Traditional spate irrigation and wadi development schemes

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1. Introduction

Spate irrigation is important in arid regions, such as the South-West part of the Arabian peninsular, where catchments are rocky and steep and the annual rainfall—which may vary from 50 to 400 mm in the mountainous areas—is seasonal. This seasonal rainfall produces spate flows of short duration and these are the main source of irrigation water, since there is very little direct rainfall on the larger cultivable areas located in the deltas of the wadis, where layers of alluvial silt have been deposited.

Spate irrigation greatly affects the livelihood of the inhabitants of these regions as they are largely dependent on agriculture and animal husbandry. When the floods arrive, farmers organize immediate water distribution with occasional disputes over water rights; but in general there is a commonly accepted system of water rights in each wadi.

In these regions there is a need for better control of spate flows and improved irrigation facilities to stabilize, as much as possible, the agricultural area under cultivation in any one year, thus allowing food crop cultivation, mainly sorghum, and perhaps a cash crop (cotton, melons etc.) by a single watering.

2. Traditional irrigation methods

Traditional irrigation methods tend to be elementary but in overall terms are effective to a limited extent only. Local farmers traditionally build an earthen bank or "Ogma" of wadi bed material across the low flow channel of the wadi, with the object of diverting the entire low flow channel of the wadi, with the object of diverting the entire low stage of the spate flow to their fields. During a large spate, as there is no privision for a spillway, the "ogma" is either breached deliberately or it is over-topped and breaches as the flood rises. On such occasions a major section of the "Ogma" is washed away, often before its total command area has been watered, and water cannot therefore be diverted again to the fields until the "Ogma" has been rebuilt. How soon this can be effectively achieved will depend on subsequent wadi flows, availability of machines or animal power and occasionally the "Ogma" cannot be rebuilt before the ensuing spate.

Another local system of diversion is by short lengths of small earth banks projecting into the wadis in the form of spurs, which deflect a portion of the spate flow over the adjacent fields.

The traditional systems are relatively cheap to build, but usually very expensive to maintain. The initial capital cost and the annually recurrent maintenance costs are often the same. If small to medium size spates arrive, the "Ogma" can be effective, but medium to large spates can result in the expenditure of much effort and money with very little benefit, as all the "Ogmas" and spurs are swept away to the sea or into the desert. However, the basic principle is sound enough—that of diverting water at low stage and of allowing large spates to pass unchecked.

The primary canals taking off from the wadis have a large capacity (duty) in relation to the area irrigated because of the short duration of the spate flows. The primary canal sub-divides to smaller canals as it reaches the irrigable area, and farmers exercise traditional forms of control so that the higher lands receive water first. Lower-lying areas are then irrigated after the upper lands have received a sufficient supply, or when flood levels are too low.

There are virtually no permanent structures for the control and distribution of spate flows in the canal system. Diversions are made by blocking the canals and distributaries with temporary earth bunds and cutting them when demands are met. Irrigation supplies within the command area are distributed on a field-to-field basis, the basin bunds (about 1.0 m high) being breached once an adequate depth of water (about 0.5 m net) has been applied to the field.

The construction and replacement of the "Ogmas" and distribution of flows through the canals are communal activities organized by the farmers. Costs are shared on the basis of benefits received, which depends on the area of land, its evaluation, and its proximity to the irrigation supply.

3. Characteristics of spate hydrology and establishment of flood warning systems

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. Cropped areas and crop production vary considerably over the years because of the large variation in wadi run-off from year to year, season to season and day to day. In addition, the wadis are subject to devastating floods, which damage or destroy irrigation structures and agricultural lands.

Flood hydrographs characteristically indicate a sharp rise to the peak discharge but of short duration. A flow is reported to have increased one hundred times in 15 minutes on a Tihama Wadi in YAR. On Wadi Tuban, PDRY, the flow on 8 September 1959 increased from 14 m^3/s to 2114 m^3/s in one hour, an increase of 151 times. On Wadi Hajr, PDRY, on 4 April 1964, the flow rose from 114 m^3/s to 3 400 m^3/s in 2 hours, an increase of 30 times. The peak flow reduces by a factor of 20 to 50.

The slopes of the wadis are very steep—up to 1 percent—and this produces high velocities. The sediment load is generally very high, from 3 to 7 percent by weight with particle size varying from silt to the very large boulders. Floating debris and trash is often a very serious problem. Trees and branches create blockages in the canal head regulators and sediment excluders, and are difficult to clear before the water recedes; thus the flow is lost. Existing headworks are generally inaccessible to machine for clearance. At the new diversion weir on Wadi Rima, 600 m of trash built up at the canal head regulator in one night. Thus project design must take particular account of critical factors such as:

- flow frequency and sediment analysis;
- the exceptionally high sediment loads and the effects of the coarse fractions (gravel and boulders) carried by wadi flows; and
- the quantity and size of the floating debris and trash.

Although data have become available from the different wadi studies in YAR, PDRY and Saudi Arabia, little continuity and coordination in hydrometric data collection and processing is evident.

A better insight into spate hydrology and the possible introduction of a flood warning system may significantly improve spate water management and distribution, but this also requires a very good system of communication. In the case of excessive floods and warning system may reduce the loss of human life, livestock and settlements.

4. Assessment of water resources, sediment transport and optimal water balance

The assessment of surface and ground water resources is one of the most crucial aspects for the development of spate irrigation and, frequently when feasibility studies are commissioned, there is little or no rainfall or flow data on which to base an assessment. A preliminary assessment often has to be made while data are being collected, and this has to be carried out by correlation with other wadis which have records of flows and groundwater availability. It is important to decide whether the data collected in the first year or two fall into the category of a dry, wet or average year by correlation with data from other similar areas. In the same way, sediment transport must be measured and compared with data from other wadis as it might not always be possible to measure during a wide range of flows. Sediment transport capacity of these wadis is generally under-estimated.

An overall water balance needs to be prepared when alternative development concepts are being studied. A very approximate water balance for the Abyan Delta in PDRY is shown in Table 1. It indicates that a more efficient irrigation scheme, which reduces losses and thus groundwater recharge, will result in a smaller groundwater development. Benefits on a delta-wide basis must be thoroughly assessed for each option.

Table 1 Overall water balance in Abyan Delta (Mm^3)

	Surface Water	Groundwater recharge	Groundwater discharge
Inflow (mean annual)			
Wadi Bana	+162		
Wadi Hassan	+32		
Wadi Maharia	+2		
Total	+196		
Surface water use/losses			
Net consumption (500 mm on 13 200 ha)	-66	-	
Wadi Seepage Losses (30% of inflow)	-60	+55	
Canal and Field Application Losses (25% of inflow)	-50	+40	
Escape to Sea, D/S of Ogma Sada (10% of inflow)	-20	+10	
Total	-196		
Groundwater abstraction/losses			
From Wells for Irrigation (Net of Return Flows)			-60
From Wells for Domestic Use			-5
Evaporation and Evapotranspiration Losses from Shallow Water Table			-30
Subsurface Outflow to Sea and Adjacent Areas			-10
Totals		+105	-105

The rapid expansion of deep tubewells has considerably lowered groundwater levels in several wadis and is a very serious threat to areas of permanent agriculture. Older and shallower wells have dried up as water levels have dropped below present pump intakes. Deterioration of water quality for irrigation has also taken place in several areas adversely affecting agricultural production. Groundwater extraction therefore requires close monitoring and continuous data collection.

The critical points to keep in mind when deciding which overall concept to adopt for planning purposes are firstly, that a great deal of flexibility should be built into the overall scheme design because of the general paucity of data and secondly, that the planned development must be based on a realistic water balance which will maximize overall wadi production per unit of water.

5. Soils and land capability

The most important factor in soil classification for spate irrigation is the water retention capacity. The classification for spate schemes is based on this and a modified USBR standard.

The soil classification in wadi developments usually conforms with the order of water rights as silt-laden flood water seems to improve soil structure. The soils with the best water retention capacity are usually to be found in the upper part of the wadi alluvial fan. Some of the best soils in these wadis can only hold 35cm of available water and thus it may be inefficient and wasteful to provide a net field application depth of more than 40 cm on average for the whole spate scheme area until improvements to the distribution system are carried out.

Traditional spate irrigation is based on a field-to-field system of distribution and though a field may be filled to a depth of 80 cm, the water is not allowed to stand long enough to soak-in before the field bund is cut and the water drawn down and transferred to fields downstream. Thus it is doubtful whether a net field requirement of more than 40 to 45 cm can actually be beneficially utilized, due to the water retention capacity of the soils and with the traditional field-to-field system of spate irrigation.

6. Land tenure and water rights

These are absolutely essential aspects of any feasibility study for improvement of spate irrigation. A cadastral survey to define land ownership and a study of water rights are required, not only for proper planning and design of the distribution system and operating procedures, but also for the recovery of O and M and development costs by assessment, levying and collection of irrigation charges.

7. Alternative cropping patterns for wadi development

Alternative cropping patterns will be postulated at the feasibility stage and will depend, to a very large extent, on the forecast of water which will become available as a result of the development plan adopted. Such a planned cropping pattern can only be enforced on State farms, but independent farmers will only change their cropping pattern in response to market demand and an improvement in the probability of receiving an irrigation supply. Only when his subsistence is no longer at risk will the farmer change to higher value crops.

The cropping pattern will comprise a variety of crops such as bananas, fruit trees, vegetables etc., that can be grown on the small area (about 10 percent of the total area) in the upper reach of the wadi which can be irrigated almost perennially with the spring flow from the wadi bed. A further area (about 30 percent) can grow two crops on two waterings per crop and the remaining 60 percent will only be able to produce one crop per year on a single irrigation. This area will have a probability of irrigation from 30 percent to 70 percent. The area irrigated from groundwater will have a cropping intensity possibly slightly over 200 percent and will be able to produce a variety of high value crops.

8. Economic development concepts

8.1 Storage reservoirs

The possible construction of a storage reservoir on the wadi would provide a costly, though technically attractive, means of regulating the highly variable spate flows on short duration with very sharp peaks, into an almost perennial irrigation supply. The heavy silt load carried by the floods would, however, cause a rapid loss of live reservoir storage at a rate of the order of 3 percent per annum.

In the wadis of the South-West Arabian peninsular, large storage dams would command relatively small areas and involve high capital investment per hectare, in addition to the cost of the distribution system. Also the operation and maintenance of the perennial water supply system would require a complete change in traditional irrigation and agricultural practices. As the reservoir silted up, large flood flows would begin to overtop the spillway more frequently and the wadi irrigation system would gradually revert to traditional methods of diversion. The construction of a storage dam sometimes deprives farmers in the lower wadi area of their former supply of spate water, however erratic it may have been.

8.2 Spate breakers

A spate breaker is a small dam with a reservoir capacity of say, 8 m to 15 m which would be sufficient to absorb the larger spates with high peak flows that would otherwise wash away almost all of the "Ogmas" of the traditional system. These large spate flows would be immediately routed through the spate breaker and the storage would be drawn down in 2 to 4 days, perferably before the ensuing spate arrived.

Unfortunately spate breakers, besides being very costly, have a very much shorter life than that of a storage reservoir, due to rapid sedimentation. This is caused by the smaller storage capacity, the low ratio of storage volume to average annual flow volume, and high sediment loads. The proposed spate breaker at Khola on Wadi Zabid in YAR was estimated to have an effective life of 5 to 10 years and was therefore not implemented.

8.3 Schemes for spate diversion with wadi training and bank protection works

The water resources of the Yemen Tihama wadis fall into three fairly clearly defined categories:

i. the base flow and minor spates;
ii. spate flows;
iii. groundwater.

The base flow and minor spates are generally sufficient to provide two crops per year on about 30 percent of the traditionally irrigated areas. With improved irrigation this area could be increased to about 40 percent.

Spate flows provide irrigation for just over one crop on about 60 percent of the traditionally irrigated area but with a variable degree of probability.

Groundwater is abstracted both in traditionally irrigated areas and rainfed areas of the Wadi. The cropping intensity is about two crops per year.

In order to optimize the use of surface and groundwater within a situation of water balance, alternative concepts, which seek to maximize the overall value of wadi production per unit of water and in economic terms, need to be thoroughly examined and discussed. The alternative with the highest overall project efficiency or the lowest cost per hectare irrigated will not necessarily be the best scheme to adopt. Other factors, both economic and social, are very important and also need to be carefully considered.

Two different concepts for utilization and diversion of spate flows have been implemented in Wadi Zabid and in Wadi Rima.

In Wadi Zabid the concept of improving spate diversion throughout the length of the wadi was adopted. The farmers in the middle and lower reaches of the wadi who formerly had to cope with the larger unmanageable spates have been provided with a more reliable means of diversion to their fields. These farmers have been given at least equal, if not more, attention than the farmers in the upstream areas who in the past have been able to manage the base flow and small spates without great difficulty, using their traditional methods. The incremental benefits to farmers will therefore be relatively small.

In Wadi Rima the main investment in irrigation works was made in an effort to convert a traditional spate irrigation area to a conventional perennial irrigation scheme. The total diversion capacity is 15 m^3/s from a single weir with one offtake. The commanded area is about 8 000 ha and the resulting water duty is what one would expect for a perennial scheme, but not for spate irrigation. Thus, the scheme largely benefits the farmers in the upper reaches of the wadi who already had a high probability of irrigation and the means of managing and diverting the relatively small flows that they required.

The farmers lower down the wadi have apparently not received as much assistance as they might have expected to get from the formal project works. This is evidenced by the farmers' insistence that their traditional diversion works (free wadi offtakes) and canals must be retained and culverts or aqueducts provided, where the traditional canal crosses the new canal from the headworks. The selection of the scheme seems to have been based on the overall efficiency of the irrigation system.

In Wadi Mawr one weir with an offtake capacity of 40 m^3/s is being provided to command an area of some 18 000 ha. Here again the irrigation duty of about 21 sec/ha is more appropriate for a perennial scheme than for spate irrigation. The investments in irrigation works are for improvements in abstraction of base flow and small spates; to a large extent, significant improvements to traditional works, which attempt to divert larger flows downstream, have been omitted. Further diversion works will eventually be required downstream.

A review of the overall wadi development concepts should therefore be one of the main issues to be decided in Phase 1 of any feasibility study. This is linked with the assessment of water resources and the optimal water balance. Benefits on a delta-wide basis must be thoroughly

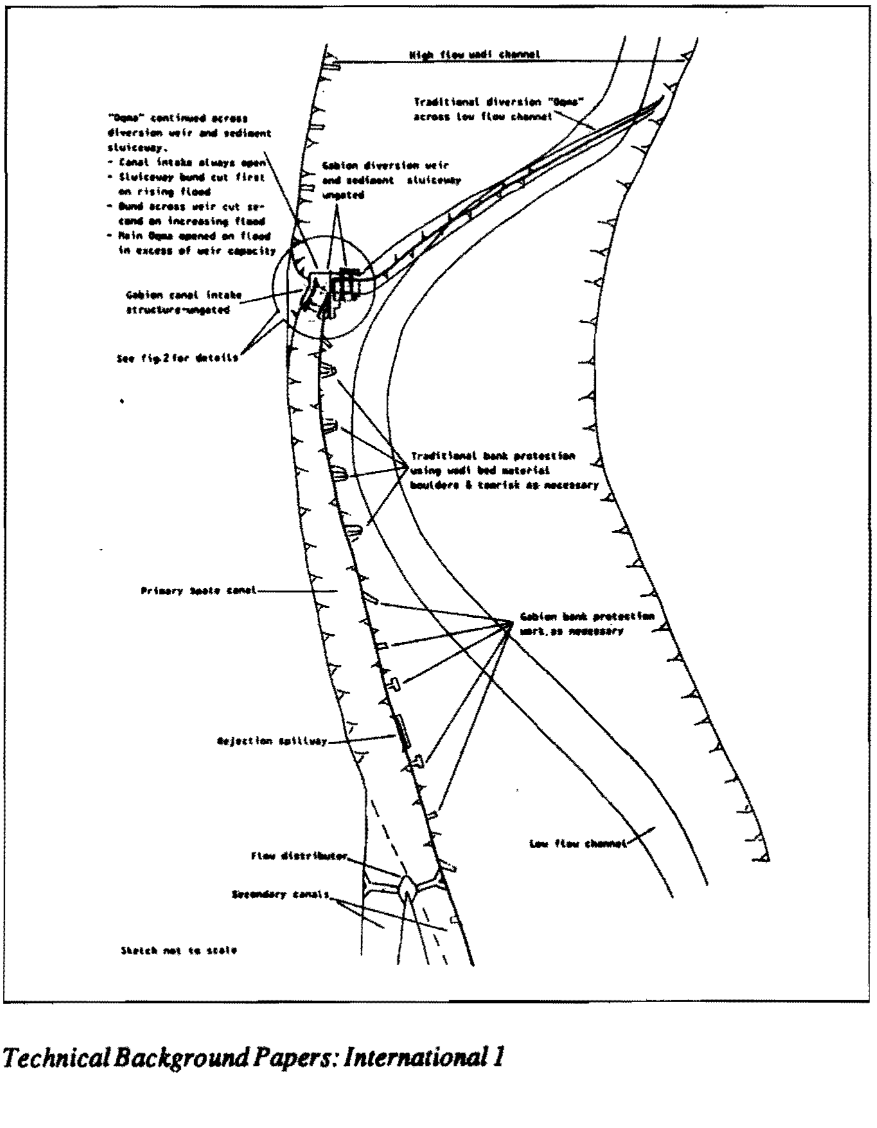


Figure 1 Typical improvements proposed for traditional spate canal intake

assessed for each option to ensure that the total water resource is being used to the best advantage of the farmers within the water right area and within an overall water balance.

It is often difficult to show that spate irrigation schemes are viable in normal economic terms. The proposed alternatives usually all show estimated returns of less than 15 percent, but some form of improvement works must be carried out if only on the basis of social need. In any event the incremental benefits from improvements to spate irrigation schemes are generally limited by the constraints of a single watering, the water retention capacity of the soil and the root zone. In the lower reaches of the wadi the lower probabilities of irrigation reduce further the already limited incremental benefit and call for unconventional solutions if we are to help farmers to improve water control.

In arid zones where water is an absolutely vital commodity, spate spreading schemes have a special significance in stabilizing agricultural production and generally improving the well-being of the people in those areas. The yardstick for the selection of a spate scheme should perhaps be the option which gives the most effective utilization of the total surface water resource yielding the highest value of production per unit of water at the least cost. If this is considered a suitable yardstick then, with the degree of reliability of irrigation of the traditional command areas reducing from the top to the lower areas of the wadi, so also will the scale of investment have to be reduced from a concrete weir and headworks with a degree of security at the head of the wadi to the traditional, simple but large, diversion bund at the lower end of the wadi. A range of diversion structures representing reducing levels of investment and increasing levels of risk needs to be designed to match the lower degree of reliability of irrigation further down the wadi giving lower returns.

The concept of 80 percent probability of irrigation usually adopted for perennial schemes is unacceptable for spate schemes. Scarce water resources are too valuable and every means must be devised to use them effectively. Thus, the third diversion structure might comprise a relatively short gabion weir with a breaching bund capable of withstanding floods with a return period of say five years. The weir would be attached to a canal head control structure and sediment excluder providing irrigation on one side of the wadi only. Any downstream weirs might be designed for floods with even lower return periods.

The traditional diversion bund, "Ogma", has no spill-

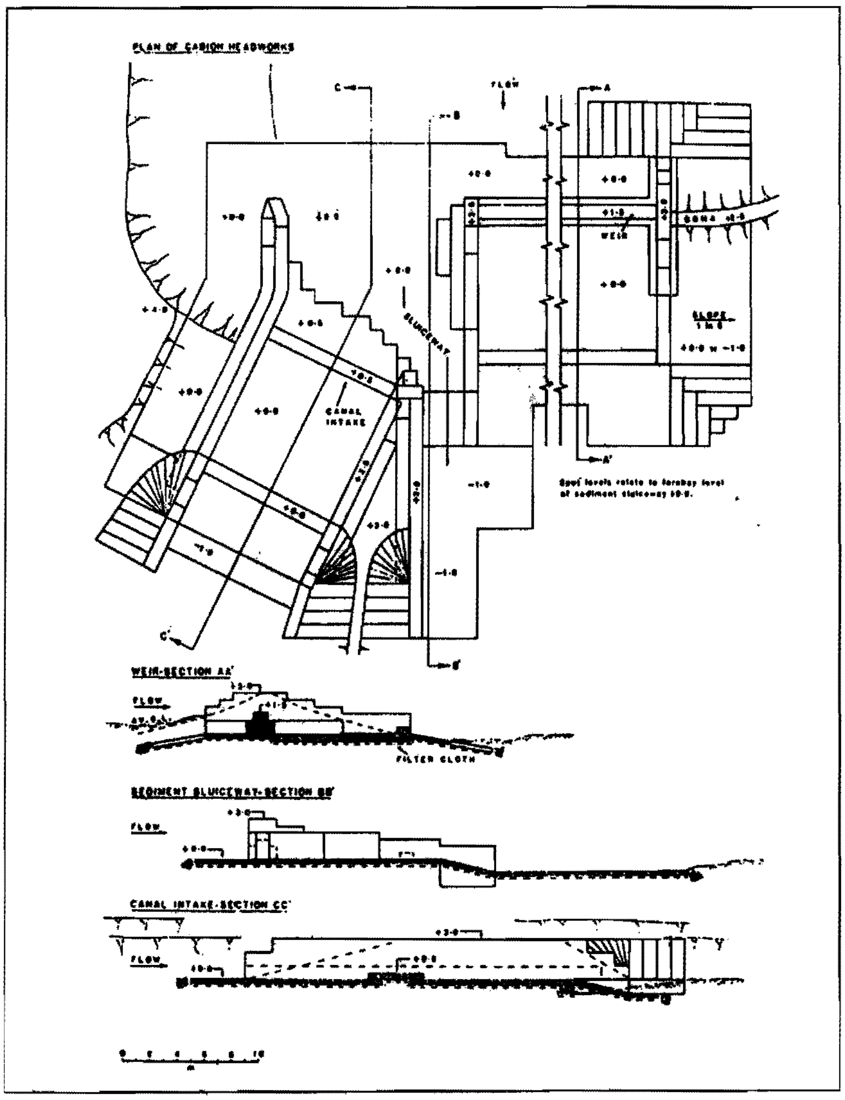


Figure 2 Sketch of proposed improvements to traditional spate diversion works using gabions

way and this is quickly breached and diversion ceases if the flood rises sharply, as it frequently does. The volume of spate flow which can be diverted can be substantially increased by installing some spillway capacity in the traditional "Ogma".

Estimates of water availability and areas irrigated, based on an analysis of simulated flood hydrographs for Wadi Jawf indicate that volumes diverted and areas irrigated can be doubled or trebled by installing a permanent weir. It should therefore be possible to obtain a modest increase of about 30 percent in the areas irrigated, where some relatively small spillway capacity is installed in "Ogmas".

The designs of the low-cost headworks must be capable of construction by groups of farmers with some unskilled labour, and with a minimum of technical supervision.

Typical layouts for such diversion works are shown in figures 1 and 2, which show the kind of improvements proposed for incorporation in a traditional spate diversion "ogma".

A typical gabion headworks (such as shown in the sketch in figure 2) would be incorporated in the "ogma" at the spate canal intake. It would provide a weir of about 100 m^3/s capacity, an ungated canal intake of 10-20 m^3/s capacity, and a sediment sluiceway of about half the intake capacity. Some wadi training groynes may be required upstream to give some protection to the headworks against outflanking, and groynes may be required downstream to protect the canal bank from scour by wadi flows.

The improved traditional spate diversion works would be operated in the manner to which the local farmers are well accustomed. A bund would be built across the front of the diversion weir to a height just below the lowest level of the "ogma", *i.e.* to about 0.5 m above the crest level of the weir. This bund would be extended across the sluiceway to a height equal to the crest level of the weir. The canal intake would always remain open. Thus, an initial small spate would be diverted to the canal intake and on a rising flood, as the canal reaches its design capacity, the bund across the sluiceway would be cut to divert some of the increasing bed load and control the rising flood level. As the flood level increases, the bund across the weir would be cut, and when the capacity of the canal intake, sluiceway and weir is exceeded the "Ogma" would be over-topped, allowing the larger floods to pass down the wadi. The "Ogma" and bunds would be replaced by bulldozers when the flood recedes.

By ensuring that the "Ogma" is over-topped at a breaching section set a good distance from the gabion headworks, and by providing aprons against scour, it is anticipated that the gabion abutment wall adjoining the "Ogma" would remain intact in all but a major flood.

9. Planning and phasing of development

9.1 Spate management planning

A good spate management plan will make the best use of several components in optimising the value of crop production per unit of water in the overall wadi area. The components include:

- surface and groundwater resources;
- soil and land capacity including a schematic layout showing all cultivable areas;
- water rights and establishment of priorities for water use;
- water retention capacity and root zone parameters of the soils;
- cropping pattern and crop requirements;
- water application depths;
- the irrigation distribution system and the operating code;
- irrigation efficiencies; and
- social implications of different strategies.

If the data on water resources are good enough, spate management planning can now be done with the help of a computer model which would study various options for water management for alternative series of diversion sites and select the best option. The model would:

- optimize and select offtake and canal capacities;
- determine the probability of irrigation of the areas commanded by each diversion work, thus providing the type and cost of improvement works which can be justified and the degree of reliability of the works which has to be accepted if capital and operational costs are to have a reasonably economic relationship to the benefits likely to be derived;
- assist in planning groundwater recharge areas and optimizing operating procedures to minimise losses to the coast or desert.

The programme would simulate the passage of a number of historical or synthesized floods over a typical series of years. For a selection of any number of weirs and any combination of canal sizings, the programme passes each flood in each year down the wadi. At each weir, water is diverted into the supply canal for the duration of each flood. The remaining flood water is passed down the wadi and bed losses and flood attentuation for the wadi reach are deducted. The flood hydrograph is then reformed at the next weir, taking account of the intervening bed losses and flood attenuation, and the process repeated.

In each year, volumes of flood water diverted to each area will be accumulated. When the total water requirement for a seasonal irrigation on an area has been satisfied, no further water is diverted in that season until all of the areas with water rights have been irrigated.

The programme's output will provide the accumulated amount diverted to each area commanded by main canals for each of the seasons considered. From this output, the total area irrigated by each alternative under each combination of canal sizing can be determined. By the area irrigated and their probability of irrigation, the most appropriate scheme for spate diversion and control can be recommended.

9.2 Phasing of development

It is probably better to plan and implement spate improvement works in two separate phases. The first phase would provide diversion and control of spate flows and deliver irrigation supplies to discrete groups of farmers in

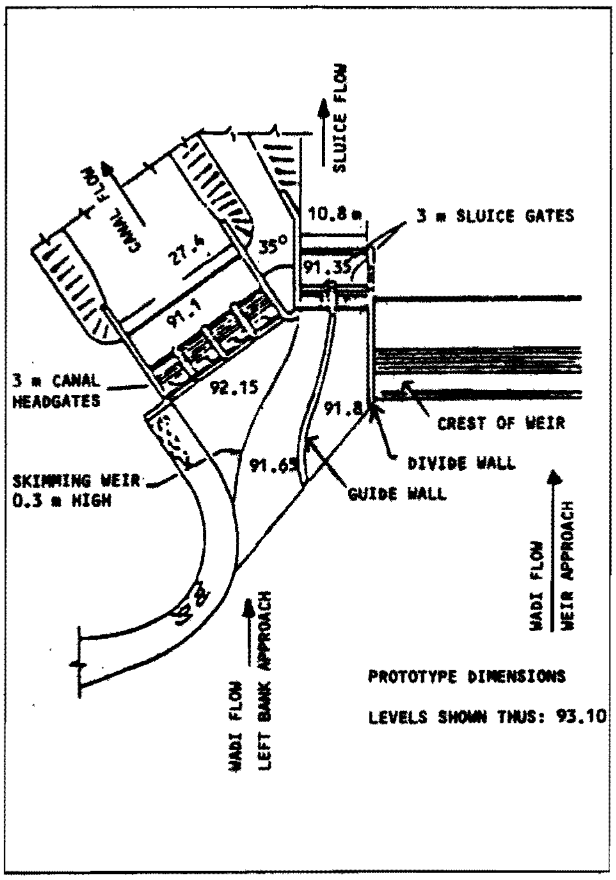


Figure 3 Headworks—preliminary layout

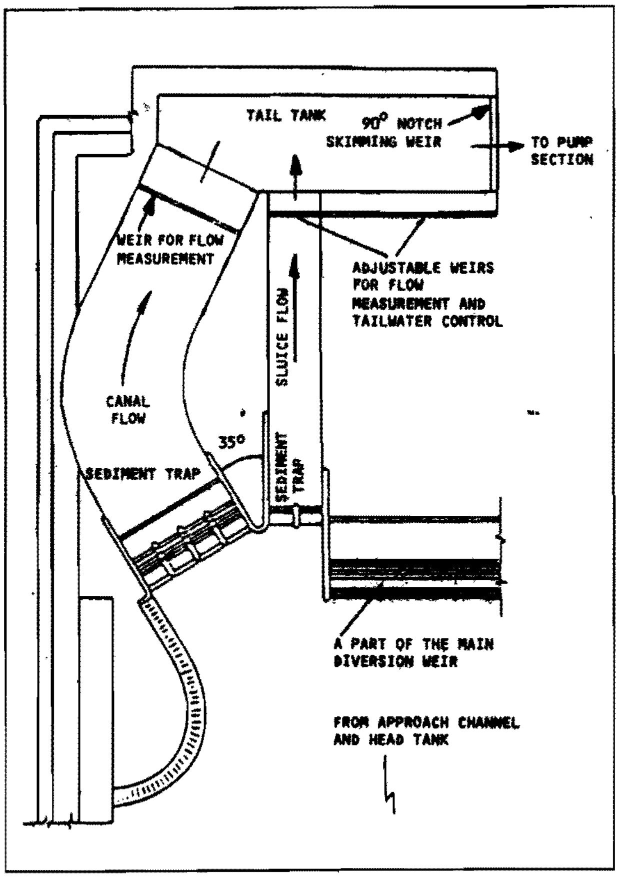


Figure 4 General layout of model area

Figure 5 Headworks as modified

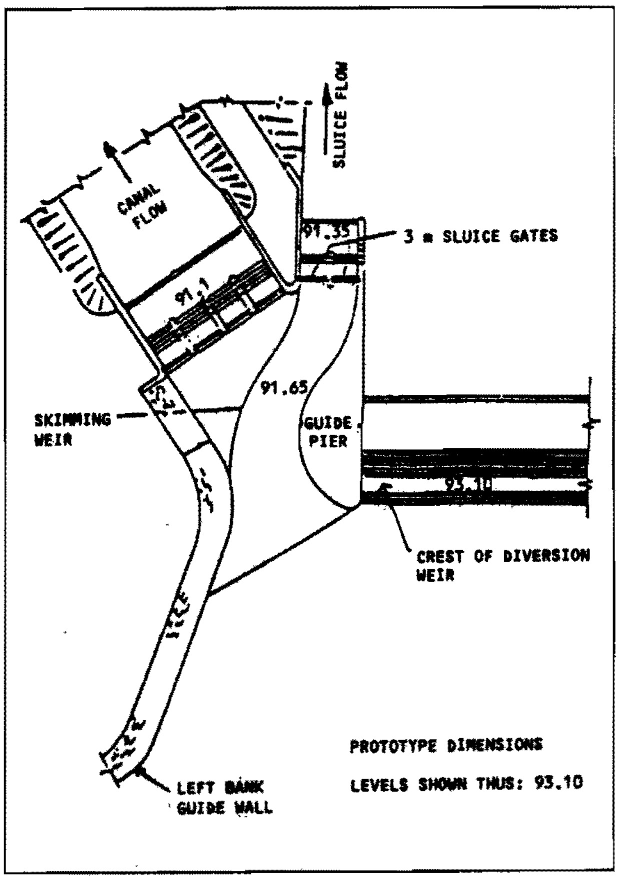
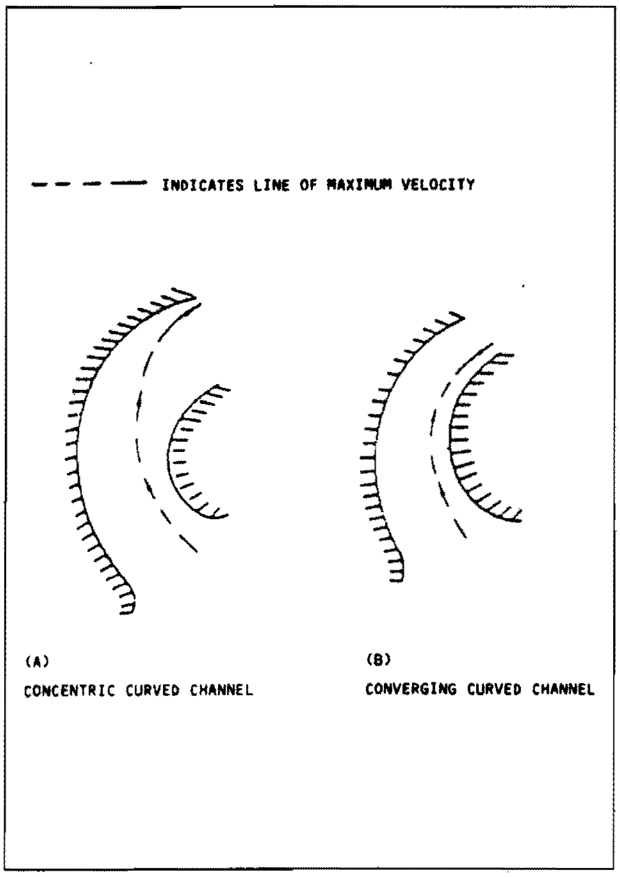


Figure 6 Lines of maximum velocity in concentric and converging curved channels



quantities that they have been accustomed to diverting. When these farmers have gained complete confidence in the improved diversion system, the next phase should be planned and executed. This second phase would improve distribution and control of the field irrigation system in the areas which are able to grow more than one crop. The field-to-field system of irrigation could be changed to a system of small distributaries delivering supplies to each field, or at least to smaller groupings of fields than at present. After the first phase development has been in operation for a few years, any requirements for minor alterations and improvements will have become evident and these can be incorporated into a second phase for improvement of the secondary irrigation system.

The second phase could be very expensive in both capital and O and M costs if minor distributaries and spate inlet structures are required for each and every field of about 2 to 5 hectares. Land levelling cost would be additional to the distribution cost and unit levelling cost would probably increase with larger field sizes. In order to keep unit costs for secondary works within reasonable limits, an economically acceptable size of irrigation unit has to be decided and this raises the question - what is a manageable quantity of spate water for a small group of farmers to handle, using traditional methods, with some inter-fields irrigation improvements? The largest quantity of spate flow that a small group of farmers could probably manage, with delivery from a single inlet structure, would be about 2m /sec and such a group could irrigate about 40 hectares in a day or two, depending on the variation of the flow.

Thus, the command areas controlled by a single distribution structure on the diversion supply canals to be provided in the first phase, could vary from 500 to 1 000 hectares, while in the second phase, the distribution canals and the structures would supply units of about 40 hectares. Groups of farmers would still have a large part to play in the management and distribution of water to their fields in each phase.

10. Design of spate schemes

10.1 Diversion weirs and canal headworks

Diversion weirs are built across the wadis to raise spate flows to a level that will enable the design full supply discharge to be diverted through the irrigation canal head regulator before the flood overtops the crest of the weir.

The weir crest level need only be raised slightly above the average wadi bed level for command purposes, but for efficient sluicing of bed load at low flows, it needs to be at least 1.5 m above average wadi bed level. This height is not ideal for sediment discharges at high wadi flows, but it may not be possible to set it higher if excessive cost of energy dissipation on the diversion is to be avoided.

The weirs are non-regulating, ungated structures designed for permeable foundations. In recent years they have been constructed with crests that slope towards the canal head regulator and sluiceway, to assist in maintaining the approach channel in front of the headworks.

The design of the weirs entails the determination of the stage/discharge relationship, flood discharges for various return periods and width of waterway. The crest level, headwater and tailwater rating curves, intensity of discharge, afflux, high flood level and free-board can then all be calculated. The downstream stilling basin level and the dimension of the energy dissipator and appurtenances, including the depth of sheet piling and length of flexible aprons, will then be determined and designed against uplift pressures and exit gradient.

The canal head regulator is designed to run at full supply discharge, with very little afflux (around 300 mm), just before the flood water overtops the weir crest. The full supply discharge will have been decided at the planning stage and the dimensions of the head reach of the canal determined separately. The width between abutments of the canal head regulator is made approximately equal to the bed width of the canal, to avoid fluming as far as possible, and to provide a skimming weir effect with the maximum intake at low heads. The gate openings and sill level can then be calculated for the full supply discharge and full supply level with minimum loss in head.

The canal head regulator will have to conform to similar design criteria as the weir and the safe downstream floor level should be checked for full supply discharge under the following two situations:

i. with upstream water level at the weir crest level, and
ii. with upstream water level at high flood level.

Condition (ii) will be critical and will determine the safe downstream floor level of the regulator. The velocity at the end sill of the canal head regulator must be checked. The value of the Froude number for this position should not exceed 0.35.

The canal head regulator is set at an angle to the sluiceway for it to function effectively. This angle is dependent on the particular features of the site, but may be varied from almost 0 to 90 degrees and may best be determined by model studies if the magnitude of the work warrants the expenditure.

The control of gravel, shingle and boulders carried into the canals by water diverted from heavy sediment-laden spate flows is a very important feature in the design and operation of wadi irrigation headworks. The problem is one of conducting as much as possible of the stream bed load material through the diversion structure, thereby avoiding its expensive removal from the canal.

The diversion headworks therefore incorporate a scouring sluiceway between the weir and canal head regulator, which is intended to provide good scouring action across the front of the regulator and to intercept as much as possible of the wadi bed load carried by the spate water being diverted for irrigation. The sluiceway also assists the sloping weir in maintaining a channel to the canal head regulator.

The performance of this type of sediment excluder at spate diversion headworks on wadis could be considerably improved by designing the approach to the canal offtake and sediment sluice with a curved converging channel and positioning the weir at the upstream end of the guide pier. In addition to these changes, the bank protection wall should be extended upstream to prevent any pronounced and unfavourable approach from that side. These findings were the result of model studies at the Hydraulics Labora-

Table 2: Mansbury-Rayyan-Bagr Canal, Wadi Zabid, YAR

Range	Discharge (m³/s) Average	% of max	Sediment concentration (ppm)	Probability %	Probability of given discharge being exceeded
0 - 1	0.5	1	1,620	21.5	78.5
1 - 2	1.5	4	2,220	20.3	58.5
2 - 3	2.5	6	2,760	15.3	42.9
3 - 4	3.5	8	3,360	10.1	32.8
4 - 5	4.5	11	3,900	7.5	25.3
5 - 7	5.0	12	4,800	6.4	18.9
7 - 10	8.5	21	6,300	6.0	12.9
10 - 15	12.5	31	8,100	5.7	7.2
15 - 25	20.0	50	11,400	4.8	2.4
40	40	100	18,600	2.3	0.1

tory, University of Southampton in 1978 and Figures 3 to 6 illustrate the basis and outcome of the study.

The most effective method of sediment exclusion is considered to be continuous sluicing adjacent to the canal head regulator in a direction about 60 degrees to the direction of diversion. However, this is not possible in the southwest coastal regions of the Arabian peninsular. Continuous sluicing is only possible when flows in the wadi exceed the full supply discharge of the canal, as wastage of any water which could be diverted would not be tolerated. Intermittent sluicing is sometimes practised when wadi flows are less than the diversion requirement.

The sediment ejector gives no protection against the "wash load" which eventually is deposited in the fields. The coarser fraction—heavy sands and gravel carried in the lower layer of flow—will also enter the headreach of the canal and should be removed by incorporating lined sediment basins and silt ejectors a short distance downstream of the headworks.

For efficient sluicing, the required sluice flow should be one-third to one-half the canal flow, with the upstream level at weir crest level. It may not be possible to set the weir crest at a level which is ideal for sediment exclusion at the higher wadi flows if excessive cost of the diversion weir is to be avoided and operational procedures may have to be instituted instead, to reduce the sediment intake during the short peak flows.

In order to preserve the curvature effects of the sluice channel, design velocities should not be too low, hence depths of flow should not be too large. The sill levels of the sluiceways are generally set about 0.6 m to 1.0 m below the sill level of the canal head regulator.

The Tihama Development authority of the YAR has gained valuable experience over the past few years in the operation and maintenance of spate irrigations schemes in Wadi Zabid and Wadi Rima. Due to the sloping weir and the geometry of the headworks at Wadi Rima, the flow intensity towards the head regulator is considerably higher than the average intensity for the wadi. This concentration of flow drives the sediment and trash towards the headworks and the forebay is likely to become blocked with trash while the sediment concentration in the canal will be higher than in the wadi. As the sediment transport capacity in the head reach of the canal will be much less than the wadi because of its flatter slope, heavy deposition of coarse sediment will occur in the head reach and considerable excavation will be frequently required unless corrective measures are taken.

The TDA suggestions for modification of future designs, in order to alleviate some of their O and M problems are:

i. head walls above the scour sluice gates should be omitted to improve the throughput of sediment and trash;
ii. overflow type, falling leaf gates, hinged along the floor, should be installed in the scour sluice, with top level of the gates at weir crest level. This will enable sediment and trash to flow over the gates during higher flows;
iii. trash racks with suitable clearance devices should be installed in front of the main canal head regulator;
iv. a lined settling basin should be provided in the head reach of the main canal;
v. the bed slope in the head reach of the canal should be increased to achieve velocities of about 2.5 m/sec;
vi. a sediment ejector should be provided at the end of the settling basin;
vii. a rejection spillway to deal with excessive discharges into the main canal should be provided;
viii. the scouring sluice and weir should be lined with stone to reduce the abrasion by large cobbles and boulders traveling at high velocities.

These are all worthy of very careful study.

10.2 Canals and distribution structures

The design of spate irrigation canals and distributaries present some unusual problems because of the need to sieze every opportunity of diverting supplies whenever the wadi is in spate. As mentioned earlier there are large fluctuations in the daily wadi flows which necessitate designing canals for a varying discharge rather than the more usual steady flow states. The canal design must provide satisfactory transport of a highly variable sediment load without causing significant scour. The choice of shape and bed slope are the key factors in design.

In the early 1960's, Lacey's equations were used to determine shape, the ratio of surface width to water depth. This ratio was determined by the discharge and the mean particle diameter of the anticipated bed material of the canal which would eventually be that of the dominant sediment load it had to carry. The ratios varied from 10 to 20 for design discharges of about 10 to 40 m /sec. However, much steeper bed slopes than those indicated by Lacey's slope equations were chosen, to provide better sediment transport capacity at the lower discharges. Little or no data were available on sediment concentrations and thus the selection of silt factor and slope was somewhat arbitrarily based on the engineer's judgement.

The equations used for canal design were based on field data mainly from India and Pakistan, where sediment concentrations were thought to be similar. This has proved to be incorrect as sediment concentrations in the wadis of the south-western Arabian peninsular are much larger than those catered for in canal design on the sub-continent at that time.

The TDA now prefers to use the Simons and Albertson method (1960) as their equations are based on a more comprehensive range of field data and cover a wide variation of sediment loads, some of which, in TDA's opinion, are similar to the heavy sediment concentrations carried by canals on their projects.

Flow frequency analysis of existing spate irrigation canals, together with knowledge of their sediment concentrations, bed slopes and information about scour or siltation, will provide a useful insight into future design. Such an analysis has been carried out on the Mansury-Payyan-Bagr canal of the Wadi Zabid Project, which has a design discharge of 40 m /sec, shown in Table 3.

On the basis of this kind of data, the TDA considers that canal bed slopes should be designed for 75 percent of the peak capacity but allowing adequate section for full discharge. They estimate that this will generate velocities of up to 7 percent greater than that by the Simons and Albertson method. Some acceptable scour may occur at peak discharges for a short time, but the canals will have greater sediment-carrying capacity during the predominant low flows. The recommendation to design the bed slope for 75 percent of the peak capacity seems very safe, as on the evidence of Table 3 the 75 percent peak discharge is only likely to be exceeded about 2 percent of the time.

The determination of canal bed slope is probably the most important design factor that influences both the capital cost of the project and its O and M costs. The extent to which canal slopes differ from natural ground slopes will determine the magnitude of the earthworks and the size and number of the water control structures. If steeper canal slopes can be safely adopted, the sediment-carrying capacity will be improved with very significant savings in project cost.

The remodelling of the traditional canals in the middle reach of the Wadi Zabid area provides some useful indicators for future design. The bed slopes of the traditional canals, which must have achieved some sort of regime over the years that accorded with the method of diversion, are shown in Table 3 below. A channel which possesses year-to-year stability is considered to be in regime.

Table 3: Bed Slopes of Old Canals, Wadi Zabid, YAR

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

The Wadi Zabid canals were remodelled with a bed width/water depth ratio of 6:1 to 8:1 and bed slopes ranging from 0.0003 to 0.0001. Sluiceways for sediment exclusion are provided at the headworks of these canals but are not very efficient as the sills are not deep enough in relation to the sills of the head regulators and the geometry of the forebay and sluice channel is unsatisfactory. Sediment ejection works were not provided. Heavy deposition took place in these canals after the first year of operation. Regular excavation of the head reaches is required to keep the intakes functioning and sediment has to be removed from the first 2 to 3 kms of the canals almost annually. The canals in their middle and lower reaches are modifying their cross-sections and attaining some measure of equilibrium with bed slopes of 1 to 2 metres/km. All the indications are that much steeper bed slopes are necessary and this very important issue requires further careful study and consideration.

10.3 Improvements to field systems

It was suggested earlier that distribution canals and control structures to improve the field irrigation system should be carried out initially in areas that are able to grow two crops. In order to keep the cost of these secondary works within reasonable limits, it was also suggested that each inlet structure should supply units of about 40 hectares. The minor distributaries and structures would be about 1 or 2 m /sec capacity so that the farm unit could be irrigated in a day or two.

On some spate schemes the time available for irrigation has been over-estimated and as a result, field inlet structures and minor canals are too small. In such circumstances the farmers make cuts in the canal bank to bypass the inlet or bulldoze a bank across the canal so that the whole flow is diverted until all their needs are met. These are the indications of inadequate design for spate conditions.

Cross control structures in the minor distributaries and field inlet structures should be kept as simple as possible. Small drop structures controlled with stop logs or large gated pipes about 1 m to 1.5 m diameter, could be operated by groups of farmers if their basic method of irrigation had not been varied too much. Farmers will wish to continue to divert the whole flow of the minor distributary in turn and it is essential to continue to involve them in water distribution and irrigation. Thus, minor canals of the order of 1 to 2 m /s with checks and field inlets to irrigate about 30 to 50 ha would probably meet their requirements. The field-to-field system could also be improved by additional contour bunding and improvement in the inter-field irrigation by use of filter fabric with boulder protection.

10.4 Farm access and communications

Access roads to the irrigation canals and control structures and farm tracks to fields must be planned from inception as an integral part of the irrigation system. These roads are usually on embankments and surfaced with gravel and fine material from the wadi. A reliable communications network is essential for good spate irrigation management because of the much shorter time available for taking decisions on operation.

Telephones and radios are required to connect field personnel with each other and with supervisory staff. The communication network must be dependable and must be maintained in good working condition. The system should include radio communications to all important diversion and distribution sites plus mobile units installed in the vehicles of senior operating and maintenance personnel in touch with a central station at Project Headquarters.

10.5 Conjunctive use of groundwater and spate irrigation

The combined use of groundwater and spate irrigation is much discussed but little practised at present. In the Abyan Delta in PDRY, out of a spate area of some 20 000 ha, less than 100 ha uses both sources. In Wadi Tuban the area of conjunctive use is larger but still only represents a very small percentage of the spate area. Does such a system optimise the use of scarce water resources? The answer is not clear. It will certainly increase benefits per unit of land. The use of both water sources must be carefully considered and planned.

The lower wadi areas, where the probability of spate irrigation might be about 20 percent to 30 percent, would be suitable for groundwater development, provided there was a suitable aquifer. In such areas the design of the tubewell system could be built into the existing spate system with distribution mains and hydrants buried in the field bunds. Specific solutions for the design and operation of such systems need to be worked out and the cropping pattern carefully chosen.

10.6 Deficiencies in planning and design of spate improvements schemes

The following deficiencies have been encountered:

- underestimation of maximum flood in the design concept;
- inadequate provision for sediment exclusion and ejection at canal headworks;
- insufficient provision of total diversion capacity from the wadi and neglect of investment in downstream areas which have a reduced probability of spate irrigation;
- underestimation of canal bed slopes and sediment transport capacity;
- inadequate assessment of the size and capacity of the irrigation inlets to the fields due mainly to a misunderstanding of the probable duration of the spate flows and the reduction in the flood wave in the irrigation channel as the wave passes downstream in the wadi.

11. Operation and maintenance of spate irrigation systems

The main problems encountered in operation and maintenance of spate schemes are concerned with:

- a clear understanding of local traditions and water rights in relation to the new operating rules;
- sediment and trash exclusion, ejection and routine clearance;
- organisation and staff;
- finance and recovery of water charges.

The avoidance of disputes after implementation, the "misuse" of water by upstream users and, in some cases, by farmers in downstream areas, requires a very clear understanding and appreciation of the traditional water rights and operating arrangements at the planning stage. The recommended scheme should give careful consideration to the social implication of any improvements in the system and traditional concepts should not be discarded without very good justification of all aspects of development. Farmers at the tail end of the traditional schemes should not be deprived of what little rights they had to water without some compensation and without good reason, such as optimisation of benefit per unit of water.

The effects of sediment concentrations in wadi flows on the operation of spate schemes is mentioned above. These problems can be alleviated by improved design but they cannot be eliminated altogether. The cost of maintenance can only be reduced to what may be considered an acceptable level.

The establishment of an O and M organisation with the necessary plant, equipment, workshops and with trained staff to run it effectively, usually takes longer than anticipated. Senior O and M staff should be sent on exchange visits to nearby countries where spate schemes are operated. In many developing countries O and M will need a reliable source of foreign currency to keep the machines in operation. O and M manuals are prepared by the consultants for their project. These should be reviewed annually and amended as the need arises.

The annual O and M cost of spate irrigation schemes should not be entirely dependent on allocations from general revenue. It is usually the first item to be cut at times of financial constraint. A practical means must be devised and instituted for recovering the cost preferably through well established procedures. Involvement of Farmers' Associations or groups of farmers in O and M should be encouraged.

12. Organization and management

The instrument for development of spate schemes need not be so different in principle from that required by other major projects; but in order to relieve the load on the Chief

Executive and his Deputy of coordinating the efforts of the various departments, it may be worthwhile to consider organising the development agency on a functional basis rather than by discipline, vis: agriculture, engineering, administration, finance and accounts. The basic functional units required would be:

Planning (including monitoring and evaluation);
Design and supervision;
Operations, both agricultural and O and M;
Administration and staff training;
Finance and accounts.

The agency must be given adequate power to perform its duties and responsibilities.

13. Concepts for improvements in spate system design and management

An approach to spate irrigation and wadi development is presented in order to stimulate discussion on economic development concepts.

Present day spate schemes are merely improvements schemes as spate irrigation has been practised for thousands of years on the alluvial coastal plains of the south-west Arabian Peninsular. This fact should not be overlooked. The systems of diversion have been developed by the farmers from experience over the centuries, to utilize and conserve their vital water resource to the maximum.

13.1 Development concepts

One of the most important issues to be decided during phase 1 of the feasibility study is the appropriate development concept to be adopted for improving the traditional spate irrigation system. Should a dam with storage reservoir be constructed or a spate breaker and series of diversion structures or one or more diversion weirs with wadi training and bank protection works?

The social, technical and economic aspects of the alternative concepts should be reviewed during the preliminary appraisal. These should include alternatives for optimal use of surface and groundwater, within a water balance, to maximize overall agricultural production per unit of water and in economic terms for the benefit of all the farmers within the water rights area.

This will entail choices concerning overall project irrigation efficiencies, optimal spate application depth for a single irrigation, and extensive versus intensive use of land. Some questions that arise immediately are:

- which is the target group to benefit from the investments and why was it chosen?
- where should the investment in irrigation facilities be made to obtain the best return per unit of water?
- what is the best means of spreading the benefits to be derived from the total water resource within an overall water balance?
- what methods are to be used for improved conservation of the total water resource?
- will conjunctive use of spate and groundwater optimize the value of the agricultural production per unit of water? and
- is phasing of the improvement works to be advocated? (The first phase for wadi diversion works and the second for improvements in the distribution network.)

13.2 Diversion structures

It is not possible in economic terms to control the probable maximum flood. Thus diversion weirs should have the canal headworks, sediment excluder sluices and sediment control works on one flank and an embankment with a 'fuse bund on the other flank.

A well-developed traditional spate irrigation system might have, perhaps, 20 or 50 or more individual diversion canals offtaking from the wadi. If this system is to be improved to provide better control of spate flows then it may be necessary to construct some 4 to 6 diversion structures to replace the 20 to 50 traditional offtakes in the wadi.

Each diversion would command an area with a different probability of irrigation. As the probability of irrigation reduces from head to tail of the wadi an analysis is necessary to determine an economic cut-off point for improvements in water control and diversion.

The cut-off point, however or wherever devined, will generally not be accepted bvy the farmers and they usually continue to reconstruct their traditional works in the lower wadi, if no improvements are carried out. This is a clear indication that engineers should always be seeking ways and means of providing better spate control but at a much reduced level of investment in diversion and distribution works in the middle and lower reaches of the wadi to match the lower returns from these areas.

In any event the incremental benefits from improvements to spate irrigation schemes are generally limited by the constraints of a single watering, the water retention capacity of the soil and the root zone. In the lower reaches of the wadi the lower probabilities of irrigation reduce further the already limited incremental benefit and call for unconventional solutions if we are to help farmers to improve water control.

The first diversion work at the head of the wadi could have a weir with a design capacity for the 1 in 20 year flood. The range of diversion structures downstream would have weirs with design capacities of shorter return periods, reflecting acceptance of an increasing degree of risk and reduced levels of investment to match the lower degree of reliability of irrigation further down the wadi giving lower returns. Thus, for example, the last two diversion structures might have a relatively short gabion weir with a breaching bund capable of withstanding a flood in the lower wadi, with a return period of, say, 3 years.

Much more data collection, research and model testing needs to be done on sediment control at spate irrigation headworks.

Diversion structures should be designed for maximum sediment exclusion. The geometry at the canal headworks should provide a converging curved approach channel to the sediment sluiceway, which should have a capacity of about 1/3 to 1/2 that of the full supply discharge of the canal head regulator. The diversion weir should be positioned at the upstream end of the guide pier and the bank protection wall should be extended upstream to prevent any pronounced and unfavourable approach flows from that side.

13.3 Spate irrigation efficiencies
The overall irrigation efficiency of a spate improvement scheme involving a series of diversion weirs is likely to be in the order of 30 to 40 percent. That is, the net consumptive use of surface water might be only about one-third of the mean annual flow. However, extensive spate spreading is probably the best means of recharging groundwater, much of it through wadi bed seepage and canal losses. Thus the overall water balance would allow somewhat greater groundwater abstraction than for schemes with higher irrigation efficiencies.

13.4 Optimal spate application depth
The optimal spate application depth for a single irrigation should be an average of 400 mm net stored in the soil. This is about as much as the field to field system of irrigation will permit and as much as the average soils in spate areas can retain.

A net water application of 400 mm will allow extensive rather than intensive production and a larger area for spate spreading and groundwater recharge.

13.5 Groundwater recharge
Groundwater recharge schemes, with specially designed recharge basins, do not appear to optimize the value of agricultural production per unit of water. Surface water should first be used for extensive spate irrigation with the wadi bed seepage and canal losses going to groundwater recharge.

13.6 Water use
Conjunctive use of spate water and groundwater on the same plot of land is to be deprecated as it will not optimize production per unit of water. Spate water could be used once in 3 to 4 years on tubewell farms for leaching purposes and to improve soil texture.

13.7 Phasing of development
This development concept lends itself to a phased programme for implementation. The first phase could provide diversion and control of spate flows and deliver irrigation supplies to the existing canal systems in quantities that the groups of farmers have been accustomed to handling.

The operation of the new canal offtakes should be handed over to the groups of farmers responsible for each canal as soon as they have demonstrated that they can handle the system without difficulty, but under general supervision of the authority concerned. When these farmers have gained complete confidence in the improved diversion system the next phase should be planned in close consultation with them.

This second phase would improve distribution and control, where necessary, on the traditional canals. In the areas which are able to grow more than one crop, the field to field system could be changed to a system of small distributaries delivering supplies to each field or at least to smaller groupings of fields than at present.

After the first phase development has been in operation for a few years, there will inevitably be some requirements for minor alterations and improvements; these will have become evident and could be incorporated into a second phase for improvement of the secondary irrigation system.

A phased series of improvement schemes seems much more appropriate and would provide continuity of technical involvement in the area until all systems were operating properly.

Above 60 percent of the total commanded area will receive only one irrigation per year or less and improvements works to deliver water by minor canals to each field will not be justified. In order to keep unit costs for improvements to secondary works within reasonable limits, an economically acceptable size of irrigation unit has to be decided and this raises the question: what is a manageable quantity of spate water for a small group of farmers to handle, using traditional methods, but with some inter-field irrigation improvements? The largest flow would be about 2 m^3/s delivered from a single inlet structure. This flow could irrigate about 40 hectares in a day or two, depending on the variation of the flow.

13.8 Water rights and operating procedures
Improvement works as outlined above will be in keeping with traditional water rights and operating procedures. The improvement will be in control of spate flows.

Thus, the command areas controlled by a single distribution structure on the diversion supply canals to be provided in the first phase could vary from 500 to 1 000 hectares, while in the second phase, the distribution canals and the structures would supply units of about 40 hectares. Groups of farmers could then continue to have a large part to play with the management and distribution of water to their fields in both phases.

The farmers' continued involvement in operation and maintenance is absolutely essential.