Groundwater recharge

Two types of aquifer are important in spate-irrigated areas. In the valleys, alluvial sediment deposits consist of generally unsorted, but coarse and uncemented material with high permeability. The deposits are found in a strip along the river bed, which may vary in width from a few meters to a few hundred meters. Strip aquifers have very favourable recharge conditions and are mainly recharged from the infiltration of spate flows and seepage zones along the wadi bed. Because of their small volume, and high permeability, the strip aquifers are quickly depleted. Another type of aquifer is found further downstream, at the level of the alluvial fans and in the plains. They are actively recharged by the floods in the wadis and may be several thousand metres thick. They may not be homogeneous and consist of a number of independent groundwater flow domains, with their own recharge and discharge zones and with varying water quality *(Van der Gun* and *Ahmed, 1995)*. In many areas, horizontal wells (*foggara* or *qanats*) are developed in the spate recharge zones. Many of these aquifers are intensively developed.

In general, aquifer recharge occurs mainly through infiltration in the wadi beds rather than from channels and fields. While recharge may be enhanced by spate irrigation, where diversions flatten the river slopes and reduce flow velocities, and diversion bunds produce ponding, most of the water diverted onto the land is accounted for by evapotranspiration, and the proportion of recharge is less. When designing spate irrigation systems, a careful assessment of the changes in water balance in the river must therefore be performed to understand the implications of spate diversion on the overall hydrology of the wadi. Results will vary from one site to another, as a function of the characteristics of the floods and of the aquifers. Of particular relevance is the potential impact of spate diversion on the recharge of major aquifers in the alluvial fans and in the plains where water productivity through groundwater-based irrigated agriculture is, in most cases, much higher than in spate irrigation.

FIGURE 10.3
Recharge weir in Hadramawt, Yemen

Options for groundwater recharge also exist beyond spate systems. An unusual and highly innovative recharge structure was constructed by farmers in Wadi Hadramawt in Yemen (Figure 10.3). The structure consists of 1 m high lime-mortar wall across the river that serves to slow down and spread the flood to maximize recharge. Another important practice is to leave the stone armouring of wadi beds intact, as the presence of large stones and boulders reduces the water velocity and encourages river bed recharge.

The ephemeral wadi beds carry a substantial subsurface flow, which is often the main source of aquifer recharge. Caution is needed not to interfere with these subsurface flows through cutoff weirs or impervious bed stabilizers, as downstream well water supplies may depend on these flows for their recharge. An example of a spate irrigation project gone wrong in this respect is the Wadi Siham in Yemen. The weir was cutting-across the traditional flood channels, blocking the subsurface flow in the river, and depriving a large number of downstream well owners of their source of water.

Groundwater use in spate schemes

Access to groundwater in spate irrigation radically changes farming opportunities. Where groundwater is available, the unpredictability associated with spate irrigation largely disappears, and farmers can rely on a safe supply of water for their production. Wherever groundwater development has been possible, farmers have taken advantage of it and harnessed water in a much more productive way than that expected from traditional spate systems.

Since the modernization of the Wadi Zabid system in Yemen, the area under cultivation has increased substantially. There is evidence that this is related to the increase in groundwater use, rather than any increase in the diversion efficiency provided by the new structures in the spate-irrigated areas. In Wadi Zabid, wells are used in conjunction with spate-water supply and as the only sources of irrigation water. Since the 1970s there has been a rapid increase in well development, mainly shallow wells with some extensions. In 1988, there were 1 411 wells in Wadi Zabid, of which 1 221 were functional. These were almost all used for irrigation but, at the same time, served as an important source of drinking-water. As a result, the area under banana has increased from 20 ha in 1980 to more than 3 500 ha in 2000. Similarly in Wadi Tuban in Yemen, agricultural production has changed dramatically since the 1980s mainly because of the remarkable increase of shallow wells; about 2 300 ha are now under high value vegetable production.

Groundwater quality in the coastal region of Yemen where Wadi Zabid and Wadi Tuban are located, is generally good enough for irrigation, unlike that in spate areas in Eritrea, Pakistan and Tunisia. In wadi Labka, Eritrea for instance, groundwater salinity ranged from 2 250–2 650 µS/cm. In areas with high salinity, irrigation from groundwater is not an option. However small prisms of freshwater, stored in the bed of the spate rivers, can be an important source of drinking-water supply in areas with generally saline groundwater.

The intense use of groundwater, and the higher water productivity associated with groundwater-based irrigation, raises questions on the relation between spate irrigation and groundwater recharge. One issue, related to in situ water management, is whether the best spate-water management strategy should maximize recharge, or agricultural productivity of the spate-irrigated areas. Another issue is the relationship between upstream and downstream water users. It is exemplified by the recent debate on water distribution in Wadi Zabid in Yemen, where a system of time-based water allocation is in place. Under this regime, the downstream command area is entitled to floods in the off-season only. As the occasional spate flows are able to recharge shallow aquifers for a long time, downstream land users are now requesting their share of spate floods in the peak season. Such conditions, where wealthier downstream users would take advantage of water used by upstream spate farmers, could be the basis for application of the concept of payment for ecosystem services, where part of the gains obtained from additional recharge downstream could be used to compensate upstream farmers for losses incurred with reduced water supply.

WATER STORAGE AND DAMS

The reliability of spate irrigation would be greatly increased if water from flood peaks could be stored, and then released when needed for irrigation. This makes the construction of small dams a very popular activity in semi arid areas. However, the benefits to local communities for irrigation and groundwater recharge, need to be balanced by the adverse impacts on downstream spate water users. Hydrological studies on Wadi Zabid and Wadi Tuban in Yemen suggest that in the 1990s the inflow to the spate irrigation areas may have reduced by about 30 percent and the reduction was attributed to the development of a large number of small dams in the upper catchments *(IIP, 2002).* These upstream developments change the runoff pattern, with low flows and the earlier parts of the flood wave being intercepted by the dams, while downstream systems receive the large floods that cannot be retained. This can have an impact on diversion efficiencies in the downstream spate systems as most of the water resource in spate rivers flows in the range of low- to medium-discharge.

Besides the upstream-downstream issue, dams are rarely an option in arid areas because of the rapid siltation rates that occur when they are supplied by floods carrying very high sediment loads. Dams with a very large initial capacity would be needed to provide enough storage for sediment deposits to achieve a reasonable economic life. The use of dams in the spate-irrigated areas in Eritrea, where sediment loads can be as high as 10 percent by volume, has been ruled out as an option for this reason, moreover, dams in the Rif Mountain in Morocco suffer from rapid siltation. Another example is the Gomal Zam dam in DI Khan in Pakistan. A series of feasibility studies have highlighted the heavy sedimentation, which threatens the longevity of the dam, and may be detrimental to spate-irrigated agriculture downstream.

Another illustrative example is the discussion around the construction of a dam on Wadi Surdud in Yemen, one of the major ephemeral streams of the Tihama. With the present system, an extensive area, which is supplied by spate flows and well irrigation, is under high value crops. In the existing system, sediment is not a problem but rather an asset as it serves to constantly renew soil fertility. On the positive side, the dam would supply perennial irrigation water to an irrigation scheme in the upstream part of the wadi and provide protection against floods. On the negative side, downstream spate and groundwater recharge will be affected, high evaporation losses and serious sedimentation will take place, and it is expected that the dam will also trap seeds and other sources of high biodiversity and will produce relatively ‘sterile’ water at best.

Kowsar (1998) made a case for storing water in a shallow aquifer rather than in dams in semi-arid areas where spate irrigation is practised. He argues that reservoirs in Iran amount to 30 km^3 and that the cost of developing this capacity is US$0.20 per cubic meter. The total potential storage capacity in debris cones, alluvial fans and colluvial soils in Iran is 4 300 km^3, equivalent to 10 times the natural precipitation in the country. Hence, the identification of possible sites for recharge hence should not pose a problem. The cost of creating 1 m^3 of storage capacity under artificial recharge – using the model experimented in Gareh Bygone in Iran – is US$0.0008. The cost of creating 1 m^3 of water actually stored, based on average precipitation and a conservative figure of 30 percent effective recharge, would be US$0.027 even if the costs of pumping will reduce this cost advantage to some extent.

These examples show that it is important that all the impacts of the proposed investment be understood and assessed for their costs and benefits, to take economically sensible decisions. However, decisions are often driven by the tendency to respond to the water crisis by building more dams, even in situations where there may be more viable alternatives. A comparison of water resource development through spate irrigation and perennial dam-based irrigation is given in Table 10.3.

TABLE 10.3
Comparison of spate irrigation with perennial dam-based irrigation in arid areas

Spate irrigation	Perennial irrigation (dam-based)
• Supplies are insecure, but this insecurity could be reduced if spate flow is combined with groundwater irrigation.	• Supplies are secure.
• Water storage is in soil profile.	• Water storage is in reservoirs, high evaporative losses in shallow dams.
• Investment cost per m^3 of water stored is low.	• Investment cost per m^3 of water stored is high.
• Sedimentation positively contributes to soil fertility.	• Sedimentation causes reservoir siltation and reduces the useful life of the reservoir.
• Peak flows cannot be utilized.	• Peak flows can be stored.

Chapter 11

Recommendations for interventions in spate irrigation

INTRODUCTION

While spate irrigation is relatively marginal in absolute terms, it represents a valid development option for rural populations in many arid countries. By harnessing floods from wadis, it allows farmers to secure crop production and therefore contributes to food security and poverty alleviation. The benefits of spate irrigation go beyond increased productivity of water use and include increased functionality of domestic water, groundwater recharge, fodder for livestock and environmental services such as flood control and biodiversity conservation.

This chapter provides recommendations for improving or developing spate irrigation systems and is divided into three parts. The first part summarizes lessons learned from three decades of spate irrigation projects, on which this report is based, and provides conclusions on factors affecting the successes and performances of spate irrigation interventions. The second part provides general recommendations that apply to most situations and concern mostly development approaches and policy issues. Specifically, it lists recommendations particular to engineering, design and management interventions. The third part provides a more specific set of recommendations applicable to the different types of spate irrigation systems described in Chapter 1.

LEARN FROM PAST EXPERIENCE

Over the past three decades, spate irrigation development has been supported under a range of national and international programmes. The type of external support falls into one or more of the following categories:

- investment in major civil engineering to provide new spate-irrigation infrastructure;
- support to traditional systems; and
- provision of earthmoving equipment at subsidized rates.

Extensive investments have been made in large spate-irrigation systems in the 1970s and 1980s in Yemen and Pakistan and, to a lesser degree, in Eritrea, Ethiopia, the Sudan, Algeria, Morocco and Tunisia. The large-spate irrigation improvement projects have been dominated by a heavy engineering approach where numerous traditional, independent diversion structures have been replaced by one or two permanent gated diversion weirs supplying new canals. Experience with most of these projects tells that future interventions in spate irrigation should favour low-cost diversion structures and avoid sophisticated technical solutions, which have proved to be economically unjustifiable and difficult to operate properly. The main lessons learned from the experience with spate irrigation development to date can be summarized as follows:

- Investment costs for large schemes involving new permanent diversions and main canals have been high. It is clear, in most cases, that they cannot be justified in purely economic terms, by the returns from spate systems that are already diverting and using most of the available water.

- In large agency-managed schemes, the role of farmers changed from being the active irrigation managers they were in the pre-project situation to passive receivers of irrigation water, whose access to water became totally dependent upon the performance of the agencies managing and maintaining the intakes and canals.
- The operation and maintenance of the larger diversion structures and canal systems can be difficult and expensive. In particular sedimentation at intakes and in canals is often not properly controlled in modernized systems. The need for frequent canal de-silting results in excessive maintenance costs that cannot be met without continuing external support, usually from government.
- The planning and design of rehabilitation and/or improvement works in large schemes have mostly been carried out without effective partnership with farmers and land users. Farmers' knowledge of the local situation, and their preferences, regarding the scope and type of works and changes in the layout of their irrigation system, were often not properly considered during the design process.
- Economic considerations have often led to the design of diversion structures with a much lower diversion capacity than traditional ones, prompting farmers to revert to their traditional structure to take advantage of the flood peaks bypassing the new permanent intakes.
- In many cases, new and more robust permanent structures have promoted inequity in the distribution of irrigation water and led to the collapse of traditional water rights. Modernized diversion structures give much larger control over spate flows to favoured groups of the upstream farmers than traditional structures.

Experience with smaller farmer-managed systems, where incremental structural reinforcements have been introduced to improve the reliability of existing traditional intakes and reduce maintenance costs have generally been more successful and cost effective than large-scale interventions. Farmers have maintained a much higher level of ownership of their schemes and kept the overall responsibility for operation and maintenance, therefore ensuring higher level of sustainability and less dependence on external support.

Another important programme supporting the improvement of traditional structures has been the provision of earthmoving equipment to alleviate labour requirement for the maintenance and reconstruction of bunds. In such programmes, bulldozers and front loaders are made available against rates that typically cover part of the running costs but none of the capital charges. With bulldozer programmes, farmers are given new means to build or restore diversion works – especially earth bunds – or improve the command area ranging from gully plugging to repairing canal bunds to making new flood channels. In countries where bulldozer programmes are in place, they tend to be uniformly popular and have developed into the lifeline for spate irrigation.

On the downside of the bulldozer programmes is the fact that traditional water distribution systems are sometimes jeopardized because upstream farmers are able to build larger bunds. In addition, most bulldozer programmers have faced serious maintenance problems: their challenge is to have the rental price cover the total cost of running the bulldozer they also have to stimulate local entrepreneurs who rent out earthmoving equipment. Where public support to bulldozer programmes has been discontinued for financial reasons, this usually led to a major crises as farmers were no longer able to construct and repair flood bunds.

In 1992, IFAD, published a report in which it presented its experience of large spate-irrigation systems modernized with gated, permanent, diversion structures and new irrigation should favour low-cost diversion structures and avoid sophisticated technical solutions, which had proved to be economically unjustifiable and difficult to operate properly. It recommended (a) that farmers should be more involved in the development of improved spate schemes; (b) that spate-irrigation systems should be self-reliant insofar as routine operations and repair are concerned, with some backstopping from technically competent public sector units as appropriate; and (c) that governments should not be expected to provide the bulk of resources for maintenance.

In spite of these findings, and widespread adoption of the rhetoric of participatory irrigation management, not much has changed in the engineering approach applied in the recent past, in particular in relation to modernization and rehabilitation of large spate systems carried out with financial support from international partners.

DEVELOPMENT APPROACH

The selection of an appropriate development concept for spate irrigation systems of any scale requires a clear understanding and appreciation of a series of issues that are specific to the spate irrigation context. Clearly different approaches are needed for schemes with different characteristics, levels of development, access to external support from local or national governments and NGOs. However the success of any intervention in spate irrigation will largely depend upon a set of principles that are valid in all cases. These issues and principles have been discussed in details in this report and are summarized below.

Place spate irrigation within a broader development context

Alleviation of poverty in spate-irrigated areas cannot be achieved through technical improvements to spate irrigation alone (see Box 11.1).

BOX 11.1

Designing structural improvements within a broader development perspective: Example of the Gash project

The rehabilitation of the Gash spate system is an example of how a good project needs good engineering embedded into a sound development perspective. There was a strong change of emphasis in the rehabilitation of the Gash spate system in Sudan, where, since 2002, IFAD supported a sustainable livelihood regeneration project that chose to put livelihoods and institutional reform at the core of its development approach (IFAD, 2004). The main thrusts of the project were community development, capacity building and empowerment, animal production and rangeland management, control of mesquite invasion of farm lands, financial services and marketing and institutional support. Structural improvements included river training, de-silting to return canals to their original design and improvements of field layouts.

It is too soon to judge whether this approach will achieve more than the top-down approaches described earlier in this report. Initial indications are that, despite many constraints, considerable results have been obtained for equitable land distribution, security of tenure, empowerment of local communities and enhancement of livelihoods. However, poor progress with the physical rehabilitation of the irrigation system and institutional changes to management may compromise its success. A reliable water supply is the foundation of any irrigation project and must clearly be given a high priority in project design and implementation.

Water is not the only constraint to development and many poor households rely only partially on spate-irrigated agriculture for their incomes. Successful poverty alleviation will also depend upon a series of actions, among which the most frequently needed are:

- improvement of access to extension services, credit and marketing;
- improvement in livestock production – by restocking, exchanging breeds, improving fodder production and rangeland improvement, as well as the processing and marketing of livestock products;
- improvement in local forestry – by developing local agroforestry, improved marketing of non-timber produce, by uprooting invasive species;
- improved access to domestic water, both through locally appropriate facilities, wells and pumps and, where appropriate, groundwater recharge;
- flood protection measures of villages and river banks;
- creation of opportunities for wage labour and off-farm income, in particular for landless households; and
- in some cases, eradication of diseases such as malaria and tryposonamis.

While not all projects will have components covering the range of livelihood issues, these issues should be considered when projects are being planned. At the minimum, improvement projects need to be screened for their impacts on livelihoods, to ensure that unintended negative consequences are not introduced.

Two issues stand out in particular that have significant bearing on the quality of life. The first is the availability of water for domestic purposes. Where spate-irrigated areas are underlain by a shallow aquifer with freshwater, drinking-water can be supplied from village wells. This is reliable during good and normal years, but may be affected by a prolonged drought. Spate projects can have unintentional negative impacts on drinking-water downstream of diversion sites when they are not carefully designed.

Another issue, particularly in old spate-irrigation systems, is the high deposition of sediments that has raised farmland levels above the level of village areas, thus increasing the risk of flooding of the villages. Besides this problem there is the risk of riverbank breaching, damaging farmland and residential property in the process and causing the inhabitants to loose the very basis of their existence.

The production of wood and fodder and terrain stabilization all benefit from systematic efforts towards agroforestry in spate-irrigated areas. Agroforestry can be managed in several ways, including allowing natural vegetation to grow in the command area actively protecting natural vegetation. In addition planting of indigenous tree species will help stabilize bunds and river courses, and provide fuelwood and fodder. A reverse side to the promotion of agroforestry, is the introduction of new species, such as mesquite (*Prosopis juliflora*), often imported to fix dunes, which has turned into a major pest in many spate-irrigated areas, including in the Sudan (both Tokar and Gash) and Yemen, the Tihama Plain. The eradication of mesquite requires major efforts through mechanical and manual uprooting.

Livestock is of prime importance to the household economy in arid areas. Enhancement of the productivity of livestock, includes improving access to animal feed (i.e. fodder crops and spate-irrigated pastures), watering points and veterinary services, closure and management of grazing areas, as well as the processing and marketing of livestock products and restocking after a catastrophe.

Many of these issues are not gender-neutral. Women are usually in charge of domestic water fetching, they raise small livestock, prepare and sell dairy products and collect fuelwood. They are also involved in producing handicrafts for sale at local markets. All the above points are therefore of great relevance to them and a careful consideration of these issues in spate programmes can help balance benefits among women and men.

Understand the socio-economic context

An understanding of the socio-economic context and the strategies that farmers adopt to cope with the unpredictability associated with spate irrigation is essential to ensure effective and sustainable improvements to traditional spate-irrigation systems. This knowledge can help planners and designers to avoid the unintended negative consequences that result from some past spate irrigation improvement projects.

Of particular importance is the understanding of traditional water rights and operating and maintenance arrangements, how these are enforced and how water sharing, maintenance arrangements and the policing and enforcement of these arrangements would be affected by the project.

Projects should be planned with adequate time and resources to fully understand farmers' perceptions, the socio-economic circumstances and their risk avoidance strategies. Long-term programmes are required to allow stakeholders to adapt to changed technologies. Unfortunately, this recommendation often conflicts with the time bound programmes of typical investment projects.

Local capabilities, access to construction materials, indigenous skills, the availability of financial resources needed for farmers to carry out maintenance of any improved irrigation infrastructure must be carefully considered. In this regard it is important that the design and complexity of proposed infrastructure match the local capacity to operate.

Adapt design to arid zone context

Spate hydrology is characterized by a great variation in the size and frequency of floods, which directly influence the availability of water for agriculture and the design of diversion and distribution structures. Spate floods typically have very high peak discharges and short periods of flow. In designing spate irrigation improvement projects, the trade-offs between investment costs, maintenance costs and the level of service deserve more attention than for conventional irrigation. In particular, the specific characteristics of spate floods require a different approach towards risk management. Moreover, provision for re-building of parts of the system after major floods are often a more cost-effective option than designing more permanent structures.

The extreme characteristics of wadi hydrology make it difficult to determine the volumes of water that will be diverted to fields and hence the potential cropped areas. Reliance on farmers' experience is a better way to estimate potential than through classical crop-water requirement methods.

Wadis typically transport very high sediment loads (up to 10 percent in weight) which can be two or more orders of magnitude larger than those encountered in most perennial irrigation systems. Management of sedimentation is, therefore, a key factor in spate irrigation and must be given particular attention when designing spate projects. In particular, wherever possible, structures would have to be designed with stop logs on the main intake that can be raised in line with rising river bed levels and command areas.

Take a basin-wide approach to planning – Understand the water balance

Water is scarce in spate areas. A careful understanding of the water balance at the level of the river basin is necessary to avoid unintended negative consequences of spate interventions. Spate schemes should therefore be considered in the context of a succession of water uses in the basin and not as an isolated development. This is particularly the case in over-committed spate rivers, when even floodwater never reaches the sea. In such cases, all the water is already allocated to some use in the basin, and increased withdrawal at some point in the basin translates directly into reduced supply further downstream.

Spate irrigation modifies the different elements of the water balance in the basin. Typically, it offers opportunity for in situ groundwater recharge but, at the same time, reduces possible recharge downstream. In addition, most of the water diverted onto the land by spate irrigation is accounted for by evapotranspiration, and the proportion of groundwater recharge at the level of the river basin is therefore less. Only a water balance approach at the level of the river basin can help assess the impact of interventions on the overall productivity of water use.

One of the objectives of many projects is to increase the efficiency of agricultural water use. However, the scope for improving the efficiency of water diversion and distribution in traditional systems, which often already use a large proportion of the spate flows available for diversion may be limited. Improvements in water distribution and moisture conservation in the soil profile may be more beneficial than focussing solely on improving the efficiency of diversion from spate flows. In addition, water perceived as being ‘lost’ to a particular spate system may, in fact, recharge groundwater or be used downstream for useful, non-agricultural purposes such as riverine forest or rangeland.

Design with farmers

In all but the largest and most technically complex schemes farmers should drive the planning, design and execution of the rehabilitation and improvement works, as well as any amendment to existing water rights to facilitate the improvement of allocation and distribution of spate water. Engineers need to provide a range of technically and economically viable options and then assist farmers in selecting the most appropriate improvements for particular schemes.

Any improved water distribution system should ensure that farmers understand and agree with the implications of any implied changes to water distribution and, where new canals are needed, agree to provide the additional land required to construct the canals. This additional land will almost certainly be taken from previously irrigated land.

Farmers’ involvement is particularly relevant in projects aiming to improve existing traditional spate systems (see Figure 11.1). They are generally the ones most able to identify the opportunities and possibilities for improvement in the water distribution, their limitations, the potential for extension, and the likelihood of success of any of the proposed interventions.

Adopt an incremental approach to spate improvement

Spate irrigation systems are, by their nature, dynamic and need to adapt to changing physical and socio-economic conditions. Physical changes in traditional spate-irrigation systems typically include changing wadi morphology, raising field levels, and destruction of irrigation infrastructure by large floods. In response, farmers have reconstructed damaged structures, and moved intakes upstream to regain command and capture base flows. Most traditional spate-irrigation systems have evolved and have been modified over time in reaction to these influences. Improvements were, in most cases, implemented by the spate irrigators themselves and were developed over long periods.

Changes in socio-economic conditions may happen within a relatively short time and affect the overall conditions in which spate irrigation takes place. They include changes in the local power structures that control access and distribution of water, access to new technologies that reduce labour requirements for maintenance or irrigation, easier access to roads, markets and labour opportunities, and policies that affect agricultural production and business.

FIGURE 11.1
Headwork discussions, Wadi Mai Ule, Eritrea

Whenever possible an incremental approach to spate irrigation improvement is a preferred option. It mimics farmers' approach and is flexible enough to accommodate the above-mentioned changes. Continuous support is preferred over a one-time project-type improvement to accompany these changes. The incremental approach is valid for infrastructure design as well as for operations and maintenance

Adapt design to operation needs

In large projects, the replacement of several independent traditional diversion structures by a single permanent diversion structure makes sense in engineering terms as it eliminates the need for farmers to rebuild diversions after floods and increases control over flood flows. However the experience has shown that concentrating diversion, by means of a permanent structure at one location, can result in conflict between upstream and downstream farmers related to the changes in distribution of, and access to, spate water. It is suggested that this approach should only be adopted when (a) downstream water users are not disadvantaged; (b) the sedimentation problems linked with permanent structures can be managed; and (c) appropriate sustainable levels of maintenance can be assured for technically advanced diversion structures.

In most cases low-cost, simple and maintenance-friendly technology should be used to improve existing traditional intakes. This might include providing access to bulldozers, constructing more durable diversions from local materials, and limiting the flows

entering the canals. Interventions should ensure that farmers are able to finance and have access to the skills and materials needed to carry out maintenance and repair works.
A rudimentary canal network with field-to-field irrigation is in place in many existing spate schemes. While improved canal networks, supplying water to controlled field outlets, can give better control and overcome some of the disadvantages of the field-to-field water system, changing the water distribution system will probably affect water rights. Any improved water distribution system should therefore:

- ensure that irrigation can be carried out quickly, in the short periods that spate flows occur. This requires canal and water control structures that have a much larger discharge capacity in relation to the area served than would be used normally in perennial irrigation systems;
- support the stability and manageability of the distribution network by creating structures that stabilize the bed of the flood channels, reinforce field-to-field overflow structures and ensure that gullies are quickly plugged; and
- ensure that water is spread over, and does not irretrievably disappear into the lowest parts of, the command area.

Ensure institutional arrangements for maintenance and operation

More than in any other type of irrigation, maintenance is key to the success of spate irrigation. The need for collective action is the basis of traditional spate irrigation practices, and the viability of spate systems is determined by the strength of the organizations involved in their construction and maintenance. Large, integrated systems can require relatively elaborate organizations, whereas small diversion structures can be operated more simply. The larger the system the more difficult it becomes to organize common maintenance activities, not least because some areas will always have a larger likelihood of receiving otherwise unpredictable flood supplies. While farmer management exists at some level in all spate systems, there are essentially three types of management arrangement (a) predominantly farmer-management; (b) where there is some involvement from local government or other external support; and (c) management by a specialized irrigation agency. In the latter, farmers may become passive recipients of water delivered to their turnouts.

For farmer-managed systems development projects should not attempt to unnecessarily formalize the agreements for maintenance. These have to be left as much as is possible to farmers. Projects should ensure that:

- there is clear leadership in farmer-managed systems, preferably by committees accountable to a wide constituency of land users and not to a limited interest group;
- there are clear and specific arrangements for maintenance. Maintenance arrangements must be able to cater for prolonged periods of crop failure;
- overhead and transaction costs are kept low and fixed tenure for official posts and positions are avoided;
- in large schemes sub-groups should be encouraged and strengthened so they can mobilize contributions to maintenance and enforce rules on water management at a local level; and
- extending the role of local organizations to crop management and, where appropriate, local groundwater regulation should be considered.

For agency-managed schemes:

- agency management is vulnerable if long-term routine financing cannot be guaranteed. Strengthening roles of both farmers and local government and reducing the role of specialist agencies should be promoted whenever possible. Public financial support is better directed at recovering from unusual damage and by investing in extension and farmer support rather than routine maintenance, which should generally be left to farmers;
- maintenance of the relatively complex infrastructure, found in some agency managed systems, has to remain a specialist activity. Involvement of the private sector, rather than employing a large full-time staff, in an irrigation agency may be appropriate;
- promotion of effective communication mechanisms is important to avoid a gap in perception and culture between agency staff and farmers; and
- farmer representatives elected from a wide constituency should play an important role in the management of agency schemes. Marginalization of farmer representatives, or undue influence by powerful interest groups, has to be resisted. Councils of user representatives, local government representatives and service organizations may be the most appropriate method of management.

Invest in soil moisture-management and improved agricultural practices

Interventions in spate systems have mostly concentrated upon improving the diversion of spate flows rather than improving the productivity of irrigation water. Improved soil management to maximize soil-moisture conservation may have an important impact on crop production. It should therefore be considered as an integral component of spate improvement projects in schemes where soil-moisture conservation is not currently practised.

Mulching, ploughing, pre-irrigation land preparation, breaking soil crust, the prevention of gullies and the adequate maintenance of field bunds can have a very large impact on crop production and water productivity. Small field-to-field structures, or the division of large fields into smaller more manageable areas, can sustain these improvements. Accurate estimates are difficult to get but better moisture management may multiply crop yield by a factor 1.5 to 3.

In particular, it is recommended that soil moisture conservation techniques be promoted in spate irrigation improvement projects where they are not currently practised. Field experiments in cooperation with farmers are a means of identifying and promoting the most appropriate measures.

Agricultural improvements are needed to raise water productivity. Generally, however, agricultural extension in spate-irrigated areas is poor and often lacks the resources and the specialist knowledge to meet the needs of spate farmers. Improving the quality and reach of extension services in spate-irrigated areas is obviously important, but is primarily a matter of regional or national priorities.

Research and training of extension workers and farmers could help increase the returns to marginal spate irrigators. A wide range of agronomic topics need research that is specific to spate-irrigation conditions and are described in this report. Possibly the most important of there are the development or dissemination of (a) higher yielding but drought-resistant varieties of spate-irrigated crops; and (b) improved water management and soil-moisture conservation practices. Other important subjects include the integration of indigenous technical knowledge with scientific knowledge, improvement of existing mixed/inter-cropping systems and the establishment of seed banks. Better grain storage to reduce post-harvest losses is often mentioned as being of major concern.

Protect fragile ecosystems

Ecosystems in arid and semi-arid river basins are generally precarious and vulnerable to externally-induced changes. Consideration should be given to the possible effects and impacts of the development of spate-irrigation systems on natural resources as well as water quality and quantity. Spate-irrigation systems are very much part of these natural resource systems and are themselves affected by changes in the land and water resources in the river basins.

Traditional spate irrigation is usually well adapted to local environmental conditions. As such, it is a more appropriate and cost-effective alternative to the development of perennial irrigation supplied from dams in arid areas where the rivers carry very high sediment loads. Interventions that mitigate the negative impacts of traditional spate practices, such as the unsustainable use of local trees and shrubs used to construct diversion structures, should be promoted. The use of natural vegetation, specifically planted for river training, provides an environmentally acceptable and lower cost option than the use of conventional hydraulic infrastructures.

RECOMMENDATIONS FOR SPECIFIC SCHEMES

Chapter 1 presented a range of characteristics that can be used to describe spate irrigation systems. Recommendations for basic types of schemes drawn from these descriptions on the basis of scheme size and management arrangements are made in this section.

Small schemes under farmer management using traditional diversion practices

These schemes are usually found on small wadis where the flood flows can, for the most part, be easily handled by farmers using relatively simple diversions. The main engineering requirement is to reduce the labour involved in re-building diversion spurs and bunds. One option is to provide farmers with mechanisms for accessing bulldozers to repair or construct diversions, provided effective arrangements for breaking of earthen spurs and bunds and water distribution, are in place. The support required to supply and maintain earth-moving plant, and provide trained operators, will be too large for small farmer groups and is best organized on a district or regional basis through local government, or with subsidies to allow the participation of the private sector.

Another option is to provide more durable, simple, un-gated diversions constructed from gabions, rubble masonry or concrete. Such structures need to be properly designed to resist scouring and overturning and should be simple for farmers to maintain using indigenous skills (this may rule out the use of gabions where they are not locally available at an acceptable cost to farmers). Flow-restricting structures and rejection spillways need to be included at the heads of canals when improved diversions are adopted, to prevent large uncontrolled flows damaging canals and downstream irrigation infrastructure.

New schemes in areas where spate irrigation is being introduced

Former rainfed farmers or herders will generally not have the skills and knowledge to manage spate flows on small schemes supplied from small tributary wadis. The development approaches described in the previous section may be applied in these situations but provision of a simple gated permanent structure will often be a better option when farmers do not have experience of using earthen bunds and deflectors to manage spate flows.

Medium/large schemes under farmer management using traditional diversion practices

These schemes are constructed in larger wadis carrying much larger flood flows. Typically they have numerous intakes ranging from simple deflectors at the upstream end of a wadi and diversion bunds in the lower reaches. The preferred option is to continue to treat these schemes as a series of independent small systems and to apply the options described above. This approach has the advantage that the farmer groups, and arrangements for water distribution and maintenance, remain unchanged. However, much larger floods generating larger forces and scouring action will be encountered in larger wadis. A higher level of engineering is needed to ensure that diversions are robust enough to withstand some damage and provide the flexibility needed to adjust to constant scouring and sedimentation.

A second option is to provide more permanent gated diversion structures, while minimizing the extent to which previously independent canals are consolidated to reduce the number of diversions required. Cost considerations will probably dictate the choice of the most convenient option, including the use of fuse plugs (breaching bunds) to reduce the cost of diversion weirs. However, in considering the cost of different options, the linkage between design, and the ease of operation and maintenance, must be valued carefully. In many cases, more expensive investment options, such us maintaining several independent small systems, may prove more productive and sustainable in the long run as they keep maintenance costs low and manageable by farmers.

Large schemes with improved infrastructure and agency management

Larger and technically complex systems are only feasible with an element of external management ranging from technical support provided by local irrigation or agriculture departments to full agency management. Where high development costs can be justified, quite complex permanent diversion and water control structures can be considered. In most cases they would not be recommended for reasons explained in details earlier. There is also the requirement to ensure the funding of adequate levels of maintenance in agency-managed schemes and to avoid inheriting potential technical problems with ill-designed spate diversion structures.

Schemes with access to sufficient shallow groundwater

Local geological conditions determine whether spate schemes have access to groundwater or not. Where possible, spate irrigation can be used to recharge groundwater, making possible the use of shallow groundwater for irrigation and other purposes. Access to shallow groundwater removes much of the insecurity associated with spate irrigation and allows production of cash crops with high crop-water requirements that cannot survive long periods between irrigations. In areas where there is sufficient shallow groundwater of suitable quality to make pump irrigation a feasible option, the adoption of an integrated approach, involving both spate irrigation and irrigation from shallow aquifers, is recommended.

The success of groundwater development in spate systems may, however, transform into a burden if exploitation of groundwater exceeds recharge. This is the case in coastal areas, where groundwater over-exploitation induces saline water intrusion and the destruction of the aquifers. Provision of communal wells, or the establishment of groundwater users associations, could be considered. In any case, properly conducted regional water balance studies are needed before shallow well irrigation is actively promoted in spate areas.

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Spate Irrigation
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The Spate Irrigation Network is an international network of professionals and practitioners. It aims at bringing together the current knowledge and experience in spate irrigation over the world, connects the different professionals, practitioners and organizations working in spate irrigation, and supports implementing organizations through training and program development.

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65
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Guidelines on spate irrigation

Spate irrigation has evolved over the centuries and provided rural populations in arid and semi-arid regions with an ingenious way to manage their scarce water resources. It is different from conventional irrigation in many ways and therefore needs special skills and approaches that address the unpredictability and magnitude of spate floods, their high sediment load, and the associated water rights and management models.

The objective of this publication is to assist planners and practitioners in designing and managing spate irrigation projects looking at the hydrology, the engineering, the agronomy, local organizations and rules, wadi basin management and the economics. It is designed to be both a practical guidance document and a source of information and examples, based extensively on experience from across the world in places where spate irrigation is practised.

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