

Aspects of spate irrigation in PDR Yemen

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Introduction

Irrigation in the People's Democratic Republic of Yemen (PDRY), unless supplied by groundwater, depends on the diversion of intermittent wadi flows—spates—during the two wet seasons. Traditionally, an embankment of sand and stones is built in the wadi bed to intercept a proportion of the spate and direct it into a canal. Frequently this embankment, known as an ogma, is overtopped or washed away. Binnie & Partners, in association with W.S. Atkins & Partners, were engaged by the Ministry of Agriculture and Agrarian Reform (MAAR) in 1983 to report on major damage to irrigation structures in the Abyan Delta, 50 km north-east of Aden, after exceptional floods in Wadi Bana in 1981 and 1982. Most of the examples discussed in this paper are therefore from Abyan Delta, which contains some 20 000 ha of irrigable land (see Figures 3 and 4).

Five diversion weirs, constructed in Wadi Bana under the British administration between 1953 and 1966, were destroyed or outflanked in 1981-82 during the severe storms. This paper is largely based on the work undertaken in the 1983 study (W. S. Atkins *et al.*, 1984) but including more recent experiences. Binnie & Partners were appointed, in mid-1985, to study rehabilitation of the agricultural infrastructure in eight separate wadi regions of PDRY also damaged by floods in 1981-82. The work has recently been reported on to MAAR (Binnie & Partners, 1987) though at the time of writing the conclusions have not been discussed or agreed.

This paper is divided into three sections:

1. spate hydrology and the use of surface water resources;
2. diversion structures and flood protection works; and
3. canals and field distribution system.

Groundwater irrigation, which is capable of developing agriculture of a higher value and standard than spate irrigation, was not investigated in either of the two studies referred to above.

1. Spate hydrology and the use of surface water resources

1.1 Hydrological background—climate

The Abyan Delta climate is hot and arid, becoming semi-arid further inland over the Bana catchment. Rainfall is low and highly variable. Both study area and catchment lie south of the northern tropic and are subject to monsoons

and Mediterranean weather influences. Rainfall occurs from March to May, and in larger amounts from July to October. The underlying weather systems are different during each of the two seasons.

Spring rainfall is thought to arise from the convergence, over the Red Sea, of cool air (generally of Mediterranean origin) with warmer air. This convergence is known as the Red Sea Convergence Zone (RSCZ) and on occasion may produce sufficient lifting of the air mass for it to spill over on to the Arabian plateau.

Summer rainfall is caused by warm, moist south-westerly monsoon air. It is diverted along the Red Sea trough where it is lifted and converges with northerly air streams. The limit of this Intertropical Convergence Zone (ITCZ) activity lies to the north of Jeddah. Its greatest impact is felt along the southern coast of the peninsula and in the western part of the Yemeni mountains.

1.2 Rainfall

Rainfall records of varying length and quality were available, covering 62 years for Aden and 25 years for Al Kod. From the 27 stations a map of Wadi Bana and its adjoining catchments Tuban and Hassan was prepared. This shows average annual rainfalls varying from 750 mm in the high northern mountain catchments of Tuban and Bana to 50 mm in the coastal strip. Median annual rainfall in the cultivated Delta is about 70 mm; this is generally distributed in light showers which make no effective contribution to soil moisture. Catchment areas and their average annual rainfalls were calculated from the map as follows:

Table 1

Catchment	Area (km ²)	Rainfall (mm)	Rainfall input (million m ³ /a)
Bana	7 200	360	2 590
Tuban	5 090	530	2 700
Hassan	3 300	200	600

Wadi Hassan was studied in the 1985-86 work. Although it has a substantial catchment its value to irrigation in the Delta is slight.

1.3 Run-off

Based on the adopted 1951-65 record (*see below*) the mean annual run-off (MAR) of Wadi Bana at Bateis is approximately 162 million m³, or about 6 percent of the estimated catchment rainfall. There are no records of Wadi Hassan flow. Assuming that percentages of rainfall emerging as surface run-off are similar for both wadis, Wadi Hassan's runoff at Ad Dirjaj may be of the order of 40 million m³.

Approximately 90 percent of the mean annual run-off occurs during two main flood seasons from March to May and from July to October. The catchment is steep and largely covered by bare rock of low permeability; storm rainfall thus emerges as sudden spates in the wadi. Numbers of individual flood peaks (regardless of magnitude) are available for 1951 and 1953-5 (tallied and recorded in the Abyan Board water books) and have been counted for 1958 and 1963 (driest and wettest years respectively of the adopted 1951-65 record). The six years' average was 115 floods/year. The number of floods counted in this way and the total annual run-off appear to be unrelated.

Records of run-off given by previous consultants were studied, but they did not analyse flows within short time intervals. Because run-off is often extremely rapid and short-lived it was necessary to have hourly (or similar) flows for flow-duration work and the operation studies, as well as estimates of Seif and Kharif flood volumes. The records from the original Abyan water books from 1951 to 1965 had few gaps and a well-documented stage record. This period was therefore adopted for all flow-duration and seasonal run-off frequency studies.

1.4 Irrigation season runoffs

The timing of the Seif and Kharif irrigation seasons is determined both by expectations of high wadi flows and by agricultural practices. The Kharif season is the more important, both agriculturally and in terms of available run-off. The crop year commences on 1 July.

The adopted seasons are:

- (i) Kharif : 1 July to 15 October
- (ii) Seif : 16 March to 31 May

The hydrological sense behind these seasons is shown clearly in figure 1, which shows the seasonal distribution of average half-monthly runoffs. During the period 1951-65 the two irrigation seasons accounted for 90 percent of the annual runoff. Sixty-six percent was accounted for by the

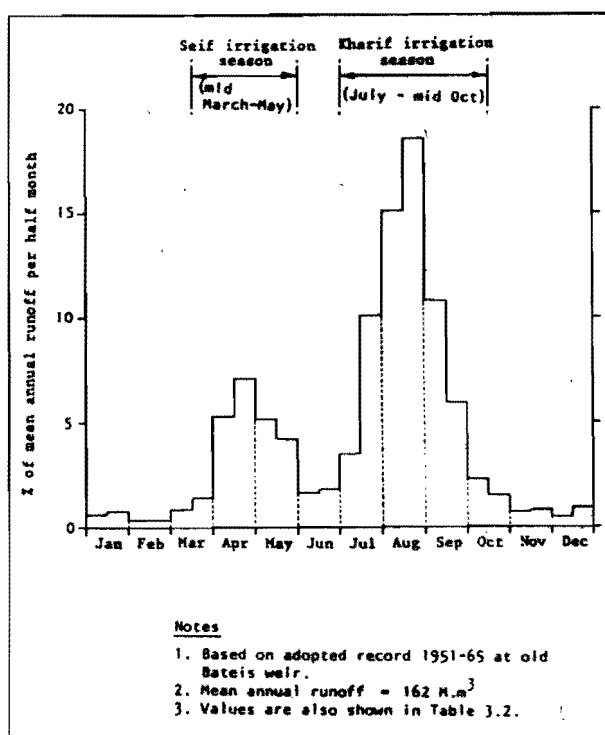


Figure 1 Seasonal distribution of Wadi Bana runoff

Kharif season alone.

In order to assess the reliability with which a given area might be irrigated by Wadi Bana, a frequency analysis of seasonal runoff was carried.

Three Kharif and three Seif seasons were selected as being nearest to the non-exceedance probabilities of 20 percent, 50 percent and 80 percent, representing respectively a wet, normal and dry year. The selected seasons were analysed using the hourly flow data during high stages and daily flows at other times. The seasons and their total runoff volumes were as shown in Table 2.

During the period 1951-65 the two irrigation seasons accounted for 90 percent of the annual run-off. 66 percent was accounted for by the Kharif season alone.

1.5 Diversion requirement

Since crop growth depends entirely upon soil moisture retained in the plant root zone before sowing, the capacity of the soil profile to retain water is crucial. These capacities were established for three grades of soil, based on work

Table 2

	Drier	Median	Wetter
Kharif season			
Year	1961	1953	1962
Volume (million m ³)	77.6	108.5	131.0
Non-exceedance probability (%)	21	50	73
Seif season			
Year	1962	1954	1960
Volume (million m ³)	10.6	23.2	70.7
Non-exceedance probability (%)	12	55	85

by Dar Al Handasah (1973).

Combining the figures given there with the expected rooting depths of the principal crops provides a measure of water availability (*see table 2 below*).

It can be seen that the desirable moisture requirement of 50 cm for cotton is only approached in the fine textured soils. It is also apparent that to apply 50 cm or more for crops other than cotton, or for any crop on medium or coarse textured soil, is ineffective and will only contribute to raising of the water table.

Since it was not judged practicable at the present time to vary the water application for either different crops or soil types, a standard field requirement of 45 cm was assumed. To this depth 3 cm was added, after analysis, to cover the extra quantity necessary to ensure 45 cm depth at points furthest from the inlet. Conveyance efficiencies are always difficult to estimate, but the high velocities and short total times of canal flows must mean that infiltration losses are less than in conventional slow-moving systems where canals are full for much of the year. Conventional systems having efficiencies of 50-65 percent also lose water through negligence and/or the inability of sub-areas to accept the whole flow: such operating losses are most unlikely to occur with a spate system. We therefore consider a conveyance efficiency of 80 percent to be reasonable.

The above figures result in a diversion requirement (implicitly in well-levelled fields) of 60 cm (45+3/0.8). Much of the area was expected to be poorly-levelled and for these lands a 20 percent increase was postulated, leading to a diversion requirement of 72 cm. Available data on actual diversion depths is extremely sparse, but the selected values are consistent with those appearing in early Department of Agriculture and Al Kod research station reports, which range from 59 to 91 cm.

Gross irrigation depths taken from Department of Agriculture and Al Kod reports are as follows:

- (i) 1957 (Department of Agriculture)
Kharif season: total of 13 000 ha irrigated by 83 million m³ diverted (0.64 m depth)
- (ii) 1959-60 (Al Kod)
Seif season: 11.8 million m³ diverted to irrigate 1 300 ha (0.91 m depth)
Kharif season: average application 0.82 m

- (iii) 1960-61 (Al Kod)
Kharif season: average application 0.59 m
- (iv) 1961/62 (Al Kod)
Kharif season: average application 0.66 m.

In an experimental direct measurement of water applied to irrigate a 43 ha sample area block between 18 and 20 July 1983, an overall application depth of 68 cm was derived. The average inflow rate to this tertiary block over 48 hours was 1.7 m³/s.

1.6 Floods in Wadi Bana

Information is available on historic annual flood peaks, with some gaps, over a 33 year period and for shorter periods on two other wadis in PDRY.

There are 25 annual maxima for Wadi Bana, 15 for Wadi Tuban and 7 for Wadi Hajr which lies east of Wadi Meifa'ah (*see Figure 2*). These records were used to produce a statistical basis for forecasting flood magnitudes of given probability. The very large floods of 11th September 1981 and 20-30 March 1982 both exceeded any peaks recorded since measurements commenced in 1949. The peak discharge on 30 March 1982 is estimated at 3 800 m³/s, while that of 11 September 1981 is put at 2 450 m³/s. The March 1982 flood persisted at a high flow for an unusually long period (more than 60 hours). Estimation of flood stage has been very difficult due to the absence of staff gauges; the one at Bateis was carried away in the September 1981 flood.

The history of the irrigation weirs and road bridges throws some light on past floods. The original Bateis weir dated from about 1953 and survived until the September 1981 flood. The lower weirs were built between 1961 and 1966. Hayja, Makhzan and Gharaib survived until the 1982 flood without major damage, but Diyyu (the first weir built after Bateis) had to be completely rebuilt in 1968 and again partially in 1974 or 1975. The 1982 flood also destroyed the two narrow bridges (span approximately 120 metres) built side by side to carry the Aden-Zingibar road across the wadi. The earlier of these bridges dated from the 1950s and the later from the 1970s.

The analysis of flood events results in the following figures for Bateis as shown in Table 4.

Table 3

Soil type texture	Water holding capacity (cm per m)	Cotton		Water melon		Sorghum	
		root depth (cm)	available water (cm)	root depth (cm)	available water (cm)	root depth (cm)	available water (cm)
Fine	15 or more	300	45	150	23	200	30
Medium	11-15	300	39	150	20	200	26
Coarse	11 or less	300	33	150	17	200	22

Table 4

Return period T (years)	Flow rate m ³ /s
Mean annual flood	940
10	1 950
50	3 840
100	4 890

The following flood design figures adopted by the Soviet engineers for Bateis weir appear, therefore, to have return periods as shown:

Weir design without breaching: 2 500 m³/s, 10-20 years
Weir plus breaching section: 5 000 m³/s, 100 years or more.

Since our 100 years return period value of 4 890 m³/s is very close to the higher of the two Soviet design figures, the 5 000 m³/s value was accepted as the extreme flood to be used in design. Flood routing effects and conveyance losses are taken as reducing this value only slightly in the lower reaches of the wadi, and not all at Hayja.

For comparison, the maximum diversion capacity of all the offtakes at the four weir sites is of the order of 1 50 m³/s.

1.7 Operation study: Wadi Bana

An operation study by computer was performed, using six selected seasons for which full data records were available, to test a variety of irrigation design options. The complete area covered by the canal system is 16 000 ha net cultivated, but only part of the area could be irrigated in recent years due to the limitations in operation of the system. The location and operation of the weirs has an important impact on the size of the area which can be effectively irrigated. A computer model provides a useful means of simulating spate flow and the effects of the different design solutions. The model was based on the fundamental rule that upstream users take water first. This applies to the weirs in sequence, and independently to the offtakes on each canal. It is, of course, constrained by the intake/canal capacities at each weir, and long secondary canals also impose their own maximum offtake capacity. The more downstream user therefore gets water only if either:

- all users upstream have received irrigation; or
- the weir/canal upstream is already abstracting at full capacity.

The digital model was arranged to "divert" wadi flows into the most upstream canal at a rate corresponding to the canal size rating, until the volume required by that canal - the product of its area and diversion depth requirement - was satisfied. Any surplus and the next wadi spate to follow was diverted in the same way into the next ranking canal, and so on. On every occasion wadi flows in excess of canal capacity were diverted into the next ranking canal downstream. In this way the whole irrigable area fills up from the top downwards, except that often the downstream

areas are not fully satisfied. A wadi bed seepage loss, proportional to the wetted perimeter, is applied to all flows which pass below Bateis Weir.

The computer program normally displays only the total volumes diverted during the complete season to the four principal commands: Bateis, Hayja, Diyyu and Makhzan.

For Option A in Kharif 1962 (the "wetter" year), a total of 15 190 ha could be irrigated. In the median Kharif year (1953), 14 800 ha were irrigated, but both Bateis and Hayja commands were completed earlier. In all, five weir intakes and twelve main canal capacities were modelled, with the ability to vary discharge capacity and total requirement of each.

Much of the modelling was directed to options which depended on new or enlarged link canals from one or two new weirs in place of the old system of more local canals supplied from five weirs. Even without the model it had become clear that the whole 16 000 ha could only be irrigated in Kharif at 50 percent probability or less, and the 20 percent value was between 11 000 and 12 000 ha. In all cases the Bateis command of 8 700 ha took its requirement first, so that options all lay in the redevelopment of between 3 000 and 6 000 incremental hectares. A new Bateis weir was already under construction at the time of the study, but the logical extension of reconstruction operations downstream required to be evaluated.

The recommended option was to build only one new weir, at the Diyyu site, and link to it the two perimeters on the right bank previously fed from Diyyu (3 600 ha). A cross-wadi transfer was to be effected on the new weir, so that it would command left bank lands also.

2. Diversion structures and flood protection works

This section will survey the requirements for spate diversion and some methods of bank protection. Spate-fed agriculture does not generate high returns, and its irrigation diversion arrangements must be suitably simple and low in cost. It was found in the Wadi Bana study that an average cultivated area of at least 2 000 hectares was needed to justify construction of a permanent weir of concrete or masonry; in the study of eight regions for long term wadi rehabilitation (*see Figure 2*) there were no other areas approaching this size which could be considered for uniting into a single irrigation system. Outside the Abyan and Tuban Deltas conditions are not suitable for the development of large diversion headworks. As a consequence spate irrigation must continue to depend on the use of numerous simple and expendable intake arrangements.

2.1 General principles for diversion

The primary purpose of a spate intake is clearly to direct spate water into an irrigation canal. In order to perform satisfactorily the intake should ideally:

- divert all flows up to maximum canal capacity;
- permit continued irrigation diversion whilst surplus wadi flow bypasses intake;
- exclude bed load;
- be undamaged by large floods, or be quickly and economically repairable; and

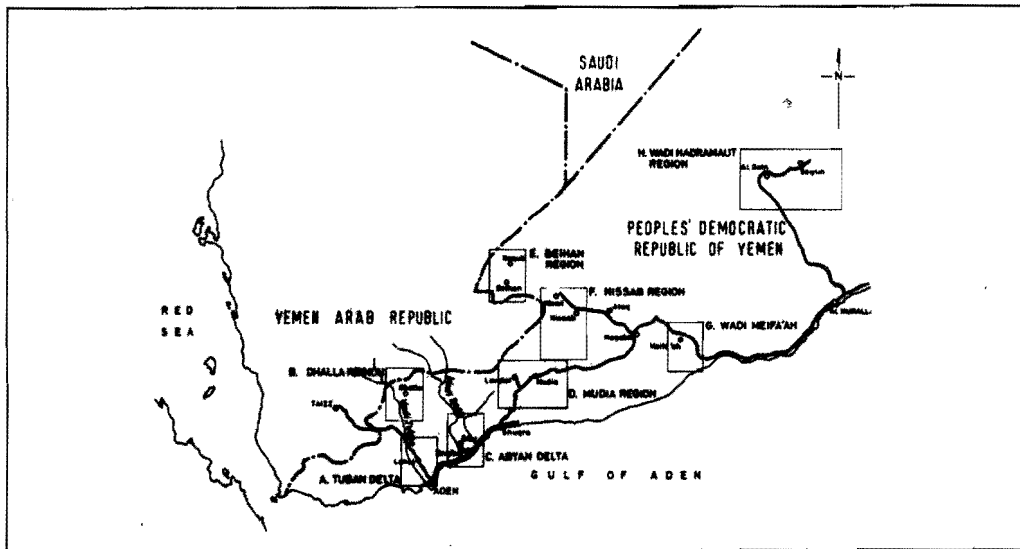


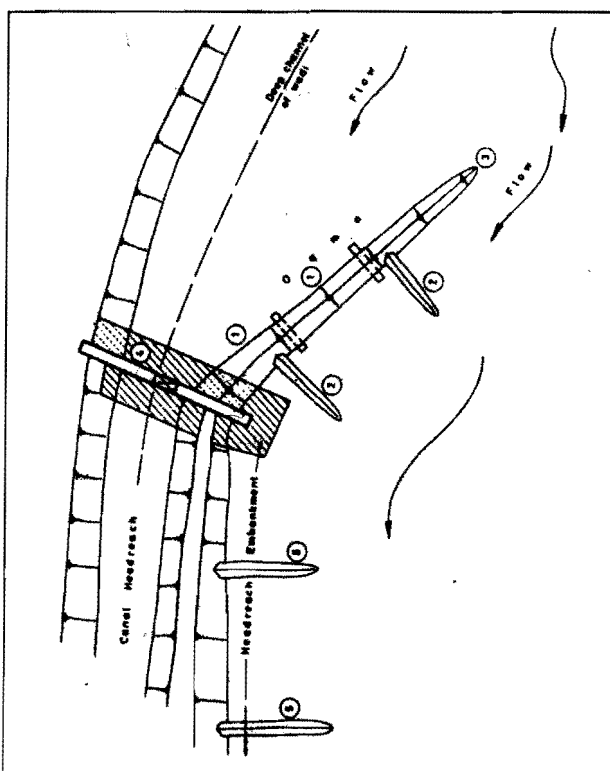
Figure 2 Key map (boxes show areas studied for wadi rehabilitation)

- continue to be serviceable with aggrading or degrading wadi bed levels.

Very often the commonest simple intake only fulfils reliably the first of the above five criteria, and not even this if the flood is large, since the diversion bank often fails before spate needs have been met. Simple diversions cannot exclude heavier sediment (sand and gravel fractions) and preserve wadi bed levels, because the exclusion of the sediment will itself caused the bed to aggrade.

Diversion structures on sediment-laden rivers or wadis, whether simple or complex, must preserve the intakes in the low bed of the watercourse in order to be able to divert small flows. If the intake acts, as it is almost bound

Figure 3 Intake definition sketch



to, as an obstruction which reduces water velocity, then sediment will be deposited. Canal head reaches need to have a flatter gradient and lower velocities than wadis, so they cannot carry as large a sediment load. There are really only two answers to the problem of sediment at intakes; either a complex structure is built with provision for scouring (sluicing) excess sediment downstream, or a simple diversion is built with the expectation of being destroyed in periodic floods as part of the natural process of flushing the sedimentation and re-establishing the line of the low bed. It follows that there is only a limited place for structures to aid diversion which do not include permanent gated scouring works. One is to protect against bed degradation by means of a weir "submerged" in the alluvial material, and another is an intake control to limit the damage caused by excess flow into canals; in both cases the simple and impermanent diversion bank (ogma) remains an essential part.

2.2 Types of intakes

The commonest intake in PDRY is the ogma, an embankment of the local alluvium usually bulldozed upward to one to three metres in height and inclined across the wadi in an upstream direction from the intake point. An ogma is easily washed out by a wadi flood, perhaps once a year on average, and this may or may not occur before the intake's commanded land has been irrigated. Although ogmas are rebuilt with ease in the dry season, it would be difficult to do so quickly in the middle of the spate season, as ogmas can be very numerous.

There are two risks more serious than mere destruction of the ogma: they are flood damage to the intake canal and its irrigated land due to the diversion of an excessive flow, and the degradation of the whole wadi bed causing loss of command. This second effect was widespread as a result of the 1981-82 floods; beds have been lowered by up to two metres. Refinements of the ogma diversion can be introduced to counter a number of its weaknesses.

The following list shows, in ascending order of cost and effectiveness, the range of intake types considered:

- A. Simple ogma
- B. Ogma with measures to restrict breaching, and/or to protect against scour downstream.
- C. Ogma as above, with measures to restrict flow into canal and to discharge excess flow from canal to wadi.
- D. Ogma as above, but built on, or upstream of, a "submerged" gabion weir
- E. Gabion weir with elevated crest
- F. Gabion weir with gated intake and sediment scouring works
- G. Permanent weir

Gabion weirs, as suggested in D, E, and F are relatively expensive compared with A, B and C, but may be justifiable for diversions commanding 200 ha or more. Gabions require much maintenance, perhaps equivalent in cost to replacing them every ten years.

2.3 Ogma intake improvements

In the wadi rehabilitation study we identified six elements for ogma improvement, though it must be emphasised that none of them is intended to make the ogma itself semi-permanent. It is intended that the canal headreach and downstream works in the command may be rendered semi-permanent, and the ogma destroyed less frequently. Some of these measures can be justified economically for commands as small as 30 ha.

Figure 3 shows five of the six elements; the first three relate to the ogma itself and the remainder to the canal headreach. The elements are:

- i) *Breaching section(s) in the ogma:* of value in conjunction with item 4, though destruction may naturally be limited when flood flows are of moderate size. The costs of a gabion end wall to prevent an unlimited widening of a breach are excessive for the benefit gained.
- ii) *Small spurs to protect downstream face:* often used by farmers with brushwood/stones to reinforce them; a low cost measure which can be treated as part of the ogma costs.
- iii) *Upstream strong point:* high ground, trees or boulders which serve to prevent the lateral movement of the low flow channel. This is rather a question of good siting for the ogma than of extra construction work.
- iv) *Intake throttle:* the recommended defence, together with 6, against excess canal inflow. It is a vertical gabion wall with a central slot, surrounded by gabion mattress for scour protection. The throttle is ex-

pected to stay in place after the ogma is washed out.

- v) *Canal headreach protection:* this is often the most critical bank protection situation in any region, excepting villages. There is no standard solution, and the small spurs shown are merely indicative. Headreach protection is not always required but may be needed for up to 500 m of canal bank, and the averaged budget cost of this was taken as three times that of the intake throttle.
- vi) *Canal side spillweir:* this is a necessary complement to the intake throttle, and must be sited far enough along the canal to be above wadi flood level. A gabion weir with a 10 metre long crest was adopted for costing.

The items normally proposed for rehabilitation of small spate system intakes were types iv and vi. The benefit is derived from a raised cropping intensity corresponding, in general, to one additional crop in a 5 year period.

2.4 More reliable intakes

The improved ogma may be used in conjunction with a "submerged" gabion weir, type D of the preceding list of intakes. This option has been proposed for two sites in the upper part of Tuban Delta. The gabions of the weir would be excavated to 2.0 m below wadi bed, and include a downstream mattress or apron 5 m wide behind the flush "crest". In the event of degradation downstream the apron would deform into a sloping profile: further protective works after such an event might be necessary, but the main purpose is to sustain upstream bed levels during the passage of the flood.

A very much more massive gabion weir, in effect a wadi drop structure, to fulfill the same function was built in 1985-86 on Wadi Saghira at Manasirah (Tuban Delta). This weir commands 360 ha.

An even larger gabion weir was built in 1984-85 at Congdon on Wadi Hassan (Abyan Delta). The siting is of interest in that it is angled upstream, like an ogma, with its upstream end anchored into a substantial island; an example of element iii in the improved ogma listing. This Wadi Hassan structure has not yet been tested under flood conditions. It is feared that floods and large spates will cause upstream siltation leading to difficulties with the canal capacity. Congdon intake commands 1 000 ha, and in view of its importance the wadi rehabilitation study recommended the construction of a gated intake and sediment scouring structure. If built, then the Congdon diversion works would be promoted from type E to type F on the preceding list of intakes.

Permanent weirs have been proposed for Wadi Bana, as mentioned already. Outline designs for the Diyyu and Hayja sites were made for the 1983 study. Costs of the weirs and outlet works, without wadi training, were YD 2.9-5.0 million. The designs followed conventional United States Bureau of Reclamation (USBR) design rules for the stilling basin with a main structure of mass concrete. At the low Froude Numbers which develop (between 3.0 and 4.2)

a long stilling basin of length about six times the conjugate depth is necessary. A range of main weir ratings was considered, with the balance of the 5 000 m³/s design flood being passed through an "emergency spillway".

The simple concept of a fuse plug embankment protecting an emergency waterway, which would only flow in extreme flood was not considered suitable. The large quantities of sediment in movement, and uncertainty about the patterns of erosion and deposition before onset of the design flood, would make it impossible to predict either the threshold value for breach of the fuse plug, or the relative discharges in the two channels in the hours which follow an initial breach. The alternative investigated was to have a guide wall in gabions, forming the training wall upstream of the weir, which acted as a side spillway when discharge reached a certain value. At Hayja this training wall would be on the left bank, since the offtake is at the right. Although the use of the side spillway in gabions was intended to provide a "low-cost" option, extra maintenance would be needed on gabion works which could receive significant hydraulic damage. This meant the cheapest option would cost as much as 89 percent of the total required for a concrete weir designed to pass 4 500 m³/s. The slightly more costly design has great advantages in operational reliability, reduced maintenance charges and, in the cases of Diyyu, the ability to supply irrigation canals both at the left and the right side.

2.5 Flood protection works

Designs for wadi training or flood protection works in PDRY almost always depend on the use of gabions, either in box or mattress form. Alternatives have been investigated such as masonry, precast concrete, riprap and sandbags but they are either much more expensive, less reliable or require technical skills which are not available. Most wadis contain cobbles of sufficient size for use in gabions,

at distances which are not excessively expensive. Otherwise the case for rock quarrying may be justified, for example near Nissab town where flood defences are badly needed. A new method which should be tried on an experimental basis in areas having no cobbles or rock is the use of soil-cement. Soil-cement, mixed in-situ in 0.15 m thick layers 2.0 m wide could form the front face of a sloping embankment formed of wadi alluvium.

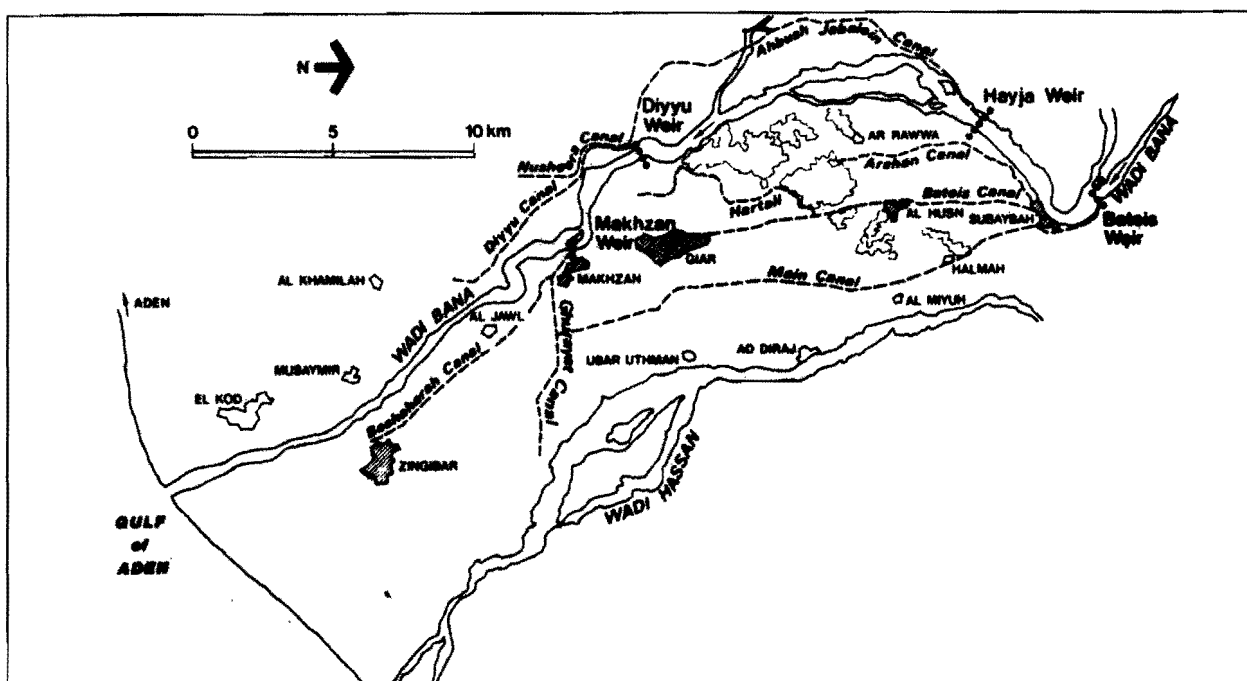
In all cases bank protection must allow for scour below the current bed surface. For this reason either the protection must be continued down in an excavation below the bed, or a falling apron built in front of the embankment. In the absence of detailed hydraulic analysis at any particular site we recommend that scour depths of 2.0 m below average bed level are allowed. This requires excavation for protection down to that depth, or provision of a falling apron 5.0 m wide on the surface. Gabion spurs and other works seen around the country have frequently suffered from undermining due to the absence of scour protection.

The lowest cost flood protection is normally proposed. It consists of a gabion mattress 0.3 m thick laid on a compacted embankment having slopes of 1:2 on the wadi side, a 4 m wide crest and a 1:3 slope on the landward side. With its 5 m wide apron this requires 11 m² of gabion per metre run for a wall 2.5 m high.

All works are recommended to be built as high as the energy level of flow in the design flood, or one metre above water level which ever is less. Village protection works are designed for a flood of 50 year return period, and those such as wadi training and canal headreaches for a 10 year return period.

Since high flows in the wadis are more often than not supercritical, or at least have Froude Numbers in excess of 0.8, the use of spurs is not supported; rather the use of revetment banks parallel to the flow is proposed. Spurs are at risk of direct attack by supercritical flows, and even when

Figure 4 Abyan Delta project



the spur resists attack it causes, in doing so, diagonal standing waves which tend to attack the opposite bank downstream. Examples of damage from these causes are frequently seen.

All forms of wadi training and bank protection which can resist the high velocities of PDRY wadis are expensive—the cheapest type of revetment only 1.5 m high costs YD 100/- per linear metre or more—and they cannot therefore be justified as protection to agricultural land. Protection must be limited to towns and villages and the key components of irrigation systems, such as weir approaches and canal headreaches.

3 Canals and field distribution system

3.1 Introduction

Spate irrigation differs from other methods of application in that water is only applied once for each crop—in very large quantities and at rates of flow which, in most cases, a growing crop could not withstand. The method, therefore, depends on the existence of a fine grained soil able to retain adequate amounts of water in the root zone before the crop is planted. For Abyan Delta the available water per metre of soil depth has been shown (*see 1.2*). In the past, cotton was an ideal crop for this irrigation method due to its rapid development of a root system down to 3.0 m. For economic reasons cotton cultivation has declined, and the major Abyan Delta crops are now sorghum, both for grain and fodder, sesame and millet. Water melons are also popular, and other vegetables in lesser degree.

For uniformity of distribution to saturate the fields a very high flow rate is necessary, and inflow to one field may be at 1.0 m³/s lasting for as long as is needed to develop a water depth of up to 0.5 m. Conventional canals, with the structures usually provided for continuous irrigation systems, would clearly not be adequate in capacity to serve equal areas of spate irrigation at the tertiary and field level; furthermore the value of the crop, on a unit area basis, is usually much smaller for spate than for conventional irrigation. Lastly the field irrigation system may only expect to be in use for a period of 12 to 48 hours once, or at most twice, a year. As a result of these factors the works have, by economic necessity, to be extremely simple and of minimum cost.

The same arguments must apply to the main supply canal, and secondaries if any, in situations where the annual spates are few in number. Many wadis only experience five individual spates per year or less, and in these circumstances conventional gated control structures are unrealistic. It is only in the Tuban and Abyan Deltas, where the spates in one season may number 50 or 100 separate peaks, that main canals and their structures can resemble those of conventional perennial systems.

3.2 Operating requirements

The spate irrigation system has to be geared to delivering water to the fields at times and discharge rates which cannot be planned in advance. In addition to supplying water to the fields at very high rates of flow, the system must cater for very high loads of suspended sediment.

Velocities must be high and canal slopes correspondingly steep.

Sophisticated sediment exclusion systems tend to be impracticable both on cost and on operating grounds. Furthermore farmers welcome the sediment to which they attribute, with doubtful justification, important gains in fertility. An irrigation system developed on traditional lines will admit nearly all the sediment carried by natural wadi flows, and will convey it with reasonable efficiency to the fields. Any attempt to modernize such a system with a sediment excluding intake runs the risk of leaving canals and fields deprived of the silt to which they are accustomed, leading to unacceptable scour.

Field levelling is an obvious need when one views the irregular pattern of existing fields, but maintenance of a better levelled field may require considerable periodic costs, since the spate inflows create their own scour and deposition within each field. Where water does not enter a field from a structure it enters through a breach in the bund surrounding the field. A scour hole is thus made and a channel with a sandy bed is often made across any field which is used for supply to an adjacent field. On steep ground the effect is accentuated. At present, for these and other reasons, most fields are not all level so that varying water depths are applied and yields vary greatly. Furthermore unevenness is caused when breaches are closed by machines, removing soil from the fields before further irrigation. Soil from the fields is also "borrowed" by bulldozers in order to raise or repair bunds between fields.

The foregoing comments are based on the belief that existing spate systems are usually quite effective, even though they may be inefficient and inequitable in their allocation of water. Any improvements proposed for such systems must be carefully evaluated for their overall effect on the movement of sediment as well as water.

The customary water rights existing in PDRY allow upstream users of water to take their share first, those further downstream get water which is in excess of upstream needs. In Abyan Delta this rule is extended to limit the upstream abstractions to one complete spate "saturation irrigation" per season; that is, upstream users cannot take water a second time in the same season unless their first irrigation was at the tail end of a spate and thus inadequate. However it can frequently happen that upstream users receive water both in Seif and Kharif seasons when downstream users receive none.

The overall mode of operation is to run main canals at full capacity where possible with the whole flow being abstracted at up to 5 or 6 offtakes, initially those nearest the wadi. When they are satisfied, priority having been given to the upstream ones, then the next offtake downstream is opened up for the next spate, and so on down. The same system, with 2 or 3 offtakes in use at a time, will be used in smaller main canals and secondary canals. The longest canal in Abyan Delta has a capacity of 12 m³/s with 45 offtake structures in its 18 km length.

Although in theory canal capacity is required to be constant throughout the length, in reality there will be infiltration losses to reduce the discharge, and the fact that downstream reaches are in use less often means that vegetation

and windblown deposits will encroach. Since ground slopes will also tend to be less, velocities will be lower and sedimentation can become a serious problem. Canals from intakes on major wadis, sited a long way downstream from the upper intakes having abstraction priority, have similar design problems. Incompatible hydraulic demands may result due to the wide variations in discharge. Such canals are designed for a higher discharge per unit area than those upstream.

3.3 Abyan Delta system

Figure 4 shows the main features of the Abyan Delta spate system. There are four principal diversion points, at sites of the weirs destroyed in 1981-82. Not all have been fully recommissioned. A completely new weir has been built at Bateis, the point where the wadi enters the delta from its mountainous catchment. The weir supplies a left bank system. Of the other weirs downstream two supplied the right bank and one the lower areas of the left bank. The main canals in the Bateis command, "Maincanal" and Bateis canal, supply the 9 000 ha which have the most assured water supply and provide the majority of the Delta's farm production. They run downhill, averaging two drop structures per kilometre and having lengths of 15 and 18 km. The head reaches of the canals are rated at 16 and 12 m³/s respectively. Although original designs have not been seen and checks at design flow were not possible, velocities in these canals will reach 1.5 to 2.0 m/s at capacity. The third major canal on the left bank Al Ghurayat, was designed for the much larger flow of 37 m³/s, although it only serves 3 500 ha.

Three of the most important secondary canals are also shown on Figure 4, Arshan and Hartali fed from Bateis canal and Bashaharah fed from Al Ghurayat. The canals supplied from Bateis weir have large numbers of offtakes, usually combined with a drop structure, which can be stop-logged to stop flow past the structure.

In the Maincanal and Bateis canal commands, about one third of the area is served by secondary canals. The remainder is served directly by smaller branch canals covering up to 300 ha each but often serving less than 50 ha. There is no clear distinction between the secondary and branch canals, each of which may have several branches themselves. Such branches may start at masonry structures but often are only controlled by the use of earthworks. Offtakes lead to secondary canals, branch canals, field canals, and sometimes directly into fields. There is no clear distinction between these canals. In many places field canals also lead off main canals. The network is not rectangular or regular as it was built to suit the topography and grew in an unplanned fashion.

The range of size of canal structures varies greatly, though a general trend of reducing capacity downstream may be seen. While there are many offtake structures on the secondary and branch canals water is diverted with oqmas—earth banks re-built annually across the canals—in other places. Though many fields are served from canals far more are irrigated from water flowing across other fields (field-to-field irrigation). The land lying close to the right bank of Wadi Hassan can be supplied from Maincanal

or from a complex transfer system whereby water from Bateis weir on Wadi Bana is discharged into Wadi Hassan and then diverted out of the wadi further downstream. A major gabion weir has been built at Congdon near Ubar Uthman to abstract Wadi Hassan flows, although since the 1982 floods no significant spates have flowed into the Delta from the Hassan catchment.

The supply to lands in the Makhzan command is quite different. This large area of 3 500 ha does not receive dependable water annually. It has been developed after the Bateis and the right (west) bank commands, and was only cultivated, in 1983, to a relatively low intensity. The Makhzan command is fed largely by field-to-field methods, and there are few canal offtakes except on the Bashaharah secondary. Offtakes from the principal two canals, shown on Figure 4, and a shorter secondary to Al Jawl lead straight into fields without branch or field canals i.e. as field-to-field irrigation.

The areas on the right bank of Wadi Bana, supplied from Hayja and Diyyu weirs, total some 4,200 ha. Much of this area was redeveloped in the 1970s, with the old field pattern and its canals being superseded by a completely new distribution system and field layout. Known as the Phase I redevelopment, this area was not included in the 1983 study; however the possibility of extending irrigation to it and, in addition, to unimproved right bank lands amounting to a further 2 800 ha, was studied in the water resources context.

3.4 In-field systems

The existing in-field distribution methods were described earlier. They have developed empirically over a long period (much longer than the 29 years since fixed weirs appeared). The pattern of fields and bunds is as irregular as any unplanned farm development, but it includes many small patches of ground, left between the original fields and bunds, which have not been levelled and which act as effective "drops" with trees and grass to help destroy the energy of water being spread.

Four sample areas averaging 40 ha each were selected for the design of improved systems as part of the 1983 study. They were surveyed at a large scale (1:1 000) and carefully studied on the ground to establish the directions and sequences of flow used to irrigate them under present arrangements.

As the Phase I redevelopment on the right bank had experienced difficulties, instructions were received from the Ministry not to attempt redesign of the whole field layout. Detailed proposals were made and costed for the sample areas. The designs preserved existing field patterns and bunds, but amalgamated the smaller fields having similar ground levels into new "basins" averaging two hectares. The present layout contains individual fields which are usually only one hectare or less, even without deducting bunds and uncultivated ground which were surveyed as occupying 15 percent up to 21 percent of the gross area.

Figure 5 shows the 48 ha sample area at Khanfar, southeast of Giar. It is supplied through the Al Awalek secondary which is fed from Maincanal. Most of the existing bunds, which also form the steps of the terracing

system, are retained as basin boundaries but a few which would not be required should be removed, or reduced in size to act merely as boundary lines.

The concept for the areas differed because some possessed the rudiments of a tertiary canal system whilst others did not. Fields were smaller and drops were higher in the upstream areas. In the final analysis land fed from Bateis (upstream area) was excluded and only the downstream (Makhzan) area was treated for cost: benefit studies. Overall ground slopes varied from 0.8 percent at the most upstream area to 0.3 percent at the lowest. Earthworks were predominantly for field levelling (1 000 m²/ha), with banks for new ground-level canals requiring 180 to 350 m³/ha. The earthworks costs were fairly constant at US\$2 000 per ha in three sample areas, though the fourth only required \$1 600 per ha.

The structures for the Makhzan area formed a much more expensive part of the required improvements than the earthworks. New feeder canals were sized at 5 m³/s with the intention to supply four basin inlet structures simultaneously at around 1.0 m³/s. Cross regulator/drop structures were needed at about one per 5 ha and drop inlets averaged one per 2 ha. The costs of these structures, which were of rubble masonry and used stop-logs, came to \$6 000 per ha which gave a combined total cost with earthworks of \$8 000 per ha.

Labour costs are high in the country due to the influence of high wages in the Gulf. Whereas earthmoving by machine can be quite economical the high labour component of masonry makes it very expensive (\$175/m²). Concrete rates are similar but its use is not yet sufficiently common for reliable on-farm construction. Precasting of drop inlets

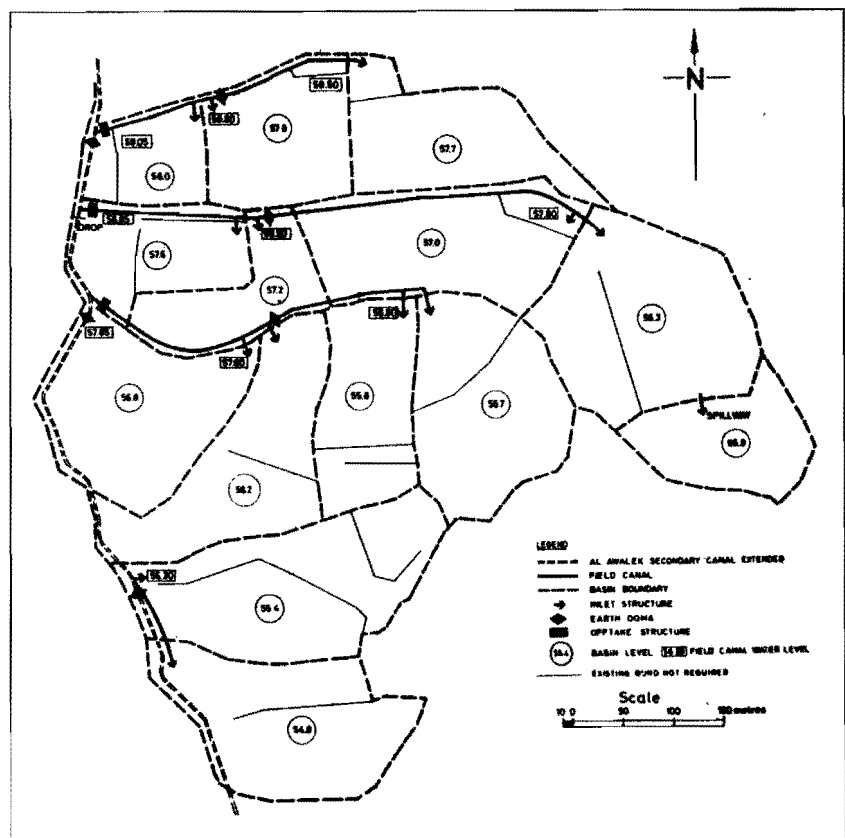
remains another possibility, but it was not followed up. The variety of bund shapes and drop distances would make standardization difficult, and leakage round precast structures could be a hazard. For comparison, the system evolved for the upstream areas was significantly cheaper due to the absence of tertiary canals with cross regulators; the total for structure and earthworks being \$4 700.

In cost/benefit analysis it became clear that farm production could not sustain in-field improvement costs of the order of \$5 000 per hectare and more. It was reluctantly decided to limit the improvements to field levelling and canal earthworks costing \$2 000 per ha approximately. New canals would average 40 m per ha. Regular re-levelling of the fields near to irrigation breaches is included in the O and M costs. The concept for on-farm works at Abyan is that development should proceed slowly, with full farmer co-operation, carried out by a small departmental work force over a 10 year period.

3.5 Operation and maintenance

In the Abyan Delta weirs, intakes and the main and secondary canals are controlled and operated by Ministry staff under the direction of the Project Manager of the Traditional Irrigation Project. Since 1982-84 a very large staff has been employed, principally to operate a large fleet of earthmoving equipment brought in to maintain spate diversions by ogmas after the destruction of the weirs. With the rebuilding of permanent weirs this large labour force has contracted, but it retains the weir and canal "gate" operators. Apart from the headworks the gate function is provided by stoplogs and considerable skill—which includes swimming in the Main canal from time to time to

Figure 5 Khanfar sample area: proposed improvements



recover them—is required of the operators.

The situation in 1986 was described by Camacho, 1986. The annual O and M budget was YD 500,000 of which about two-thirds were for salaries and allowances and one-third for plant operation. The staff breakdown showed that labour involved in operating the traditional system (excluding work in the wadi) was just under one man-day per hectare. This represents full time employment of 45 men, who are engaged on simple maintenance tasks outside the irrigation seasons.

An anomaly now exists between Abyan Delta and the smaller and more distant agricultural wadis. Because of the necessary aid to the area following the destruction of weirs in 1982, the farming community has come to expect all types of on-going bank protection and maintenance done at central government expense. In other areas the degree of government assistance remains severely limited; normally only technical advice and some gabion wire boxes are given. As stated previously the costs of wadi bank protection when only farmland is at risk are uneconomic.

For more dependable planning of future works an improved programme of monitoring and recording data in all agricultural wadis has been recommended. The essential data include dates and magnitude (water stage level) of all major floods, dates of spates and their size in terms of land irrigated, total areas irrigated each season, listed by wadi or canal system, and so on.

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