F I E L D R E P O R T

TECHNICAL ASSISTANCE PROGRAM FOR THE MINISTRY OF WATER RESOURCES SULTANATE OF OMAN

TASK 5: WATER MANAGEMENT
TASK 6: TECHNOLOGY DEVELOPMENT

WADI GAUGING NETWORK RATIONALIZATION AND UPGRADE
Part 3

WASH Field Report No. 353
December 1991

WATER AND SANITATION for HEALTH PROJECT

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Part 3

WADI GAUGING NETWORK RATIONALIZATION AND UPGRADE

Prepared for the Omani-American Joint Commission
under WASH Tasks Nos. 254 and 255

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ACRONYMS

ASR	aquifer storage and recovery
cm	centimeter
CSR	center sampling rotary
EC	electrical conductivity
FAO	United Nations Food and Agriculture Organization
GIS	geographic information system
GPS	ground positioning system
H.E.	His Excellency
H.H.	His Highness
H.M.	His Majesty
in	inch(es)
JICA	Japanese International Cooperation Agency
km	kilometer(s)
l	liter(s)
l/s	liters per second
L.S.	lump sum
m	meter(s)
m^2/d	square meters per day
m^3/d	cubic meters per day
m^3	cubic meters

MAF	Ministry of Agriculture and Fisheries
mcm	million cubic meters
mcm/yr	million cubic meters per year
MEW	Ministry of Electricity and Water
mm	millimeter
MM/WH	Mott MacDonald International, Limited in association with Watson Hawksley
MMP	Sir Mott MacDonald and Partners, Limited
MOC	Ministry of Communications
MOD	Ministry of Defense
MOH	Ministry of Housing
MOI	Ministry of Interior
MSS	multispectral scanner sensor
MWR	Ministry of Water Resources
NASA	National Aeronautics and Space Administration
NSA	National Survey Authority
OAJC	Omani-American Joint Commission for Economic and Technical Cooperation
pop	population
PAWR	Public Authority for Water Resources
PVC	polyvinyl chloride
R.O.	Omani Rials
SCTP	Supreme Committee for Town Planning
SFWMD	South Florida Water Management District

tm	trademark
TEM	transient electromagnetics
TM	thematic mapper sensor
TPM	team planning meeting
uS/cm	micro Siemens per centimeter
USAID	United States Agency for International Development
UTM	universal transverse mercator
WASH	Water and Sanitation for Health Project

EXECUTIVE SUMMARY

The Omani-American Joint Commission (OAJC) and the newly established Ministry of Water Resources (MWR) of the Sultanate of Oman have a common interest in the water resources of the nation. Early in 1990, OAJC requested the Water and Sanitation for Health Project (WASH) to assist the fledgling Ministry in:

- Strengthening all aspects of its operations
- Establishing a strong technical base
- Developing policy and procedures

The WASH team worked in Oman and in the United States from May through August 1991 to complete Tasks 5 and 6 of the scope of work and also work under Tasks 3 and 4 that was interrupted by the Gulf War.

Following Parts 1 and 2, which provide a general introduction and background, each of the six parts of the report on Tasks 5 and 6 covers a different area of study and contains a summary of conclusions and recommendations to which the reader can refer for a quick review.

MAJOR FINDINGS AND RECOMMENDATIONS

Part 3 ... Wadi Gauging Network Rationalization and Upgrade

More surface water gauging stations are needed in MWR's wadi gauging network to provide information on the process of groundwater recharge and the effectiveness of recharge enhancement schemes. But the expansion of the network should not delay the processing and publication of the large volume of data already in hand.

Surface water data collection is limited by various physical and practical constraints, and all users of these data would greatly benefit from an understanding of these limitations and of the methods employed by the Surface Water Department.

The department's effective relations with other agencies and private sector groups interested in surface water and floods should be cited as a model for other MWR departments.

Part 4 ... Salt Water Intrusion Monitoring and Remediation

MWR faces a serious problem of saline intrusion and upconing in the Batinah coast region. Past efforts at control have lacked a focus and a defined policy. Emphasis must now change from observation of the advancing intrusion to a detailed program designed to find a solution. This can begin with concentrated efforts to protect municipal and public water supply systems from upconing and lateral intrusion in areas where severe impacts and economic dislocations are expected.

MWR should set up a section to undertake this work urgently after reviewing and, if necessary, modifying the policy and goals recommended. Unless this is done, the saline intrusion program will continue to lack direction and purpose.

Part 5 ... Alternative Well Technologies for Use in Saline Groundwater Systems

The WASH team investigated several alternative well technologies to pump fresh water from saline aquifers. The separation of fresh water from saline groundwater is called skimming by some hydrologists. Of the methods investigated, three show the most promise in Oman:

- Conventional low-drawdown wellfields
- Scavenger wells
- Water collection galleries

Existing conventional wells with high drawdowns are prone to upconing and sea water intrusion, whereas low-drawdown wells can extract a similar amount of water without inducing salt upconing. MWR should enhance its capacity to advise others on the use of this technology.

Scavenger wells separate salt water and fresh water into two discharge streams. More work needs to be done to define their potential for specific sites in Oman.

Collection galleries may find some application in coastal areas to provide agricultural or potable water supplies. They must be operated with care and, to be most effective, should be pumped continuously at very low drawdowns.

MWR should work on these methods to provide a leadership role in their use. There are many opportunities for applying them as part of a broad regional water management strategy rather than to improve water quality in a few wells while the regional groundwater system deteriorates.

Part 6 ... Small Basin Management

The WASH team quickly discovered that the inhabitants of the upper basins and small catchments have a thorough understanding of the water resources that sustain them. Much of this knowledge has neither been recorded nor considered of any value in water resources management in these areas.

MWR should set up a Small Basins Reconnaissance Section to draw upon this knowledge in a collaborative plan for water resources development that would take the villagers' ideas into account.

Cultural, political, and human considerations are no less important than technical concerns in the planning and implementation of water related work. Although the guidelines provided relate to small basins, they can be profitably applied to many other MWR projects.

Part 7 ... Applications of Geophysics

There are several methods of geophysical exploration that could help MWR in its assessment work. However, many of these are expensive and, experience suggests, could lead to poor results unless they are properly utilized. Recommendations are offered on staff organization to develop the necessary skills and on appropriate training, equipment, and computer software.

The author of this part, Dr. Kendrick Taylor of the University of Nevada, is willing to sponsor one or more Omani students for graduate studies in the application of geophysics in Oman. The OAJC would finance these studies.

Part 8 ... Applications of Remote Sensing

Remote sensing has many useful applications but its products are expensive and MWR must be sure that they would advance its work. The range of available products, their costs, and their uses are dicussed. A pilot project to test the technology in defining water use along the Batinah coast and an incremental process that moves ahead as useful results are obtained are suggested.

Working Paper ... Discussion Paper for a Staff Orientation Document

The WASH team worked with almost the entire MWR staff from August 1990 to August 1991. Although it noted much progress in that short time, it also observed that many new staff members knew very little about Oman and its water resources and had poorly formed ideas about the nature of MWR's work. In spite of the fact that most policies and goals have been defined, the information has not yet filtered down to the rank and file of the organization. Given its rapid growth this is not surprising.

The discussion paper is an attempt to summarize important information that senior staff members should have as they begin their work. It reviews MWR's policies and approaches and explains what the Ministry is and why it was formed, what they should know about working in Oman, and how they can help the Ministry to reach the important goals ahead.

The paper is intended to fill an immediate need and should be followed by a similar document that is enlarged and refined as MWR gains knowledge and experience.

In Conclusion

To assist decision makers, the report on Tasks 5 and 6 provides the approximate capital and recurrent costs of the programs recommended. The earlier reports on Tasks 1 through 4 contain similar data.

OAJC and WASH hope that the information provided here will be useful to MWR in its important work in Oman. The OAJC staff and its managing director, H.E. Hamoud Halil al Habsi, are anxious to be of continuing support.

Chapter 1

INTRODUCTION AND GENERAL OVERVIEW

The wadi system of Oman is a network of streams that are dry most of the year but can be transformed into raging floods, sometimes of extraordinary magnitude, when it rains. The concentrated runoff is believed to be a major source of recharge to groundwater aquifers of the coastal plain and interior. Infiltrating surface water provides upland basins with sources for aflaj and groundwater well systems. These same wadis also carry powerful floods that can cause property damage and loss of life.

Improved management of Oman's water resources can be achieved with a well-organized and dependable wadi and rain gauging network. A better understanding of the relationship between rainfall, runoff, and aquifer recharge can help in:

- Improving the ability to determine safe water consumption limits
- Enhancing aquifer recharge
- Predicting the magnitude and extent of floods to prevent property damage
- Managing the country's water resources

The present wadi gauging network operated by the Ministry of Water Resources (MWR) has been under development since the mid 1970s. Older gauges were installed by several government agencies, private consultants, and international development organizations, including the Ministry of Agriculture and Fisheries (MAF), the Ministry of Electricity and Water (MEW), the Ministry of Defense (MOD), the Japan International Cooperation Agency (JICA), and the Public Authority of Water Resources (PAWR), MWR's predecessor organization. Flood discharges throughout the Sultanate are presently monitored by a network of 134 gauges, some of which were installed by these groups.

This report reviews the wadi gauging network operation. It describes the characteristics of Oman's hydrography and its effect on the installation and operation of a wadi gauging network, and discusses the practical application of network data. It explains some fundamental hydraulic concepts to help the reader understand the methods of indirect flow measurement and to show what constitutes a good gauging site. The report describes the type of equipment used to record flood levels and points out each device's strong and weak points. It presents the findings of the field investigations and makes recommendations for future field work, discusses the Surface Water Department's ability to operate the expanded network and the importance of representative basin study, and includes a cost analysis and suggestions for improved training of Omani technicians.

Chapter 2

SCOPE OF WORK

The scope of work included the following tasks:

- Review existing plans to upgrade and expand the wadi gauging network
- Visit suggested sites for new gauging stations and determine the feasibility and usefulness of the locations
- Specify exact locations and equipment of gauging stations at feasible sites
- Summarize network upgrade, expansion, and long-term operational costs
- Evaluate the need and ability for training Omani technicians

Chapter 3

SUMMARY OF CONCLUSIONS

- More rain and wadi gauging data are needed to advance the understanding of groundwater recharge and to support water management on the Batinah and in the upper basins.

- There are gaps in coverage by the existing wadi gauging network that need to be filled. Several sites are identified where new gauges should be installed.

- While the wadi gauging network needs to be expanded, a detailed plan for maintenance and operation is essential to ensure maximum effectiveness of existing and planned gauges.

- A large amount of unprocessed data exists, dating back to 1985. Network expansion should be carried out at a rate that balances with the need to process and publish the data.

- The Surface Water Department is well organized and aware of what is required to improve and expand existing programs.

- Omani technicians need more training to be effective in operation and maintenance of the network. Fundamentals such as general math skills and map reading should be the first areas covered, with subsequent training in hydraulics and hydrology.

- Extreme fluctuations of funding for the gauging network have been a factor in the past and may be in the future Adaptability to changing budgets should be considered in planning the expansion, maintenance, and operation of the network.

- Physical siting requirements for indirect measurements limit the type and location of sites that can be measured.

Chapter 4

USES OF WADI FLOW DATA

The discharge rates and total flood volumes obtained through gauging wadi floods are used to:

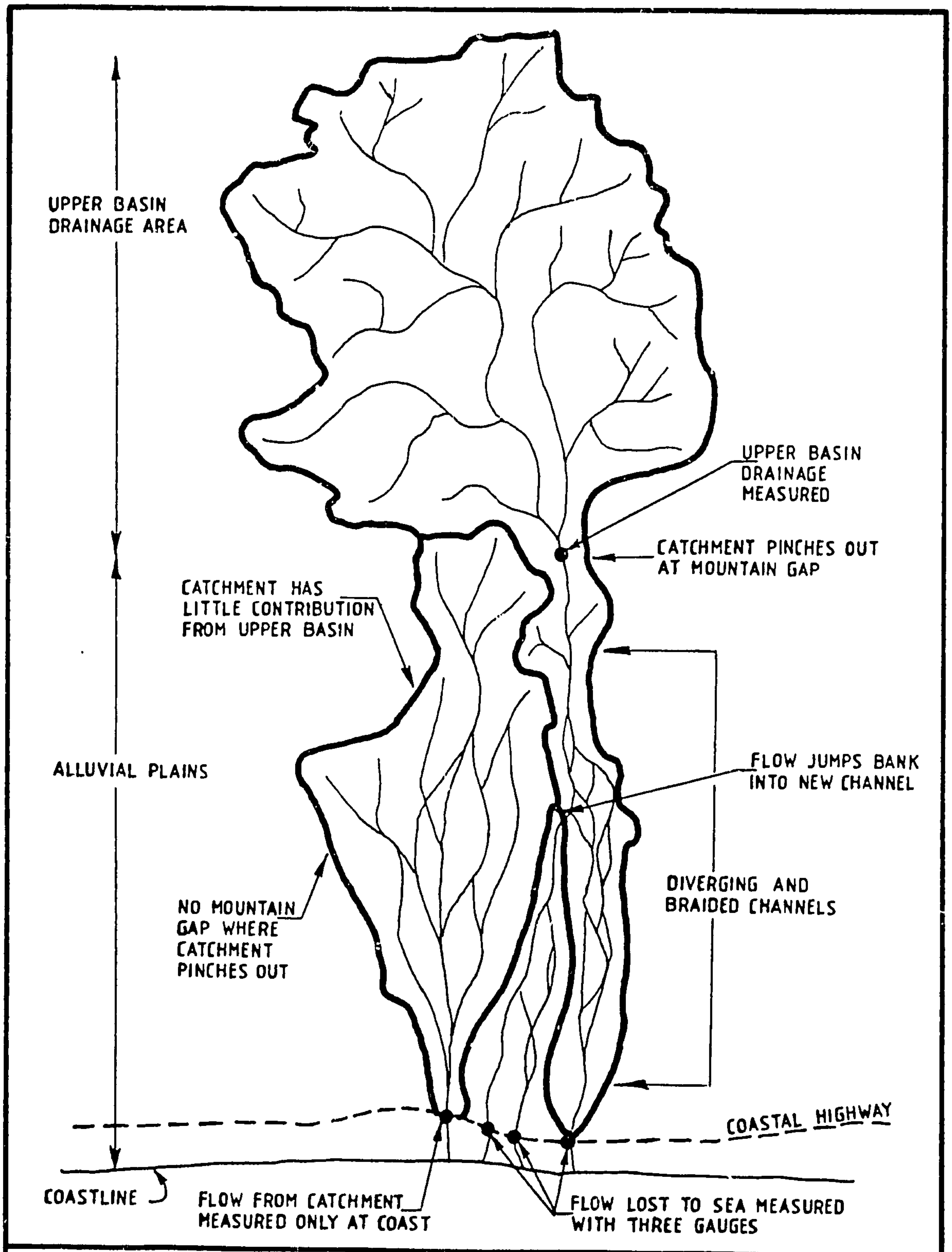
- Assess the volume of runoff recharged into the ground for a given reach of wadi
- Determine how much water is lost to the ocean or desert
- Gain a better understanding of a basin's characteristics with respect to rainfall, runoff, groundwater recharge, and wadi throughflow
- Determine flood recurrence statistics
- Aid flood plain analysis
- Help in the design and placement of dams, roadways, bridges, and buildings
- Assist in the placement of additional gauges to better accomplish the above goals

4.1 Using Wadi Flow Data to Determine Groundwater Recharge

From a water management standpoint, one of the most important uses of wadi flow data is the determination of recharge volumes to the groundwater system. Quotas for water consumption are based upon the volume of water which enters the ground each year. Effective management would curtail pumping rates in years when recharge is below normal and allow increased usage in above-normal recharge years.

Recharge in a section of wadi can be calculated by measuring the volume of water which flows between two points in a given channel. Several wadi gauges have been installed in pairs—one at the mountain gap and another at the highway crossing near the coastline (Figure 3-1)—to assess the volume of water recharged along the Batinah plain. In the simplest analysis, any decrease in volume between the mountain gap and the coast would be attributed to recharge. Additional losses might be attributed to channel storage or evaporation.

Figure 3-1



RECHARGE ESTIMATION WITH WADI GAUGES

NOT TO SCALE

But there are some difficulties in accurately determining groundwater recharge in this manner.

- When a wadi overtops its banks during large floods and spills onto the plain, its channel tends to diverge and braid, and water flows down smaller channels which bypass the gauge on the main channel. When this happens, more water is lost to the sea than is recorded, and the computed recharge is greater than actual.

- When gauges are placed at the mountain gap and the coast, it is assumed that most of the precipitation from storm systems falls on the upper basin and only a negligible amount is added to the flood on the plain. If water is added to the flood below the upstream gauge, calculated recharge values will be lower than actual.

- Most channels which are gauged at the coast receive much of their discharge from upland basins. Some channels, however, have most or all of their catchment on the alluvial plain. These catchments do not narrow to a point where all the flow from a large drainage area passes through a narrow gap. It is difficult to determine where the upstream gauge should be placed because water is not funneled to an ideal measuring point. In such cases, recharge can be calculated only if the volume of precipitation on the contributing catchment can be accurately estimated. Doing this requires a high-density rain gauge network, which is expensive.

4.2 Using Wadi Flow Data to Define the Hydrology of Regions through Representative Basin Studies

A representative basin is an area chosen for intensive study because it is hydrologically representative of other basins in the region and is configured so that the measurement of hydrological processes is at least feasible and at best ideal. Oman needs a representative basin study to:

- Determine whether or not an understanding of upper basin hydrology is important to the management of its water resources; since such a study has never been undertaken, it is not known whether important hydrologic processes are being overlooked

- Understand the pathways by which water moves from upper basins to the lower alluvial plains

- Understand percolation in upper basin alluvium and fractured bedrock

- Understand the mechanics of water loss to deep storage and evapotranspiration

- Determine the utility of densely spaced networks

- Gain a quantitative understanding of a single basin and a qualitative understanding of the dynamics of upper basin hydrology

- Obtain data to verify the credibility of present and previous modeling efforts

- Understand the dynamics of transient runoff within a single basin.

Upper Basin Water Balance

A comprehensive study of upper basin dynamics would calculate the following inflows and outflows:

- Rainfall (the only inflow)

- Wadi surface runoff leaving the basin

- Wadi throughflow leaving the basin

- Hardrock percolation leaving through the bedrock

- Evapotranspiration

- Artificial removal from the limits of the basin (i.e., pumping water and using it outside the catchment)

These six components make up the water balance equation of an upper basin. The outflows together must equal the volume of rainfall. Three components of the equation—rainfall, surface runoff, and throughflow—can be measured directly. On the assumption that the artificial removal of water is nominal, the balance is that lost to evapotranspiration and hardrock percolation. Evapotranspiration can be estimated with the help of evaporation station data. Percolation can be computed only after determining all the other components in the water balance.

A rain gauge network of adequate density will allow approximation of total volumetric rainfall. The time frame in which the basin is studied dictates network density, the required density for event-based data being much higher than for annualized data. At the very minimum, one gauge for 25 to 50 km^2, or 20 to 40 stations for a 1,000 km^2 basin, would be required for event-based studies. Rain gauging and the use of rain gauge data in Oman are discussed in Tasks 3 and 4.

A wadi gauging network that divides a basin into subcatchments can more easily locate points where surface flows are lost to the ground. It can also lead to a better understanding of rainfall-runoff relationships in various parts of the basin. The most important gauge is the one at the mountain gap, which measures the total volume of water leaving the basin as surface flow.

While the surface of most wadis in the Sultanate remains dry throughout the year, water may flow continuously in porous sand, gravel, and fractured rock beneath their beds. This is often referred to as wadi "throughflow" or "underflow." Occasionally, the sand and gravel beds that convey throughflow are constricted, and the water flows above ground briefly before returning underground. In these conditions, throughflow can be determined accurately and at relatively low cost by means of a concrete weir anchored in the rock and a continuous recording device mounted upstream from the weir. A single baseflow gauge at or near the mountain gap will indicate how much water leaves the basin as wadi throughflow.

A relatively sparse network of evaporation stations, depending upon climatic variations within the basin, will enable estimates of the volumetric loss to evapotranspiration. Accurate determination of evapotranspiration is the weakest component in the water balance relationship.

4.3 Using Wadi Flow Data for Flood Studies and Dam Design

Assessing flood risks accurately requires an understanding of the relationship between the recurrence of flood events and their corresponding magnitudes, and is possible only if historical flood flow data are available. Knowing where to build and what the risks are can prevent capital investment loss due to flood damage.

Flood recurrence assessments predict the magnitude of floods for various intervals. A "10-year flood event" means that a flood of such magnitude has a one-in-ten chance of occurring each year. Over a long period, events of this size will recur, on average, every 10 years.

For recurrence statistics to be resolved with confidence, accumulated data must cover a long period. The shorter the period for which flood data have been collected, the higher the chance they will not represent average conditions. In an above- or below-average period of rainfall, the recurrence discharges will be too high or too low respectively. As more data are accumulated, above- and below-average periods balance each other out and have less effect on the calculated averages.

Flood plain analysis determines the extent of flood events and their recurrence. The discharges of 5, 10, and 25-year floods can be used to predict what land along a wadi will be flooded. Flood plain analysis is crucial in deciding where it is safe to build and in determining bridge clearances, culvert sizes, and dam specifications. All these assessments depend upon continuous historical flood data from wadi gauging stations.

Chapter 5

OMAN'S HYDROGRAPHY

An understanding of the types of watercourses and the nature of runoff in Oman is essential to installing and operating a wadi gauging network. This chapter explains some of the characteristics of Oman's watercourses and the difficulties they impose, and the effect of runoff on the structure of the network.

5.1 Oman's Natural Watercourses

The characteristics of a channel, such as its bed material, the rate at which its geometry changes in time and space, the condition of the water it conveys, and how often it flows, have profound effects on the ability and worth of gauging it and the methods by which this should be accomplished. A brief review of Oman's watercourses and their effect on wadi gauging should explain the choice of the methods of measurement.

The natural watercourses of Oman can been classified in four categories (FAO: Hydrology of Arid Climates):

Type I

Stable, rocky, steep, deeply incised, irregular channels that almost entirely contain the mixture of water and sediment they convey and are changed slowly by it

Type II

Channels incised in hard rock or terrace deposits where the water's depositional energy has been sufficiently low to allow the recent accumulation of loose alluvial sediments

Type III

Unstable, disorganized, diverging or braided alluvial channels whose slope, depth, shape, and bed form are controlled by water/sediment flow characteristics and are in a state of dynamic equilibrium with them

Type IV

Minor watercourses in flat alluvial plains or at the terminal reaches of basins where flows seldom reach

Impacts of Channel Characteristics on Wadi Gauging

In Oman, Type I watercourses are either deep canyons in the mountains or steeply walled channels cut through the terrace deposits of the piedmont. These watercourses complicate discharge measurements with high velocities, high turbulence, heavy debris load, and lack of dependable debris lines to determine water surface profiles. Gauging stations are rarely installed in Type I channels.

Type II channels are found as a wadi leaves the mountains when it is in transition from Type I to Type III, or in the terrace deposits and wider valleys of upper basins. These channels are characterized by steep, rocky, and reasonably stable walls that normally contain their flow, and alluvial beds that are changed moderately by the water/sediment mixture they convey. Changing geometry, due to bed scour and deposition, and occasional bank collapse are the main difficulty in gauging these channels. Most MWR gauge sites are stationed in Type II channels.

Type III watercourses are found on the alluvial plains of the coast and interior. The geometry of these streams changes frequently, constantly maintaining equilibrium with the differing sediment loadings, discharges, and hydrographs that occur. Many of the channels at coastal highway crossings fall into this category.

Channel rating is the process of developing a relationship between water level and discharge that will be consistent from one flood to the next. Rating a channel which undergoes regular bed scour and deposition is difficult because the relationship between water level and discharge is constantly changing. A rating that applies to one flood may not apply to the next. Some uncertainty is inevitable in determining flood volumes for channels of this nature. This is the main difficulty in gauging Type II and III channels.

Type IV channels in Oman occur as braided and diverging stream systems along the lower part of the coastal plain and near the terminal reaches of flow in the interior. They also occur in locations where percolation into the alluvium removes surface flow faster than it can be replenished. Type IV channels are seldom gauged because their flows are small and infrequent.

Determining discharge of a Type III watercourse often requires more than one gauging station. This is the case along the Batinah coast. Runoff leaving the mountains is typically contained in one channel, and a single gauge will effectively measure its discharge. As the runoff pours onto the plain, however, the wadi splits and braids, breaking down into smaller channels. At the coastline, the water is often conveyed in two or three main channels and a number of Type IV channels that see flow only in extreme events. To accurately determine the total flow of the catchment, gauges should be installed on all the main channels. The smaller channels are not usually gauged because they fail to produce enough data and are difficult to rate. Determining discharge to the ocean can be difficult and expensive, but it provides important data to estimate groundwater recharge and water loss to the sea.

5.2 The Nature of Runoff in Oman

While the characteristics of watercourses dictate the feasibility of gauging at specific points along a channel, the nature of arid region rainfall and runoff affects the design of the gauging network.

Runoff in Oman has the following attributes:

- Highly scattered in time—a wadi may flood several times in one year and see no flow the next
- High spatial variability—one basin, or one area of a basin, may experience major flooding while adjacent areas may not
- Short duration in time—a flood of extraordinary magnitude may occur within a few hours
- Rapid peak development—flood hydrographs, especially in the upper reaches of a wadi, peak and dissipate very rapidly
- Heavy sediment and debris loads—sediment loads are usually greatest at peak discharge
- Rapid percolation—as the flood moves downstream, significant volumetric losses occur because of infiltration into the bed of the wadi, but these vary widely from point to point because of differences of terrain and geology

The high variability of flooding, both spatially and temporally, underlines the importance of network density and dependability.

The Need for High Network Density

The convective storms that produce much of Oman's rainfall are very localized. One rain gauge may record heavy precipitation while another only 10 km away may record nothing. The geology of Oman also changes dramatically from point to point. Since surface runoff is a function of both rainfall and geology, runoff is also highly variable spatially.

For example, suppose two gauges are placed 20 km apart along a wadi, the upstream gauge just below the confluence of two wadis of equal size. Readings show that only half the water passing the upstream gauge reached the downstream gauge. This poses several questions.

- Where did percolation occur? At a constant rate over the entire 20 km stretch of the channel, or quickly along a very short section?

- Are there specific geological characteristics related to the points and manner of percolation?

- Did all the recharge flow in wadi alluvium or did some flow through fractures in the rock?

- How much water really percolated? Was more water added along the reach from additional rain, indicating greater recharge than the gauges indicate?

- Can it safely be assumed that water flowing in a nearby wadi will behave in the same way?

- What was the contribution of the two branches above the upstream gauge?

All these questions could have been answered by data from a high-density network, which would pinpoint where recharge actually occurs and suggest how water enters the ground and where it goes after that. More rain gauges could help determine if more water is recharging than the wadi gauges indicate. Placing a gauge on each of the two contributing wadis above their junction will tell more about how each one contributes to the downstream flow. As for the nearby wadi, the only way to be sure it behaves in the same way is to gauge it as well.

The Need for Network Dependability

The high temporal variability of rainfall in Oman influences the dependability of a wadi gauging network. Since events are infrequent and isolated, the equipment installed to record wadi flow must work whenever a flood takes place. Sensing devices must be able to "sleep" most of the year while wadis are dry, and "wake up" when a flood occurs.

In wet climates, the loss of a day of rainfall or runoff data is not as crucial as in an arid zone. In a temperate region, where it might rain 50 days a year, failure to record one event represents a 2 percent loss of data. In an arid region, where it might rain only twice a year, failure to record one event represents a 50 percent loss of data. Network dependability is important everywhere but is critical in arid regions, where a single event might supply most of the year's data.

While reliability is so essential, runoff in arid zones tends to degrade equipment quicker than in temperate zones. Floods in Oman carry very heavy debris and sediment loads that can destroy the structural components of a gauging station, silting up transducers and standpipes. Equipment should be selected and structures designed for durability, resistance to high temperatures, and ease of maintenance. Regular and rigorous inspection, repair, and calibration are also crucial to maintaining a gauging station that will work when needed.

Chapter 6

FLOW-MEASURING TECHNIQUES

The flow-measuring techniques used by the Surface Water Department are described below. Understanding the limitations of each method is important for deciding how gauges should be sited for maximum benefit. The methods are divided into two categories:

- **Direct measuring techniques**

  The average velocity at a channel cross-section is measured with a current meter or other device and multiplied by the cross-sectional area. By doing this for a range of water levels, a rating curve can be derived relating the water depth, or "stage," to the total discharge.

  Direct measuring techniques are not easily implemented in Oman for the following reasons:

  - Most wadis rarely flow
  - Flooding of fords on all major roads makes accessibility difficult in wet weather
  - Storms cause rapid and dangerous rises in water levels
  - Most wadis lack bridges or other structures from which currents can be measured
  - Channel shapes change during current measurement
  - Flows have high velocities
  - Debris and sediment loads impede current measurements
  - Flood peaks often occur at night when darkness complicates access and current measurement

- **Indirect measuring techniques**

  Indirect measuring techniques use mathematical relationships to determine discharge. They are termed indirect because velocity of discharge is not measured directly but is arrived at from parameters such as bed slope, channel roughness, and culvert size. The parameters used depend upon the indirect method employed. Indirect methods, although less accurate, are much more effective in arid zones but are limited by:

- Difficulty in obtaining accurate water-level records because of waves and high sediment loads
- Changes in cross-section shape before and after the flood peak
- Lack of effective natural flow controls because of the high mobility of alluvial material

MWR uses three indirect methods to measure wadi discharge and derive rating curves: the slope-area method, the flow over dams method, and the culvert rating method.

6.1 Slope-Area Method

The slope-area method, the most commonly used by MWR's Surface Water Department, computes discharge on the basis of a uniform flow relationship. A knowledge of open-channel hydraulics is necessary to understand this method and uniform flow.

The discharge rate of a channel at any cross-section is equal to its cross-sectional area multiplied by the average velocity in the cross-section. For a given discharge rate, the variables of area and velocity are inversely proportional (i.e., as one variable increases, the other decreases). If the width of a channel remains constant, the only way to change its cross-sectional area is to change the depth of flow. For a given discharge in a channel of constant width, the velocity will increase as the depth decreases, and vice versa.

Conservation of energy implies that as water flows down a channel, it adjusts its velocity to dissipate energy at the same rate as the channel falls. Flowing water dissipates energy through friction with the channel bed. If a channel bed changes slope, the water's rate of energy dissipation adjusts itself to match the rate at which the channel drops. In open-channel flow, two factors govern the dissipation of energy: velocity and channel roughness. For a given section of channel bed, the greater the velocity or channel roughness, the greater the dissipation of energy. Channel roughness is represented by Manning's *n*-value coefficient. The greater the *n*-value, the higher the channel roughness.

Conservation of mass implies that, in a uniform flow channel reach, the rate of flow into and out of the reach must be equal. If 20 m^3/s are flowing into a channel reach, then 20 m^3/s will be flowing out of the channel.

By definition, flow in a channel reach is said to be uniform if the depth of flow is the same at every section in the reach (Chow), in which case the water surface will be parallel to the channel bed. In a natural channel, true uniform flow is rarely, if ever, achieved because channel irregularities prevent the slope of the water surface from being perfectly parallel to the bed. Since the slope-area method is based on a uniform flow relationship, reaches selected for measurement should approximate uniform flow conditions.

Selections are usually made when the channel is dry, so it is difficult to verify if the water surface profile will be parallel to the channel bed. Differing depths usually represents a change in area, which indicates a change in velocity. When water encounters new channel characteristics that necessitate a change in velocity, the flow will accelerate or decelerate and the depth of water will change. Figures 3-2 and 3-3 illustrate channel characteristics that change velocity and flow uniformity.

Questions to be asked in assessing the suitability of a reach for slope-area measurement are:

- Can high-water marks be obtained? A channel reach may have perfect geometry, but if high-water marks cannot be obtained there is no way to verify whether the flow is truly uniform.

- Does the channel cross-sectional shape change? Dramatically contracting or expanding cross-sections cause changes in velocity and channel depth.

- Does the slope change? If the bed slope gets steeper or flatter, the velocity and area may not be uniform.

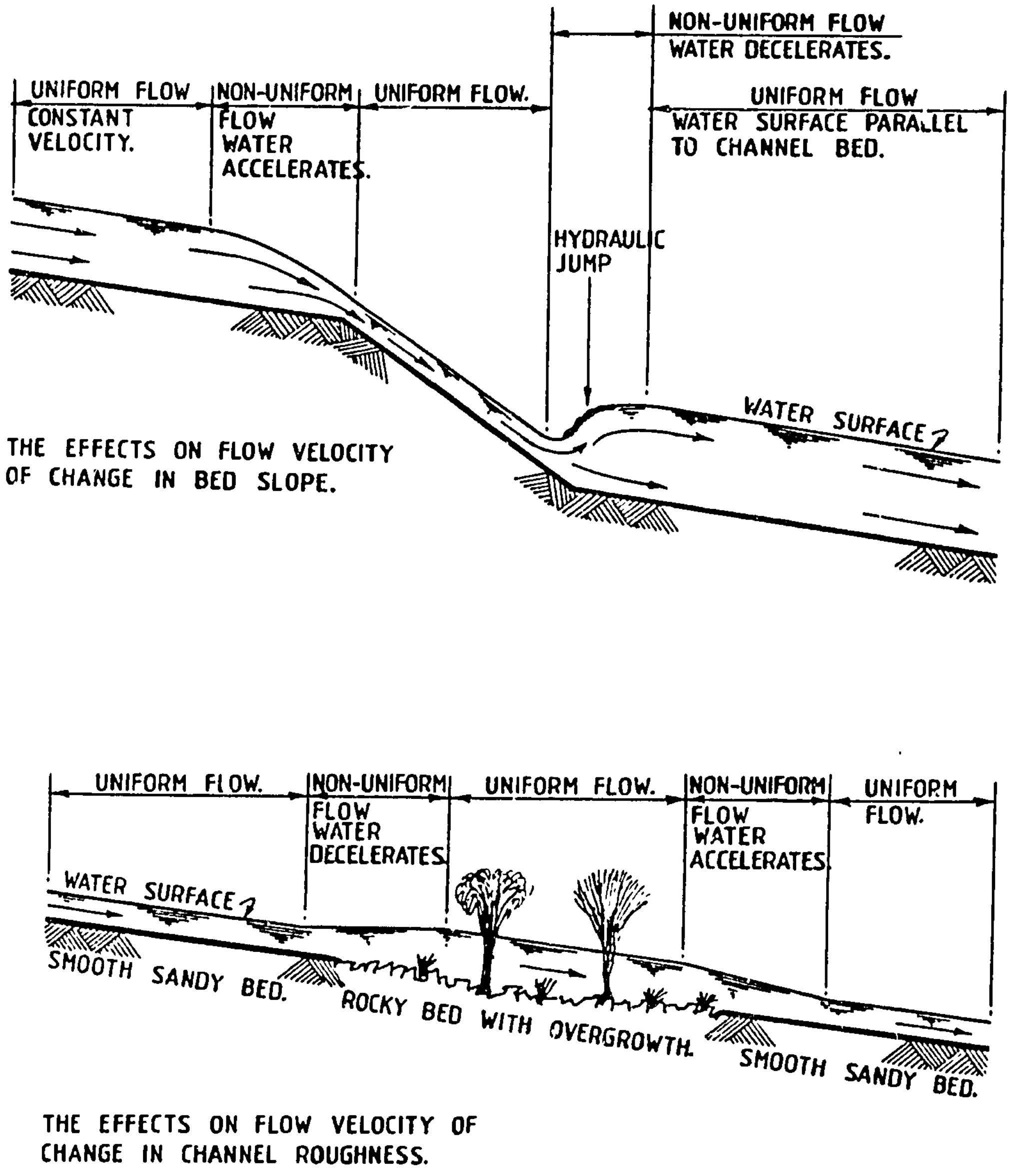
- How variable are changes in cross-section and slope? Few natural streams have constant cross-section and slope. However, the less variable these two components are, the more dependable the measurement will be.

- Does roughness differ from one point to another? Water flowing from a clear channel section to one with trees could slow and cause a change in area.

- Are there any controls downstream that affect the slope of the water surface? Large obstructions downstream may affect velocity by creating backwater conditions.

- Is the channel relatively straight? Channel bends cause velocity profiles to vary from one bank to another.

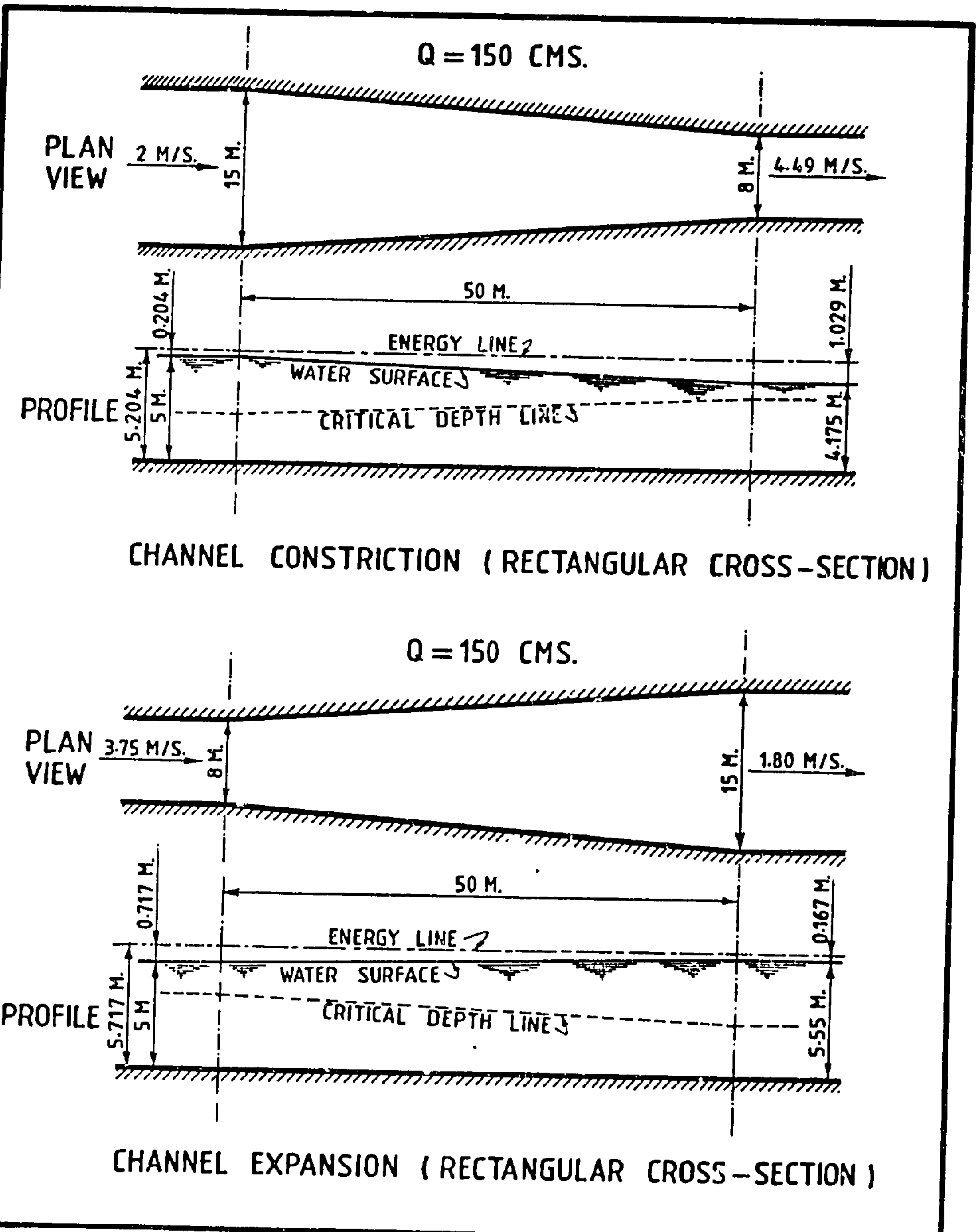
Figure 3-2



OPEN CHANNEL FLOW VELOCITY EFFECTS

NOT TO SCALE

Figure 3-3



THE ENERGY PRINCIPLE APPLIED TO DIVERGING AND CONVERGING CHANNEL SECTIONS

NOT TO SCALE

- Is the flow deep enough? It is difficult to determine channel roughness when flow is too shallow.

- Is there another channel entering the reach? This will cause the discharge to change in the course of the reach.

- Is the channel reach at least twice as long as it is wide? The slope-area method requires measurements of three or more cross-sections in the channel reach. Cross-sections should be at least one width of flow apart.

- Is the water surface slope sufficient? As a general rule, a drop of 0.1 m is recommended along a slope-area reach.

The slope-area method requires surveying the site of a recent flood to determine the cross-sectional area of the channel and, from high-water marks, the slope of the water surface profile. With this information and the channel roughness, the peak discharge of a flood (the discharge at the water's highest point) is calculated. A rating curve for the channel is derived from calculations of discharge at a number of flood levels, and flood volumes are computed from recorded hydrographs.

Using Step-Backwater Calculations to Rate Slope-Area Reaches

The standard step-backwater method uses the energy equation to determine water surface elevations upstream from a given point. As the calculation steps its way upstream, the solution approaches the water surface elevation of normal depth. For a given condition of discharge, slope, and roughness, normal depth is the one possible depth for maintaining uniform flow. Therefore, if several elevations at a downstream section are assigned the same discharge, they will all converge to the same value, which is normal flow, as the solution for each elevation is stepped upstream. Performing these calculations by hand is extremely tedious, but computer programs have been developed to provide rapid solutions.

The channel geometry of a site selected for slope-area measurement may be ideal, but no high-water marks may be obtainable. This is often the case in deeply incised channels with steep rock walls. In such situations, the step-backwater method can be used to rate the channel. A gauge site is selected according to the same criteria as for any other slope-area reach, and 6 to 8 cross-sections downstream are surveyed and assigned representative *n*-values of roughness. The flow profiles can be calculated back upstream to the gauging station from selected elevations in the downstream section. Doing this for a variety of discharges will provide a dependable rating curve from which flow volumes can be calculated.

Mel Johnson of the Surface Water Department suggested this method, which he used when working for the U.S. Geological Survey. It is not normally used to rate channels in Oman but perhaps should be given more consideration. Many critical channel reaches presently are ungauged because of the inability to obtain high-water marks.

6.2 Flow Over Dams Method

Discharge across road crossings is calculated using the flow over dams method. A road crossing behaves like a dam by retaining water behind it until it is overtopped. This type of barrier is referred to as a broad-crested weir.

A weir is an overflow structure built across an open channel for the purpose of measuring flow. A classic weir is a wall built across a stream channel. The water ponds up behind it, flowing evenly across the top of the wall until it reaches "critical flow," which is the depth and velocity of flow that most efficiently conveys discharge. This often occurs when there is an obstruction in the channel. Any channel obstruction that forces the water through critical flow is termed a "critical control." At a critical control section, the relationship between depth and discharge is definite and independent of channel roughness, slope, and other uncontrollable factors (Chow, 1959).

Weir flow calculation depends upon three factors:

- Weir characteristics—broad-crested or sharp-crested, shape, roughness of material, etc.
- Head—the height of the water above the crest of the weir
- Length—the length of weir over which the water flows

The criteria for computing flow over a roadway using this method are:

- The roadway must act as a control. It must be high enough across the entire channel bed and have a sufficient drop on the downstream side. A roadway that sits flush across a channel bed will not act as a control.
- Results are best if the roadway is perpendicular to the flow of the water.
- The roadway must remain intact during a flood. Earthen road crossings that wash out during a flood are not suitable.

6.3 Culvert Rating Method

Culvert crossings, where discharge is conveyed beneath a roadway, offer another dependable method of determining flood flows. Mathematical relationships have been developed between culvert conveyance and the following factors:

- Headwater conditions—conditions at the inlet of the culvert
- Tailwater conditions—conditions at the outlet, which may or may not be submerged
- Culvert material—different materials have different roughness factors, e.g., corrugated metal has a higher roughness than concrete
- Culvert slope
- Culvert geometry—circular, rectangular, oval, etc.
- Inlet and outlet losses

Culvert hydraulics are complicated and require careful consideration of headwater and tailwater conditions.

6.4 Combined Culvert Flow and Flow Over Roadway

Most wadi crossings with culverts are not designed to handle maximum floods. During a flood where the capacity of a culvert is exceeded, flow will overtop the roadway while also passing through the culvert(s). Under these conditions both culvert hydraulics and weir flow calculation are used to rate the crossing.

Chapter 7

WATER LEVEL RECORDING DEVICES

The Surface Water Department operates three types of stage-recording devices. The advantages and disadvantages of each device are reviewed to show why the present system is deployed at new sites.

7.1 Float Gauges

The float gauge is the simplest and oldest of the three types used in Oman. It is a large standpipe with a float inside connected to a recorder by a wire or tape passing over a wheel and counterweighted. As the flood passes through the wadi, the standpipe fills with water and the float rises, driving a pen on a rack-and-pinion mechanism that marks a rotating strip chart.

Two types of chart recorders are in operation at present. The OTT recorder system uses a chart that lasts for two months and a mechanical clock that runs for either 32 or 60 days, depending on the model. Sites with a 32-day clock must be inspected once a month. The Leopold and Stevens system uses charts that last for one year and manual clocks that run for 4 months. Sites using this system must be visited at least three times a year. Electric clocks for the system are also available.

Float gauges are simple in concept but subject to some limitations:

- Strip charts and clocks must be maintained regularly. Failure to wind a clock or replace a chart may result in failure to record an event.
- The tall standpipe in the wadi is easily damaged by large debris washed down in major floods. Reinforcing it is expensive.
- Standpipes are large and cumbersome.
- If silt collects in the bottom of the standpipe, little or no information may be recorded on the receding limb of the hydrograph.
- Records may lag behind the actual flood level if the intake system becomes silted and does not operate efficiently.
- The data on the strip chart must be reduced and analyzed by hand.

7.2 Bubble Gauges

Bubble gauges measure the water stage by slowly bubbling nitrogen through a small tube into the wadi at a fixed elevation. The pressure in the tube corresponds to the water depth above its orifice, and is transferred to a mercury manometer that operates a pen on a strip chart.

The bubbler has advantages over float gauges. Costly standpipe structures are eliminated, and, since only a small tube is needed to transfer the pressure, the recording structure can be located a good distance from the measuring point. While strip charts and clocks need to be maintained, the recording structure can be situated far enough from the flood zone to avoid water damage. The main disadvantage is the danger of mercury poisoning if the manometer is ruptured. Enough pressure must be maintained in the nitrogen tank to keep the bubbler running. Sediment may hinder the pressure reading of the bubbler, but, unlike a float gauge, the record would still indicate some pressure differences and give information about the receding limb of the hydrograph.

7.3 Dataloggers

The recording device chosen for installation at new gauging stations is the datalogger. The datalogger is wired to a pressure transducer placed in a screen and set into the bed of the wadi. Two types of dataloggers are currently operated by the Surface Water Department. The Datapod I system takes one reading every 24 hours, regardless of pressure change, while the Datapod II system records one reading every 8 hours. Both systems are programmed to record one reading every five minutes if a change in water level of 2 cm. or more is detected. Each reading of date, time, and pressure is saved on a 32K computer chip. When the site is visited, the digital information from the chip is dumped into a computer and taken back to the office for analysis. The datalogger has numerous advantages over the other two methods.

- Data do not have to be manually reduced for analysis. Because they are in digital format, computer programs can perform calculations from them more efficiently and accurately than with strip charts.

- Information for an extended period can be stored on a single chip.

- Even if the transducer becomes covered with silt, it still senses pressure and records information.

- A well-maintained datalogger is normally more precise than a float gauge.

Chapter 8

NETWORK EXPANSION AND UPGRADE

The Surface Water Department operates 127 wadi gauging stations—111 that have continuous recording devices and 16 that record peak discharge only (see Drawing 1). The installation of 16 confirmed wadi and baseflow gauging stations and the immediate investigation of 8 unconfirmed wadi and baseflow gauges are recommended (see Drawing 2). Drawing 3 shows the network after the addition of the 24 confirmed and unconfirmed gauges.

Conclusions and Recommendations

- The first priority is proper operation and maintenance of the existing network.

- The number of new gauges installed should balance the Surface Water Department's ability to adequately maintain and operate the system.

- If the reduction and analysis of raw data prove difficult at the outset of the expansion, data should be collected and stored in an organized manner to be reduced and analyzed at a later date.

- The upgrade of 86 existing gauges is under way to improve the dependability and accuracy of the network.

- Wade, baseflow, and rain gauges should be installed for a representative basin study of the Wadi Ahin drainage basin. This report does not specify the placement of rain gauges.

8.1 Suggested Locations for New Gauge Sites

Sites for 18 new wadi gauges were investigated; 15 of these were found suitable for indirect measurements and should be equipped with continuous recording devices. One baseflow gauge site was confirmed and is recommended. Table 3-1 summarizes the site investigations.

One of two gauge configurations is suggested for each site. Type 1 houses the datapod recorder in a water-tight length of well casing anchored to the wadi bed. The transducer housing, composed of four nested screens with gravel between the two outer screens, is connected to the datapod housing. Type 2 houses the datapod recorder in a shelter on a

Table 3-1

Wadis Investigated for Proposed Gauging Stations

Wadi Name	Location	Recommended	Type
Ahin	Near Hayl	Yes	Baseflow
Ahin	Above Confluence with Wadi Hashimi	Yes	Type 1
Ahin	Near Maydah	Yes	Type 1
Ahin	At Al Wuqbah	Yes	Type 1
Dayqah	Between Mazara & Hayl Al Ghaff	No	—
Halfayn	Near Adam	Yes	Type 2
Halfayn	At Izki (Present Gauge Site)	Yes	Type 2
Hashimi	Near Wadi Ahin	Yes	Type 1
Jizzi	At Present Gauge Site	Yes	Type 1
Khaburah	At Highway	Possible	Type 1
Lusayl	Above Wadi Jizzi Dam	Yes	Type 2
Mabrah	Near Mabrah	Yes	Type 1
Mabrah	At Highway	Yes	Type 2
Sarin	At Highway	Yes	Type 1
Shafan	At Mountain Gap	Yes	Type 1
Shafan	At Highway	Yes	Type 1
Sudari	Near Confluence with Wadi Ahin	No	—
Taww	At Halban	Yes	Type 2
Taww	At Highway	No	—

bank safe from flood damage. The transducer housing is the same as in Type 1, except that it is anchored to a large cement block embedded in the wadi bed or to bedrock.

Each site was investigated with the following considerations in mind:

- Feasibility of indirect discharge measurements—whether the site was a slope-area reach or a roadway crossing, the ability to make accurate measurements was of primary concern

- Accessibility—the ability to reach the station after a flood is a major consideration when the wadi channel itself is the route of access

- The need for a gauge at the location and the benefits it would provide

- The gauge configuration (Type 1 or Type 2) best suited for the site

Detailed descriptions of the site investigations are provided in the Appendix. Each site was marked with paint for easy identification. Photographs were taken, grid coordinates were recorded, and a road log or map to the site was completed. A file on each site was left with the Surface Water Department.

Time did not permit the reconnaissance of several other sites considered suitable for new gauge stations. They are listed in Table 3-2 and should be investigated.

Table 3-2

Gauge Sites Suggested for Investigation

Wadi Name	Location	Type
Adawnib	At Highway Near Salalah	Wadi
Aiden	At Highway Near Airport	Wadi
Bani Ghafir	Near Hawqayn	Baseflow
Bani Kharus	Near Abyad	Baseflow
Jafnayn	Near Jafnayn	Wadi
Khabbah	Near Gubrat At Tam	Wadi
Nar	At Highway Near Salalah	Wadi
Thimrin	At Highway Near Salalah	Wadi

8.2 Network Maintenance and Operation

The Surface Water Department has a sound plan to maintain the network during and after expansion. It is in the process of hiring 6 surface water hydrologists, 5 senior technicians, and 17 field technicians for its district offices, each of which will have a senior technician or surface water hydrologist supervising one or two field technicians. Field technicians will install, maintain, and operate rainfall, wadi, and aflaj gauges and be responsible for:

- Visiting wadi gauging stations regularly to ensure that equipment is well calibrated and in good working condition
- Visiting sites after floods to survey for indirect measurements and retrieve data from dataloggers and strip charts
- Processing raw data at the office to determine peak discharges and flood volumes
- Continuously updating rating curves and the flood information database

The installation of gauges at the recommended sites and the investigation of other sites should not be postponed. Data should be accumulated even if immediate processing is not possible and data have to be stored for later analysis and incorporation into the database

8.3 Equipment Upgrade

The Surface Water Department plans to upgrade 86 gauging stations by the end of 1991 so as to:

- Improve access to dataloggers and pressure transducers for data extraction and equipment maintenance
- Reduce sediment infiltration to the transducer housing by installing a series of nested screens and placing rounded and washed gravel between the outer two screens
- Replace datapod housings with instrument shelters, where possible, to protect recording instruments and remove them from areas where they are susceptible to water damage

8.4 Selected Representative Basin

The Wadi Ahin basin is recommended for a representative basin pilot study because it has several advantages:

- The wadi is already gauged at the mountain gap and the coast
- There are three rain gauges in the basin and a fourth may be reactivated
- It has an ideal site for a baseflow gauge
- The basin is near the Sohar office, which can provide support for the maintenance and operation of the network

Wadi Ahin is well contained as it flows over the coastal plain and is ideal for a series of crest gauges between the mountain gap and the coast to determine where recharge on the coastal plain occurs. Sites for the crest gauges were not selected in this study.

Chapter 9

COST ANALYSIS

The capital and long-term costs of 30 new gauge sites are summarized in Tables 3-3 and 3-4.

Capital Costs

Planning and preliminary costs cover the time and resources required for a consultant to site new gauges. An average of 8 hours of consultant time per gauge is estimated for selection at the office and verification in the field. Construction and inspection costs are based on the installation of 30 gauging stations, 10 with Type II shelters and 20 with datapod shelters, assuming two days per gauge installation. Costs include consultant supervision of the construction at R.O. 225 per day. Datapod loggers and transducers will cost R.O. 1,600 each, Type II shelter setups will cost R.O. 400 per station for materials and fabrication, and datapod housings will cost R.O. 120 per station. Costs of 30 transducer housings are figured at R.O. 220 each, and of 4 crest gauges installed at each site at R.O. 50 each. Construction costs are figured as a lump sum for a five-man crew with one engineering supervisor, a truck and an air compressor, and miscellaneous expenditures of R.O. 4,000. Final calibration of the datapod and transducer and surveying in elevations are estimated to cost R.O. 100 per site. The total capital cost of 30 gauging stations is estimated at R.O. 129,000, or R.O. 4,300 per station.

Long-Term Costs

Long-term recurrent costs are based on the assumption that within 10 years all 30 datapod loggers will have to be replaced. The average annual cost for these will be R.O. 4,800. Crest gauges and transducer housings are often damaged by flood debris and rendered inoperable by silt deposition. Annual replacement costs for these are estimated at R.O. 1,800—the replacement of one gauge every other year at R.O. 2,000, and of crest gauges, transducer cables, and transducer housing every other year at R.O. 1,600. If gauges are inspected once a month, two men at four hours per station will cost R.O. 580 per station annually. If two floods per station occur annually, a survey crew of two men working eight hours at R.O. 5 per hour to gather slope-area data will cost R.O. 160 per year. Reduction and processing of data, including the updating of rating curves and databases, will cost R.O. 200 per station annually. Total estimated recurrent costs will be R.O. 1,160 per station.

9.1 Costs and Benefits

Estimating surface water recharge to aquifers on the coastal plain and in the interior is essential to setting safe pumping rates. The two methods of obtaining data are a dense rain

Table 3-3

Capital Cost Schedule

Item or Cost Center	Quantity	Unit Price (R.O.)	Amount (R.O.)
PLANNING AND PRELIMINARY			
Consultant Siting of Gauges	30	250	7500
Misc. Planning Outlays	L.S.	1000	1000
PLANNING AND PRELIMINARY SUB-TOTAL			8500
CONSTRUCTION AND INSPECTION			
Inspection and Supervision	60 days	225	13500
Datapod Loggers & Transducers	30	1600	48000
Type II Shelters	10	400	4000
Datapod Housings	20	120	2400
Crest Gauges (Avg. 4 per Site)	120	50	6000
Transducer Housing	30	220	6600
Construction Costs	L.S.	37000	37000
Survey and Calibration	100	30	3000
CONSTRUCTION AND INSPECTION SUB-TOTAL			120500
APPROX. TOTAL PROJECT COST			129000
APPROX. CAPITAL COST PER GAUGE			4300

L.S. = Lump Sum

gauge network and a strategically placed wadi gauging network. The capital cost of installing a rain gauge network for dependable rainfall-runoff modeling is enormous when compared with that of a wadi gauging network which measures runoff directly. Even with a dense rain gauge network, some wadi gauging would be required to determine water loss to the sea. Thus, the most cost-effective method of estimating recharge is a well-planned and properly maintained wadi gauging network.

Wadi gauging is also useful for flood studies and for determining the economic feasibility of various investments. From the calculations in this report, it would cost R.O. 16,000 to install

Table 3-4

Long-term Recurrent Costs (Based On a 30-Gauge Network)

Item or Cost Center	Interval	Annual Cost Per Gauge (R.O.)	Total Annual Cost (R.O.)
Replacement of Datapods	10 Years	160	4800
Replacement of Damaged Gauge Structures	Continuous	60	1800
Gauge Inspection (8 hr/mth @ R.O. 6/hr)	1 Month	580	17400
Surveying for Discharge Measurements	6 Months	160	4800
Reduction and Processing of Data (20 hr/yr @ R.O. 10/hr)	Continuous	200	6000
Approximate Annual Totals		1160	34800

one wadi gauge and maintain it for 10 years. But this gauge would supply critical information in determining whether recharge dams costing between R.O. 1.5 million and R.O. 50 million are technically feasible or even necessary. On a smaller scale, the same wadi gauge would supply flood recurrence information on which to base sensible restrictions on construction in flood-prone areas.

Chapter 10

TRAINING

Nothing hinders the operation of the Surface Water Department more than the lack of trained technicians. Most new technicians need substantial course and on-the-job training to expand the knowledge with which they enter. There are plans to send some of them for additional course work, but it takes time to obtain government approval. In general,

- Lack of fundamental math skills limits the type of work many technicians can perform. This should be the first area strengthened through course work.

- Map reading is a practical skill which most technicians lack. Simple exercises with orienting maps to find specified locations would be useful. Creative training ideas like competitive map and compass courses might be an effective way to spur interest.

- Understanding how their work relates to the Ministry's goals will give more meaning to their daily tasks. Thus, learning how wadi flow data can influence the design of a large recharge structure will stimulate more interest in what they do.

- If Omanis eventually are to run the Surface Water Department, they must have an understanding of hydraulics and hydrology. Promising technicians should be singled out for extended training.

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Appendix

FIELD RECONNAISSANCE NOTES

WADI AHIN BASEFLOW GAUGE AT AL ASHAKHARIN
DM559567 (NG 40-14F)
Tuesday, June 11, 1991

A baseflow gauge was suggested for measuring throughflow leaving the Wadi Ahin upper basin and for inclusion in the proposed representative basin study (WASH Tasks 3 & 4). Two sites were located near the present JICA gauge.

Site #1
The site is located below a large house off the road into the village. Directions to this site are as follows:

> Take the main road into Hayl and turn left at the sign saying "To Jabal Al Ashakharin." Follow this road for 2.3 km (past the rain gauge on the left), at which point a road turns off towards a large house on the right. Take this road around the left side of the house to the bottom of the hill behind it. Go through the garden (there is a falaj) and down to the wadi where the water flows over bedrock.

This is an ideal site for a weir to measure the baseflow of the wadi. At the time of the visit, the water was much lower than the villagers claimed was normal during the winter months. A "V" shaped weir conforming to the general shape of the bedrock could be easily constructed and rated. It would have to be approximately 2 m across to handle the higher water levels encountered in the winter months.

Site #2
The site is located 250 m to 350 m downstream from the existing JICA gauge and just upstream from the last group of date palms on the left bank. The stream at this point is about 2 m wide. The weir would be approximately 6 m to 8 m in length. On the right bank no digging would be necessary, but on the left bank approximately 1 m of alluvium would have to be removed to anchor the weir into bedrock.

WADI AHIN ABOVE MOUTH OF WADI HASHIMI
DM448566 (NF 40-2B)
Tuesday, June 18, 1991

A gauge was suggested here as part of the Wadi Ahin Basin representative study (WASH Tasks 3 & 4)

This site on Wadi Ahin is only fair for slope-area measurements, and access further up the canyon is so poor that gauge locations are limited. One reasonable site was located about 400 m-500 m above the mouth of Wadi Hashimi. A smaller wadi joins Ahin just upstream from the Wadi Hashimi confluence on the left bank. The proposed location is on the left bank about 200 m upstream from the entrance of this smaller wadi. High-water marks are poor to fair on the left bank, and none were found on the right bank. Marks are better about 100 m downstream on the left bank, but the channel is expanding at this location and the incoming wadi appears to be causing backwater conditions. The right bank consists of very fine sands and vegetation and will not hold debris lines for very long after a flood. The low flow is marked by alkali deposits and moves from the left to the right bank in the course of the reach. Within the slope-area reach the channel appears to diverge slightly. A red reference mark was painted on the left bank ledge. A datapod housing with type 4 screen is recommended.

WADI AHIN NEAR MAYDAH
DM430610 (NF 40-2B)
Tuesday, June 18, 1991

A gauge was suggested here as part of the Wadi Ahin representative basin study (WASH Tasks 3 & 4)

A gauge is recommended just below the confluence of the east and west forks of Wadi Ahin. The proposed site is about 200 m-300 m below the confluence and is an excellent location for a gauge. Four excellent high-water marks were located on the left bank and a few dependable marks were found on the right bank. A 1 m cemented gravel ledge in the center of the channel contains the low flows and provides a good anchor for a datapod housing and type 4 screen. The reach is straight and the cross-section very constant. A red reference mark was painted on the cemented gravel ledge. The site is just downstream from a house on the left bank.

WADI AHIN AT AL WUQBAH
DM430906 (NF 40-2B)
Tuesday, June 18, 1991

A gauge was suggested here as part of the Wadi Ahin representative basin study (WASH Tasks 3 & 4). The wadi was investigated along several kilometers. Two sites were selected.

Site #1
This is about 400 m-500 m upstream from a mosque on the left bank. The reference mark is painted on a rock about 40 m downstream from the only house on this part of the right bank. The main channel is narrower here. The left bank is sloped and the right bank is steep and rocky. The channel is divided at very low flows but moderate-to-high floods should fill it. High-water marks on the right bank should be well preserved where attainable, but those on the left bank will probably be disturbed shortly after an event.

Site #2
The second site is located 150 m-250 m upstream from the first site, also on the right bank. At this cross-section a resident of the village confirmed that the flow is divided for all but very large floods. The slope-area reach is good for high flows, but two gauges would have to be installed to measure smaller flood discharges accurately. High-water marks were good on both banks, which are similar to those in the first site, but the channel is much wider.

WADI DAYQAH BETWEEN MAZARA AND HAYL AL GHAF
FL965050 (NF 40-3F)
Sunday, June 9, 1991

A gauge was suggested here to gather information about recharge into the limestones of this wadi.

Excessive scouring, alluvium deposition, and lack of debris lines because of steep bedrock walls in this wadi make this a poor site for indirect measurement. In addition, access was very difficult at the time of the visit and would be much worse after a major flood.

WADI HALFAYN NEAR ADAM
EK688083 (NF 40-7E)
Thursday, June 6, 1991

A gauge was suggested on this wadi to learn about flows entering the interior (Curry, 1991).

This site is located in the main channel of Wadi Halfayn approximately 7 km above its confluence with Wadi Dawh. The wadi was investigated up and down stream about 10 km to 15 km and the only possible site was found on the right bank at the base of a large rock outcrop. The channel at the site is 150 m-200 m wide. Extreme high-water marks on the right bank were approximately 4 m above the channel bed. The main channel will contain low and moderate flows and there is a wide overflow area for high flows. The reach is fairly straight and the slope appears reasonably constant. Some backwater conditions are apparent from the debris lines. The screen can be anchored in the rock outcrop and a shelter stationed above, well protected and easily accessible. This configuration would require 30 m of pipe.

WADI HALFAYN NEAR IZKI
EL738426 (NF 40-7B)
Thursday, June 6, 1991

The gauge at this site is no longer effective because of excessive bed scour and needs to be relocated. Two new locations were chosen.

Site #1
The first site is on the left bank about 300 m downstream from the present datapod gauge. A datapod housing with a type 4 screen could be used. A type 2 shelter with a type 3 screen and 18 m of pipe would also be effective. One CSI wall mount and two conventional mounts would be required.

Site #2
The second site is about 1 km downstream from the present datapod gauge on the right bank. At low flow the earthen road crossing the wadi will provide good control, but at high flow it may wash away and the rating may change. A type 2 shelter with a type 3 screen could be used and the CSI mounts would be conventional. From a construction standpoint this site is easier than the first. Channel expansion below the chosen gauge locations prohibits placing the new gauge any further downstream.

WADI AL HASHIMI
DM444878 (NF 40-2B).
Tuesday, June 11, 1991

This site was suggested as part of the Wadi Ahin representative basin study (WASH Tasks 3 & 4).

Directions to the site are as follows:

> Follow the Wadi Ahin road from Sohar 58.4 km to where it leaves Wadi Ahin and turns up the Wadi Al Hashimi channel. Drive up the road 0.8 km to where it leaves the wadi channel up the left bank. Instead of following the

road, continue up the wadi about 0.6 km past a large tree in the channel. The proposed gauge site is on the right bank.

The low flow at this site runs along the right bank. Both channel sides are bedrock and the reach is sufficiently straight and long to obtain three good cross-sections. One very good high-water mark was found on the left bank, but the quality of debris lines at extremely high flows is uncertain. There is some growth on the right bank above the main channel where the gauge would be installed, but it would not cause any serious backwater effects. A datapod housing with a type 4 screen is recommended.

WADI JIZZI AT PRESENT GAUGE SITE
DM388643 (NG 40-14E)
Wednesday, June 19, 1991

Low flow at the present Wadi Jizzi gauging site shifts back and forth from the left to the right bank as the bed changes after major floods. The visit was to see if a new site might capture low flow under all conditions.

Alkali stains indicated that the low flow occurs on the right bank where the gauge is situated. The stains cross from the mouth of Wadi Hayl upstream on the left bank to the right bank, where they continue for some distance down the slope-area reach. An additional gauge should be placed on the left bank directly across from the present gauge. A datapod housing with a type 4 screen is most suitable. The current crest gauges need to be checked and cleaned and the existing datapod should also be inspected.

KHABURAH, LOCAL DRAINAGE AT HIGHWAY
EM140899 (NF40-3A)
Wednesday, June 19, 1991

A reasonably large wadi from local drainage crosses the highway in Khaburah and is conveyed beneath the highway through two box culverts and two circular pipes. A gauge might be considered here.

A datapod housing with type 4 screen could be installed at the inlet to the culverts, which are 2.7 km south of the Khaburah roundabout. Flood studies are underway in this area, and deployment of a gauge should be postponed until their findings have been presented.

WADI LUSAYL ABOVE CONFLUENCE WITH WADI JIZZI

DM488655 (NG 40-14E)
Wednesday, June 19, 1991

This wadi contributes flow to the Wadi Jizzi Dam, and a gauge is suggested to collect discharge data (Curry, 1991).

The wadi was inspected upstream about 3 km to 4 km from the selected site and downstream to its confluence with Wadi Jizzi. The proposed location is well protected and high-water marks on the right bank are very consistent. There is some question as to whether backwater conditions from the filling dam may hinder slope-area measurements. Before a gauge is placed here, it may be a good idea to perform a slope-area measurement of a recent flood to verify this. The right bank is a steep rocky cliff and the left bank slopes upward gently. Low flow occurs in a single channel along the cliff on the right bank. The proposed location will include flow from a wadi that enters about 1 km upstream and will avoid divided flow, which is prevalent along most of the wadi investigated. Access to the site is along a well-developed road and requires about 1 km of off-road driving. A reference mark was painted on the rock at the proposed site. At high flows the channel is very wide and some trees grow in the flow path. High-water marks on the left bank are not as distinctive as those on the right bank. A type 2 shelter with a type 3 screen may be installed, requiring approximately 25 m of pipe.

WADI MABRAH NEAR MABRAH

EM126186 (NF 40-3A)
Monday, July 1, 1991

A gauge is suggested here in conjunction with another at the highway to determine recharge volumes (Curry & Johnson, 1991).

The proposed location is on the right bank about 100 m to 200 m upstream from where the road leaves the wadi on the left bank. The wadi was checked about 1 km upstream from the road crossing, but no satisfactory sites were found. Access further upstream through the wadi would be difficult after a major event. This channel is cut through cemented gravel and the banks are steep. There are a few locations where the banks have collapsed and left reasonable slopes from which debris lines might be obtained. These collapsed banks, however, are not very stable, and dependable high-water marks would have to be surveyed soon after an event. At the selected location, the channel begins to diverge downstream. The proposed gauge site will detect low flow, and the rating curve could be developed from slope-area measurements just upstream from the station, where they would be more accurate.

WADI MABRAH AT THE HIGHWAY

EM244209 (NF 40-3A)
Monday, July 1, 1991

A gauge is suggested here in conjunction with another near Mabrah to determine recharge volumes (Curry & Johnson, 1991).

This wadi intersects the highway 17.1 km southeast of the main Khaburah roundabout. There is a bridge over the wadi here and a crest gauge. The bridge columns could be used to anchor a float gauge here, or a datapod housing with a type 4 screen could be installed.

WADI SARIN AT HIGHWAY CROSSING

FL779472 (NF 40-3F)
Sunday, June 9, 1991

Existing gauges upstream from this location have been damaged and only crest-stage indicators remain. A new gauge is recommended at the highway crossing (Curry, 1991).

Low flow occurs along the left bank and in the middle of the channel. The gauge can be installed on a rock on the left bank. There is a large building at the top of the cliff above the site. A datapod housing with a type 4 screen and conventional CSI mounts is recommended. Just upstream from the gauge location the channel is divided by a rock outcrop. At extremely high flow the upstream cross-section of the slope-area reach may cross this channel division.

Another possibility is to station the gauge beneath the bridge, where the cross-section will not change. The cross-section could be rated from slope-area measurements upstream.

WADI SHAFAN AT MOUNTAIN GAP

DM738984 (NF 40-2C)
Tuesday, July 9, 1991

A gauge is suggested here in conjunction with another at the highway to determine discharge volumes (Curry & Johnson, 1991).

Terrain in the vicinity limits wadi access to just a few points. The wadi was investigated up and downstream 2 km in each direction from where the catchment narrows down. Most sites visited were unsuitable for slope-area measurements. One good site was found just below the village of Bu'ayq (DM737783), but it did not include flow from Wadi Kanut, which enters Shafan 700 m below the site. The selected site on the right bank was marked in silver paint; a map gives detailed directions to it. There are a lot of jeep trails in the area and it is easy to become disoriented. The gauge can be placed in a reasonably protected site and will pick up low flow on the downstream side of the rock with the reference mark. To rate the station, slope-area measurements will have to be made just upstream from the gauge, where the high-water marks are available and channel conditions are favorable. A datapod housing with type 4 screen is recommended for this station.

WADI SHAFAN AT HIGHWAY
EM052728 (NF 40-3A)
Monday, July 1, 1991

A gauge is suggested here in conjunction with another at the highway to determine discharge volumes (Curry & Johnson, 1991).

The highway crosses the wadi exactly 10 km northeast of the main Khaburah roundabout. There is a crest gauge at the site and the crossing may already be rated. A datapod housing with a type 4 screen is recommended.

WADI SUDARI
No Gauge Sited (NF 40-2B)
Tuesday, June 18, 1991

This site was suggested as part of the Wadi Ahin representative basin study (WASH Tasks 3 & 4).

This is a poor site for slope-area measurements because the wadi is deeply incised and has steep walls, leaving little possibility for continuous high-water marks. On the map there appears to be a small establishment about 3 km upstream from the mouth, and a site may exist there. Time did not permit investigation of this. One possibility here might be to rate the channel by the step-backwater method. Crest stage indicators could be used to verify the water slope.

WADI TAWW NEAR HALBAN
FM004932 (NF 40-3C)
Saturday, June 15, 1991

A gauge was suggested here in conjunction with another at the highway to determine recharge volumes and gather data for a dam being built on Wadi Taww (Curry, 1991).

Some slope-area measurements were made in the vicinity of this site in the early 1980s. It was hoped that the new gauge could be located at the same site to take advantage of previous measurements for rating. Unfortunately, old reference marks could not be located and the earlier measurements could not be verified. Two possible sites were selected.

Site #1
The first site is 200 m downstream from the road crossing on the right bank. The left bank in this channel reach is moderately sloped and should supply good high-water marks. The bed in this reach slopes gently down to the right bank where a cemented gravel ledge contains the flow. The reach is straight and does not appear to expand excessively. On the topographic map the channel is shown to split about 500 m below the road crossing, but the selected site is above this point. Time did not permit much exploration below the selected site. A type 2 shelter with a type 3 screen is ideal for this location. Approximately 10 m of pipe would be required. A reference mark was painted on the cemented gravel wall of the right bank but will probably be washed away by the first major flood.

Site #2
The second site is 100 m to 200 m downstream from the Halban date palm gardens. The channel bed here is cemented gravel and clear of any loose sand and gravel. Bank to bank flow at this point is around 75 m and well contained. Just downstream from the site extremely high flows will overtop the bank and spill into another channel that appears to join the main wadi again 1 km downstream. High-water marks on the moderately sloped left bank were fair, but good marks should be seen if the site is visited shortly after an event. The right bank is steeply sloped cemented gravel and high-water marks will probably not be as dependable as on the other bank. The gauge would have to be stationed in a 1 m deep baseflow channel cut through bedrock at the center of the main channel. A datapod housing with a type 4 screen is the only arrangement possible. The gauge will probably have sufficient protection from flood debris, but high velocities and turbulence in this baseflow channel should be considered.

WADI TAWW AT THE HIGHWAY
FM011867 (NF 40-3B)
Saturday, June 15, 1991

A gauge was suggested here in conjunction with another near Halban to determine recharge volumes and gather data for a dam being built on Wadi Taww (Curry, 1991).

The main channel of this wadi where it intersects the highway has been filled, with no apparent consideration for allowing the flow to pass the road. Downstream from the highway the channel has been filled in and is now a farm. Water flows over the road at this crossing only during very high discharges; otherwise it flows parallel to the highway and passes beneath the road through several culverts. The flow is not contained info one road crossing. In addition to this complication, a dam is scheduled to be built upstream from the highway.

It is recommended that consideration of this site be postponed until dam construction is complete and the main discharge channel has been determined.

REFERENCES

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