Diversion structures and protection works

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1. Introduction

Spate irrigation has been practised for many years in the Tihama Coastal Plain. In the Wadi Zabid area, in particular, there is an intricate system of water allocation based on well defined traditional water rights, (general location map, Figure 1). It is quite possible that the development of algebra, said to have originated at the University of Zabid, was a result of the necessity to achieve a well balanced water allocation schedule.

The traditional irrigation system was first applied along stretches of the wadis where diversion of the flow was relatively easy. In most wadis such reaches were found 10-15 km downstream of the apex of the alluvial fan, where the topography of the wadi bed and banks allowed easy construction of a deflector in the wadi bed and a canal to nearby fields. Gradually, the canals were enlarged and additional irrigation systems were installed at more difficult locations along the wadi. In more recent times the construction of deflectors and the excavation of canals has become more mechanized.

The availability of modern equipment enabled the farming community to reconstruct deflectors and earthen bunds (ogmas) faster and under more difficult conditions. However, the loss of valuable spate water after breaching, and high costs of maintenance, have provided an impetus to plan and install more permanent structures for the diversion of spate flows, although for the diversion of the low off-season perennial flows such expensive structures are not required.

The introduction of semi-permanent and permanent diversion structures increases the reliability of the supply of spate waters from the wadi, but will change the pattern of

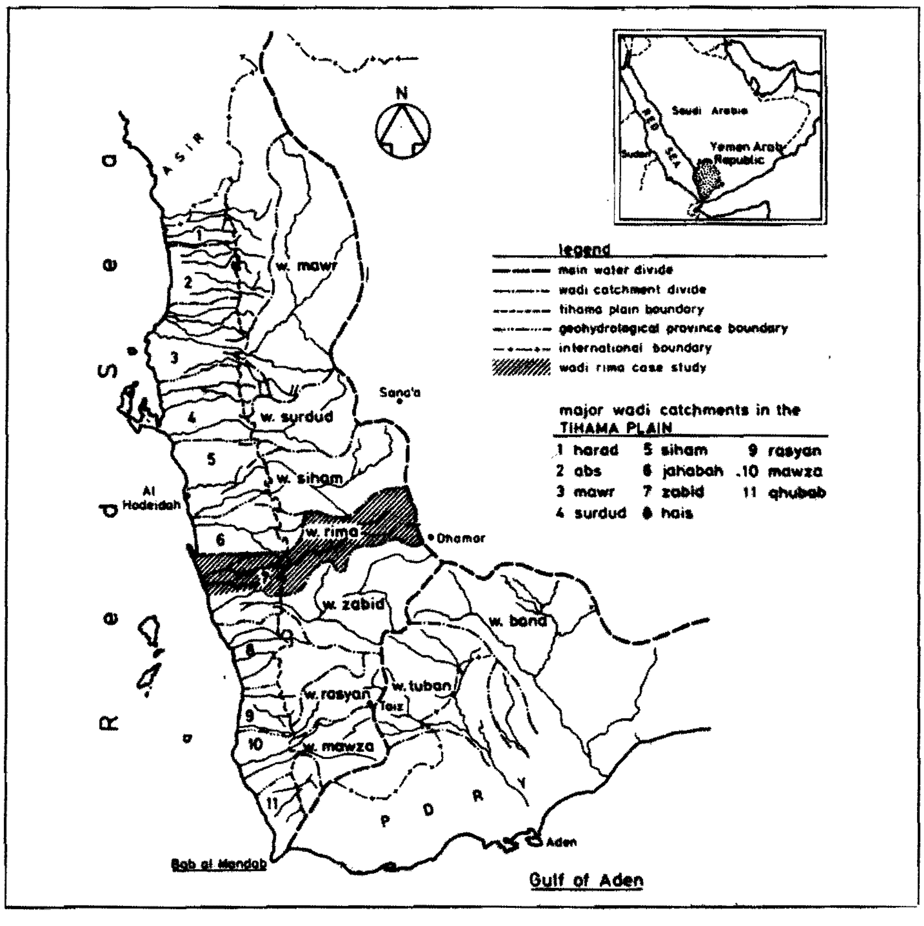


Figure 1 Major wadi catchments in the Tihama Plain

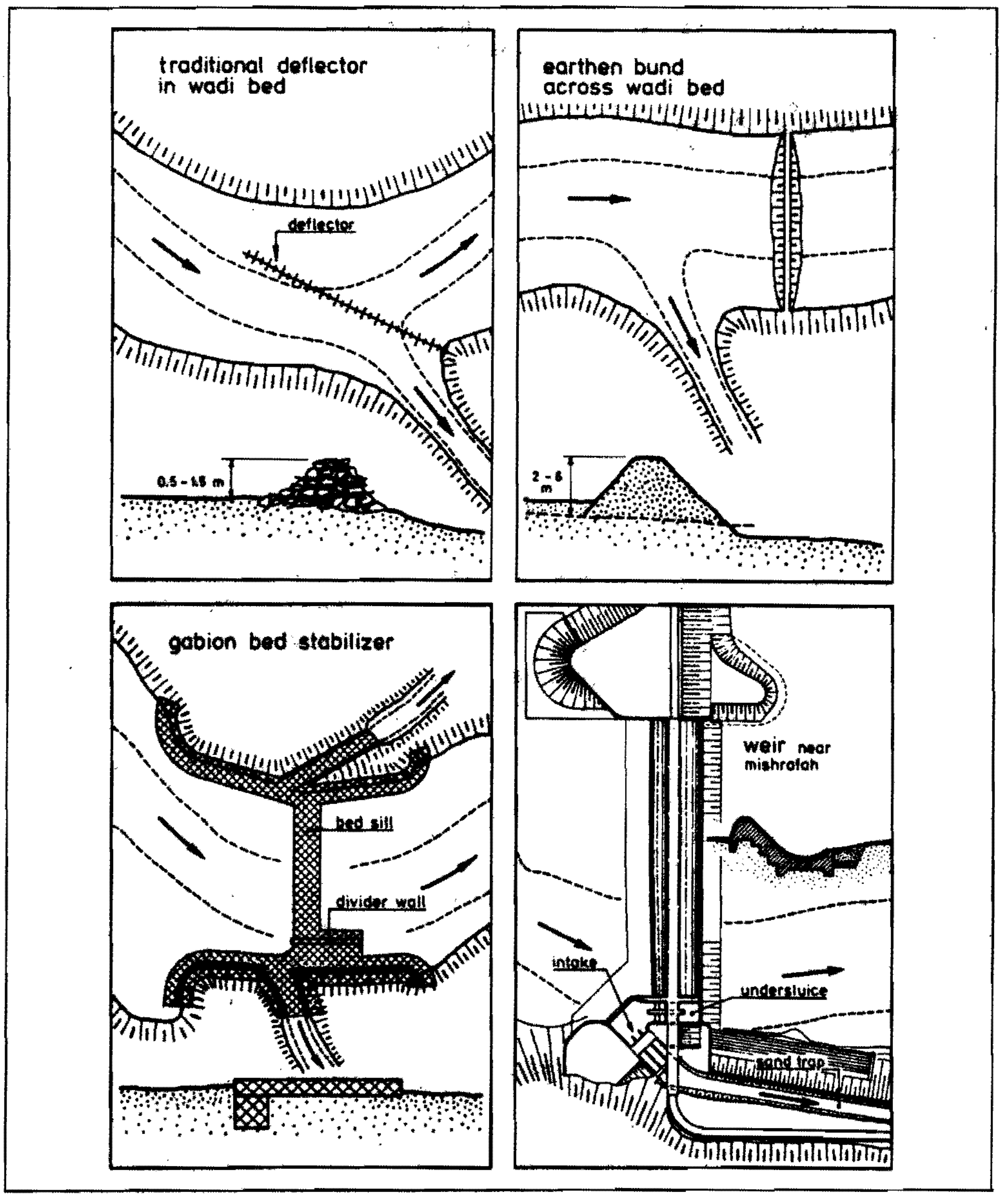


Figure 2 Diversion structures in Wadi Rima

water allocation. Since these changes may lead to social unrest, the new diversion works and canal system must be sufficiently flexible, so that they can follow the traditional water distribution as well as enabling a more equitable distribution of the precious spate waters.

2. Traditional diversion systems

The traditional diversion systems can be divided into the following categories:

i deflectors: low earthen bunds, protected with brushwood and stones from the wadi extend into the minor bed of the wadi at a acute angle to the bank (see figure 2); and

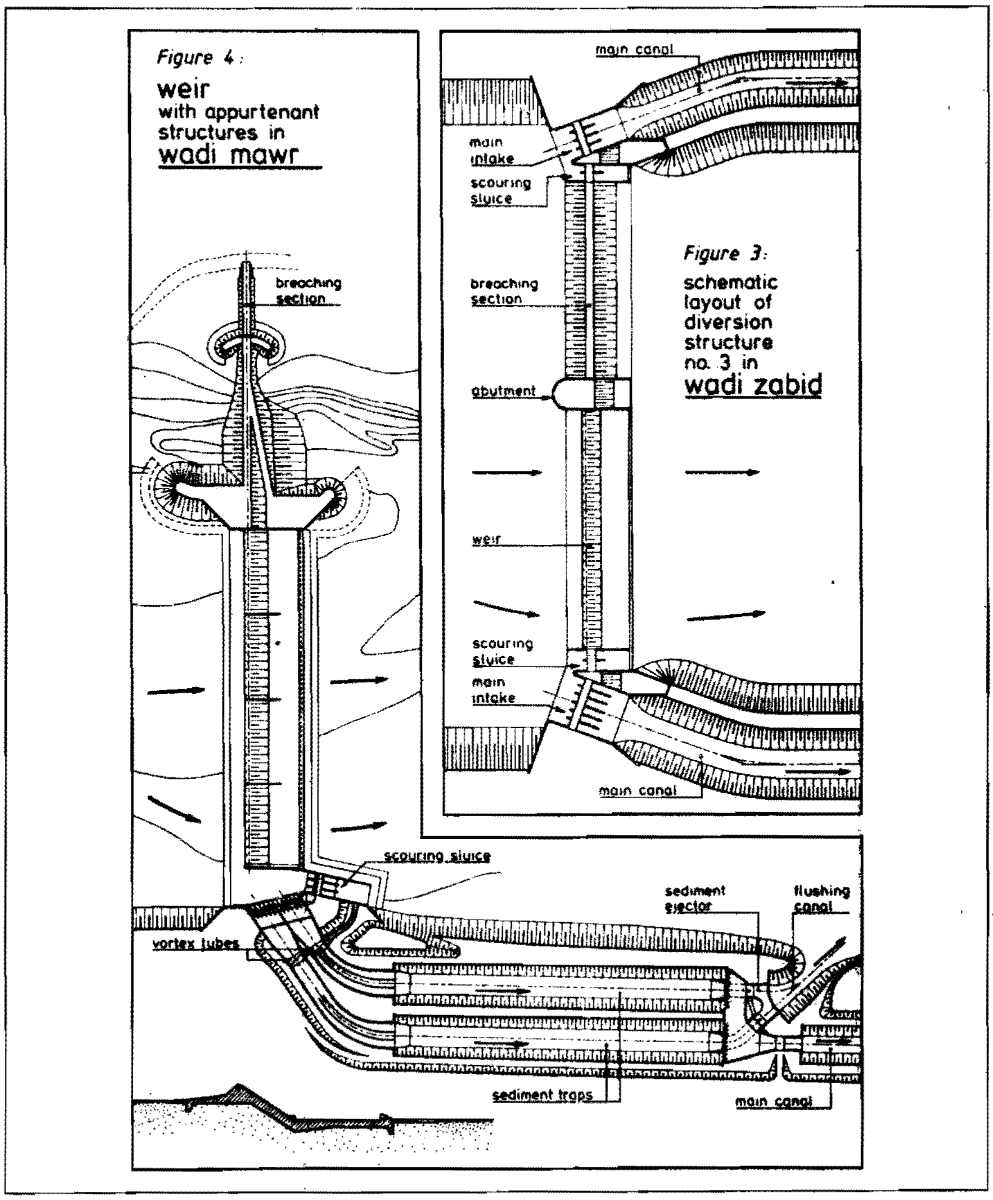
ii. high earthen bunds more or less at right angles to the wadi and extending over the its full width (see figure 2).

The flows into the canal systems are not controlled by gates or orifices built at the head of the canal; if required, side spillways are constructed in the canal bank while the capacity of the canals is usually attuned to the occasional large flows.

Deflectors are mainly constructed in the upper and middle reaches of the wadi, where even small spates have not yet lost their violence. The better protected deflectors may withstand small spates but will be damaged or washed away during the occasional heavy spate.

The farmers know from experience whether it is worthwhile constructing their deflector with a strong protection of brushwood and stones or not. Their decision depends on their dependence on the spate water, the reliability of the spates, the area commanded by the deflector and the risk of destruction of the deflector during normal spates. The tendency is to construct the stronger deflectors downstream where the farmers are more dependant on less reliable spateflow and the risk of destruction is less. As soon as all fields commanded by a deflector have been supplied with water from the wadi, or once the period of supply in accordance with the water law has ended, the deflector is left unrepaired until the next season or period.

In the middle and lower reaches of the wadi the farmers prefer to build relatively high earthen bunds, perpendicular to the wadi bed. Deflectors are less useful here because



Figures 3 and 4 Weir with appurtenant structures in Wadi Mawr, and diversion structure no 3 in Wadi Zabid

of the low frequency of spates, and the short duration of the actual flow. These bunds store the spate flow upstream until breached by overtopping. During ponding the farmers receive large quantities of water in a very short period. After breaching, the stored water flows to the next bund and is temporarily stored again. If a large spate occurs, a number of bunds are washed away and systems further downstream will receive water.

Spates only reach the Red Sea after extreme rainfall in the mountains. These devastating floods not only cause loss of life but also completely sweep away all deflectors and bunds and cause damage in the upper part of the canal systems.

3. Planning and design of wadi diversion systems in the Tihama Coastal Plain

So far, wadi diversion systems have been designed and constructed in three wadis: Wadi Zabid (1979), Wadi Rima (1983) and Wadi Mawr (1987); a diversion system has been planned and designed at feasibility level for Wadi Rasyan (1983) and Wadi Siham (1985). The planning and designs for these systems were executed by different Consultants. Different concepts have been developed and certain knowledge and experience gained in one wadi area have not been applied to the full benefit of the next wadi.

The diversion structures and flood protection works had to be designed to cater for the exceptional flow conditions that occur after very local thunderstorms in the mountain range. Wadi flows can increase from base flow (up to a few m^3/s) to more than 1000 m^3/s in a matter of 10-30 minutes. The very high discharges are only maintained for a short period, 5-60 minutes, with the flood recessions lasting 4-6 hours. Occasionally multi-peaked spates occur with the individual peaks 0-2 hours apart.

The slope of the wadis is steep, up to 1 percent near the apex of the alluvial fan of the wadi, resulting in high water velocities and an exceptionally high sediment load, often 8 percent by weight. The size range of the sediment is also large, ranging from silt to cobbles and in some cases even boulders of up to 1 m in diameter but the distribution is different to that in rivers with a smaller bedslope, usually that part of the load with grain sizes less than 0.062 mm.

However analysis of wadi sediment suggests that fractions up to 0.200 mm have to be considered as washload.

The quantity of washload in transport is mostly determined by the availability in the catchment as opposed to local hydraulic conditions. This means that the fine sand fractions cannot be removed at the headworks, even with a suitable layout of the intake, but will pass into the canal system. In the canal sections with a much smaller bed slope, the sand fractions will change from washload to (suspended) bed load. During spates large quantities of trash are carried by the water which have to be taken into account when designing certain components of the diversion structure.

Spates with peak discharges in the order of 50-100 m^3/s destroy the weak deflectors and carry the floating materials and trash in the wadi bed, further downstream. Peak discharges, of 100 m^3/s and more, progressively sweep the wadi bed and banks clear of any floating materials, thus destroying all dèflectors in the wadi bed. The really big spates erode the wadi banks and uproot vegetation like trees, bushes, clumps of reed and grasses growing in the wadi bed and carry floating materials from the catchment.

The diversion structures in the different wadis and of the Tihama plain are based on different design concepts. Schematic layouts of the headworks in the three wadis that have been developed so far, are presented in figures 2, 3 and 4.

For Wadi Zabid the existing deflectors have been included as far as possible and each combination of individual canals receives water from its own headworks in the wadi. The flow from the headworks is divided at the division structures in the main canals. The system consists of five concrete diversion dams with nine head regulators, serving 16 canals allowing the available spate flows to be allocated in close accordance with the traditional water law. The diversion structures do not have adequate sediment removal works; a vortex tube has been installed at the most upstream diversion structure only.

The layout of the intake/scour sluice is not suitable for the exclusion of sediment during spates; for the wide intakes the effect of the sluice is very limited. There is no provision to remove sediment from the canal system by hydraulic flushing; a schematic layout of structure no. 3 of the Wadi Zabid project is presented in Figure 3.

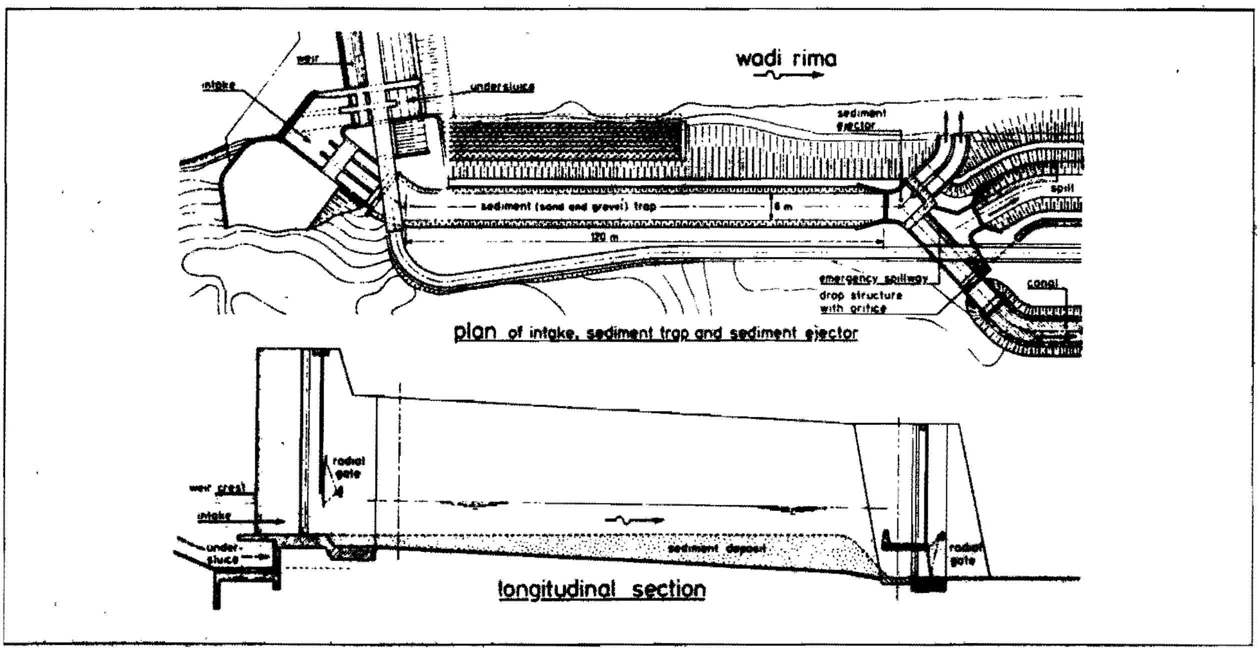
In the preliminary planning stage for the development of Wadi Rima, the system selected comprised seven diversion structures constructed with gabions, serving 15 traditional canals. Becasue of technical considerations and an economic analysis, only one diversion structure, combined with a syphon across the wadi, has been built in Wadi Rima. The existing canals have been supplied from main supply canals running parallel to the wadi and a small sand and gravel trap, with an ejector to flush out the sediment deposits, has been included in the system just downstream of the head regulator (See figures 2, 5 and 6).

A water allocation plan was prepared, taking into account traditional water distribution, while aiming at an equitable allocation of the scarce resources. In actual practice the new system has caused a considerable change in the division of flows; the original water allocation plan will be adjusted in 1988 on the basis of three years of operation of the system and monitoring of the flows.

A system with only one diversion structure with one intake was also chosen for the development of Wadi Mawr; the capacity of the main canal at the headworks being about 42 m^3/s (figure 4). The main supply canals run parallel to the wadi and supply about 30 existing primary canals. A syphon, with a capacity of 22.5 m^3/s conveys part of the flow across the wadi at a distance of some 4 km downstream of the headworks.

From the experience gained in Wadi Zabid and Wadi Rima, the sediment removal works in Wadi Mawr have been designed to cope with enormous quantities of sediment carried by the spate waters (fig 4). The crest of the

Figure 5 Wadi Rima, longitudinal section



weir slopes towards the intake, to direct the minor bed of the wadi towards it. To make optimum use of the short spates, the time required for hydraulic flushing is minimized by a twin settling basin downstream of the intake. During spates, one basin is in operation, while the other is being flushed with part of the spate flow, to remove the sediment deposits. Vortex tubes have been installed in both basins to remove gravel and cobbles entering the intake, and will only be operated when sufficient flow is available.

For Wadi Rasyan, a diversion system has been designed at feasibility level. The diversion structure is in a narrow gorge of the wadi; the proposed dam height is about 12 m above the wadi bed to avoid deep excavation for the upper part of the canal. This has been given a low priority, and the definite development of a modern irrigation system is not foreseen in the near future.

The irrigation system for Wadi Siham is still in the planning stage. Here two diversion structures have been planned, again with the intake on one bank of the wadi and a syphon to convey flow to the other bank at some distance downstream. The second diversion structure is located at a "natural" damsite, where a large traditional deflector has already been in operation for a long time. Each diversion structure has been provided with sediment removal works, including facilities for hydraulic flushing.

4. Case Study: Wadi Rima diversion works

4.1 Surveys and site investigations

For the planning and design of the Wadi Rima diversion and protection works the following surveys have been done:

- ❑ topographical surveys of the reach of the wadi with potential weir and syphon sites;
- ❑ topographical surveys of sections of the wadi with bank erosion problems;
- ❑ surveys of alternative canal alignments in relation to planning of the diversion works and the wadi crossing; and
- ❑ geotechnical investigation of the wadi bed at the proposed weir site.

The bearing capacity of the sand/gravel mixture of the wadi bed is adequate, unless layers of soft silt or clay are present at some depth. The permeability of the coarse bed materials has to be investigated at the bottom side of the weir in order to estimate the seepage losses at the structure.

4.2 Design approach

In contrast to the Wadi Zabid development, which includes the construction of five diversion structures with nine headworks, the Wadi Rima irrigation system consists of only one diversion structure with one headworks and a syphon to convey part of the diverted flow across the wadi. The original design included at least six diversion structures consisting of gabion bed stabilisers; however the uncertainties with regard to the performance, and the maintenance requirements in relation to the cost of construction, made the Tihama Development Authority look for other more conventional solutions for wadi flow diversion.

From regular inspection of one of the trial structures in Wadi Rima it appeared that the structure had withstood several years of spate flow, sustaining only limited damage even without any repairs. As bank protection, this structure is still functional seven years later. Damages are limited and could easily be repaired. The second structure, further upstream in a relatively narrow section, failed during the first two spate seasons.

The results of the model tests on the water diversion were not confirmed in the field. It is doubtful whether more control of the minor bed would be possible even with an improved layout of the structure. Moreover simulation in a hydraulic model of the movements of the wadi bed, with its large range of bed material sizes, its unstable erodable banks upstream of the structure and the violent character of the spate peaks with extreme sediment transport capacities, cannot be very reliable. In actual practice, gabion bed stabilisers will be more efficient than the traditional deflectors but local intervention will still be required to ensure efficient water diversion.

From experience at the diversion structures of Wadi Zabid, it is obvious that even with proper operation of the gated sluiceways, huge quantities of sediment enter the canal system. Therefore the ungated scour channel of the gabion structure is expected to be very inefficient as a sediment excluder. As a result the bottom of the canal will be raised quite rapidly by sediment deposits and diversion of flow will be hampered. Sediment extraction will require sufficient head, which will be not be available at the headworks, but at some distance downstream.

The traditional deflectors are much more flexible in relation to changing canal levels; moreover the volumes of sediment entering the canal system will be much less because of the early breaching of the deflector in the case of a medium or large spate.

Bearing in mind the problems with water diversion at the Zabid structures, the following approach has been adopted for the final design of the weir and headworks of the Wadi Rima diversion works:

- ❑ ensure that the design capacity is maintained throughout a spate
- ❑ ensure that the minor wadi channel always passes the intake
- ❑ prevent coarse sediment particles (coarse sand, gravel and cobbles) from entering the intake
- ❑ prevent floating trash from entering the intake
- ❑ remove sand and gravel still entering the intake
- ❑ ensure that the maximum discharge entering the canal will not surpass the design capacity by more than 10-20 percent even if the gates are not operated in time during a spate.

4.3 Diversion works

The weir across the wadi has a length of about 70 m. The crest is cylindrically shaped with a radius of 2.25 m and the stilling basin is of the submerged bucket type, with a radius 4.5 m (fig 2). The crest slopes towards the intake, to which it directs the low flow channel. The difference in crest level between the left and right sides is 1 m. Combined with the influence of the scouring sluice, this difference appears to be sufficient to maintain the minor bed at the intake.

The solid bucket has functioned properly so far, but only in the absence of extreme spates. Although the deepest scour holes formed downstream of the bucket during the peak of the spate it will be partially filled again during the recession; no evidence has been noticed of dangerously deep holes.

Because of the sloping crest, the discharges across the weir will be greatest close to the scouring sluice and decrease towards the left bank. This will induce three-dimensional flow and may result in relatively deep scour in this area. However no influence of the sloping crest on the scouring pattern was observed during model investigations at the Technical University of Delft. The cut-off wall of the bucket is about 5 m below its lip and the scour holes will always be formed at some distance from the lip. The coarse bed material, cobbles and stones tend to armour the bed and will reduce the scour hole depth.

The weir was constructed of mass concrete, protected on the outside against the abrasive action of coarse sediment moving in the flow, by hewn river stones. The necessity of such a protection was quite obvious at the upstream diversion structures in Wadi Zabid where the downstream face of the weir, the chute blocks and in particular the bottom of the sluiceways, all made of concrete, were severely damaged after only a few years of operation.

So far the protection has required very little maintenance or repairs; a few stones that broke loose during a spate had to be replaced. However the stones and joints of the bottom of the scouring sluice already show considerable abrasion and will have to be replaced or repaired much earlier than at the weir. It is obvious that the scouring sluice is the most vulnerable part. High concentrations of gravel and stones will pass whenever the scouring sluice is operated during a spate. The upstream weirs in Wadi Zabid have now got stone protection.

4.4 Head regulator and sand excluder

The headregulator is one of the sensitive and vulnerable components of the diversion system, (figs. 5 and 6), and has to perform the following functions:

- ❑ limiting the diverted flow to a maximum;
- ❑ preventing of sediment transported by the spate flow from entering the canal system; and
- ❑ preventing large size drift or trash from entering the canal system.

The flashy and unreliable character of the spate flow requires special attention in the design of regulators, and clear guidelines for operators on setting and manipulating the gates to regulate the flow into the system. Very often it may be apparent that a spate is coming, after thunderstorms in the catchment. However, the spates may not materialise for days or even weeks and then, arrive in the middle of the night. Although the gate operators are supposed to be at the headworks at all times, a floodwarning system is needed to alert the staff in the field when a spate is imminent. Such a system is planned for Wadi Rima.

Since waterlevel and discharge change very rapidly in the wadi, the movement of the gates should be relatively fast and the operation easy. It is advisable to install a gate hoisting system that can be operated both manually and mechanically/electrically.

The headworks were located at the end of an outer bend in Wadi Rima, in order to take advantage of the helical flow pattern that sweeps the bottom layers, containing relatively high concentrations of coarse sediment, away from the intake. In actual practice the effect appears to be limited, mainly because of the shallowness of the water, even during sizeable spates, combined with the high turbulence of the flow and the unstable, meandering wadi bed upstream.

The sediment excluder installed at the headworks is of the undersluice type; the bottom layers of the spate wadi flow, carrying the coarser bedload, will be passed through the culverts of the undersluice to the wadi bed downstream of the weir. Two radial gates have been installed to regulate the flow through the undersluice. The original set-up included a float in a chamber connected to the upstream waterlevel that would open the radial gates as soon as the flow overtopped the weir.

In theory this system was to ensure a most efficient exclusion of coarse sediment; in practice the system failed because trash, in combination with fine sediment, very quickly choked the connection by which the chamber was filled. Efficient sediment exclusion can now only be ensured by attentive manual operation of the undersluice gates.

Downstream of the head-regulator gates a small sand and gravel trap has been constructed. This trap is about 120 m long, a bottom width of 6 m, and a bed slope of about 1 percent. Only about 1000 m^3/s of sediment can be stored in the trap, and have to be removed by regular flushing.

The trap, in combination with a sediment ejector, functions effectively provided that the operation rules are strictly adhered to. The gates of the ejector structure must be opened when sufficient flow is available to remove the bottom layers at the end of the trap and to flush the basin as soon as it is filled to capacity.

Hydraulic flushing of the sediments from the trap should be accomplished in a very short period to limit the loss of valuable spate water to a minimum. About half an hour is required at a flow rate of 15 m^3/s, and the ejector gates opened and closed at maximum speed. The velocities in the trap are sufficient to remove gravel and even cobbles deposited in the basin. In order to generate these high velocities the head difference between the pool upstream of the weir, and the water level downstream of the ejector, is substantial. Without this head, efficient and fast flushing would not be possible, resulting in a higher annual budget for canal maintenance.

Most of the coarse sand and larger fractions settle in the trap; smaller fractions are transported through the canal system to the fields. The design velocities of the Wadi Rima main canal are sufficient to prevent the sediment deposits found in the less steep canals of Wadi Zabid.

A floating boom has been installed in front of the intake

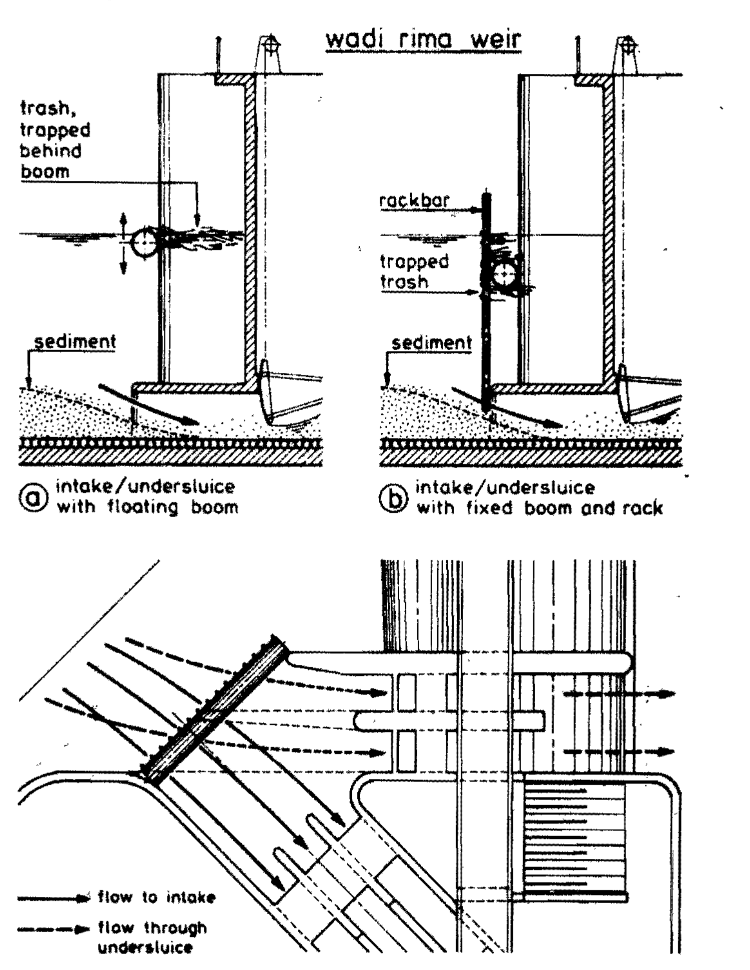


Figure 6 Intake/undersluice, Wadi Rima weir

to deflect trash floating on the water towards the weir section of the structure as shown in figure 6. The boom has a diameter of 1.20 m and is submerged to 70 percent of its diameter. During small spates the boom functioned satisfactorily, most of the floating trash was carried over the crest of the weir. However during medium spates the water surface becomes very wavy and and the flow pattern irregular; part of the flow entering the area in front of the intake along the abutment flows back along the pier of the scouring sluice. As a result, unexpectedly large quantities accumulate in front of the intake and may block it completely, as happened once during a medium-size spate occurring early in the season.

To remedy this the boom has been fixed to the structure as support for a trash rack in front of the gates. Originally the bars, consisting of standard water supply pipes with a dimeter of 0.1 m, were spaced at 0.60 m. However, with these spaces, the rack was blocked very rapidly in the early stages of the spates. Later, the spacing was increased to 1.20 m. This has reduced the risk of choking, but clearing the racks after spates is difficult because part of the trash is wrapped around the bars and is mixed with silt.

4.5 Wadi crossing

To irrigate the lands on the south bank of Wadi Rima, an inverted syphon was constructed in the bottom of the wadi. The syphon consists of two barrels, length 420 m, diameter 1.20 m; the available head is about 16 m. The maximum velocity in the pipes at the design capacity of 10 m^3/s is about 4 m/s. The cover on the pipes in the wadi bed is about 4 m under average bed level conditions.

A gabion spur was built on the right bank of the wadi to prevent erosion. To stop trash entering the syphon pipes, racks with a downward slope were placed on the top of the inlet chamber and a small gravel trap was included just upstream of the inlet chamber. The outlet of the syphon is a vertical shaft to facilitate draining of the pipes for clearing and maintenance works.

So far the syphon has operated satisfactorily, although at the beginning there were problems with trash. It was expected that the trash would slide down the sloping rack, which would be more or less self-cleaning. However the slope of the rack and the shape and distance of the rackbars in combination with the quantity, type and size of the trash at the syphon, were not adequate to ensure uninterrupted flow through the syphon. Because of the height of the syphon inlet above groundlevel, the risk of the racks choking should be minimal. Moreover, precious spate flow should not be lost because of choked trash racks.

During the first few spates, excessive effort was required to keep the racks clean. The racks now have a steeper slope with a larger distance between the individual bars. Now, more of the small size trash, that is easily transported, passes through the syphon pipes. Larger trash is less common, and readily slides down the slope of the racks. The maintenence efforts are now quite acceptable.

Air vents had been included in the original design. However, since such sensitive components would easily be blocked by sediment/trash, they were not installed during construction. Instead the intake chamber was enlarged in the hope of ensuring that most of the air escaped before the water entered the syphon pipes.

In actual practice, large quantities of trapped air were swept into the pipes and large air cushions moved through the pipes to escape at the downstream shaft. These air cushions caused irregular flow through the pipes and water hammer effects, such as sudden outspurts and undesirable pneumatic shocks.

After the old type racks had been replaced, the air trapped in the intake chamber was greatly reduced, curing the irregular flow and sudden outspurts. Although the cause of the original problems has not been analysed in detail, it must be assumed that the distances between the bars in the original racks produced intensive spraying of the water below the racks, trapping air. The shape and spacing of the new bars causes the water to fall in sheets, which apparently minimises the problems of air cushions in the pipes.

4.6 Protection works

Protective works have been installed at a number of locations in Wadi Rima, mainly to prevent wadi bank erosion, where structures (sediment ejector and syphon) have to be protected, and where there is a threat to valuable land. In addition two experimental bed sills, fabricated from gabions, have been built to allow assessment of the durability of gabion irrigation diversion structures (figs 2 and 7).

The bank protection in Wadi Rima consisted of either gabion spurs, a continuous gabion protection, or a combination of both. The scour apron of gabion mattresses is essential to ensure durability of the structure as shown in figure 7. At a section of gabion bank protection, without the scour apron and constructed downstream of the weir, bed erosion and scouring caused the protection to collapse. A flexible toe protection must be included so that any deep local scour can be followed by the flexible gabion mattresses, until a stable depth has been reached.

All other bank protection works have functioned well so far, the wadi banks were stable and maintenance was very limited. The majority of the gabions are still in very good condition following three years of exposure to spate flow conditions; in some sections only, the stonefill has slumped but this does not reduce the effectiveness of the protection.

Although some of the wires of the mattresses failed due to boulder impact or abrasion, the woven gabions with 3 mm wire diameter appear to offer sufficient durabilty and flexibility. However, really large spate peaks have not been experienced in recent years, so the new protective works have not been tested to their limits yet, therefore it is not possible to make a reliable estimate of the lifetime of gabion protection works, nor to estimate the maintenance cost with reasonable accuracy.

The experimental structures have been in place for about seven years now, without regular maintenance and repairs. Judged from the point of view of bank protection, the main structure has performed very well, even during some major spates.

5. Evaluation of wadi diversion and protection works

In evaluating the wadi diversion structures and comparing them with traditional ways and means, the following factors have to be considered:

- efficiency of the diversion works;
- impact on water distribution;
- risk of failure of a diversion structure or wadi crossing;
- availability of well-trained staff to operate the system; and
- cost.

5.1 Diversion efficiency

To enable estimation of the incremental benefits from the installation of modern diversion works as a replacement for traditional deflectors, estimates have to be made of the efficiency of diversion. This can be defined as the percentage of the total annual flow in the wadi, at the apex of the alluvial fan, that is diverted at the new headworks into the canal system downstream of sediment removal works, and of all traditional deflectors and bunds still in operation along the wadi. For the traditional system, the efficiency is defined as percentage of the total flow that is diverted by all deflectors and bunds downstream of the same point in the wadi.

Losses at emergency spillways (constructed close to the diversion points to avoid overloading of the canal system) have to be taken into account in both cases. Although it may be possible to estimate the efficiency of the modern diversion structures with reasonable accuracy, so far diversion efficiencies of the traditional deflectors in the Tihama are mere guesswork. They are not only dependent on natural phenomema like flood patterns, flood hydrographs, flood attenuation and infiltration into the wadi bed, but also on the capability of the farming community to (re)build and maintain their deflectors and bunds.

Flows in traditional canals are being measured in the framework of the on-going Tihama Basin Water Resources Study. The diversion efficiency estimated during the feasibility study for the Wadi Rima Irrigation System was 80 percent for the combination of the new weir and operational deflectors/bunds and 60 percent for the traditional diversion system.

More recent calculations for the preparation of a water allocation plan indicate somewhat lower efficiencies:

traditional system before project	55-60 percent
with project	70-75 percent
with project, including contribution of existing deflectors downstream of weir	75-80 percent.

5.2 Impact on water distribution

The modern diversion works have a great influence on the distribution of the base flows as well as the spate flows.

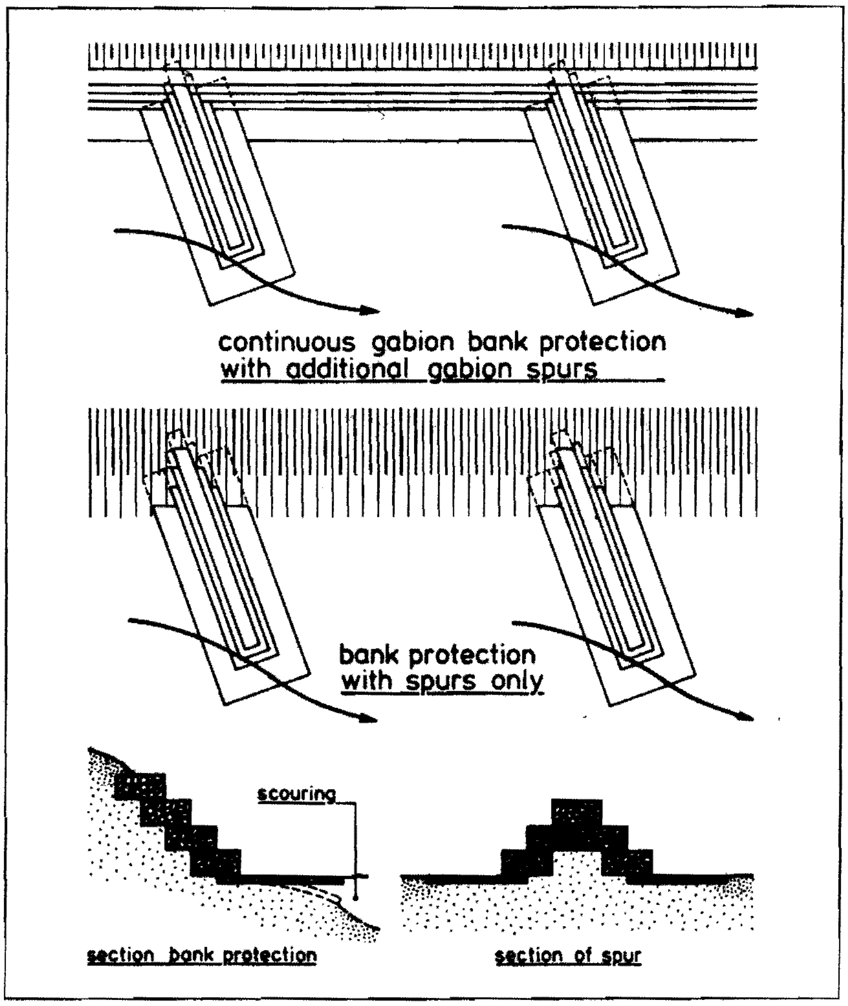


Figure 7 River bank protection

Because of the shape of most spate hydrographs, the volume of water in the small and medium flood peaks passing the weir will be much less than the volume of water arriving at the diversion structure; for very large floods, however, the difference will be small. Therefore the spate waters will always be available in the canal system connected to the weir; individual farmers will receive water according to the water allocation plan established for the command area of the diversion structure.

As soon as the flow recedes below the design discharge of the system, the flow into the wadi bed downstream stops completely. As a result, downstream deflectors cannot benefit as they used to from the easy-to-divert recession flows. Traditional deflectors in the upper part of the wadi tend to be destroyed during medium and bigger spates, which, in the past, ensured a natural distribution of spate flow; further downstream, however, less spate flow will be received.

The traditional water rights were established on the basis of this "natural" division of flow along the wadi. The new permanent structures will continue to divert water throughout a spate, which will disturb the existing pattern of water availability at the traditional deflectors further downstream in the wadi.

5.3 Risk of failure

The hydraulic design of a diversion structure is based on a spate peak with a certain frequency of occurrence. Usually, a discharge occurring on the average once in fifty or a hundred years is selected for use in the design of river diversion works. However, data on spate hydrology are still scarce and not very reliable, therefore analysis of the frequency distribution is difficult and the results are seldom reliable.

Occasionally calamitous floods occur in one or more wadis as a result of extreme rainfall. To decrease the risk of failure in such events, it is advisable to include a low cost breaching section in the design of the wadi diversion structures. The breaching section can be built with wadi bed material, and the toplevel based on the premise that the embankment will be overtopped by a flood with a return period of 10-15 years, which is quite acceptable to the authorities. The loose part of the embankment will be washed away in a short time and a large part of the spate peak will pass through the gap.

This system has been used in diversion structures Nos. 1, 2 and 3 of the Wadi Zabid Irrigation System. A few floods with peaks exceeding the design discharge have occurred since the system became operational in 1978/1979 and the breaching sections were washed away. The concrete weirs and abutments sustained only minor damage and the embankment of the breaching section could be repaired within a few days after the spate had receded.

Other phenomena influencing the risk of failure of a system are aggradation or degradation of the wadi bed. Aggradation, or raising of the bed levels, will hamper removal of sediment from the sandtrap and, in very bad cases, can result in operational failure. Severe aggradation can be caused by debris flow, a mixture of water, fine sediments and stones. Large quantities of sediment will be dumped where the wadi bed becomes wider and its bed slope less steep, hampering the operation of a diversion structure in this reach of the wadi; the upstream control in the wadi bed may be lost and it will become very hard to remove sediment by hydraulic flushing.

Degradation of the wadi bed, either temporarily or permanently may endanger the stability of the structure as a whole. This can be caused by deep scouring downstream of the cut-off of the stilling basin, resulting from sweepout of the hydraulic jump from the basin. The cover on an inverted syphon installed in the wadi bed may be reduced by degradation; the barrels may even be exposed and washed away. Scour aprons of continuous mattress bank protection and spurs may not be sufficiently wide or flexible to follow the degrading bed, which may result in the collapse of the protective works.

Little relevant data is available on the mobility of the wadi bed, therefore the designs should be relatively conservative.

5.4 Availability of qualified staff

The diversion of spate flow requires well-qualified and well-trained staff in order to ensure continuity in supply. Staff training is still very essential, both on-the-job and overseas. In particular, operation of the headworks and sediment ejector gates requires a good understanding of the sediment transport during spates, as well as of the problems related to the large quantities of trash in the spate waters.

5.5 Cost analysis

To make an economic evaluation of the wadi diversion works, the cost of construction as well as the annual cost of operation and maintenance at feasibilty level has to be determined. After the preparation of detailed designs, a more accurate engineer's estimate is required for financing purposes as well as for comparison with bids during evaluation of contractors' tenders.

Cost figures can be prepared following common engineering practice, however a few items may still be difficult to estimate. Works in the wadi bed should be carried in the the dry season between October and March. However, freak floods have to be accounted for. Furthermore, the wadi bed consists of a mixture of sand, gravel and stones and has a very high permeability and the cost of the dewatering cannot be estimated accurately.

Good quality sand, gravel and stones can be found in the wadi bed near the construction sites. Reinforcement steel, structural steel, gabion boxes, cement and mechanical and electrical installations usually have to be imported.

The annual cost of maintenance cannot be determined accurately before the system has been in operation for some time. Even then the results may be biased if this period of observation happens to be dry or contains a number of big spate peaks.

6. Conclusions and recommendations

- spate diversion works have to be designed taking into account the particular shape of the spate hydrograph, the high sediment load in the spate waters and the large quantities of floating drift and trash carried in the flow during spates;
- topography permitting, a breaching section could reduce damage to the main diversion structure in exceptional floods. The section may be breached once in ten to fifteen years;
- in the design of the stilling basin of the weir, sufficient allowance should be made for differences in bed levels;
- the wadi bed upstream of the weir will be filled with sediment within one flood season and the bed configuration will change continuously, either naturally or through human interference. This should be taken into account in establishing the discharge coefficients or the effective length of the crest of the weir;
- the crest of the weir should have a slope towards the intake of about 1 per cent to channel low flows to the intake. If water has to be diverted to both banks of the wadi, the intake may be located somewhere in the middle, with the weir crest sloping towards the intake. From the intake the flow can be diverted to the banks through culverts in the weir body;
- the openings of the scouring sluice should be without a breastwall and should be at least 5 metres wide. This type will facilitate the passing of trash. The intake opening should be submerged during a spate and have a straight breastwall more or less parallel to the direction of the flow in the wadi during spates;
- the hoisting devices of the intake and scour sluice gates should be both manually and electrically/mechanically operated; a relatively high gate speed is required in order to follow the the rapid changes in water levels;
- the design of the intake/scouring sluice must ensure a minimum volume of sediment entering the canal system;
- the tunnels of an undersluice type sediment excluder may be blocked by tree trunks or large size trash. These will be stopped by steel pipes which extend from the roof of a tunnel to 0.50-0.75 m above the tunnel bottom. Suitable equipment to clear the tunnels must be available with the operational staff;
- a sand and gravel trap must be included at the headworks. The trap should be 150-200 m in length. The bottom width of the trap will depend on the sediment fraction that still has to settle in the trap; however the discharge per m bottom width during flushing of the basin should not be less than 2.5 m^3/s;
- the bottom level of the trap depends on the volume of sediment to be stored between flushes. The level of the bottom at the downstream end of the trap in

relation to the wadi bed level should be such that flushing will not be hampered by back water effects during the recession of the spate. Therefore, the vertical movement of the wadi bed (aggradation) has to be taken into account;

- the sandtrap should be flushed with discharges in the order of 1.25 times the design discharge. Hydraulic flushing, however, requires a large initial investment both in the intake/scour sluice and the sediment basins;
- basins with a large surface and storage capacity are not recommended since they will be filled with silt, which is costly to remove. Silt is also much appreciated by farmers and should not be removed from the spate flow. Therefore, small basins are preferable. However, spates may occur for five days in a row and the first spate may fill the trap completely. Dredges cannot be used because of the short duration of the spates. In practice, even with mechanical removal, the quantities of sand settling in the canal system will be substantial;
- vortex tubes, installed just downstream of the intake, may be capable of ejecting coarse sand and gravel during spates. The design of the tube system should take into account trash entering the system; easy access for cleaning of narrow openings will be essential;
- continous ejection of the bottom layers in the sand trap during spates will reduce the quantities of sand entering the canal system, in particular after the basin has been filled to capacity and flushing is not possible because of high water level in the wadi at the flushing structure;
- the flow into the canal system should be limited by installing baffle distributors, orifices or other flow regulating structures at the headworks. Small openings should be avoided because of the risk of blockage by trash. It is not recommended to rely on limitating the discharges into the system by operation of the gates only;
- small openings (trash racks, orifices, pipes etc.) and automatic devices should also be avoided in regulating and conveyance structures (e.g. syphons);
- attentive and accurate operation of the headworks and sediment removal works will require a highly motivated and well-trained operational staff; and
- gabions are a viable construction material for bank protection works in wadis. However, regular inspection and routine maintenance would be required. Once a gabion structure has been damaged it must be repaired quickly if a rapid and progressive failure during subsequent spates is to be avoided. A scour apron is considered an essential part of gabion protection works as it has the flexibility to follow the movement of the wadi bottom and will reduce the risk of undermining of the slope protection or spurs.

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A number of unpublished reports have been submitted to the Tihama Development Authority and other authorities of the Government of Yemen Arab Republic.

These reports mainly concern Feasibility Studies for the development of wadi areas or information on specific technical aspects of wadi irrigation in the Tihama coastal plain and are kept in the library of TDA.