Design of diversion structures and bank protection for three Tihama wadis

P. H. von Lany, Senior Engineer, Sir William Halcrow and Partners Ltd
and R.M. G. Hewett, Independent Consultant
(formerly Senior Engineer, Sir William Halcrow and Partners Ltd)

1. Background

1.1 Introduction

Sir William Halcrow and Partners (Halcrow) were engaged as consultants in connection with developments on three major wadis which flow from the mountains of the Arabian peninsular across the Tihama, or coastal plain, and into the Red Sea. This has involved the study, design, supervision of construction, and operation and maintenance, of spate irrigated development in the three wadis.

This paper concentrates on the design of the diversion structures and wadi bank and flood protection works.

1.2 General description

The three wadis all rise in the mountain range which forms the western scarp of the Arabian peninsular. The two most northerly wadis, Jizan and Dhamad, lie adjacent to each other some 220 kilometres north of Wadi Surdud.

Table 1 gives basic data on the catchment hydrology and irrigated areas prior to development on the three wadis.

The wadis studied are typical of many which cross the Tihama, the south-west coastal plain of the Arabian peninsula. Infrequent but often intense rainstorms in the steep upper catchments result in floods of short duration and of very high peak discharge.

Table 1 Basic data on the wadis studied before development

Data	units	Wadi Jizan	Wadi Dhamad	Wadi Surdud
Catchment characteristics				
1) Area	km^2	1 100	1 000	2 500
2) Length	km	50	45	70
3) Average width	km	22	22	36
4) Highest elevation	m	2 500	2 500	3 000
Catchment rainfall				
5) Average annual rainfall	mm	475	450	500
6) Average annual catchment rainfall	Mm^3	520	450	1 250
Hydrology				
7) Mean annual flow volume	Mm^3	80	60	98
8) Mean annual runoff coeff (7 divided by 6)		0.15	0.13	0.08
9) Mean annual flood	m^3/s	1 000	980	1 200
10) 10 year flood	m^3/s	1 900	1 700	2 300
11) 100 year flood	m^3/s	3 100	3 000	4 000
Irrigation				
12) Total area bunded for spate irrigation	ha	6 300	8 600	15 000
13) Water harvesting ratio (1 divided by 12)		17.5	11.6	16.7
14) Area irrigated in average year	ha	3 700	4 600	5 700
15) Area of cropland in average year	ha	4 200	5 300	6 500
16) Perennial wadi irrigated area	ha			1 200
17) Overall spate irrigation efficiency*	%	26	44	33
18) Average water requirement (7 divided by 15)	m^3/ha	19 000	11 300	15 100

* defined as (item 15) multiplied by 5 000 m^3/ha divided by (item 7)

Traditionally these spates have been diverted by the farmers from the wadis using earth banks ('ogma') sometimes as high as 6 or 8 metres. Frequently the banks are destroyed by the floods, but building them higher only results in too large a flood flow being diverted, with consequent damage to the distribution channels and to the fields. However with the benefit of collective experience evolved over several centuries the farmers have become expert in gauging the optimum height of the banks so as to balance the risk of damage to their lands and canals against the risk of losing the water downstream.

A complex system of water rights has evolved in most of the wadis, details varying for each wadi. In general the three wadis studied follow the traditional Islamic Shari'ah water law which allows for the uppermost users to take water first, after which their banks across the wadi are broken and the water allowed to low to the next user downstream.

Irrigation is usually from field to field, each field being treated as a large, unlevelled basin, which is filled up until the field bunds are nearly overtopped—often to depths exceeding 1 metre—when the bund is breached and the water allowed to flow into the next field. Few secondary or tertiary canals exist and the large flows (5-25 m^3/s) can cause considerable damage and scouring to the fields, especially in the area around the breached bund.

The major crops grown under spate irrigation in the wadis are sorghum, millet, sesame, cotton and tobacco. Melons, cowpeas and other pulses are often undersown. Groundwater is used, mainly for the cultivation of fruit, vegetables and some fodder.

1.3 State of water resource development at time of study

No surface water development had taken place in Wadi Dhamad beyond the traditional system of irrigation, at the time of study.

On Wadi Jizan, a dam and storage reservoir had been constructed at Malaki following studies and designs by other consultants, under the auspices of the Food and Agriculture Organization of the United Nations (FAO). The dam started impounding in 1969 and was constructed to catch the spates and allow controlled release for irrigation. Recent estimates on sedimentation indicate that full regulation of wadi flows will only be possible for about 25 years from the time of impounding in 1969. After this the remaining reservoir will act as a spate breaker by attenuating the peak flows.

At Wadi Surdud, no permanent structures had been constructed across the wadi. However, a 1 200 hectare state farm, constructed with aid from the USSR, had been developed using the perennial and some seasonal flow from the wadi, supplemented with groundwater pumped from boreholes.

Some groundwater development had taken place in all three wadis, generally using deep well pumps either in hand dug wells or boreholes and direct driven by diesel

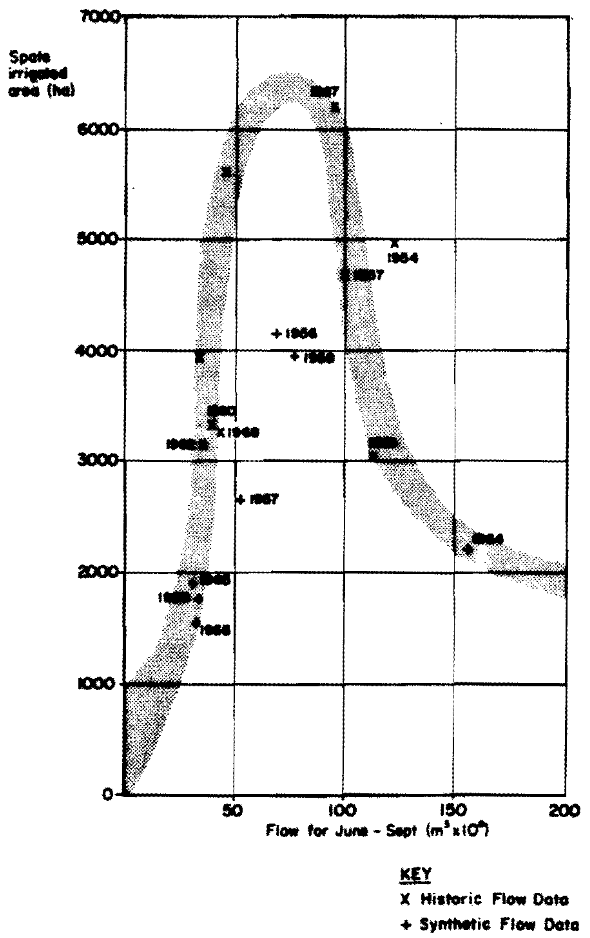


Figure 1 Relationship between wadi flows and irrigated areas from analysis of Zakat records

engines. The state farm at Wadi Surdud was an exception with a central generating station supplying power to submersible pumps in the boreholes.

2. Case studies—Wadis Jizan, Dhamad and Surdud

2.1 Data collection

Studies on Wadi Jizan to enable a more efficient use of surface and groundwater for agriculture commenced under FAO in 1951, providing a longer database than for most other wadis in southern Arabia.

Rainfall data existed at four stations in the catchment with records stretching from six to eighteen years at the time of study. Flow records at Malaki for some eleven years were intermittent but were infilled using linear and multiple correlation.

The application of more rigorous flow-synthesis techniques was not thought likely to narrow the wide confidence limits in the prediction or provide more reliable information.

Prediction of mean annual and monthly surface flow was based on the available records.

Estimates of the irrigated area for each year of the flow record were compared with the 'zakat' records. The 'zakat' is a charitable tax levied on crops and traditionally paid in kind. There appeared to be a clear relationship between the areas recorded for 'zakat' and the flood flows (see figure 1). It was interesting to note, however, that in unregulated conditions the largest irrigated areas were recorded in years of average rather than extreme flows.

To estimate design flood flows, B D Richards' and other statistical methods were used. Estimates of sedimentation in the reservoir were also made.

Since Wadi Dhamad is adjacent, and closely similar, to Wadi Jizan, it was possible to study it more briefly. The main differences between the two wadis were examined, thus avoiding repetition of much of the agronomic and economic studies.

Orthophotomapping and soil studies were undertaken as well as a cadastral survey to determine land ownership and water rights.

Field studies included careful particle size analysis of wadi bank and bed material, which ranged from boulders to sands. Almost no silt existed anywhere in the wadi bed in the area proposed for development.

At Wadi Dhamad, the only reasonably reliable flow records were some seventeen months of depth record with few current meter gaugings to produce a discharge curve. Mean monthly and annual flows were therefore predicted using several comparative and regression methods. Peak flood flows were estimated using the Boldakov method. No reliable direct field measurements of sediment load were available for Wadi Dhamad, and indirect methods of estimation were considered to give the best results. It was assumed that sediment transport in Wadi Dhamad would be similar to that in Wadi Jizan.

Some flow data were available for the three years 1965-1967 from three stations on Wadi Surdud giving a useful indication of the yearly pattern of flows and the magnitude of losses. However, in view of this short record it was decided to estimate the median annual and seasonal flows by analogy with other wadis in the area.

Flow data from Wadi Bana, which has an uninterrupted record from 1953-1961, were used, and daily flows for Wadi Surdud were synthesised on the basis of the ratio of the catchment areas of the two wadis. It was estimated that a flood flow at Wadi Surdud can be expected to rise and fall to one quarter of the peak flow in less than 3 hours.

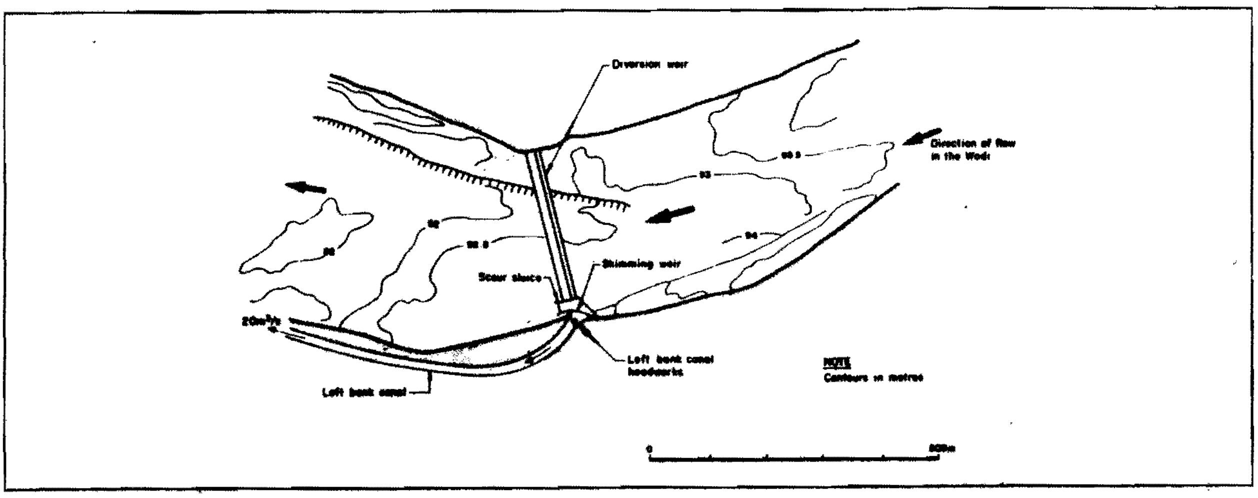
2.2 General approach to the design of diversion weirs and offtakes

The design concept in all three wadis aimed to replace one or more traditional 'ogma' with permanent diversion weirs and canal headworks. This provides more control over diversion of flows into the irrigation network. New main canals connecting the headworks to the existing irrigation system were also considered to allow better management of water distribution, resulting in less damage to the fields, more even watering, more efficient water use, and increases in unit crop yields and areas cropped.

The developments were aimed at preserving the integrity of the wadi course by reducing damage to it and adjacent lands from wadi bank erosion, and overbank flooding.

In Wadi Jizan, it was considered necessary to design

Figure 2 Location plan of a typical diversion weir



the irrigation diversion works for the eventuality that the reservoir would fill with sediment and act only as a spate breaker.

For Wadis Dhamad and Surdud, it was proposed not to construct a reservoir in view of difficulties in finding a suitable site and the likely short reservoir life because of siltation. In addition, the local farmers had clearly indicated that they preferred to receive the silt on their fields. Furthermore the farmers at the downstream end of the wadi also felt disadvantaged by the greater control a reservoir would place on flood flows.

For both these wadis, with high peak flows during spates associated with high sediment loads, there was a need for studies to optimize the design of the diversion weirs, headworks and sand excluders.

The positioning of the weir and offtake relative to the geometry of the wadi is important to minimize sediment intake into the canals and to encourage the low flow channel to the offtake and sand excluder. The sites were therefore chosen to satisfy the following aims:

- to replace one or more 'ogma' and to feed into the existing irrigation system;
- where possible to use a single offtake located on the outside of a bend; and
- where offtakes on both sides of the wadi could not be avoided, to locate the diversion weir on a straight stretch of wadi.

In order to maximize their effectiveness, the headworks and its sand excluding devices had to be able to operate during as much of the rapidly changing flood period as possible. Designs were thus required to consider three main operating conditions:

i. when the flow in the wadi does not exceed the diversion canal capacity;
ii. when the flow in the wadi exceeds the canal capacity but does not exceed the combined canal and sand excluder capacities; and
iii. when the flow in the wadi exceeds the combined canal and sand excluder capacities.

A computer program for routing a typical series of floods down the wadi was devised for Wadi Dhamad in order to establish the appropriate capacities of headworks and main canals. This program was refined for the Wadi Surdud designs.

2.3 Model tests for diversion weirs and offtakes

For Wadi Jizan, with attenuated peak flows, the design of the diversion weirs and offtakes was based on methods and geometry developed in South Yemen before independence, which has proved effective.

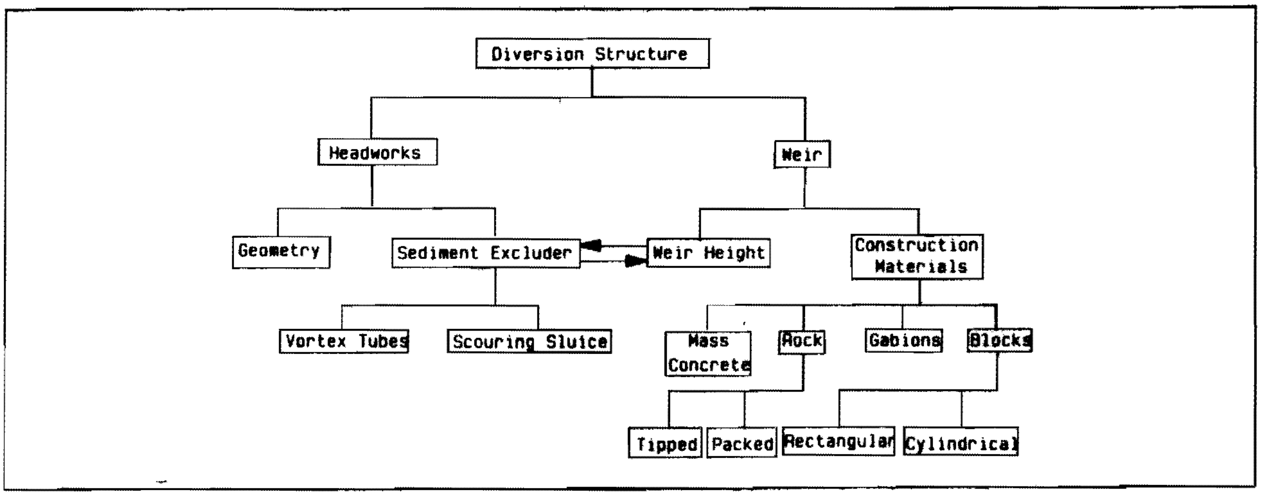
A typical layout is shown in Figure 2. In this design a long concrete weir acts as a control structure. Diversion is through a head regulator, consisting of a set of four 5 metre wide undershoot radial gates. A skimming weir and guide wall are designed to catch the heavier sediments and divert them into the sand excluder sluice. Vortex tubes on the apron upstream of the canal intercept smaller particles which have not been caught by the skimming weir and divert them to an outlet downstream of the sand excluder sluice gates. There is no control sluice on the vortex tubes which would operate continuously when the wadi is in flood. Canal design flow was $20 m^3/s$ and the sand excluder flow varied up to $14 m^3/s$ maximum.

For Wadi Dhamad, where peak flows were estimated to be much higher than for Wadi Jizan, and sediment loads greater, it was felt worthwhile to try to optimize the effectiveness of the vortex tube and scouring sluices and excluders under different conditions, and a series of model tests was carried out.

Model tests related to Wadi Surdud were developed to investigate the minimum head loss possible over the long diversion weir, consistent with effective and adequate operation of the scouring sluices sand excluders. Alternative means and materials for the construction of weirs, other than the traditional mass concrete or masonry designs, were also investigated. A schematic representation of the different aspects studied in the various tests is given in figure 3.

2.3.1 *Model testing of headworks.* Initially a series of tests was developed to investigate the performance of the origi-

Figure 3 Schematic diagram showing interrelationships of model testing for diversion weirs



nal headworks design. Observation trials followed to see how the headworks performance could be improved. From the trials, the most promising improvements to the layouts were tested to quantify their performance. These layout improvements were grouped as follows:

i. preliminary layout based on the design used in Wadi Jizan (figure 4);
ii. designs with a shaped guide pier but with canal headworks and vortex tube layout unaltered (figure 5); and
iii. as (ii) but with five vortex tubes instead of four discharging through two collector pipes.

Within these three blocks of tests the following parameters were varied:

i. the downstream conditions in the canal and sluice;
ii. the direction of approach of the flow (along the bank or from the general direction of the weir—the two extremes);
iii. the shape of the crest of the skimming weir (some five alternatives were tried)(figure 6); and
iv. the position of the main weir in relation to the headworks.

The model was set up to represent the whole of the canal intake, the sluice channel and a relatively small length (some 30 metres) of the main diversion weir. The weir length was kept short, as otherwise the scale of the model would be too small. Horizontal and vertical scales of 1:30 were selected. The resulting velocity scale was 1:5.48.

The material used for modelling the sediment was crushed bakelite, which with its relatively light weight and angularity simulated well the movement of sediment, and provided, as far as possible, hydraulic similarity in bed movement and suspension.

In general the conclusions of the tests indicated that the original design, though effective, was very dependent on the direction of approach of the flow. The effect of introducing the guide pier annd moving the weir crest upstream relative to the headworks was to stabilize the flow into the headworks. This gave considerable improvement in sediment exclusion. The tests indicated a reduction in the total sediment entering the canal from about 60 percent of that entering the headworks to about 15 percent when the direction of approach was generally from the weir. When the direction of approach was generally from the bank, the corresponding reduction was from 45 percent to 25 percent. None of the skimming weir options tried showed any significant advantage over the simple right angle type(shown in figure 6 (a)).

Setting the canal headgates back, including an extra vortex tube, and modifying the geometry of the collector pipe, considerably improved the performance of the vortex tube sand excluders but at the cost of increasing the percentage of canal flow discharged through them from 5 percent to 7.5 percent. With these improvements, and under conditions where the wadi flow did not exceed the main canal capacity, up to 50 percent of the sand load could be discharged down the wadi with only 7.5 percent of the flow.

In general, where flows were sufficient for operation of the scouring sluice, the sand exclusion was more effective if the canal headgates were slightly closed, resulting in an

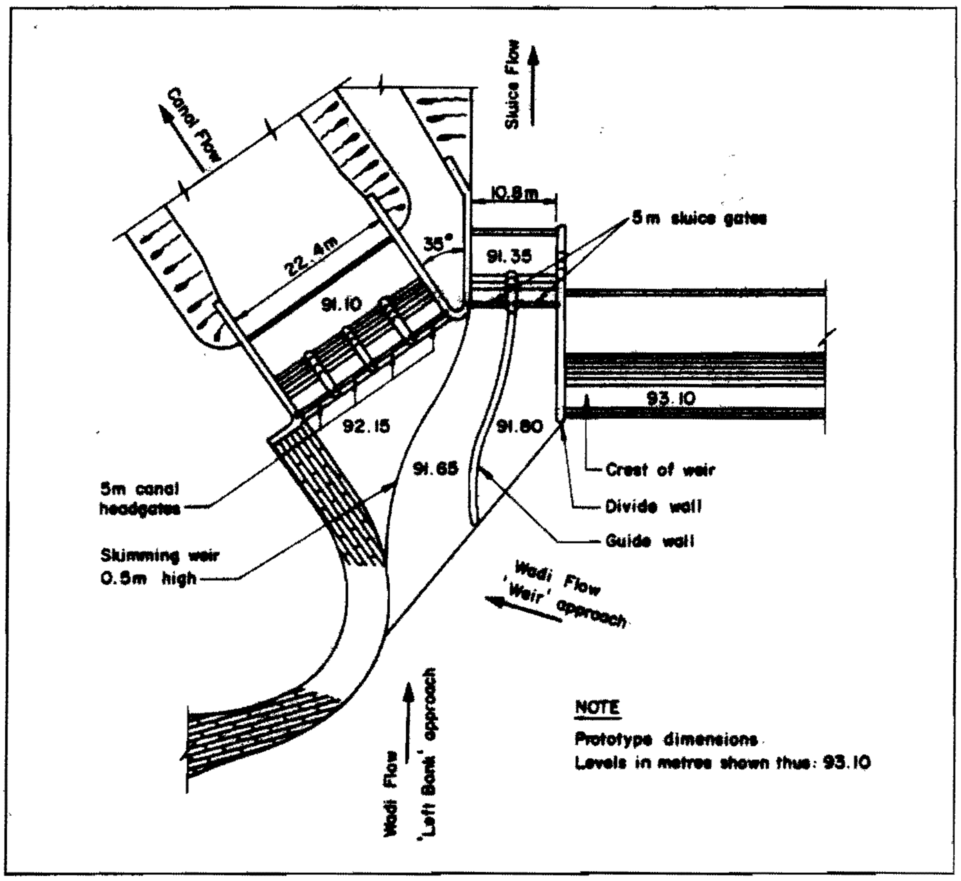


Figure 4 Preliminary layout of headworks for model tests

increased depth of water over the apron in front of the headgates. The extent of this is obviously limited by the height of the weir crest.

For Wadi Surdud, the same model was used to investigate the minimum height of the weir relative to the wadi level bed, in order to determine the lowest height (and cost) of structure consistent with effective sand exclusion. No vortex tube examination was included in these tests.

It was assumed that a guide pier design would be adopted and that other improvement deduced from the tests for Wadi Dhamad would be implemented. The test procedure was thus much simpler. The tests indicated that 35 percent of the canal flow was necessary for efficient sediment exclusion with the design layout chosen. To obtain this discharge, at least 0.5 metres of head should in practice be available for discharge capacities appropriate to canal flow of around 20 m^3/s.

Under high flow conditions, a second series of tests showed that the tailwater level would always need to be 0.2 metres below the main crest level and that 0.6 metres of head was required for effective sluicing and to maintain the sluice channel clear of sediment. This may be difficult to achieve under very high flows, and in such circumstances it may be necessary to close the canal offtake intermittently.

2.3.2 *Tests of weirs of different construction* Model tests were carried out on weirs of tipped and packed rock, gabion and pre-cast concrete block construction. Each of these types of weir was based on the principle of locally raising the bed of the wadi, and then protecting the slope back to the natural wadi gradient with a permeable armouring.

Rock weirs: Tipped rock was initially considered likely to prove the most suitable, and was thus the most thoroughly investigated. However, it emerged that selected packed rock was also a promising material, and although tests on it were limited by time available, useful results were obtained, leading to alternative outline designs for the weirs.

First, tests were carried out on models with solid beds of plywood fixed to the flume, on which the layers of stones were directly placed. The relative performance of different types of stones could be compared, with minimum delay in rebuilding a model after failure. Designs were then tested in a model with a sand bed, to simulate actual conditions in the wadi.

The rock was modelled using sub-angular crushed limestone aggregate, specific gravity 2.7, selected by the use of sieves. The underlayer between the rock-fill and the bed of the model was composed of natural gravel.

For a solid-bed model a typical run would begin by laying the underlayer of smaller stones on the fixed sloping board, and a measured amount of larger stones on top of them. The flume discharge would then be increased in steps of around 5 percent to 10 percent until the slope failed, and the recorded failure discharge taken as the average of the discharge at failure and the previous discharge. Between each increase in discharge the stones were carefully observed, and the discharge not increased until all stone movement (that is rolling down the slope rather than rocking or quivering in place) had ceased. At low discharge all such movement usually ceased within a few seconds of the discharge being increased.

Failure of the slope developed quite rapidly and was unmistakable. As the discharge was increased, stones

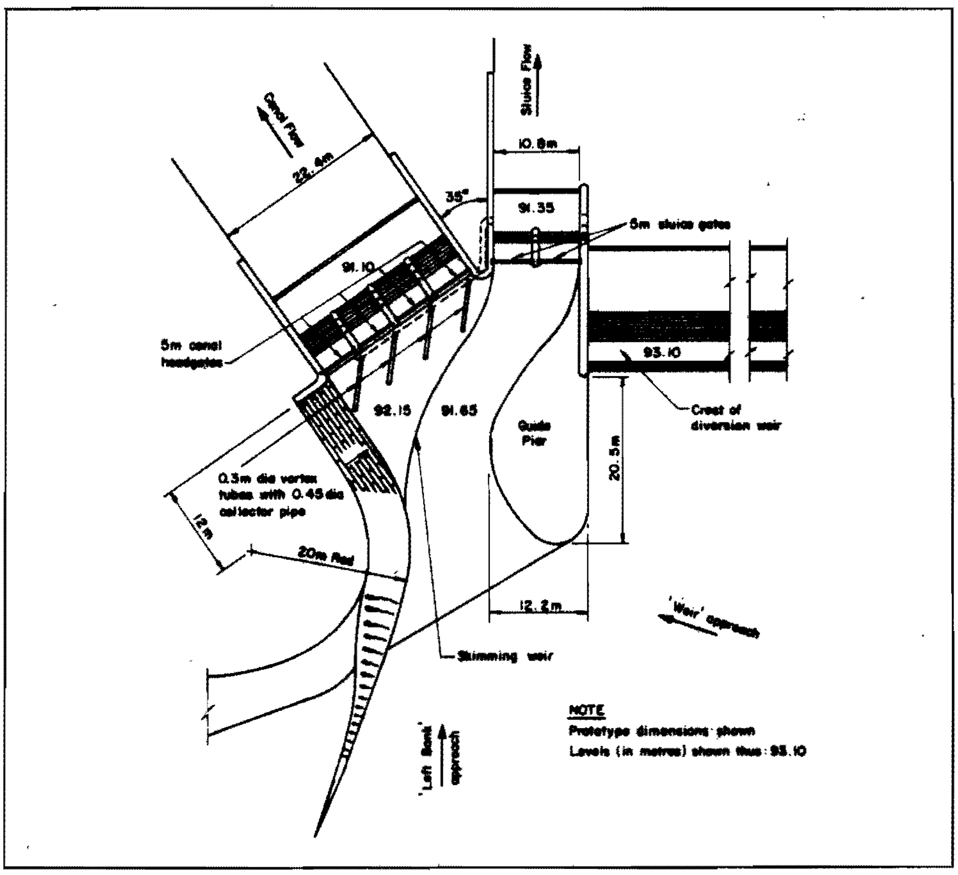


Figure 5 General layout of headworks for model tests

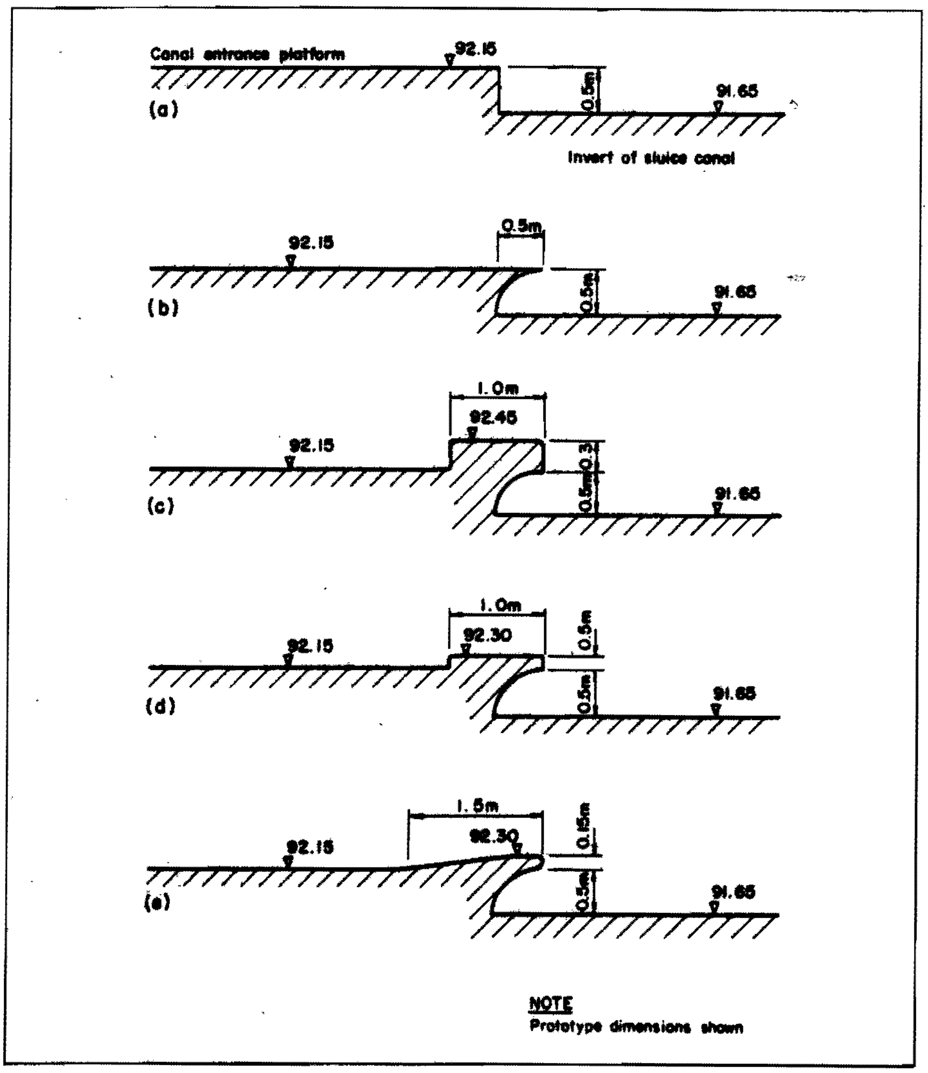


Figure 6 Skimming weir details for different models

would be removed and settle at random, resulting in a variation in the layer thickness. Ultimately the removal of stones from a thin patch, and their deposition immediately downstream on a thick patch, became progressive, unstoppable and accompanied by a strong surface wave.

For the tests on sand-bed models, the median sand size was 0.2 millimetres corresponding to a prototype sand size of about 0.7 millimetres, considerably finer than the coarser fractions of the prototype bed material on which the amount of scour in the prototype would depend. The fine sand was chosen for two reasons. First, if sand was washed out through the underlayer, this would show up better. Second, indication of deep scour was required in the models both upstream and downstream of the weir to examine its resistance to attack in this way. The depth of sand under the weir corresponded to about 10 metres in the prototype.

Tests were carried out under uniform flow and with a solid bed on single sized sieved stones sprinkled on stones three to six times smaller and at two different slopes (1:10 and 1:30). Other tests were made using tipped and packed rock under uniform flow and clearly indicated the potential increase in failure discharge which resulted from packing stones upright. For example, with a stone length-to-width ratio of not less than two, the failure discharge for the same weight of stones is ten times that for random tipped rock. The effects of underlayer size, slope and slope length were also investigated.

Tests also related minimum weight of rock per unit area to weir slope and length, and illustrated the advantage of achieving as short a slope as possible in the weir design to minimize the distance over which local acceleration of flow occurs.

The solid bed model tests indicated the most promising designs to try with a sand bed. Four models with sand beds were tested, two with abutments. These latter two were tested to failure. In all cases, the sand bed models behaved in a way predicted by the solid bed model tests, with failure values slightly higher than expected from the solid bed test results. It appeared that the sand bed had no significant effect on the failure discharge.

The stones in the underlayer of the model were about a quarter of the size of the rocks in the top layer with the bed sand free to move through it. This only happened immediately downstream of the crest membrane, where it was turned up to meet the flume sides, when the water was ponded at crest level upstream. There was no sign of movement of the sand bed beneath the weir, even at very high flows. This shows that the underlayer need not be designed as a filter. However, it should not be taken to indicate that no erosion of the sand by the seepage velocities in the underlayer would take place, if the stones in the underlayer were scaled up to prototype size, owing to the

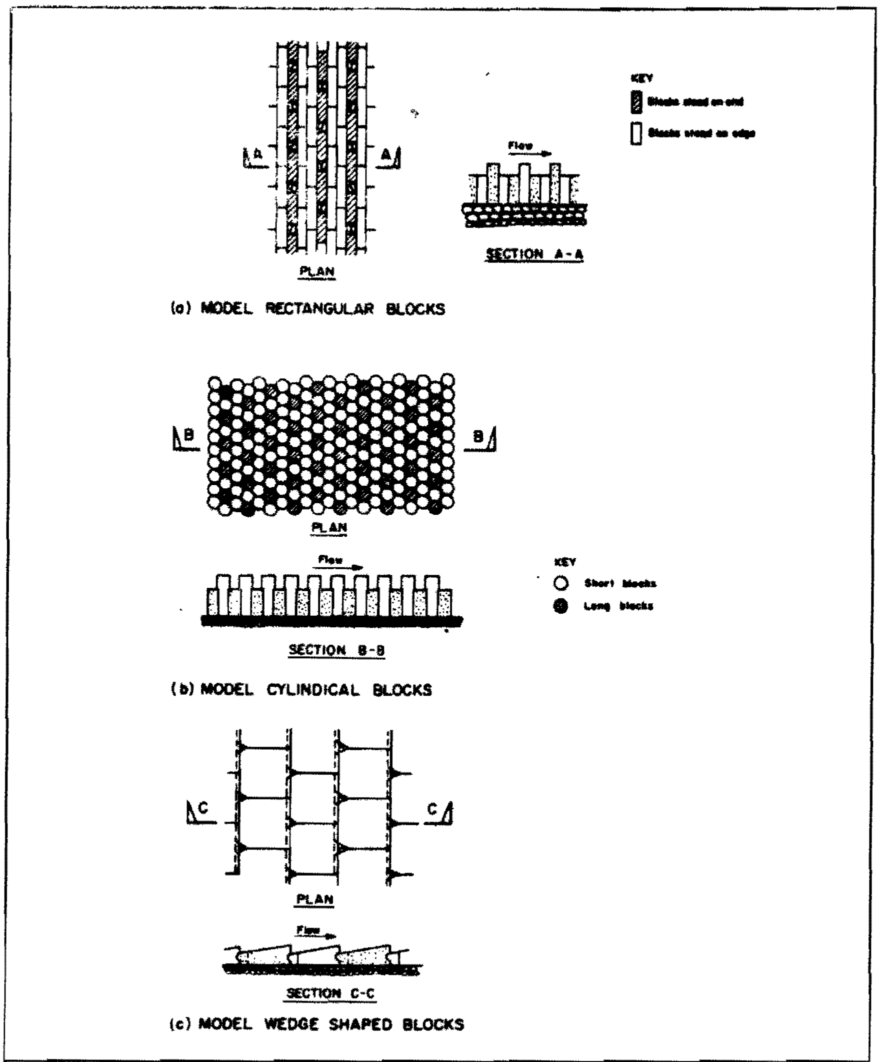


Figure 7 Model blocks for concrete block weirs

non-Froudian scaling of the problem.

Gabión mattress weirs: A series of tests on weirs constructed in a similar fashion but with gabion mattress protection were carried out, showing that the theoretical analysis to determine the point of failure by sliding was borne out in the model. The mattresses should be securely tied to each other to prevent one being flipped out of its position on the slope. The underlayer should be suitably graded to prevent it passing through the mattress. Other results concerning the underlayer, scour protection and membrane depth were in line with the tests on tipped rock weirs.

The tests did not attempt to provide any indication of the durability of the gabion material itself. Gabion structures, observed in rocky wadi beds in YAR and in eastern Africa, do appear to have very short lives, the wires apparently being cut by the moving rocks and stones in the bed material unless protected in some way.

Concrete Block Weirs: Following the successful rockfill and gabion tests, and recognizing the improved performance to be gained from a reduction in pressure under the top layer, a series of tests was carried out on models of pre-cast concrete blocks. Three shapes of block were used: rectangular, cylindrical and wedge shaped. Tests were planned with a view to replacing a rock face protection with blocks that could be easily mass-produced in areas where no suitable rock fill was available.

The blocks were modelled in aluminium which was the most practical material with an appropriate specific gravity. The test procedure was generally that used for the solid bed tests for the rock fill tests. The blocks were arranged on the slope as in Figure 7.

The tests indicated that the rectangular and cylindrical block weirs were unstable and failed at considerably lower flows than predicted by theory. The wedge shaped blocks appeared to perform very well but further testing and trials with different shapes and designs of wedges is required.

For weirs with slopes protected by wedge shaped blocks, the blocks would need to be sufficiently thick to withstand impact from wadi bed load and the underlayer would need to be graded to prevent material passing through the openings between the blocks.

2.3.3 *Outline design procedure for tipped rock weir*: The design procedure for a tipped rock weir can be summarized in outline as follows:

i. select location, height and width of weir;
ii. take into account the design flood and a safe intensity of discharge;
iii. calculate the tailwater level downstream of the weir

allowing for retrogression of the bed;

iv. select a downstream slope for the weir: generally 1 in 20 but possibly 1 in 10 under some circumstances;

v. calculate the draw-down curve on the weir slope using an appropriate rock size while taking account of the tailwater level; this enables the position of the hydraulic jump to be located and the stilling basin level and length to be determined;

vi. using the results of the model tests, select the size and weight per unit area of tipped rock layer to withstand the hydrodynamic forces on the weir slope; and

vii. select the underlayer size and thickness to suit the size of the top rock layer.

2.4 Design of wadi bank and flood protection works

The design approach used for Wadi Jizan concentrated on providing localized scour protection of the wadi bed and banks to ensure the integrity of the permanent diversion weirs and canal offtakes. There was initially no requirement for flood protection works because of the controlled flood releases. For the same reason, wadi bank erosion was not considered to be an important problem.

For Wadi Surdud, too, provision was made for localized scour protection of all permanent diversion structures as well as of the semi-permanent tipped rock deflectors proposed for the upper reaches of the wadi to enable diversion of the base flow. An outline geomorphological study was carried out to assess the overall stability of the wadi course and to identify the pattern of overbank flooding.

In the design of the proposed improvements to the spate irrigation system no attempt was made to confine the largest floods to the main wadi course. Calculations of the natural capacity of the wadi showed that the largest floods are contained within the main wadi channel only part way into the Tihama. This was confirmed by interviews with local people. The proposed diversion weirs were designed to pass only the bank-full capacity of the wadi channel. Bank and flood protection works, designed to minimize damage at higher flows, were located as indicated by the geomorphological study.

In the Wadi Dhamad, a more detailed geomorphological study was carried out to provide a background to the whole bank protection problem. It comprised the analysis of aerial photographs and a field survey. The stability of the wadi channel was considered at two levels:

i. that of the banks and bed of the wadi within its present alignment; and

ii. that of the present alignment of the wadi channel within the context of its long-term geomorphological record.

Important wadi channel features, including the bed and bank morphology, material types and vegetation were catalogued. This provided data for physical and mathematical models of the wadi set up to determine design parameters for the wadi-bank and flood protection works. In addition, a morphological definition of the natural limits of the wadi was obtained which was used to fix the alignment of flood protection works.

The design of protection works was based on a set of studies interacting with the geomorphological study. These comprised:

i. a soils survey to map and sample all the soils forming the banks and boundaries of the wadi channel;

ii. a physical and a mathematical model to provide design parameters and flood levels down the wadi; and

iii. a scour study to estimate maximum scour depth during the passage of a flood.

The overall stability of the wadi course was assessed by integrating a study of the wadi geomorphology with mathematical and physical modelling of flows down the wadi. The main advantage of this approach is that the evolutionary morphology of the wadi is taken into account in selecting areas for bank protection. It enabled identification of those areas which might result in a major change of the wadi course into a paleo-channel (scar of an old watercourse) during a large flood.

At a more detailed level, information from an engineering soils survey of the wadi bed and banks was combined with geomorphological data on the water-course and the results from hydraulic modelling to investigate the behaviour of the low-flow channel within the wadi bed. Control of the low-flow channel prevents it undercutting the wadi banks and is also important in ensuring the performance of canal headworks and scour sluices.

2.4.1 *Mathematical and physical modelling.* A mathematical model of Wadi Dhamad covering 22 kilometres of wadi downstream of the second weir site was set up using the ONDA suite developed by Halcrow. ONDA is based on the full hydrodynamic open-channel flow equations and allows simulation of watercourses and control structures. Cross sections of the wadi channel were included at approximately 600 metre intervals. The model included the diversion weirs proposed for the irrigation development.

There was insufficient measured flood data against which to calibrate the model. A range of roughness values was therefore derived from the dominant material types making up the wadi bed: the higher scale roughness values were used to obtain flood levels; and the lower scale roughness values gave velocity maxima for use in the scour calculations.

Physical modelling was found to be more appropriate for the steeper upper stretch of the wadi over the 4.5 kilometres between the first two diversion weir sites. This enabled the pattern of the high velocity streams within the wadi course to be studied. Of particular relevance to the scour study is the ratio between stream velocity along the wadi banks and the average cross-section velocity across the wadi. This ratio was found to be of the order of 1.2 in straight reaches and up to 1.4 on bends.

For the wadi downstream of the second weir site, these ratios were applied to the mean channel velocities obtained from the mathematical model in order to calculate scour depths and provide design paramaters for scour protection.

2.4.2 *Scour study.* Equilibrium scour depths adjacent to proposed protection works along the wadi banks were calculated from the factored average channel cross-section velocities obtained from the physical and mathematical models. The estimated sediment concentration at the flood peak was derived from regime considerations. Given the variation in average cross section velocity, calculated scour depths ranged from around 1 metre, in straight reaches with a relatively uniform wadi bed topography, to greater than 6 metres on the outside of bends in areas with a complex bed topography.

2.4.3 *Protection works design.* In a relatively steep fast flowing watercourse such as Wadi Dhamad, groynes and spurs as bank protection were considered inappropriate since they themselves would be subject to severe erosion and might direct high velocity streams at vulnerable points along the wadi banks. A permeable flexible revetment was preferred since it would be able to follow local settlement, minor erosion and undercutting. It could also be easily repaired. The general type of protection therefore proposed was a toe trench revetment with the trench taken down to below the anticipated scour depth.

3. Evaluation

Since the designs and layouts resulting from the model tests of diversion weirs and offtakes, and the bank protection studies, have not yet been implemented, full evaluation in the field is not possible. However some field experience has been gained from which certain conclusions can be drawn.

In the head works constructed at Wadi Jizan, it was found that the vortex tubes tended to block for all but the smallest sizes of sediments. Vortex tubes were therefore omitted from the model tests and design for Wadi Surdud. It is recommended that they only be considered downstream of the headworks on the main canal, where large particles have already been excluded or have settled into basins or other devices.

The authors are also aware of experience gained in the development of other wadis on the Tihama; in particular that of the Tihama Development Authority in YAR. Much of this experience has been gained since the model tests were undertaken and suggests some modifications to the design of the headworks. For example, the headwalls on the scouring sluices should be omitted and the types of gates used should be reviewed. This does not however detract from most of the general conclusions reached as a result of the model tests, which are summarized in the following section of this paper.

Regarding rock fill weirs, a tipped rock weir of a similar but not identical design to that tested for Wadi Surdud was constructed for the Amibara Irrigation Project in Ethiopia, on the perennial Awash River. The weir enables diversion of 13 m^3/s from the River Awash into a primary irrigation canal, and was designed to pass a maximum of 700 m^3/s under free flow. A model of the weir was tested to a prototype ultimate flow of 2 000 m^3/s. Since construction in 1979 the weir has withstood a flood of approximately 1 200 m^3/s, well in excess of its design flood.

4. Conclusions

The model testing programmes carried out for the design of the diversion structures for two wadis showed that considerable improvements in sediment exclusion performance could be made. Skimming weirs were effective but different crest designs showed little improvement over a simple right angle. It was not recommended that vortex tubes be used in headworks as they are liable to block, unless larger particles have been effectively excluded from the bed load.

The tests showed that significant improvements in the performance of the scouring sluices could be achieved by providing a curved converging channel at the approach to the canal headworks and locating the diversion weir towards the upstream end of the guide pier that lies between the weir and the scour sluice. To reinforce the local flow pattern and to guard against unfavourable curvature of the approach flow, protection of the wadi bank adjacent to the offtake should be continued sufficiently far upstream.

For efficient sediment exclusion from the canal intake using the arrangement tested, around 35 percent of the canal flow was required to pass through the scour sluice. In order to preserve the curvature effect of the sluice channel and to keep the scour sluice channel clear of sediment, at least 0.6 metres of head was required with the tailwater level at 0.2 metres below weir crest level. At very high flows this may be difficult to achieve and under such circumstances it may be necessary to close the canal offtake intermittently.

Weirs with a face protection of tipped rock appear to be cheaper in many instances than traditional concrete or masonry designs. Packed rock, using selected stones, offers considerable savings in material and may be attractive where labour costs are not too high.

Though gabion mattresses performed satisfactorily as a face protection, they can only be considered where the wadi bed material is fine enough not to damage the mesh of the gabions. Wedge-shaped (concrete) blocks performed well and could be an attractive alternative to tipped rock protection.

The design of wadi bank and flood protection works should be carried out within the context of both the short and long term behaviour of the wadi. This requires consideration of the stability of the wadi channel within its present alignment as well as the stability of the present alignment within the long term geomorphological record of the wadi. The usefulness of integrated studies involving mathematical and physical modelling has been demonstrated.