Journal of Arid Environments (1995) 31: 349–369

Techniques of ground-water recharge estimates in arid/semi-arid areas, with examples from Abu Dhabi

W. R. Osterkamp, L. J. Lane & C. M. Menges

U.S. Department of the Interior, Geological Denver Federal Center, Denver, Colorado, U.S.A.

(Received 23 November 1993, accepted 10 June 1994)

A water-balance approach to estimate ground-water recharge is developed for ungaged basins of Oman and Abu Dhabi, United Arab Emirates. The technique uses a distributed transmission-loss model for ephemeral streamflow in arid/semi-arid areas that is calibrated using relations between channel morphology and discharge characteristics, and between drainage-basin areas and flood magnitudes. Inputs for the transmission-loss model, including precipitation, may be determined using geomorphically established outflows from selected basins. Recharge is estimated by routing discharge of an index storm downchannel, accounting for channel losses and adjusting for interchannel recharge during low-frequency precipitation events.

©1995 Academic Press Limited

Keywords: ground-water recharge; transmission-loss model; Abu Dhabi; Oman

Introduction

Sound water management in arid and semi-arid areas generally requires quantification and modelling to ensure that rapid depletion of the ground-water resource does not occur. Reliable data from these areas are often sparse, and several components of a water budget, particularly ground-water recharge, may be difficult to measure or estimate. Various approaches to recharge approximation for sites or small areas, such as lysimeters, neutron tubes, tensiometers, and other types of instrumentation to measure soil moisture or evapotranspiration, are useful for small-scale studies, but have limited utility at watershed and areal scales. At these scales, for areas of 10^1 to 10^3 km^2, estimation of recharge for ground-water modelling generally has used empirical water-balance approaches in which recharge is a function of precipitation or runoff. These approaches require reliable precipitation or runoff data, neither of which are usually available in arid/semi-arid areas undergoing economic development.

This paper proposes an empirical water-balance approach to the estimation of ground-water recharge for hydrologic modelling at watershed to areal scales. The method differs from previously developed water-balance approaches by being based largely on a distributed transmission-loss model for channelized streamflow (Lane, 1982, 1985) that is calibrated using established relations between channel morphology

0140–1963/95/030349 + 21 $12.00/0 © 1995 Academic Press Limited

and discharge characteristics, and between drainage-basin area and flood magnitudes. Thus, input variables for the transmission-loss model, including precipitation if data are otherwise unavailable, are determined using geomorphically established outflows from selected drainage basins and these input variables are then applied to model calculations for other drainage basins. Recharge is estimated by routing index discharges, resulting from an index storm, downchannel, accounting for channel losses during these flows, and adjusting to account for interchannel recharge during low-frequency precipitation events.

Overview of technique

A variety of techniques has been developed to estimate transmission losses from ephemeral stream channels. Among these techniques are loss-rate equations for known inflows (Burkham, 1970), inflow-loss power relations (Lane *et al.*, 1971; Sinha & Sharma, 1988), simple differential equations for loss rate (Jordan, 1977; Lane, 1980), storage routing as cascading leaky reservoirs (Lane, 1972; Wu, 1972; Peebles, 1975), and kinematic-wave/infiltration models (Smith, 1972). All of these techniques depend on either (1) specified inflows that are routed downchannel, or (2) magnitudes and distribution of precipitation events that can be converted to an indirect measure of streamflow.

Summary of the model

Techniques described in this paper are derived largely from a distributed runoff-simulation model for estimation of runoff volumes and peak discharges from watersheds of arid and semi-arid areas (Lane, 1982). Use of the model for a flow event at two or more sites along an ephemeral-stream channel provides comparisons of discharges and therefore transmission losses between sites (Lane, 1983). The model computes runoff volume, V_a, from upland areas of stipulated runoff characteristics resulting from a precipitation event, P, of specified magnitude (depth) and duration characteristics:

$$V_a = \begin{cases} 0 & P \leq 0{\cdot}2S \\ \dfrac{(P - 0{\cdot}2S)^2}{P + 0{\cdot}8S} & P > 0{\cdot}2S \end{cases} \qquad \text{(Eqn 1)}$$

The runoff characteristics of upland surfaces, and expressed by the curve number (Soil Conservation Service, 1985), are used with empirically determined relations for retention of soil water, S, to yield threshold-dependent estimates for streamflow. Peak discharge, Q_p, and duration of streamflow, D_s, are calculated as functions of both precipitation (runoff volume) and drainage-basin area, A:

$$Q_p = d(V_a / D_s) \qquad \text{(Eqn 2)}$$

$$D_s = yA^h \qquad \text{(Eqn 3)}$$

where d is a coefficient expressing hydrograph shape for watersheds of arid and semi-arid areas, and y and h are parameters determined empirically from hydrograph analysis.

Routing a floodwave down an ephemeral-stream channel to yield estimates of infiltration or transmission losses is accomplished through a time-averaging process to

produce an ordinary differential equation describing losses in terms of channel length, X, channel width, W, upstream inflow, V_u, lateral inflow, V_l and hydraulic conductivity of channel alluvium (Lane, 1982, 1985):

$$dV_u/dX = -gW - pWV(X,W) + V_l/X \qquad \text{(Eqn 4)}$$

the solution of which is:

$$V(X,W) = m(X,W) + n(X,W)V_u + F(X,W)V_l/X \qquad \text{(Eqn 5)}$$

in which $V(X,W) \geq 0$ is the outflow volume, g is a parameter in the differential equation (Eqn 4) for loss rate of flow, p is a decay factor in the differential equation for loss rate, m (X,W) and n (X,W), respectively, are the regression intercept and slope for a channel of specified length (X) and width (W), and F (X,W) is a lateral-inflow coefficient.

Use of the transmission-loss model requires inputs of contributing areas of runoff for upland and lateral area, channel dimensions, hydraulic conductivity of channel alluvium, mean annual precipitation, and magnitudes of storm events and runoff properties for each of the watershed elements. Model output consists of single-storm, or event, water-balance estimates for runoff, expressed as volumes and percentages of rainfall, channel loss, and overland loss relative to a site at a specified channel length. Also provided are estimates of peak discharge from the watershed elements and mean annual runoff. Primary assumptions and restrictions in the model include:

(1) Runoff characteristics and precipitation magnitudes and duration specified for subwatershed elements are uniform over those elements.
(2) Streamflow occurs only by overland flow to channels; all flow in channels results in transmission losses and flow reduction.
(3) No streamflow occurs until a threshold volume has been satisfied; inflow volumes in excess of the threshold are linearly related to outflow volumes.
(4) Channel properties are uniform with length, but as a floodwave without additional runoff contributions is routed downchannel, values of hydraulic conductivity and channel width can be changed to reflect changing conditions in bed material and channel morphology.
(5) The volume and storage capacity of unsaturated alluvium available to receive recharge from a flow event is large relative to the volume and infiltration rate of recharge water; that is, rejection of recharge does not occur.

The runoff-simulation model described here, as well as the other approaches cited, is event-based and does not provide a long-term estimate of mean recharge useful in modelling of large ground-water systems. To convert from a single-event, water-balance model to a representation of water fluxes through decadal or longer temporal scales, an integration of events to a measure of mean runoff and infiltration is required. Two related methods, both geomorphic, to accomplish this scale transition are suggested. Conversion to a time-integrated estimate of ground-water recharge in arid/semi-arid areas necessitates consideration of possible interchannel recharge during low-frequency precipitation events; a technique to incorporate this component of total recharge is also suggested.

Geomorphic inputs

Records adequate to define long-term precipitation averages in arid and semi-arid watersheds are scarce, and streamflow records of sufficient length to yield dependable discharge characteristics for highly ephemeral streams are rare. Two indirect methods to evaluate runoff are described here, and either can be used as model input.

Channel-morphology/discharge relations

A widely used technique to estimate discharge characteristics at ungaged sites on streams is the development of channel-geometry relations (Hedman, 1970; Hedman & Osterkamp, 1982; Osterkamp & Hedman, 1982). The basis of the channel-geometry technique is that alluvial stream channels are self-adjusting to accommodate the flows that they convey. By measuring channel properties, especially geometry, at numerous sites of known discharge characteristics, power functions for discharges of specified frequency are related to geometry measurements through the continuity equation for stream discharge:

$$Q_i = WDV \qquad \text{(Eqn 6)}$$

where, in consistent units, Q_i is instantaneous discharge, W is flow width, D is mean water depth, and V is mean velocity for a flow at the measured channel section. Expanding Eqn 6 to power form yields:

$$Q_i = k' W^b D^f V^m \qquad \text{(Eqn 7)}$$

where k' is a regression coefficient and b, f, and m are exponents dependent on drainage-basin properties, particularly the amount and sizes of the fluvial sediment load. Equation 7 can be expressed as three simple power relations:

$$Q_i = aW^b \qquad \text{(Eqn 8)}$$

$$Q_i = cD^f \qquad \text{(Eqn 9)}$$

$$Q_i = kV^m \qquad \text{(Eqn 10)}$$

Because Eqns 8, 9, and 10 give an instantaneous discharge for which width, depth, and velocity must be measured, use of the equations is impractical. Water-related measurements, therefore, are avoided by restricting consideration to the geometry of the channel section and the particle-size characteristics of the bed and bank material. The most reliable relations, with the lowest standard errors of estimate (Hedman & Osterkamp, 1982), are those that yield a discharge characteristic, such as mean discharge, Q_a, or a flood with a 5-year recurrence interval, Q_5, from width measurements grouped by channel-sediment properties, climate, or vegetation. Rather than using water-surface widths, channel widths are measured from a geomorphic reference level coincident with a break in bank slope that, for channels of perennial streamflow, generally approximates the stage corresponding to mean discharge. For channels of highly ephemeral streamflow, the stage corresponding to mean discharge is usually lower than the reference level (Fig. 1, A–A'). Using geometry data from numerous gaged sites, power relations between width and discharge characteristics are developed that permit estimates of streamflow at ungaged sites (Hedman & Osterkamp, 1982).

A flow of specified frequency, therefore, can be estimated for an ungaged channel site. If drainage-basin area is known and necessary basin characteristics are estimated, input data to the runoff-simulation model representing a precipitation event with a 5-year return period, for example, permit evaluation and iteration of input variables to represent the field-determined 5-year flow event. Having established input variables, the model is used to route the 5-year flood downstream. Calculated differences in peak discharge or flow volume between any two channel sites provide estimates of transmission losses and recharge to the ground-water reservoir.

Drainage-basin/discharge relations

In inaccessible areas or where channels have been altered and are not readily measured, an alternative approach is the use of area/discharge relations. From gaged channel sites in basins of similar climate, envelope curves are developed to relate

discharge characteristics to drainage-basin area. Data from highly ephemeral streams of the Mojave and Sonoran Deserts, south-western United States (Hedman & Osterkamp, 1982; Osterkamp *et al.*, 1982; Boughton & Renard, 1984), were used to define relations between unit discharges and drainage-basin area (Fig. 2). Among these relations is a curve for the mean-annual flood, $Q_{2\cdot33}$, often defined as the flow with a recurrence interval of 2·33 years. It is assumed that the mean-annual flood in desert areas results from runoff of the mean-annual precipitation event, the storm magnitude of short but unspecified duration having a return frequency of 2·33 years. Casual inspection of streamflow records from various gaged channels of the south-western United States suggests that the volume of flow for $Q_{2\cdot33}$ passing a site on an ephemeral stream channel approximates the volume of mean annual discharge at that site. The mean-annual precipitation, or index, event, therefore, is used among initial input data to indicate a flow volume approximating that of mean-annual discharge. Input values, including the magnitude of the index storm, are modified as necessary to yield an outflow volume that equals the mean-annual discharge indicated by Fig. 2. Program output includes duration of flow, in hours, as determined by a double-triangle unit-hydrograph approach suggested by Ardis (1973) and related to drainage-basin area by Murphey *et al.* (1977).

The approximate equivalency of mean-annual flow volumes to those resulting from the mean-annual floods is suggested by a 20-year daily precipitation record, 1971 to 1990, from the Al Ain Agromet Station, United Arab Emirates (UAE) (Dr H.L.

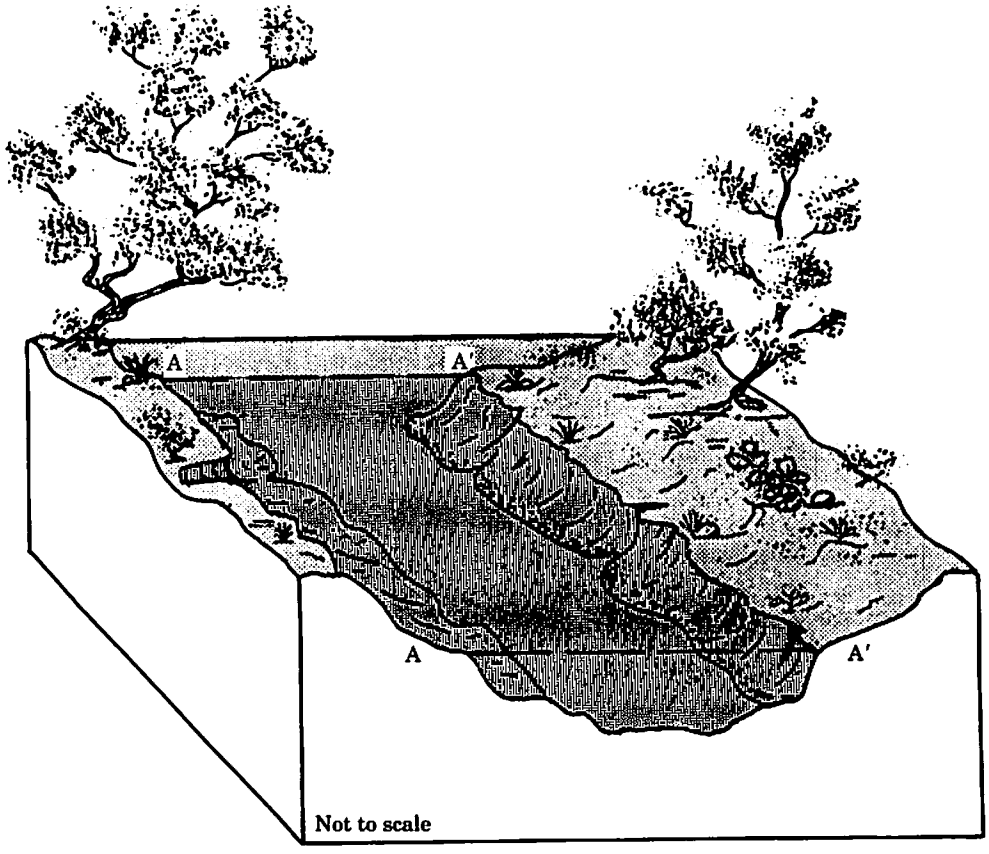

Figure 1. Block diagram of an ephemeral-stream channel, showing the geomorphic reference level, A–A', that is coincident with a break in the bank slope.

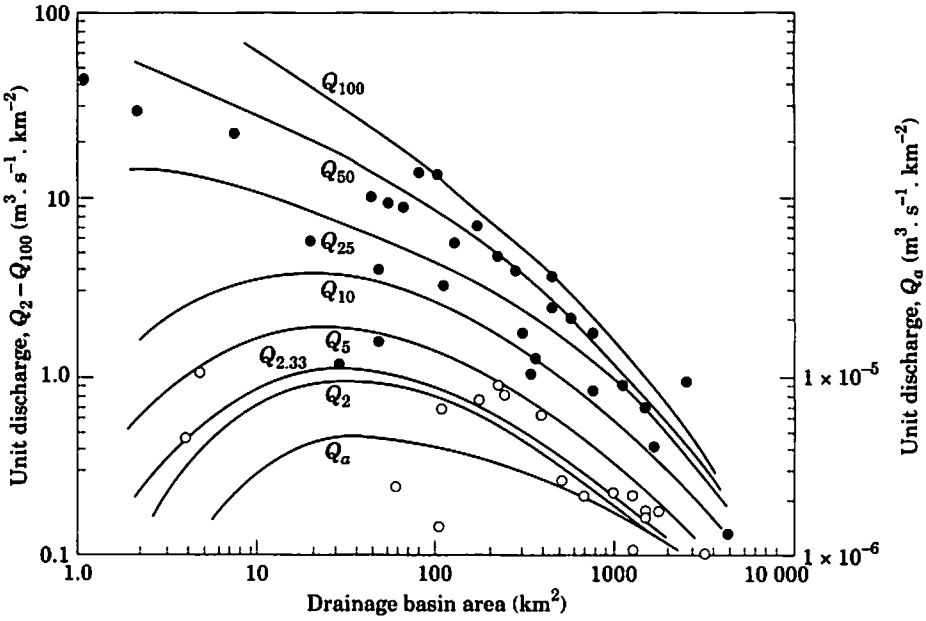

Figure 2. Envelope curves relating discharge characteristics to drainage-basin area, south-western United States. Data are for Q_5 (O) and Q_{100} (●); data not shown define the relations beyond the limits of the graph.

Hamid, National Drilling Company, UAE, pers. comm., 1991) and use of the CREAMS model. The Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model of the U.S. Department of Agriculture (Knisel, 1980) was developed to evaluate non-point-source pollution from agricultural fields. The model contains a water-balance component that permits the sequential calculation of daily runoff, evapotranspiration, soil moisture, and deep percolation (recharge) below the vegetation rooting zone. Computations require records of daily precipitation and estimates of monthly mean temperature, monthly mean radiation, rooting depth, soil properties, and a leaf-area index.

Maximum annual precipitation events, in mm, from the 20-year Agromet record were used to relate peak precipitation amounts, in mm, to recurrence interval (Fig. 3):

$$RI_P = (n + 1)/m \qquad \text{(Eqn 11)}$$

where RI_P is the recurrence interval, in years, of a specified peak precipitation amount, n is the number of years of data (20), and m is the rank (1,2,3,···,n) of the precipitation amount. From Fig. 3, the mean-annual precipitation event ($P_{2\cdot33}$) at Al Ain is 31 mm.

Water-balance summaries for the period 1971 through to 1990 were compiled using the Agromet precipitation record and the CREAMS model. Soil and vegetation variables were estimated from field observations, and temperature and radiation inputs were based on data from Yuma, Arizona, and China Lake, California, respectively, which were selected as sites of similar climate and latitude to those of Al Ain. From the CREAMS-generated water-balance summaries, a regression relation was developed between annual totals (volumes) of runoff (R_a), in mm, and annual peak precipitation amounts (P_P) measured at the Al Ain Agromet Station (Fig. 3), in mm:

$$R_a = 0{\cdot}755P_P - 10{\cdot}6 \qquad \text{(Eqn 12)}$$

(n = 20, R^2 = 0·66, standard error of estimate = 11·6). For a mean-annual precipita-

tion event at Al Ain of 31 mm, an annual runoff total is calculated by Eqn 12 to be 12·8 mm. In comparison, water-balance calculations for 20 years of runoff using the CREAMS model yield an average of 12·7 mm at Al Ain. Thus, use of the runoff volume from the mean-annual precipitation event to approximate total annual runoff volume is assumed to be justified.

The approach suggested here, therefore, whether based on mean discharge estimated from field measurements or from envelope curves relating area and discharge, requires the defining of an index precipitation/runoff event. The flow volume of the index event is a surrogate for mean discharge and is presumed to result in transmission loss and recharge equal to the sum of flow losses that typically occur in a year. If 20% of an index storm of 50 mm is calculated as transmission loss (10 mm), the annual water-budget loss is computed as a 10-mm loss of mean-annual precipitation in the basin, perhaps 5% if annual precipitation averages 200 mm. In this example, channel losses are less than 10 mm during most years, but generally exceed 10 mm in years when the index storm is equalled or exceeded.

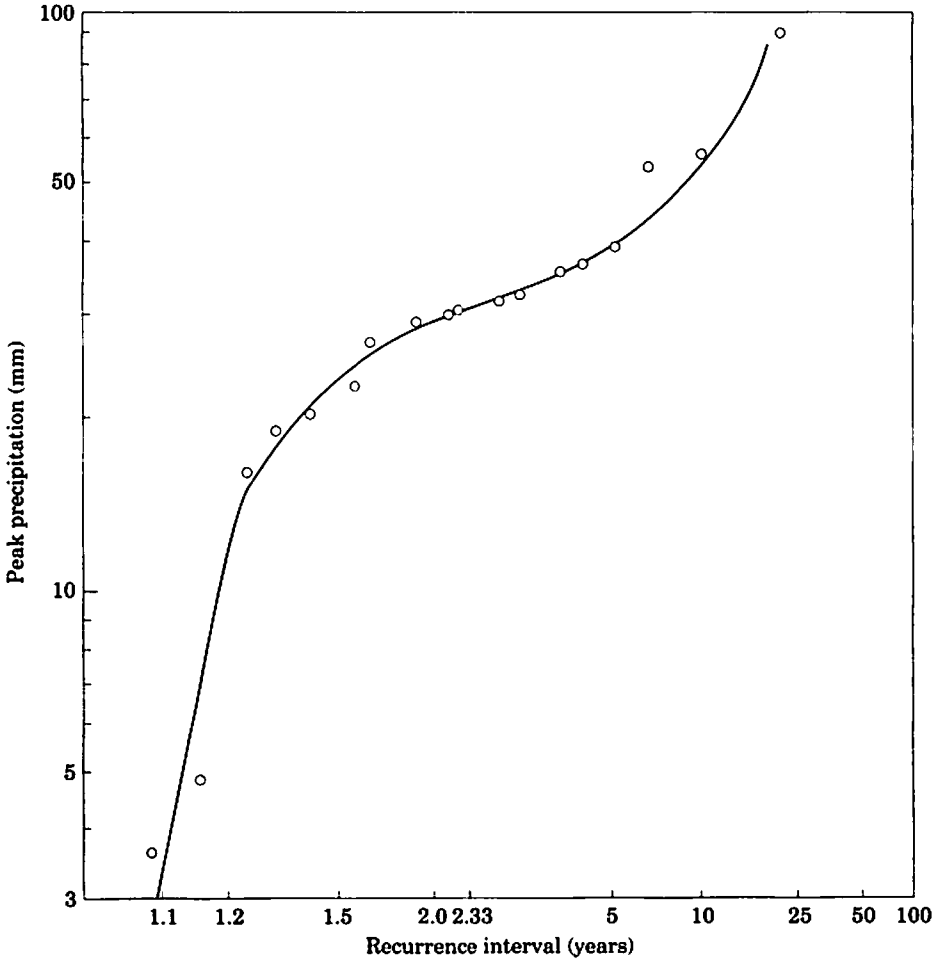

Figure 3. Plot of recurrence intervals for annual peak precipitation events, Al Ain Agromet Station, 1971–90.

Upland recharge

Inter-rill or upland recharge to unconsolidated or poorly consolidated rocks of arid and semi-arid areas is assumed to be a generally small but finite part of total recharge. The runoff-simulation model evaluates overland loss as a water-balance component of precipitation, but does not estimate the amount of overland loss representing ground-water recharge. A technique to account for inter-rill (upland, inter-*wadi*) recharge in arid/semi-arid areas (Lane & Osterkamp, 1991) requires daily precipitation and other input data to the CREAMS model. The technique has the assumption that recharge occurs in uplands and other inter-rill areas when water percolates below the plant-rooting depth, an infrequent occurrence in arid/semi-arid areas that can be evaluated by the CREAMS model. Preliminary results suggest that in areas of the south-western United States with sparse vegetation and high infiltration capacities, several percent or more of mean precipitation may become ground-water recharge. Depending on soil characteristics, high-magnitude storms with return periods of perhaps 10 years or more may be necessary to initiate upland recharge.

Ground-water recharge basins of Abu Dhabi and the Oman Mountains

Ongoing investigations to evaluate and model the fresh to slightly saline ground-water resource of Abu Dhabi, UAE, include efforts to determine rates of mean-annual recharge to the ground-water reservoir. The Emirate of Abu Dhabi is the largest of seven emirates that comprise the UAE, and has a rapidly expanding population and petroleum-based economy. Potable surface-water supplies are meager in Abu Dhabi, which has led to extensive development of ground-water supplies to accommodate economic and population growth.

The Abu Dhabi ground-water studies were proposed by officials of the Emirate of Abu Dhabi. The investigations have been conducted by personnel of the National Drilling Company, Abu Dhabi, UAE, and the U.S. Geological Survey.

Setting

Abu Dhabi, with an area of about 67,000 km^2 or about 80% of the UAE, occupies a north-eastern section of the Arabian peninsula (Fig. 4). Much of the UAE population of nearly 2·5 million lives along or near the northern coastal part of the Emirates, bounded by the Arabian Gulf, and has access to water provided from desalinization plants. A notable exception is the Abu Dhabi city of Al Ain, which lies near the western base of the Oman Mountains about 110 km south-east of the Arabian Gulf coast. Ground water presently comprises most of the water supply for Al Ain and nearby areas of irrigation agriculture; about 8% of the water supply is piped from a desalinization plant at the city of Abu Dhabi (Woodward & Menges, 1991).

The Al Ain area of Abu Dhabi has an arid subtropical climate of high summer temperatures and limited humidity. Precipitation at the Al Ain Agromet Station, 1971 through 1990, averaged nearly 99 mm per year, most of which was from frontal storms in February and March. Based on the 20-year Agromet precipitation record, isohyetal contours developed by Halcrow & Partners (1969) were modified to an isohyetal map for the Oman Mountains-Al Ain area (Fig. 5). The interpretation of rainfall patterns in the Oman Mountains provided estimates of mean-annual precipitation to rainfall-simulation computations.

Surface runoff in the vicinity of Al Ain is largely limited to channels that head in mafic bedrock areas of the Oman Mountains and generally trend west. Streamflow in the western Oman Mountains is mostly on coarse, incised alluvium deposited between

crests of complexly-folded and faulted Triassic to upper Eocene clastic, metasedimentary, and volcanic rocks. Streams emerge from the mountains through gaps cut into overthrust ridges, and then flow westward on Quaternary piedmont deposits before disappearing in eolian sand and silt (Brown *et al.*, 1991; Woodward & Menges, 1991).

Stream channels in the Oman Mountains and where they are incised into valley fill adjacent to the bedrock core are mostly single-thread streams, possibly reflecting neotectonism (Woodward & Menges, 1991, 1992; Menges & Woodward, 1992). Conversely, channels of the piedmont and of the lowermost thrusted and folded areas are aggradational and exhibit complex patterns of braiding and anabranching. Drainage divides and drainage-basin size in many depositional areas are indistinct and may change significantly by shifts in channel position during large flow events.

Recharge to the ground-water reservoir of the Oman Mountains-Al Ain area occurs principally in mountain drainage basins above the gaps in the overthrust ridges. Thus, hydrologic modelling of the ground-water resources in the Al Ain area is largely based on estimates of recharge in 17 basins, numbered consecutively from north to south, draining the west side of the Oman Mountains (Fig. 5). Eight of the 17 basins were divided into two or more subbasins to facilitate use of the runoff-simulation model by routing flows from one subbasin to another. All streamflow leaving the 17 hydrologic basins of the Oman Mountains passes through gaps in the bedrock at the western edge of the mountain front. Calculations of runoff to the gaps provides a basis for estimating water-balance components in the basins upstream and for routing floodflows downstream on the alluvial plain. Constriction of streamflow at or near some gaps results in morphology measurements usable in channel-geometry relations; elsewhere,

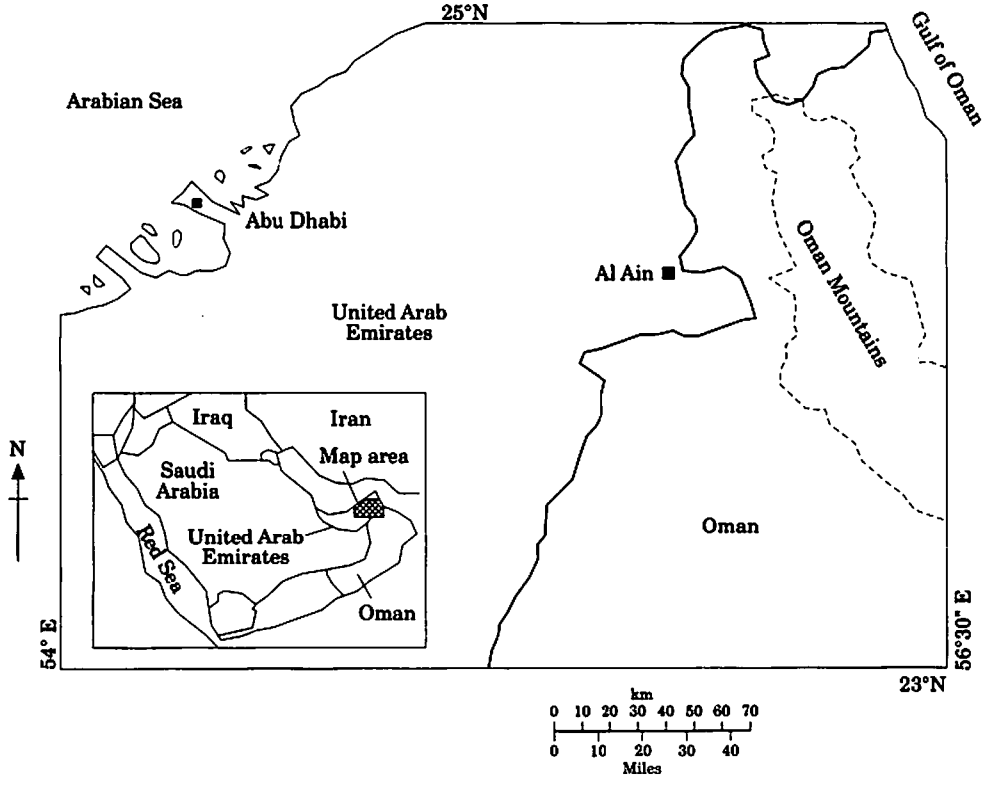

Figure 4. Map of north-eastern Arabian peninsula showing the Oman Mountains–Al Ain area.

channel incisement of valley fill or pronounced braiding on the piedmont largely preclude the collection of reliable channel-morphology data. Gaps are numbered for

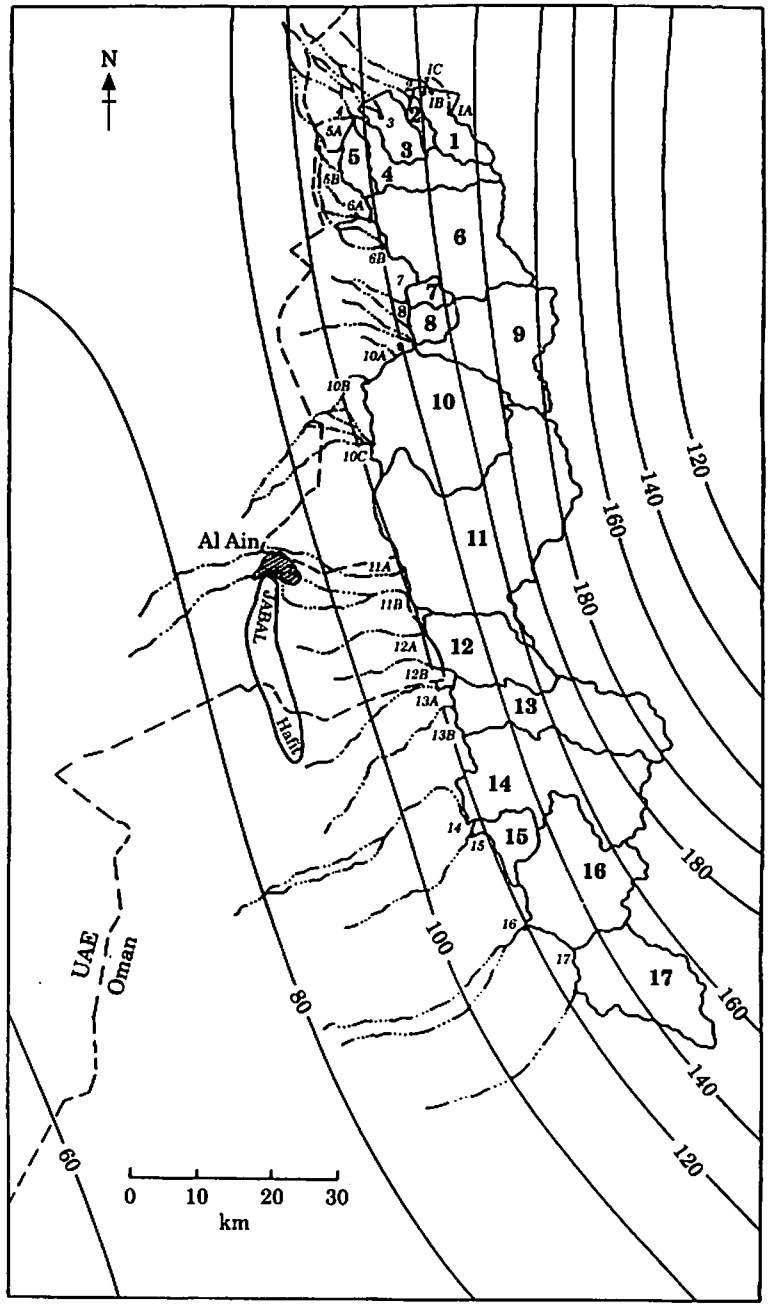

Figure 5. Map of 17 hydrologic basins draining the west side of the Oman Mountains. Bold numbers identify each hydrologic basin; contours (modified from Halcrow & Partners, 1969) are isohyets of average annual precipitation (mm). Italic numbers identify gaps, and paths of flood flows along *wadis* are shown by broken lines.

the basin each drains; outflow from seven basins is split among two or more gaps for which subscript letters are used for identification (Fig. 5).

Recharge

Most ground-water supplies for the Al Ain area are pumped from poorly consolidated Quaternary piedmont deposits and underlying clastic rocks of Miocene to Pleistocene age (Woodward & Menges, 1991). Recharge to the ground-water reservoir occurs mainly as transmission losses along the entire length of *wadis*. Much of the *wadi* recharge that occurs in alluvial basins of the Oman Mountains probably moves through bedrock fractures and is discharged directly into piedmont or fan deposits as subsurface mountain-front recharge along the western edge of the mountains (D.G. Woodward, U.S. Geological Survey, pers. comm., 1992). Inter-*wadi* recharge probably occurs throughout the Oman Mountains-Al Ain area, but for modelling purposes in this paper, inter-*wadi* recharge in the piedmont area west of the Oman Mountains is considered separately. Recharge to valley fill and bedrock fractures above gaps is discharged to fan and piedmont deposits and underlying rocks of the Al Ain area by (1) ground-water flow through *wadi* alluvium and valley fill at gaps, and (2) mountain-front recharge. This paper attempts to quantify these processes of recharge in the mountains with *wadi* recharge below gaps to provide estimates of recharge from mountain-basin precipitation to the ground-water reservoir of the Al Ain area. These estimates, when combined with calculations of inter-*wadi* recharge in piedmont areas west of the Oman Mountains, yield estimates of total ground-water recharge in the Oman Mountains-Al Ain area.

Transmission losses

Ground-water recharge from transmission losses in *wadis* was estimated for each of the 17 hydrologic basins by means of the runoff-simulation model (Lane, 1982). Required data for model computations (input) were either measured or estimated:

(1) Drainage-basin boundaries were identified on composite satellite imagery and each basin and subbasin was digitized to obtain the area above gaps. Lengths of principal *wadis* in each hydrologic basin above gaps were estimated from the satellite imagery, as were areas (elements) of runoff contribution from parts of the drainage basin defined as either upslope or lateral to the principal *wadis*.

(2) Mean-annual precipitation, as a basin average, was estimated from isohyets of Fig. 5. The mean-annual precipitation event, or index storm, for each basin was based on the 20-year precipitation record at the Al Ain Agromet Station, adjacent to Wadi Al Ain at the north end of Jabal Hafit (Fig. 5), where the mean of the annual single-storm precipitation maxima was 31 mm. This precipitation amount was increased proportionate to annual isohyets, but was decreased relative to drainage-basin area.

(3) Field measurements of *wadi* width were used for selected hydrologic basins. These width (W, in m) measurements were related to drainage-basin areas (A, in km^2) to yield:

$$W = 40A^{0.15} \qquad \text{(Eqn 13)}$$

Although poorly defined ($n = 5$, $R^2 = 0{\cdot}17$), Eqn 13 was used to calculate initial input widths for those *wadis* lacking field measurements for width.

(4) Infiltration rates in *wadis* were generalized from particle-size analyses of field samples of alluvium and from infiltration-rate tests of alluvium at gaps conducted for the Emirate of Abu Dhabi (D.G. Jorgensen, U.S. Geological

Survey, pers. comm., 1991). Results of these tests ranged from 46 to 285 mm per hour and averaged 91 mm per hour. Input values of infiltration rates were reduced with increasing *wadi* length below a gap to account for decreasing particle sizes of alluvium. The rate of reduction generally was 1 mm per hour for 3 km of channel length.

(5) Curve numbers for upslope and lateral elements of a basin were estimated from listings of the Soil Conservation Service (1985), and account for soil texture, slope, and vegetation. Values used range from 75 to 80. Curve-number estimates were influenced by infiltration-rate tests of soils near the Oman Mountains (D.G. Jorgensen, U.S. Geological Survey, pers. comm., 1991).

(6) Discharge characteristics at gaps (representing expected or targeted flows as output) were estimated where feasible using channel-morphology relations (Hedman & Osterkamp, 1982), but most estimates were derived from relations with drainage-basin area (Fig. 2). If necessary, input variables including average *wadi* width, index-storm precipitation, and curve numbers, were modified to approximate the target flow at a gap. Without changing input variables except *wadi* length, width, and infiltration rate, the computed flow at a gap was routed down the *wadi* to calculate transmission losses, the distance of flow, and channel recharge.

Upland recharge

Upland, or inter-*wadi*, recharge of the mountain watersheds was estimated using the CREAMS model (Knisel, 1980). Water-balance results suggest that in the period 1971 through 1990, two storm systems in 1972 and a series of storms in February and March, 1982, resulted in inter-*wadi* movement of soil water below the rooting zone. In all cases the inter-*wadi* recharge occurred in the months of February and March (Fig. 6), when potential loss due to evapotranspiration is relatively low and antecedent moisture (AVG SW, Fig. 6) is most likely to be high. Actual averages of monthly evapotranspiration (ET), as computed by the CREAMS model, are high in February through April, reflecting seasonal highs in precipitation and soil moisture (Fig. 6). The average annual inter-*wadi* recharge resulting from the periods of intense precipitation was calculated as 1·06 mm, or 3·42% of the 31·0-mm index storm for the Al Ain Agromet Station. Estimates for long-term recharge in all hydrologic basins include an inter-*wadi* component of 3·42 percent of index-storm precipitation.

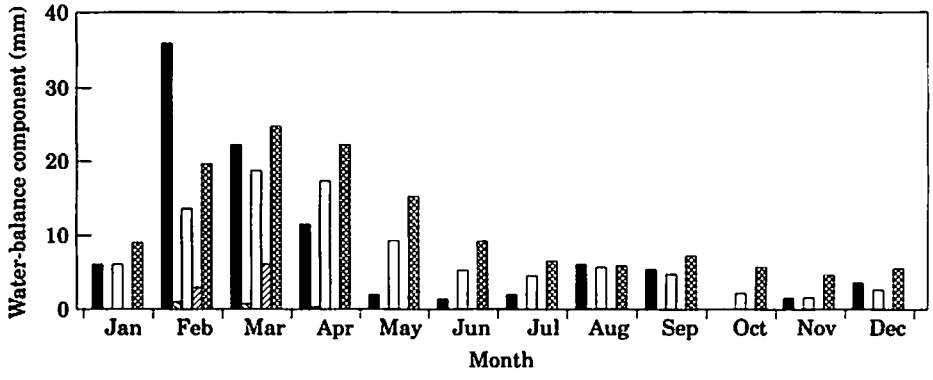

Figure 6. Bar graph of computed monthly averages for water-balance components, Al Ain Agromet Station, 1971–90 (■ = precipitation; ▨ = percolation of soil water below the rooting zone; ▩ = average soil water; □ = evapotranspiration; and ▧ = runoff).

Summary of results, mountain basins

A summary of estimated unit water fluxes (mm per year) using the rainfall-simulation model is given in Table 1 for watersheds draining to 26 gaps of the western Oman Mountains (Fig. 5). Also listed are drainage areas (AREA) measured or estimated that contribute runoff to each gap, estimated mean-annual precipitation (MAPR) for the watershed of each gap, the estimated length of channel below each gap that conveys discharge to exhaustion of flow for the mean-annual runoff event (CHLH), and the per cent of mean-annual precipitation (% *P*) represented by total estimated recharge

Table 1. *Estimated unit water-balance fluxes, watersheds draining to gaps of the Oman Mountains*

GAP	AREA (km^2)	MAPR (mm)	CHLH (km)	RNFL (mm)	RNOF (mm)	TRLS (mm)	OVLD (mm)	IWRC (mm)	TOTR (mm)	% *p*
1a	20·64	175	0	55·0	1·11	12·8	41·1	1·89	14·7	8·4
1a	20·64	175	17·7	55·0	0	14·0	41·1	1·89	15·9	9·1
1b	20·64	170	0	55·0	1·11	12·8	41·1	1·89	14·7	8·6
1b	20·64	170	17·7	55·0	0	14·0	41·1	1·89	15·9	9·4
1c	20·64	165	0	55·0	1·11	12·8	41·1	1·89	14·7	8·9
1c	20·64	165	17·7	55·0	0	14·0	41·1	1·89	15·9	9·6
2	18·01	160	0	52·1	1·83	9·16	41·1	1·78	10·9	6·8
2	18·01	160	21·6	52·1	0	11·0	41·1	1·78	12·8	8·0
3	56·53	150	0	54·6	1·86	9·36	43·4	1·88	11·2	7·5
3	56·53	150	30·0	54·6	0	11·7	43·4	1·88	13·6	9·1
4	91·70	160	0	52·4	1·13	9·41	41·9	1·79	11·2	7·0
4	91·70	160	55·3	52·4	0	10·5	41·9	1·79	12·3	7·7
5a	18·34	135	0	56·5	1·20	14·3	41·0	1·91	16·2	12·0
5a	18·34	135	10·7	56·5	0	15·4	41·0	1·91	17·3	12·8
5b	18·34	135	0	56·5	1·20	14·3	41·0	1·91	16·2	12·0
5b	18·34	135	10·7	56·5	0	15·4	41·0	1·91	17·3	12·8
6a	138·0	165	0	58·3	1·21	16·1	41·0	1·99	18·1	11·0
6a	138·0	165	30·0	58·3	0	17·3	41·0	1·99	19·3	11·7
6b	127·7	165	0	57·9	1·29	15·6	41·0	1·98	17·6	10·7
6b	127·7	165	35·5	57·9	0	16·9	41·0	1·98	18·9	11·4
7	21·58	155	0	56·5	2·27	13·1	41·1	1·95	15·0	9·7
7	21·58	155	13·9	56·5	0	15·3	41·1	1·95	17·3	11·2
8	34·35	155	0	57·7	2·15	14·4	41·1	1·98	16·4	10·6
8	34·35	155	6·65	57·7	0	16·6	41·1	1·98	18·6	12·0
9	209·3	180	0	53·8	1·45	11·4	41·0	1·84	13·2	7·3
9	209·3	180	30·4	53·8	0	12·9	41·0	1·84	14·7	8·2
10a	5·15	155	0	51·7	2·33	8·16	41·2	1·75	9·90	6·4
10a	5·15	155	6·24	51·7	0	10·5	41·2	1·75	12·2	7·9
10b	60·30	140	0	51·7	2·62	7·93	41·1	1·77	9·70	6·9
10b	60·30	140	51·2	51·7	0	10·5	41·1	1·77	12·3	8·8
10c	259·5	135	0	59·1	1·27	16·8	41·0	2·02	18·8	13·9
10c	259·5	135	46·8	59·1	0	18·1	41·0	2·02	20·1	14·9
11a	267·1	170	0	57·9	1·75	15·2	41·0	1·98	17·2	10·1
11a	267·1	170	64·8	57·9	0	16·9	41·0	1·98	18·9	11·1
11b	267·1	170	0	57·9	1·75	15·2	41·0	1·98	17·2	10·1
11b	267·1	170	64·8	57·9	0	16·9	41·0	1·98	18·9	11·1

Table 1. *Continued*

GAP	AREA (km^2)	MAPR (mm)	CHLH (km)	RNFL (mm)	RNOF (mm)	TRLS (mm)	OVLD (mm)	IWRC (mm)	TOTR (mm)	% *p*
12a	94·69	145	0	57·0	2·04	13·9	41·0	1·94	15·8	10·9
12a	94·69	145	40·4	57·0	0	15·9	41·0	1·94	17·9	12·3
12b	49·68	145	0	55·0	1·97	11·9	41·1	1·87	13·8	9·5
12b	49·68	145	31·3	55·0	0	13·9	41·1	1·87	15·8	10·9
13a	122·0	175	0	58·7	0·48	17·2	41·0	2·01	19·2	11·0
13a	122·0	175	25·9	58·7	0	17·7	41·0	2·01	19·7	11·3
13b	122·0	175	0	58·7	0·48	17·2	41·0	2·01	19·2	11·0
13b	122·0	175	25·9	58·7	0	17·7	41·0	2·01	19·7	11·3
14	307·7	155	0	56·3	1·19	14·0	41·0	1·92	15·9	10·3
14	307·7	155	85·4	56·3	0	15·2	41·0	1·92	17·1	11·0
15	54·24	130	0	57·4	2·78	13·6	41·0	1·97	15·6	12·0
15	54·24	130	22·2	57·4	0	16·4	41·0	1·97	18·4	14·2
16	257·8	140	0	57·8	0·99	15·7	41·0	1·97	17·7	12·6
16	257·8	140	67·2	57·8	0	16·7	41·0	1·97	18·7	13·4
17	208·3	145	0	59·3	0·72	18·0	40·9	2·04	20·0	13·8
17	208·3	145	27·7	59·3	0	18·7	40·9	2·04	20·7	14·3

MAPR, estimated mean-annual precipitation; CHLH, mean annual runoff event; RNFL, rainfall; RNOF runoff; TRLS, transmission loss; OVLD, overland losses; IWRC, inter-*wadi* recharge; TOTR, total estimatec recharge above a gap; % *p*, per cent of mean-annual precipitation.

(TOTR). For transmission loss computations, drainage-basin area is assumed not to increase with increasing channel length below a gap.

Rainfall (RNFL) is the watershed average for the index storm used as model input. Runoff (RNOF) at each gap (CHLH = 0) is the input surface runoff designated by the index event. Runoff reduction by transmission losses result in exhaustion of runoff (RNOF = 0) at the computed CHLH below each gap. Transmission loss (TRLS) is the computed streamflow loss above a gap (CHLH = 0) or through the total length of channel, both above (RNOF > 0) and below (RNOF = 0) a gap. Overland losses (OVLD) are the combined part of rainfall (RNFL) that result in evapotranspiration and inter-*wadi* recharge (IWRC). Total estimated recharge above a gap (TOTR) is the sum of TRLS and IWRC. Evapotranspiration losses (not listed) are OVLD minus IWRC.

Divides of sub-basins above gaps 1a, 1b, and 1c are poorly defined. Hydrologic basin 1, therefore, was modelled as three equal areas, each having fluxes of one third the total for the basin. Similarly, results for hydrologic basin 5 are expressed as two subbasins and channels discharging through gaps 5a and 5b. Hydrologic basin 6 has three sub-basins and two gaps. Modelling results are based on sub-basin areas and the routing of runoff from one sub-basin to a lower sub-basin to the appropriate gap.

Three gaps discharge streamflow from five sub-basins of varying areas in hydrologic basin 10. As for hydrologic basin 6, results are based on routing of flows between sub-basins and then to the gaps. Hydrologic basin 11, with seven sub-basins, has a complex network of channels that discharge through gaps 11a and 11b. Flows to the two gaps are presumed equal because the distribution of runoff to the various channels could not be determined. Modelling of hydrologic basin 12 was based on two gaps and three sub-basins with complex flow paths and distribution of flow from one sub-basin to another. Estimates of flow to the two gaps differ according to differences in the assumed contributing drainage areas. Water-flux estimates to two gaps of hydrologic basin 13 are assumed to be equal.

Ten hydrologic basins emerge from the mountains through a single gap. Several of these basins (14, 16, and 17), however, were divided into two or more subbasins, necessitating intrabasin routing of flows to the gap.

Results suggest that average-annual recharge due to precipitation and exhaustion of runoff (RNOF = 0) in the hydrologic basins of the Oman Mountains ranges from about 12 mm to slightly more than 20 mm; roughly 90 per cent of the recharge is by transmission loss of ephemeral streamflow and the remainder by inter-*wadi* infiltration of soil water following sustained, infrequent precipitation events. The amount of computed recharge varies with watershed size and geometry, channel lengths and widths, distribution of precipitation, and basin characteristics such as curve number and hydraulic conductivity of channel alluvium. Total recharge averages about 11 per cent of mean-annual precipitation if all streamflow is assumed to infiltrate without loss to evapotranspiration. Inter-*wadi* recharge appears to occur infrequently, possibly once every 10 or more years, and is estimated to average about 2 mm annually.

Table 2 summarizes water-balance results, in millions (M) of cubic meters of water per year ($m^3.year^{-1}$), for the 17 hydrologic basins of the Oman Mountains. Transmission losses of streamflow (TRLS) are listed as those occurring above gaps in the mountains and intermontane alluvial basins (AG), and those occurring on the piedmont downslope from the gaps (BG). Also listed are drainage-basin areas of the hydrologic basins. Summations of these data indicate an average of about 164M $m^3.year^{-1}$ falls as the mean-annual precipitation event ($P_{2\cdot33}$) above gaps in the Oman Mountains. Estimates of average ground-water recharge are 46M $m^3.year^{-1}$ by channel losses, nearly 6M $m^3.year^{-1}$ as inter-*wadi* or upland recharge, and 52M $m^3.year^{-1}$ for total volume of recharge resulting from precipitation in the Oman Mountains. Expressed as unit fluxes of annual water depths, these volumes are 16·0, 2·0, and 18·0 mm, respectively.

Table 2. *Estimates of average-annual ground-water recharge volumes in hydrologic basins of the Oman Mountains*

Hydrologic Basin	AREA (km^2)	RNFL (M $m^3.year^{-1}$)	TRLS (AG) (M $m^3.year^{-1}$)	TRLS (BG) (M $m^3.year^{-1}$)	IWRC (M $m^3.year^{-1}$)	TOTR (M $m^3.year^{-1}$)
1	61·9	3·408	0·069	0·795	0·117	0·981
2	18·0	0·938	0·033	0·165	0·032	0·230
3	56·5	3·085	0·105	0·529	0·106	0·740
4	91·7	4·801	0·104	0·863	0·164	1·131
5	36·7	2·072	0·044	0·526	0·070	0·640
6	265·7	15·439	0·332	4·207	0·528	5·067
7	21·6	1·219	0·049	0·282	0·042	0·373
8	34·4	1·982	0·074	0·496	0·068	0·638
9	209·3	11·270	0·304	2·385	0·385	3·074
10	325·0	18·716	0·500	4·881	0·640	6·021
11	534·2	30·954	0·934	8·102	1·058	10·094
12	144·4	8·125	0·291	1·907	0·277	2·475
13	244·0	14·320	0·116	4·194	0·490	4·800
14	307·7	17·315	0·365	4·321	0·592	5·278
15	54·2	3·116	0·151	0·739	0·107	0·997
16	257·8	14·888	0·254	4·056	0·509	4·819
17	208·3	12·423	0·149	3·745	0·425	4·319
Total	2871·4	164·071	3·874	42·193	5·610	51·677

RNFL, rainfall; TRLS (AG), transmission losses of streamflow occurring above gaps in the mountains and intermontane alluvial basins; TRLS (BG), transmission losses of streamflow occurring on the piedmont downslope from the gaps; IWRC, inter-*wadi* recharge; TOTR, total estimated recharge above a gap.

Channel lengths

Modelling results include computed estimates of the channel length below a gap (CHLH, Table 1) required to cause elimination of discharge for the index flow event ($Q_{2.33}$). Estimates of channel length (CHLH) below each gap are compared with estimates of channel length identified on color satellite-imagery maps (scale 1:50,000) of the Oman Mountains-Al Ain area (Table 3). The satellite-imagery maps show channel definition well, and estimates of channel length derived from the maps appear reasonably accurate. Complex drainage networks below gaps of hydrologic basins 1, 5, and 11, however, necessitated lumping of results and may yield unreliable comparisons. Other comparisons for channels with complex patterns also may not be fully reliable.

Results for single or double channels below a gap probably provide the most trustworthy comparisons. Whether channel lengths measured from satellite images are more indicative of flow length for the mean-annual flood or for a flood of some other recurrence interval has not been ascertained.

Water-level response to precipitation

Numerous wells in the Al Ain vicinity are monitored by the National Drilling Company, UAE, for changes in water level. Water-level data and streamflow data are inadequate to relate precipitation and streamflows to ground-water recharge quantita-

Table 3. *Comparison of channel lengths below gaps, measured from satellite imagery and predicted by model results*

Gap	Channel length below gap (km)		Channel type
	Satellite imagery	Model	
1a, 1b, 1c	18	17·7	Complex
2	19	21·6	Single
3	29	30·0	Complex
4	33	55·3	Complex
5a, 5b	14	21·4	Complex
6a	22	30·0	Complex
6b	14	35·5	Complex
7	12	13·9	Single
8	10	6·6	Single
9	28	30·4	Double
10a	5	6·2	Single
10b	27	51·2	Complex
10c	52	46·8	Complex
11a, 11b	103	129·6	Complex
12a	18	40·4	Single
12b	15	31·3	Single
13a	28	25·9	Single
13b	27	25·9	Single
14	57	85·4	Double
15	22	22·2	Single
16	56	67·2	Double
17	31	27·7	Single

tively, but water-level changes following precipitation strongly suggest a qualitative relation.

Monthly precipitation totals at the Al Ain Agromet Station and hydrographs of three observation wells (D.C. Signor, U.S. Geological Survey, pers. comm., 1991) are compared in Fig. 7. Unusually heavy precipitation culminating in February, 1990, resulted in streamflow in many *wadis* of the Al Ain area (including Wadi Shik); volumes of the streamflow, however, are not known. The wells are along Wadi Shik, which leaves the Oman Mountains at Zarub Gap, gap 11b (Fig. 5), and continues west to Al Ain. The uppermost well, GWP-18, is a short distance below Zarub Gap and to the south-east of Wadi Shik. Well GWP-17 is about a kilometer north of Wadi Shik and about 5 km west of the gap. Well GWP-15 is immediately adjacent to Wadi Shik about 8 km west of Zarub Gap.

Hydrographs of Well GWP-17 and especially of Well GWP-18 suggest an extended response to the December, 1989, and February, 1990, streamflow. Water-levels in both wells rose about a meter in the months following streamflow (Fig. 7). Water-level data for earlier months are not available, but weather records show that precipitation at Al Ain was insignificant during the 8 months prior to December, 1989. The water level in Well GWP-15, which appears to be directly affected by transmission losses from streamflow, rose about 3 m in February, 1990, and another 1 m in the following 2 months (Fig. 7). Causes of water-level changes in Well GWP-15 during the remainder of 1990 are unknown but may be related to pumping. Analogous data (D.C. Signor, U.S. Geological Survey, pers. comm., 1991) from wells along two other *wadis* in the Al Ain area show water-level rises of 3 to 7 m following floods of February 1982. The rises began a month after the flooding and continued through 1983, a period of abnormally wet weather in Al Ain.

Comparison of results with other studies

Few water-balance studies have been made for the Oman Mountains-Al Ain area. Studies by Hydroconsult (1978) and Regional Development Committee (1986) permit comparison of recharge estimates, but different techniques, drainage areas identified, and positions on *wadis* considered render some comparisons questionable. Generally, however, recharge estimates from the different studies are within 20% of each other.

Recharge estimates for the watersheds of Wadis Al Ain and Shik, Hamad, and Ajran by Hydroconsult (1978) were 10·92M, 0·88M, and 4·00M $m^3.year^{-1}$, respectively. These watersheds are assumed equivalent to hydrologic basin 11, the watershed of gap 12b, and hydrologic basin 13, for which total average recharge, respectively, is estimated to be 10·1M, 2·5M, and 4·8M $m^3.year^{-1}$ (Table 2). Estimates of recharge as indicated by the use of Darcy flow equations at gaps 11a and 11b (Regional Development Committee, 1986) suggested 8·18M $m^3.year^{-1}$. The summed estimates of this study, 9·2M $m^3.year^{-1}$, account for total recharge as opposed to underflow at the gaps, and therefore they may not be directly comparable.

*Inter-*wadi *recharge, Oman Mountains piedmont*

Flux estimates of Tables 1 and 2 account for water falling in hydrologic basins of the Oman Mountains that recharges alluvial aquifers of the Al Ain area by subsurface movement and by infiltration of ephemeral streamflow west of the gaps. Modelling results suggest that flow augmentation by runoff to principal *wadis* below gaps is minor, but that inter-*wadi* recharge may be significant. Estimates of inter-*wadi* recharge in the piedmont area west of the Oman Mountains are listed in Table 4. The

area considered lies between the edge of the Oman Mountains and surficial dune sand to the west, and is divided into 17 hydrologic areas that are rough extensions of the 17 hydrologic basins of Table 2. Thus, estimated areas of Table 4 are those of the 17 hydrologic basins (Table 2) plus the drainage area of each *wadi* system downchannel

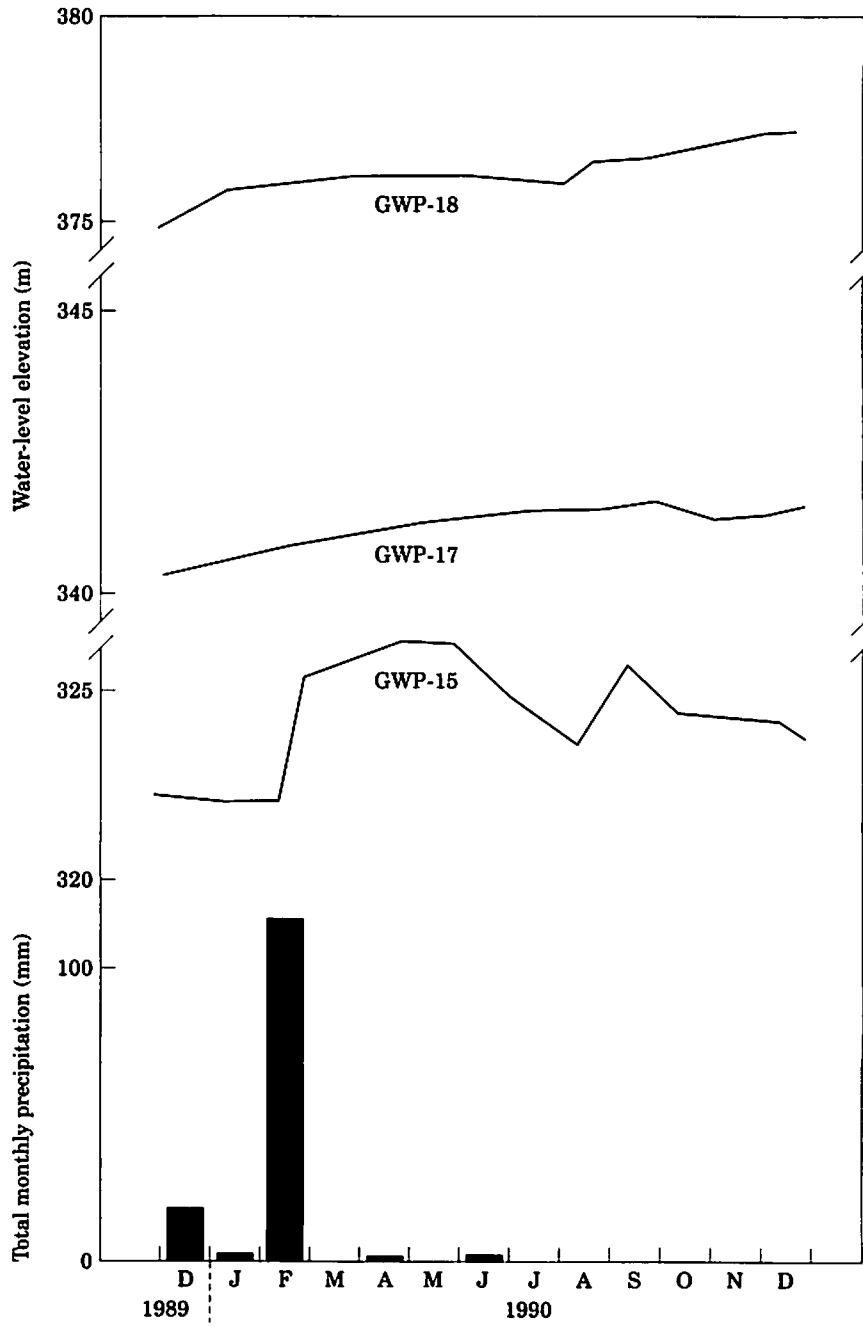

Figure 7. Bar graph of monthly precipitation and hydrographs of water-level changes for three wells in the Al Ain area, December, 1989, through December, 1990. Hydrograph numbers are those of the National Drilling Company's Ground-Water Project (GWP).

Table 4. *Recharge estimates for hydrologic areas of the Oman Mountains Al Ain area above and below gaps*

Hydrologic Area	Area (km^2)	Recharge above gaps (M m^3.$year^{-1}$)	Recharge below gaps (M m^3.$year^{-1}$)	Total recharge (M m^3.$year^{-1}$)
1	124·4	0·981	0·066	1·047
2	48·0	0·230	0·032	0·262
3	113·4	0·740	0·060	0·800
4	166·7	1·131	0·080	1·211
5	61·7	0·640	0·026	0·666
6	365·1	5·067	0·105	5·172
7	79·4	0·373	0·061	0·434
8	62·5	0·638	0·030	0·668
9	272·4	3·074	0·067	3·141
10	703·8	6·021	0·402	6·423
11	1050	10·094	0·547	10·641
12	322·5	2·475	0·189	2·664
13	609·6	4·800	0·388	5·188
14	613·3	5·278	0·324	5·602
15	427·0	0·997	0·395	1·392
16	787·2	4·819	0·561	5·380
17	483·3	4·319	0·292	4·611
Total	6290·3	51·677	3·625	55·302

from gaps to where *wadi* definition is lost. Because drainage divides and western limits of significant streamflows are difficult to interpret, the individual hydrologic areas listed in Table 4 may contain error. The total estimated area (about 6300 km^2) is assumed reasonable for recharge calculations.

Estimates of inter-*wadi* recharge for the Oman Mountains piedmont below gaps, in millions of cubic meters per year, are given in Table 4. The estimates were determined using an index storm of 31 mm, 3·42% of which (1·06 mm) becomes ground-water recharge. These estimates were combined with the recharge estimates for the hydrologic basins above gaps (Tables 2, 4) to yield an estimated total recharge for each hydrologic area (drainage basin) through which channel definition is maintained.

Total estimated average annual recharge for the 17 hydrologic areas of the Oman Mountains-Al Ain area is 55·3M m^3, about 93% of which occurs above gaps along the western edge of the mountains. Averaged over the entire area, estimated recharge is 8·79 mm per year. Substantial variation in unit recharge rates occurs among the 17 hydrologic areas, however, largely because of differences in mountain precipitation (Table 1). Comparing totals of Tables 2 and 4, about 46M m^3, or about 83% of the total average annual recharge of 55·3M m^3, occurs by transmission loss of flows along major *wadis*. If annual precipitation for the Oman Mountains-Al Ain area is assumed to average 130 mm, ground-water recharge accounts for nearly 7% of precipitation.

References

Ardis, C.V. (1973). A double triangle model for generating storm hydrographs. *Proceedings of the First World Congress on Water Resources, International Association of Hydrologic Sciences*, 4: 350–360.

Boughton, W.C. & Renard, K.G. (1984). Flood frequency characteristics of some Arizona watersheds. *Water Resources Bulletin, American Water Resources Association*, 20: 761–769.

Bown, T.M., Hadley, D.G., Brouwers, E.M. & Imes, J.L. (1991). Neogene-Quaternary tectonosedimentary evolution of a part of eastern Abu Dhabi Emirate, U.A.E. Abstracts with Programs, v. 23, no. 5, Geological Society of America 1991 Annual Meeting, p. A289.

Burkham, D.E. (1970). A method for relating infiltration rates to streamflow rates in perched streams. *U.S. Geological Survey Professional Paper* 700-D, pp. 266–271.

Halcrow, W. & Partners. (1969). Report on the water resources of the Trucial States. *Trucial States Council Water Resources Survey*, 1: 161 pp.

Hedman, E.R. (1970). Mean annual runoff as related to channel geometry in selected streams in California. *U.S. Geological Survey Water-Supply Paper 1999-E.* 17 pp.

Hedman, E.R. & Osterkamp, W.R. (1982). Streamflow characteristics related to channel geometry of streams in western United States. *U.S. Geological Survey Water-Supply Paper 2193.* 17 pp.

Hydroconsult (1987). Abu Dhabi (UAE) eastern region water resources. Nicosia: Joannou & Paraskevaides Overseas.

Jordan, P.R. (1977). Streamflow transmission losses in western Kansas. *Journal of the Hydraulics Division, American Society of Civil Engineers*, 103: 905–919.

Knisel, W.G., Jr., (Ed.) (1980). CREAMS: a field scale model for chemicals, runoff, and erosion from agricultural management systems. *U.S. Department of Agriculture Conservation Research Report 26.* 640 pp.

Lane, L.J. (1972). A proposed model for flood routing in abstracting ephemeral channels. In: *Hydrology and Water Resources in Arizona and the Southwest*, Vol. 2, pp. 439–453. Arizona Academy of Science, Hydrology Section.

Lane, L.J. (1980). Transmission losses. In: *National Engineering Handbook, NEH 4: U.S. Department of Agriculture, Soil Conservation Service.* 32 pp.

Lane, L.J. (1982). Distributed model for small semiarid watersheds. *Journal of the Hydraulics Division, American Society of Civil Engineers*, 108: 1114–1131.

Lane, L.J. (1983). Transmission losses. In: *National Engineering Handbook*, NEH 4: U.S. Department of Agriculture, Soil Conservation Service, pp. 19.1–19.21.

Lane, L.J. (1985). Estimating transmission losses. Proceedings, Development and Management Aspects of Irrigation and Drainage Systems, Irrigation Division, American Society of Civil Engineers, San Antonio, Texas, pp. 106–113.

Lane, L.J., Diskin, M.H. & Renard, K.G. (1971). Input–output relationships for an ephemeral stream channel system. *Journal of Hydrology*, 13: 22–40.

Lane, L.J. & Osterkamp, W.R. (1991). Estimating upland recharge in the Yucca Mountain area. *Irrigation and Drainage Division Proceedings, American Society of Civil Engineers*, pp. 170–176.

Menges, C.M. & Woodward, D.G. (1992). Neotectonic thrust faulting along the western flank of the Oman Mountains, northeastern Abu Dhabi, Part 1: Structural and geomorphic characteristics. *EOS, Transactions of the American Geophysical Union, Supplement*, 73: p. 188.

Murphey, J.B., Wallace, D.E. & Lane, L.J. (1977). Geomorphic parameters predict hydrograph characteristics in the Southwest. *Water Resources Bulletin*, American Water Resources Association, 13: 25–38.

Osterkamp, W.R. & Hedman, E.R. (1982). Perennial-streamflow characteristics related to channel geometry and sediment in the Missouri River basin. *U.S. Geological Survey Professional Paper 1242.* 37 pp.

Osterkamp, W.R., Hedman, E.R. & Wiseman, A.G. (1982). Geometry, basin-characteristic, discharge, and particle-size data from gaged stream-channel sites, western United States. *U.S. Geological Survey Hydrologic Data Open-File Report 82-93.* 56 pp.

Peebles, R.W. (1975). Flow recession in the ephemeral stream: unpublished dissertation, Ph.D. University of Arizona, Tucson, Arizona.

Regional Development Committee (1986). Regional water management plan. Engineering Department, Regional Development Committee, Buraimai, Oman.

Sinha, B.P. & Sharma, S.K. (1988). Natural groundwater recharge estimation methodologies in India. In: Simmers, I. (Ed.), *Estimation of Natural Groundwater, NATO ASI Series C*, Vol. 222, pp. 301–311. Dordrecht: D. Reidel Publishing Company.

Smith, R.E. (1972). Border irrigation advance and ephemeral flood waves: *Journal of the Irrigation and Drainage Division, American Society of Civil Engineers*, 98: 289–307.

Soil Conservation Service (1985). Hydrology. In: *National Engineering Handbook, NEH 4*. U.S. Department of Agriculture, Soil Conservation Services, pp. 1.1–22.11.

Woodward, D.G. & Menges, C.M. (1991). Application of uphole data from petroleum seismic surveys to groundwater investigations, Abu Dhabi (United Arab Emirates). *Geoexploration*, 27: 193–212.

Woodward, D.G. & Menges, C.M. (1992). Neotectonic thrust faulting along the western flank of the Oman Mountains, northeastern Abu Dhabi, Part 2: Hydrogeologic implications. *EOS, Transactions of the American Geophysical Union, Supplement*, 73: 188.

Wu, I-pai (1972). Recession flows in surface irrigation. *Journal of the Irrigation and Drainage Division, American Society of Engineers*, 98: 77–90.