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RECHARGE ESTIMATES USING A GEOMORPHIC/DISTRIBUTED-PARAMETER SIMULATION APPROACH, AMARGOSA RIVER BASIN[1]

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ABSTRACT: Average-annual volumes of runoff, evapotranspiration, channel loss, upland (interchannel) recharge, and total recharge were estimated for watersheds of 53 channel sites in the Amargosa River basin above Shoshone, California. Estimates were based on a water-balance approach combining field techniques for determining streamflow with distributed-parameter simulation models to calculate transmission losses of ephemeral streamflow and upland recharge resulting from high-magnitude, low-frequency precipitation events. Application of the water-balance models to the Amargosa River basin, Nevada and California, including part of the Nevada Test Site, suggests that about 20.5 million cubic meters of water recharges the ground-water reservoir above Shoshone annually. About 1.6 percent of precipitation becomes recharge basinwide. About 90 percent of the recharge is by transmission loss in channels, and the remainder occurs when infrequent storms yield sufficient precipitation that soil water percolates beyond the rooting zone and reaches the zone of saturation from interchannel areas. Highest rates of recharge are in headwaters of the Amargosa River and Fortymile Wash; the least recharge occurs in areas of relatively low precipitation in the lowermost Amargosa River watershed.

(KEY TERMS: distributed-parameter simulation; recharge; transmission loss; water balance.)

INTRODUCTION

The Amargosa River drains a mostly arid to semiarid area of about 20,000 km^2 (square kilometers) in southern Nevada and southeastern California (Figure 1). The upper Amargosa River basin (Figure 2) includes Yucca Mountain and parts of the Nevada Test Site (NTS), from where runoff flows generally south before curling west and then north to terminate in Death Valley from its southern end (Figure 1).

As part of site characterization for possible storage of high-level radioactive wastes at Yucca Mountain, the U. S. Geological Survey, in cooperation with the U. S. Department of Energy, is conducting studies of the hydrology of a region that includes a large part of the NTS. Emphasized in these studies is the hydrology of the Yucca Mountain area and downstream parts of the Amargosa River drainage basin. A principal result of the effort will be the refinement of a finite-element model simulating the present ground-water flow system that includes the Amargosa River basin (Czarnecki and Waddell, 1984; Czarnecki, 1985). The model has been used to simulate possibly larger former ground-water fluxes in the basin that resulted from wetter climatic conditions, thereby permitting the prediction of changes in streamflow, ground-water levels, and ground-water flow if long-term climate change occurs. Reliable predictive capability is essential to anticipate the effects that changing climate might have on a potential nuclear-waste repository and on the subsurface transport of contaminants if release to the ground-water system were to occur.

The study described here is in support of the basin-scale-modeling effort, and has the objective of providing estimates of mean rates of ground-water recharge in the Amargosa River basin above Shoshone, California (Figures 1, 2). Recharge, like evapotranspiration, is generally an unmeasured or poorly measured component of the hydrologic budget in arid and semiarid areas. Rates of recharge in the Amargosa River basin are small relative to evapotranspiration (for example, see Tyler, 1987). Thus, estimates of recharge as a residual in hydrologic-budget studies can have substantial error if estimates of evapotranspiration or other major components of the water balance

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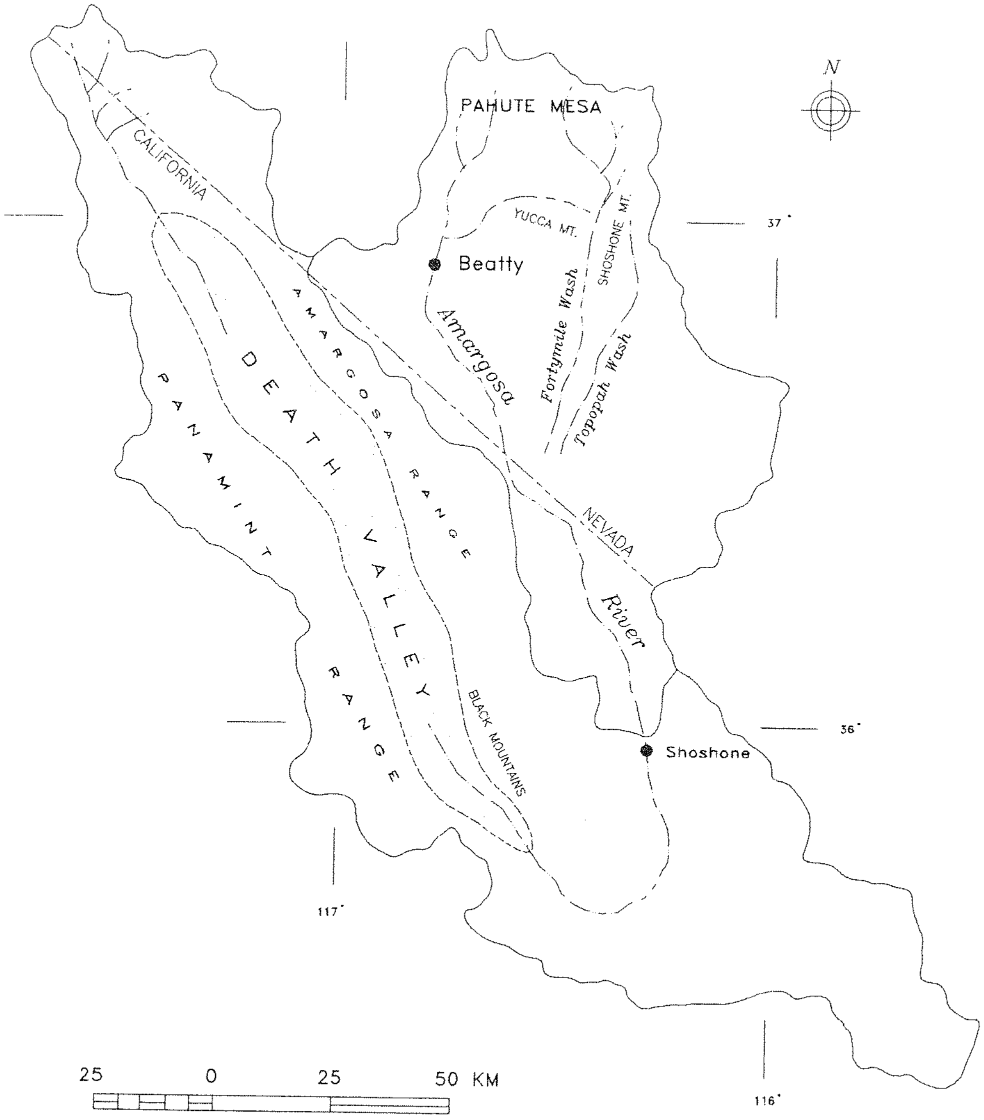

Figure 1.—Map of the Amargosa River Basin Showing Prominent Topographic Features and Watershed Divides of the Nevada Test Site/Amargosa River Study Area.

(precipitation, streamflow, and ground-water discharge) are inaccurate. Estimates of recharge provided here are based on geomorphic techniques combined with a distributed-parameter water-balance simulation model. Recharge is assumed to be nearly equal to transmission losses of surface runoff in ephemeral-stream channels. Additional recharge may occur in interfluve areas during high-magnitude, low-frequency precipitation events.

Summary Description of Amargosa River Basin

Mean annual precipitation in the Amargosa River basin mostly varies between 100 and 200 mm (millimeters), although amounts of 300 mm or greater occur locally at higher elevations of the mountains. Precipitation averages about 70 mm per year in Death Valley (French, 1983), which is the driest part of the basin. Although precipitation is distributed throughout the year, discharge records suggest that streamflow is most likely in the summer as a result of

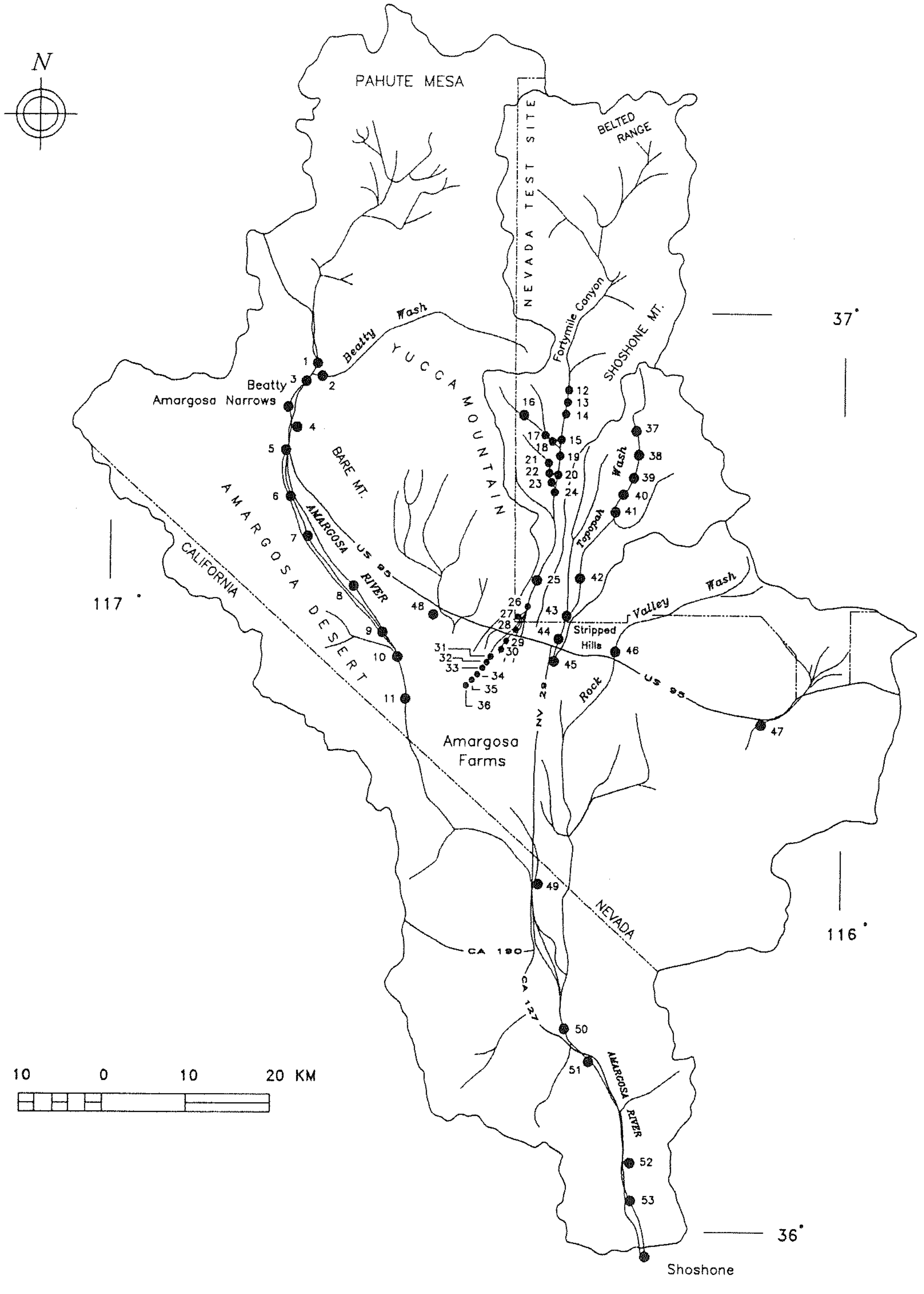

Figure 2.—Map of the Amargosa River Basin Above Shoshone, California, Showing Parts of the Drainage Network, and Drainage Divides of the Upper Fortymile and Topopah Watersheds. Numbers identify sites listed in Tables 1 and 2.

convectional storms. Floods may occur at any time, but are most common from convectional rain in the summer and from frontal storms in the winter.

The Amargosa River basin, dominated by the Amargosa Desert and uplands of Pahute Mesa to the north (Figure 2), mostly lies in the northern Mojave Desert region of the Great Basin section, Basin and Range physiographic province (Fenneman, 1931). The northern Mojave Desert is characterized by desert scrub species, especially creosote-bush (Larrea divaricata), greasewood (*Sarcobatus vermiculatus*), ragweed (*Ambrosia sp.*), sagebrush (*Artemisia tridentata*), white bur-sage (*Franseria dumosa*), and rabbitbrushes (*Chrysothamnus sp.*), in basal valley areas, and by black-brush (*Coleogyne ramosissima*), Joshua tree (*Yucca brevifolia*), pinyon (*Pinus monophylla*), and juniper (*Juniperus osteosperma*) on bajadas and mountain flanks (Allred *et al.*, 1963; Brown *et al.*, 1979). Except in upland areas and along isolated reaches of ground-water seepage, channel and riparian vegetation is sparse and is assumed to transpire small portions of streamflow.

Previous Investigations

The characteristics of the NTS/Amargosa River basin area are well known, and thus the numerous papers detailing these characteristics are not reviewed here. The ground-water geology of the Amargosa Desert was described by Walker and Eakin (1963), and a summary of extensive investigations of ground-water flow systems and their solute loads in the NTS area of the Great Basin was compiled by Winograd and Thordarson (1975). Descriptions of ground-water flow modeling on the region are provided by Waddell (1982), Czarnecki and Waddell (1984), Czarnecki (1985), and Czarnecki *et al.* (1992). Hydrogeologic interpretations based on geophysical data for the Amargosa Desert are provided by Oatfield and Czarnecki (1991). Especially pertinent to the present paper are descriptions of flood potentials in major channels of the NTS (Christensen and Spahr, 1980; Squires and Young, 1984).

TECHNIQUES

Rates of stream-channel recharge in the NTS/Amargosa River basin are estimated by repeated use of a transmission-loss model that is a modification of a distributed-parameter runoff-simulation model. Primary inputs for calibration of the transmission-loss model are empirical estimates of mean streamflow at various channel sites; the discharge estimates are developed from field observations of channel characteristics that imply changes in streamflow in the downstream direction. Possible ground-water recharge in interfluve areas due to infrequent precipitation events is estimated from long-term precipitation records and use of an agricultural field-scale water-balance model.

Runoff-simulation Model

Techniques described in this paper are derived largely from a distributed-parameter runoff-simulation model for estimation of runoff volumes and peak discharges from watersheds of arid and semiarid 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 runoff-simulation model computes runoff volume, V_a, from upland areas of stipulated runoff characteristics resulting from a precipitation event, P, of specified magnitude (depth, in mm) and duration characteristics (in hours):

$$V_a = \begin{cases} 0 & P \le 0.2S \\ \\ \dfrac{(P-0.2S)^2}{P+0.8S} & P > 0.2S \end{cases} \tag{1}$$

The runoff characteristics of upland surfaces are derived by use of the curve number, CN:

$$CN = \frac{25{,}400}{S+254} \tag{2}$$

where S, the soil water, in mm, retained during a rainfall, is determined empirically and provides threshold-dependent estimates for initiation of streamflow (Soil Conservation Service, 1985). Runoff volume (Equation 1), peak discharge, Q_p, and duration of streamflow, D_s, are calculated as functions of both precipitation and drainage-basin area, A:

$$Q_p = d(V_a/D_s) \tag{3}$$

$$D_s = yA^h \tag{4}$$

where d, y, and h are empirically determined parameters expressing hydrograph shape. Routing a simulated 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 volume, V_u, lateral inflow volume V_1, and hydraulic conductivity of channel alluvium (Lane, 1982; 1985):

$$dV_u/dX = -gW - pWV(X,W) + V_1/X, \tag{5}$$

the solution of which is:

$$V(X,W) = m(X,W) + n(X,W)V_u + F(X,W)V_1/X, \qquad (6)$$

in which $V(X,W) \geq 0$ is the outflow volume. In Equation(5), g and p are parameters dependent on hydraulic conductivity, mean duration of flow, and runoff. In Equation (6), m (X,W) is an infiltration parameter dependent on hydraulic conductivity (in mm/hr) of a specified length and width of channel (in meters) with a known duration of flow, and n (X,W) and F (X,W) are parameters derived from g, p, and the channel-reach dimensions (Lane, 1985).

For this work, the channel network, including major tributary inflows, was represented by a variable number of channel reaches, each of which had upstream inflow (V_u) from either the channel reach above or from an area of uniform surface-runoff characteristics, and lateral inflow (V_1) from two adjacent surface-runoff areas, individually of uniform runoff characteristics as well. Thus, each part of the watershed, and the entire watershed as a sum of these parts, are represented as a simple channel network, to which the runoff volumes from contributing runoff areas are computed individually and then summed (Lane, 1985).

Use of the runoff-simulation model, modified for transmission losses, requires inputs of contributing areas of runoff for upland and lateral areas, 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 the downstream end of 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 durations 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 outflow occurs until a threshold volume of inflow 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.

Required input data for model computations include areas of the upland and lateral watershed elements, mean-annual precipitation of the modeled drainage basin, average precipitation depth of the rainfall event in each of the watershed elements, channel length and average width, average hydraulic conductivity of channel alluvium, and average curve number for each watershed element. Outputs are hydrograph shape and duration, and water-balance calculations for the rainfall event of rainfall, runoff, channel-loss, and evapotranspiration volumes.

Because the runoff-simulation model described here and the other approaches cited are event based, they do not provide a long-term estimate of mean recharge useful in modeling 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. A geomorphic method to accomplish this scale transition is suggested. Conversion to a time-integrated estimate of ground-water recharge in arid/semiarid 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 and Climatic Inputs

Inputs to the transmission-loss model included direct observations of channel characteristics, and estimates of hydraulic conductivity and curve number (Soil Conservation Service, 1985) based on properties of channel material and soils (Romney *et al*, 1973; Schmidt, 1988). At each site for which water-balance calculations were made, mean discharge was estimated using channel-morphology techniques in which channel dimensions, related to discharge characteristics at gaged streamflow sites are employed as proxies to evaluate discharge at ungaged sites (Hedman, 1970; Osterkamp and Hedman, 1982; Hedman and Osterkamp, 1982). Equating with the volume of runoff for mean annual discharge obtained by this technique, a single storm approximating the 24-hour, 2-year rainfall event was distributed over the drainage basin that yielded the mean runoff volume derived by channel-morphology techniques. In this manner, the summation of all runoff events in a typical year was represented by a single event that could be treated by the modified distributed runoff-simulation model. Where channel morphology was well defined and the field measurements provided reliable estimates of mean discharge, adjustments in other estimated but unmeasured variables, such as hydraulic conductivity and curve number, were made in iterative runs to yield a set of input variables resulting in the approximate runoff volume for the design storm. These input values were used in calculations for sites where channel-morphology measurements were judged not to provide a dependable runoff volume.

The basis of the channel-morphology technique is that alluvial stream channels are self-adjusting to accommodate the flows that they convey (Leopold and Maddock, 1953). 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:

$$Q_i = WDV \tag{7}$$

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 Equation (7) to power form yields:

$$Q_i = k'W^bD^fV^m \tag{8}$$

where k' is a 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 relations:

$$Q_i = qW^b \tag{9}$$

$$Q_i = cD^f \tag{10}$$

$$Q_i = kV^m \tag{11}$$

Because Equations (9), (10), and (11) 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 and Osterkamp, 1982), are those that yield a discharge characteristic, such as mean discharge, Q_a, or a flood with a five-year recurrence interval, 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. 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 and 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 transmission-loss model representing a precipitation event with a two-year return period, for example, permit evaluation and iteration of input variables to represent the field- determined two-year flow event. The model, however, computes a water balance expressed as volumes of precipitation, runoff, channel losses, and overland losses (primarily evapotranspiration). Thus, computer runs were made for volumes of mean streamflow, estimated by channel- morphology techniques and expressed as single flow events, rather than for peak discharges.

Precipitation records for parts of the Amargosa River basin, and especially for the upper part at and in proximity to NTS (French, 1983; 1985, revised 1986; National Climatic Data Center, written commun., 1991), are much more extensive than is typical for arid and semiarid areas. These records were used as a means of estimating mean annual precipitation and the two-year, 24-hour storm magnitude averaged over the contributing drainage basin above any channel site for which model results were computed. The approximations for the two-year, 24-hour rainfall depths were used as model input to generate hydrographs at a site, from which flow volumes and losses, as a function of channel length, were computed; hydrograph shapes were partly determined by inputs of mean annual precipitation.

Upland Recharge

Interchannel or upland recharge through unconsolidated or poorly consolidated rocks (as opposed to upland surface runoff) of arid and semiarid areas is assumed to be a generally small but finite part of total recharge. The runoff-simulation model previously summarized evaluates overland loss (evapotranspiration) 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 the interchannel or upland recharge in arid/semiarid areas (Lane and Osterkamp, 1991) requires daily precipitation data and measures of spatial variability in saturated hydraulic conductivity as inputs to the CREAMS model (Knisel, 1980). The technique has the assumption that recharge occurs in uplands when water percolates below the plant-rooting depth, an infrequent occurrence in arid/semiarid areas that can be evaluated by the field-scale CREAMS model.

Preliminary results using the CREAMS model and based in part on saturated hydraulic-conductivity measurements taken near the headwaters of upper Rock Valley Wash (Lane *et al.*, 1984) (Figure 2) suggest that in areas of the southwestern 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 20 years or more may be necessary to initiate upland recharge. These results are generally consistent with soil-moisture measurements of Nichols (1986), indicating that deep percolation of precipitation occurred near Beatty, Nevada, during an 18-month period. Similar, more recent studies at the Beatty site yielded conflicting results suggesting that deep percolation has not occurred recently (Fischer, 1992).

EXPLANATION OF RESULTS

Water-balance calculations were made for 53 selected channel sites of the Amargosa River basin above Shoshone, California (Figure 2; Tables 1 and 2). Most of the channel sites are along the Amargosa River, west and south of the NTS, or are along two principal drainages of the NTS, Fortymile Wash and Topopah Wash. Other sites listed are tributary to these three stream channels. Sites are numbered in downstream order; interruptions in the order due to tributary inflow or change in basic flow conditions are indicated by lines (Tables 1, 2).

Locations are designated according to the official rectangular survey of public lands (Table 1), and are given by township (T), range (R), section, and section quadrants. Sites 1 through 48 are in Nevada and are identified by township and range south (S) and east (E), respectively, of the Mount Diablo base line and meridian. Sites 49 through 53, in California, are identified by township and range north (N) and east, respectively, of the San Bernardino base line and meridian. As examples, site 53, Amargosa River near Red Wing Mine, California, is in T22N, R6E, section 1, northwest quarter of the southeast quarter of the southwest quarter, and site 10, Amargosa River near Big Dune, Nevada, is in the center of section 19, T15S, R48E.

Drainage-basin areas (Table 1) are the actual areas above a channel site, as determined by the digitizing of areas on 1:24,000-scale topographic maps. Channel lengths were approximated from topographic maps and may be inaccurate. In addition, some channel lengths were adjusted to be compatible with the division of a drainage basin into topographic components, or elements, as required by the runoff-simulation model. Channel lengths of the Amargosa River are given in three sets (upstream from Amargosa Narrows, from Amargosa Narrows to downstream of Big Dune, and from a site above California Highway 127 to Red Wing Mine, site 53). The lengths are those that were used to model the Amargosa River as three distinct streamflow units, and do not represent actual channel lengths.

Water-balance estimates at channel sites of the NTS/Amargosa River area (Table 2) are given in millions of cubic meters (Mm^3) per year. Average annual precipitation is the volume of precipitation that typically falls in the basin above a site, average annual channel loss is the volume of channel water lost upstream from a site, average annual evapotranspiration (ET) is the volume of water that re-enters the atmosphere by evapotranspiration following precipitation, average annual upland recharge is the volume from infrequent precipitation events that percolates below the plant-rooting zone and is not lost to runoff or ET, and average annual cumulative recharge is the fraction of precipitation that is added to the ground-water reservoir. Cumulative recharge combines channel losses and upland recharge, and is an estimate of total average annual recharge for the entire Amargosa River basin or for a tributary basin above a site. For example, the estimated average annual cumulative recharge at site 36, on lower Fortymile Wash, is 3.55 Mm^3, 0.27 Mm^3, and 0.05 Mm^3, respectively, from channel losses along Fortymile, Yucca, and Drillhole Washes, plus 0.35 Mm^3 from upland recharge in the entire Fortymile Wash basin above site 36. At site 53 on the Amargosa River, the estimated annual cumulative recharge of 20.5 Mm^3 is the total of all recharge estimated for the upper and middle parts of the Amargosa River basin (13.5 Mm^3), the Fortymile Wash basin (4.22 Mm^3), the Topopah Wash basin (0.35 Mm^3), plus 2.42 Mm^3 of total annual recharge for the lower Amargosa River basin (Table 2).

TABLE 1. List of Sites for Water-Balance Computations [ab, above; nr, near; bl, below; trib, tributary].

Site Number	Site Description	Location	Channel Length (km)	Area (km^2)
1	Amargosa R ab Beatty Wash	11-47-28 NE/SE/SE	45.2	886
2	Betty Wash nr mouth	11-47-34 SW/NW/NW	45.9	248
3	Amargosa R bl Beatty Wash	11-47-33 SE/NE/NW	46.2	1140
4	Amargosa R at Amargosa Ns	12-47-20 SE/NW/NW	54.1	1220
5	Amargosa R nr Beatty	12-47-30 SE/SE/NW	2.32	1230
6	Amargosa R nr Gold Center	13-47-18 SW/NE/NE	9.03	1230
7	Amargosa R nr Carrara	13-47-33 NE/NW/NW	14.4	1610
8	Amargosa R at Ashton	14-47-24 SE/SE/SW	23.2	1620
9	Amargosa R nr Ashton	15-47-02 center	27.4	1630
10	Amargosa R nr Big Dune	15-48-19 center	34.3	2030
11	Amargosa R bl Big Dune	16-48-06 SE/SE/NE	39.1	2030
12	Fortymile Wash ab LB trib	12-50-10 NE/SE/NE	52.6	658
13	Fortymile Wash bl LB trib	12-50-10 NE/NE/SE	52.8	663
14	Fortymile Wash at Narrows	12-50-15 SE/SE/NW	54.7	671
15	Fortymile W ab Yucca Wash	12-50-27 SW/SW/NW	57.1	684
16	Yucca W ab Black Glass Cyn	12-50-18 NE/NE/SW	8.99	21.9
17	Yucca Wash ab mouth	12-50-28 NE/NE/SW	13.8	44.2
18	Yucca Wash at mouth	12-50-28 NE/NE/SE	14.2	44.5
19	Fortymile W bl Yuca Wash	12-50-27 NW/SW/SW	57.9	730
20	Fortymile W ab Drillhole W	13-50-07 NE/NE/SW	63.2	749
21	Drillhole W nr Fran Ridge	13-50-06 NE/SW/SW	11.2	39.9
22	Drillhole Wash ab mouth	13-50-07 SW/NW/NW	11.9	42.1
23	Drillhole Wash at mouth	13-50-07 NE/NW/SW	12.1	42.3
24	Fortymile Wash nr J-13	13-50-07 SW/SW/SW	64.8	793
25	Fortymile Wash bl J-12	14-49-13 centerSW	74.0	821
26	Fortymile Wash at road	14-49-35 NW/NW/NE	78.4	824
27	Fortymile W nr Lathrop Ws	15-49-03 SW/NE/SE	81.6	826
28	Fortymile W 1.6 km bl #27	15-49-10 NE/NE/SW	83.2	826
29	Fortymile W 3.2 km bl #27	15-49-16 NE/NE/SE	84.8	826
30	Fortymile W 48 km bl #27	15-49-21 SE/NW/NW	86.4	826
31	Fortymile W 6.4 km bl #27	15-49-20 NW/NW/SE	88.0	826
32	Fortymile W 8.0 km bl #27	15-49-20 SE/SW/SW	89.6	826
33	Fortymile W 9.7 km bl #27	15-49-29 NW/NW/SW	91.3	826
34	Fortymile W 11.3 km bl #27	15-49-31 NW/NE/NE	92.9	826
35	Fortymile W 12.9 km bl #27	15-49-31 SW/SW/NW	94.5	826
36	Fortymile W 13.9 km bl #27	15-48-36 SW/NE/SE	95.5	826
37	Topopah W nr Shoshone Mt	12-51-19 NE/NW/SW	9.40	55.1
38	Topopah W bl Calico Hills	12-51-34 NW/NW/NW	12.9	68.4
39	Topopah W ab Test Cell C	13-51-07 NW/NW/NE	14.9	70.6
40	Topopah W bl Test Cell C	13-50-12 SE/SE/SE	17.9	79.9
41	Topopah W bl E-MAD	13-50-25 NW/NW/SW	21.4	85.7
42	Topopah W at L Skull Mt	14-50-16 NE/NE/SW	24.8	275
43	Topopah W nr Stripped Hls	15-50-05 NE/NW/SE	36.9	309
44	Topopah W at U.S. 95	15-50-18 NE/SW/SE	41.3	399
45	Topopah W nr Lathrop Wells	15-50-19 SW/SW/SW	43.1	404
46	Rock Valley W nr U.S. 95	15-50-24 SE/SW/SW	4.02	153
47	Amargosa trib nr Mercury	16-52-14 SE/SW/NW	5.55	276
48	Amargosa trib bl U.S. 95	15-48-03 NE/NE/NW	6.03	298
49	Amargosa R at CA 127	26-05-22 NE/NW/NE	26.5	1330
50	Amargosa R nr Eagle Mt	24-06-18 NW/SE/SW	47.4	3580
51	Amargosa R bl Eagle Mt	24-06-28 NW/SE/SW	52.3	3710
52	Amargosa R nr Baxter Mine	21/2-6-24 SW/SW	66.6	3920
53	Amargosa R nr Red Wg Mine	22-06-01 NW/SE/SW	72.0	3980

TABLE 2. Water-Balance Estimates at Selected Stream-Channel Sites, Amargosa River Basin [Mm^3, million cubic meters].

Site Number	Average Annual Precipitation (Mm^3)	Average Annual Runoff (Mm^3)	Average Annual Channel Loss (Mm^3)	Average Annual ET (Mm^3)	Average Annual Upland Recharge (Mm^3)	Average Annual Cumulative Recharge (Mm^3)
1	36.0	6.40	2.78	26.3	0.49	3.27
2	5.75	.01	.23	5.43	.08	.31
3	46.2	6.61	5.14	33.8	.63	6.00
4	49.3	8.65	3.69	36.3	.67	4.59
5	.26	.01	.03	.22	–	13.0
6	.47	–	.06	.40	.01	13.1
7	7.55	.05	.19	7.21	.10	13.3
8	7.80	.05	.20	7.44	.11	13.3
9	7.90	.03	.22	7.54	.11	13.3
10	14.4	.02	.28	13.9	.20	13.5
11	14.4	–	.31	13.9	.20	13.5
12	20.9	.03	2.96	17.6	.28	3.24
13	21.0	.03	2.96	17.7	.29	3.25
14	21.2	.10	3.01	17.8	.29	3.30
15	21.6	.13	3.17	18.0	.29	3.46
16	.84	.03	.13	.67	.01	.14
17	1.69	.06	.26	1.34	.02	.28
18	1.70	.06	.27	1.35	.02	.29
19	24.4	.19	3.49	20.7	.33	4.09
20	24.8	.18	3.51	20.7	.34	4.12
21	1.01	.01	.05	.94	.01	.06
22	1.07	.01	.05	1.00	.01	.06
23	1.08	.01	.06	1.00	.01	.07
24	25.3	.05	3.52	21.4	.34	4.18
25	25.9	.04	3.53	22.0	.35	4.20
26	25.9	.04	3.53	22.0	.35	4.20
27	25.9	.04	3.53	22.0	.35	4.20
28	25.9	.03	3.54	22.0	.35	4.21
29	25.9	.03	3.54	22.0	.35	4.21
30	25.9	.02	3.54	22.0	.35	4.21
31	25.9	.02	3.54	22.0	.35	4.21
32	25.9	.01	3.55	22.0	.35	4.22
33	25.9	.01	3.55	22.0	.35	4.22
34	25.9	.01	3.55	22.0	.35	4.22
35	25.9	.01	3.55	22.0	.35	4.22
36	25.9	–	3.55	22.0	.35	4.22
37	1.87	.02	.16	1.65	.03	.19
38	2.14	.01	.16	1.94	.03	.19
39	2.18	.01	.16	1.98	.03	.19
40	2.42	.01	.17	2.21	.03	.20
41	2.53	.01	.17	2.32	.03	.20
42	6.28	.01	.17	6.01	.09	.26
43	7.34	.01	.22	7.01	.10	.32
44	9.27	–	.22	8.92	.13	.35
45	9.37	–	.22	9.02	.13	.35
46	3.31	.01	.01	3.24	.05	.06
47	6.07	.02	.02	5.95	.08	.10
48	6.57	.02	.03	6.44	.09	.12
49	23.0	.04	.37	22.3	.31	18.7
50	61.2	.04	.70	59.6	.83	19.6
51	63.5	.06	.80	61.7	.86	19.7
52	67.0	.07	1.03	64.9	.91	20.0
53	68.0	.25	1.50	65.3	.92	20.5

Amargosa River

The Amargosa River basin is divided into three parts for modeling. The upper basin above Amargosa Narrows (Figure 2) is dominated by Pahute Mesa and other uplands of bedrock geology that have higher curve numbers and receive greater precipitation, including snow, than do lower parts of the basin. Ephemeral streamflow of the Amargosa River middle basin, from Amargosa Narrows to beyond Big Dune, is largely runoff from the upper basin and from convective and frontal storms of the middle basin that flows on poorly-consolidated fan deposits before channel losses generally cause reduction and elimination of flows northwest of Amargosa Farms (Figure 2). The lowest part of the basin that is modeled is drained by the Amargosa River downstream from Amargosa Farms nearly to Shoshone, California, where ephemeral streamflow becomes intermittent owing to shallow ground water.

The Amargosa River above Amargosa Narrows, near Beatty, Nevada (Tables 1, 2), has perennial to intermittent streamflow (sites 1, 3, and 4); Beatty Wash (site 2), an ephemeral-stream channel, is a major tributary to the upper Amargosa River. Channel-morphology techniques for estimating discharge at sites of intermittent flow are subject to large errors, (Hedman and Osterkamp, 1986), and water-balance considerations for the upper Amargosa River sites suggest that the channel-morphology estimates are too high. Therefore, runoff and recharge estimates for these sites are based on the use of reasonable input variables to the transmission-loss model. Between sites 3 and 4 much of the water previously recharged to the ground-water reservoir of the upper basin is forced to the surface by bedrock in the Beatty area, thereby causing a large apparent increase in runoff and decreases in computed channel loss and cumulative recharge. Recharge water of the upper basin that reappears as streamflow near Beatty, passes Amargosa Narrows, and again infiltrates as channel losses, is treated as upper-basin recharge only. Some channel losses, of course, occur as ET, but, based on studies of ET losses per unit length of channels in Arizona (Sorey and Matlock, 1969; Renard, 1970), the loss is probably less than 5 percent.

Thus, estimates from use of the transmission-loss model of average annual cumulative recharge in the upper basin and water passing Amargosa Narrows are determined simply as the difference between precipitation and ET at site 4, (13.0 Mm^3 per year). About two-thirds of that volume (8.65 Mm^3) passes Amargosa Narrows as streamflow annually before infiltrating as transmission or channel losses; this portion of the water budget is treated as recharge occurring in the upper basin.

From Amargosa Narrows to Amargosa Farms (sites 5 through 11) where channelized flow ceases, the Amargosa River basin is treated as a unit largely separate from the basin upstream of Amargosa Narrows; only precipitation that falls in the middle basin is considered. In this part of the basin, average discharge, expressed as the mean annual flood, is determined directly from channel-morphology measurements. The composite average annual recharge above site 11, Amargosa River below Big Dune, is estimated to be 13.5 Mm^3. About 96 percent of the estimated recharge is water that falls in that 60 percent of the basin area above Amargosa Narrows. The Beatty Wash watershed, which accounts for about a fifth of the area above Amargosa Narrows, contributes only 2 percent of the upper-basin recharge.

Water-balance estimates of the lower Amargosa River basin (sites 49 through 53), including three tributaries for which comparison calculations are presented (sites 46, 47, and 48), are treated separately from those of the upper and middle basins. Estimates of average annual cumulative recharge, however, reflect additions from all upstream parts of the drainage basin, including the watersheds of Fortymile Wash and Topopah Wash. The area of the lower basin is half that of the entire NTS/Amargosa River basin study area, but the estimated annual recharge of 2.42 Mm^3 in the lower basin is less than 12 percent of the total cumulative recharge of 20.5 Mm^3 per year. Results for sites 46, 47, and 48 suggest that upland recharge in these basins and possibly others of comparable size and topographic position may be significantly greater than recharge by transmission losses.

A graphical representation of average annual runoff, average annual cumulative recharge, and average annual unit recharge ($Mm^3/km^2/yr$), as functions of channel length for the Amargosa River, is given in Figure 3. Runoff in the Beatty area increases dramatically through the 7.9-km distance between sites 3 and 4 owing to shallow ground water being forced to the surface as streamflow. Downstream from Amargosa Narrows (site 4) streamflow is quickly diminished by transmission losses, and average annual cumulative recharge and unit recharge increase accordingly Figure 3). Most flows do not pass far beyond Big Dune (site 11), and streamflow between sites 11 and 49, in the Amargosa Farms area, is generally very limited. Channel measurements suggest that streamflow volumes downstream from Amargosa Farms are relatively small, but that they increase between sites 49 and 53. Between sites 11 and 49 increases in cumulative recharge mostly reflect minor recharge additions related to large increases in drainage area from Fortymile Wash and other tributaries, but these additions reduce unit recharge (Figure 3).

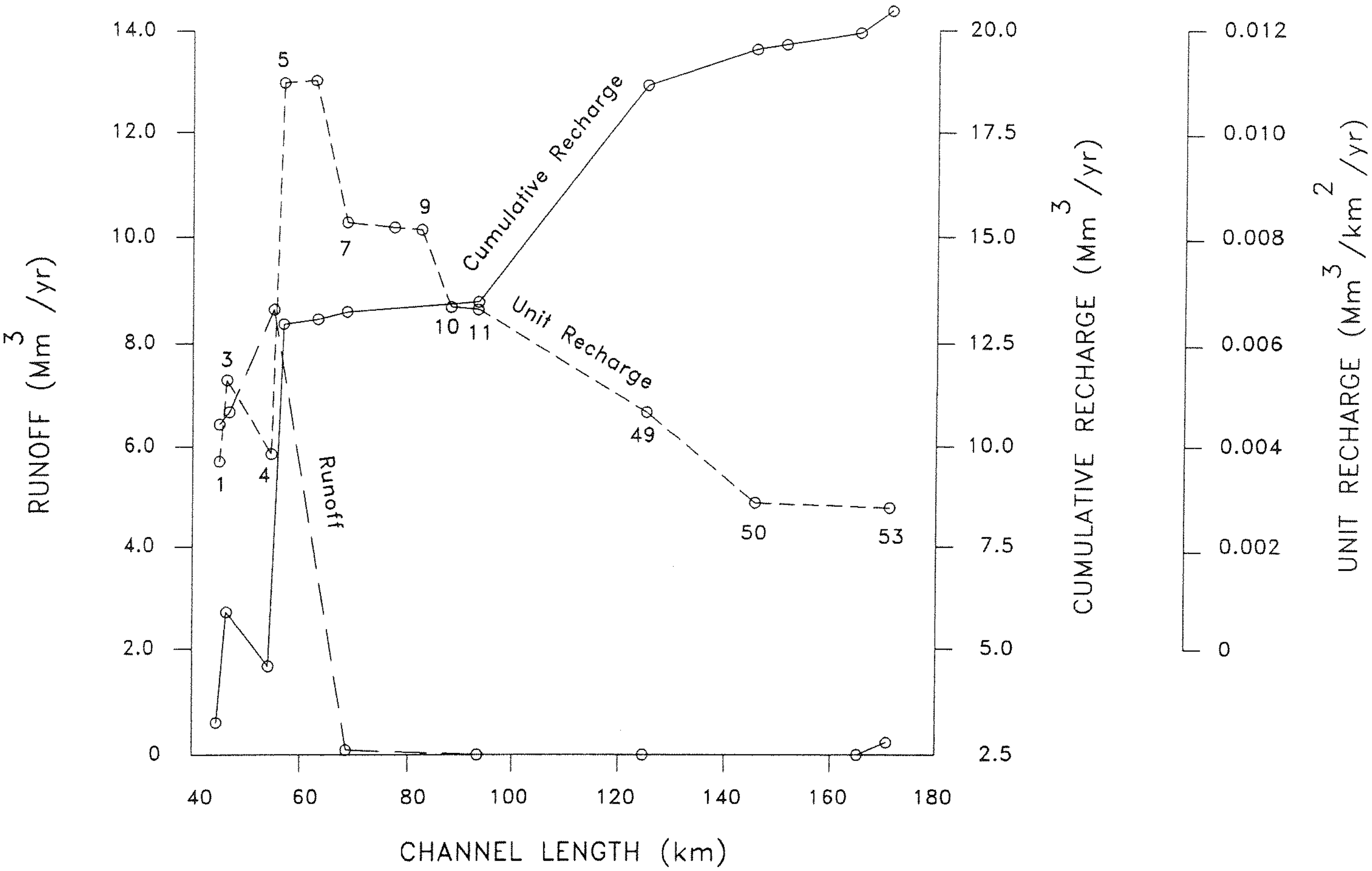

Figure 3. Graph Showing Changes in Estimated Average Annual Runoff, Cumulative Recharge, and Unit Recharge with Channel Length of the Amargosa River, Nevada and California (numbers correspond to selected site numbers of Tables 1 and 2).

Fortymile Wash

Fortymile Wash heads in the uplands of Pahute Mesa and the southern end of the Belted Range and flows south through Fortymile Canyon in the extreme western part of the Nevada Test Site between Yucca Mountain and Shoshone Mountain. South of Fortymile Canyon the wash deeply incises fan deposits before separating into numerous anabranches as it leaves the southwestern corner of the NTS. Most discharges of water and sediment in Fortymile Wash do not reach U. S. Highway 95 south of the NTS, and may rarely reach the Amargosa River. Water-balance estimates for Fortymile Wash (sites 12 through 36) with additional estimates for contributions by Yucca Wash (sites 16, 17, and 18) and Drillhole Wash (sites 21, 22, and 23) are listed as a single group (Tables 1, 2). For modeling purposes, Fortymile Wash is presumed to join the Amargosa River between the middle and lower Amargosa River basins as used above.

Streamflow in all reaches of Fortymile Wash is ephemeral. As in the mainstem Amargosa River basin, most recharge probably occurs in the highest parts of the drainage basin, but data are inadequate to demonstrate this conclusion. Modeling results comparing the two basins, however, suggest that unit recharge (volume per unit time and area) above site 12, Fortymile Wash above left-bank tributary, is about half that above site 4, Amargosa River at Amargosa Narrows (Figures 3, 4). The difference in computed unit recharge is largely the result of lower model-input values for precipitation in the Fortymile Canyon basin based on elevation differences and analyses of precipitation records (Quiring, 1968; French, 1983).

Sites 12 through 15 (Tables 1, 2) are in Fortymile Canyon, where much of the precipitation that falls on the steep bedrock and colluvial sideslopes of Yucca Mountain and Shoshone Mountain flows down to the wash. Sites 16, 17, and 18 are along Yucca Wash, a tributary that enters Fortymile Canyon from the

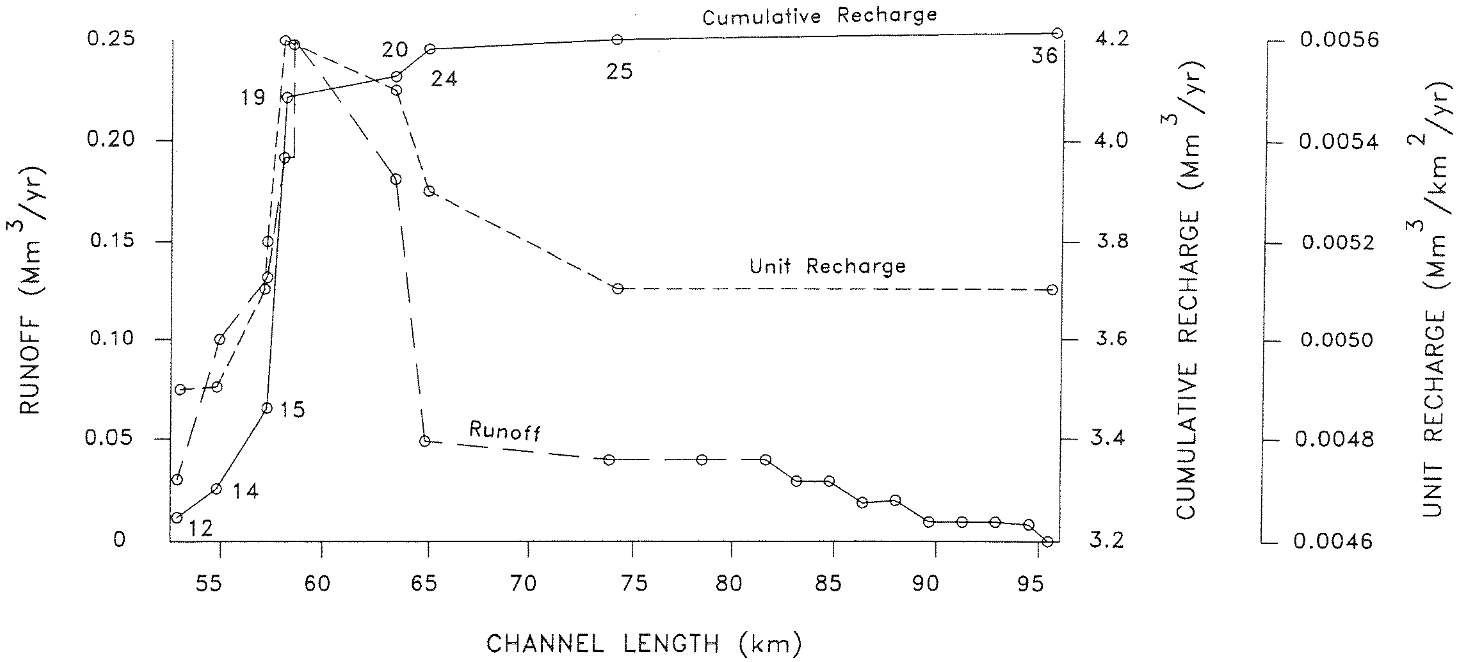

Figure 4. Graph Showing Changes in Estimated Average Annual Runoff, Cumulative Recharge, and Unit Recharge with Channel Length of Fortymile Wash, Nevada (numbers correspond to selected site numbers of Tables 1 and 2).

west. Sites 19 and 20 are on the uppermost part of the alluvial fan downstream from where Fortymile Wash emerges from Fortymile Canyon. Drillhole Wash, with sites 21, 22, and 23, is a southeast-flowing tributary to Fortymile Wash that drains part of Yucca Mountain (fig. 2). Sites 24 through 36 show progressive reductions of streamflow on the lower parts of the Fortymile Wash alluvial fan.

Figure 4 indicates changes in average annual runoff, cumulative recharge, and unit recharge along Fortymile Wash from site 12 in Fortymile Canyon to site 36, where streamflow of the index flow event is calculated to cease owing to channel losses. The combined effects of high runoff rates through Fortymile Canyon and high permeability of channel deposits cause streamflow and recharge rates of Fortymile Wash to be greatest near its confluence with Yucca Wash (Figures 2, 4). Channel measurements downstream from the confluence, at sites 20 and 24, indicate large reductions in streamflows and unit recharge, and reduced rates of increase for cumulative recharge. From site 24, Fortymile Wash near well J-13, to where streamflows typically die out at site 36, minimal changes with channel length occur owing to low rates of runoff (Figure 4).

Topopah Wash

Topopah Wash (Tables 1, 2; Figure 2, sites 37 through 45) heads in Shoshone Mountain and disappears owing to lack of streamflow, south of U. S. Highway 95; it is in the second largest basin draining to the Amargosa River from NTS. The uppermost part of the Topopah Wash watershed drains a much smaller area of bedrock geology and lower elevations than do those of Fortymile Wash or the mainstem Amargosa River. The channel of Topopah Wash is almost entirely on fan deposits grading southward from Shoshone Mountain. Thus, unit runoff to the wash from storms in the upper part of the basin may be generally lower than it is in the upper Fortymile Wash or Amargosa River basins.

Figure 5, which illustrates rate changes of runoff and recharge with channel length of Topopah Wash, demonstrates that inferred hydrologic conditions in the Topopah Wash drainage basin differ with those of both the Amargosa River and Fortymile Wash (Figures 3, 4). Highest runoff rates in the Topopah Wash basin occur in headwater areas of Shoshone Mountain, and decline in the downstream direction except where the channel receives runoff from the Stripped Hills (Figure 2). Corresponding reductions in unit recharge and the rate at which cumulative recharge increases are evident (Figure 5).

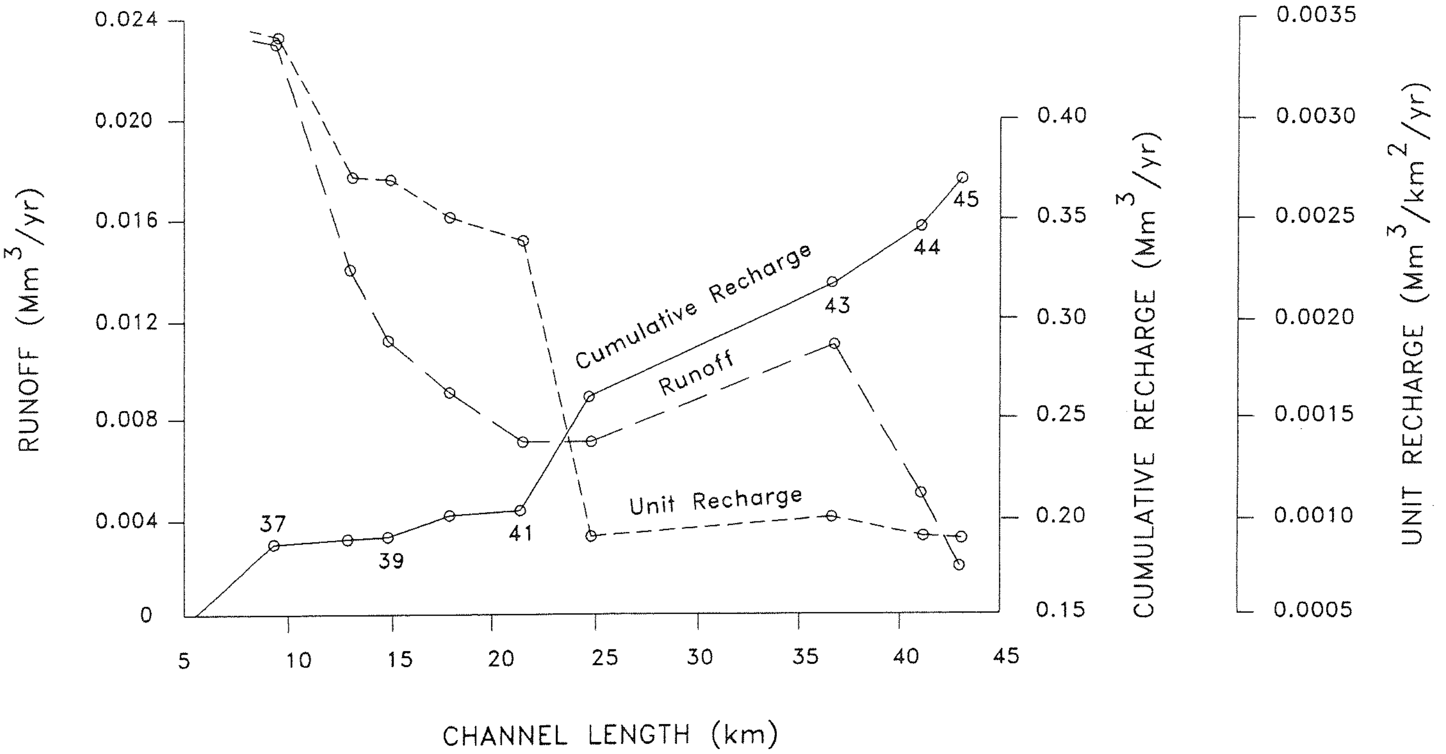

Figure 5. Graph Showing Changes in Estimated Average Annual Runoff, Cumulative Recharge, and Unit Recharge with Channel Length of Topopah Wash, Nevada (numbers correspond to selected site numbers of Tables 1 and 2).

SUMMARY OF RESULTS

Water-balance calculations, based on field observations, a distributed-parameter runoff-simulation

the lower NTS/Amargosa River area where precipitation is lowest and computed rates of ET are high. Above Beatty, Nevada, for example, about 3 percent of precipitation is computed as recharge, whereas less than 0.5 percent of precipitation that falls in the

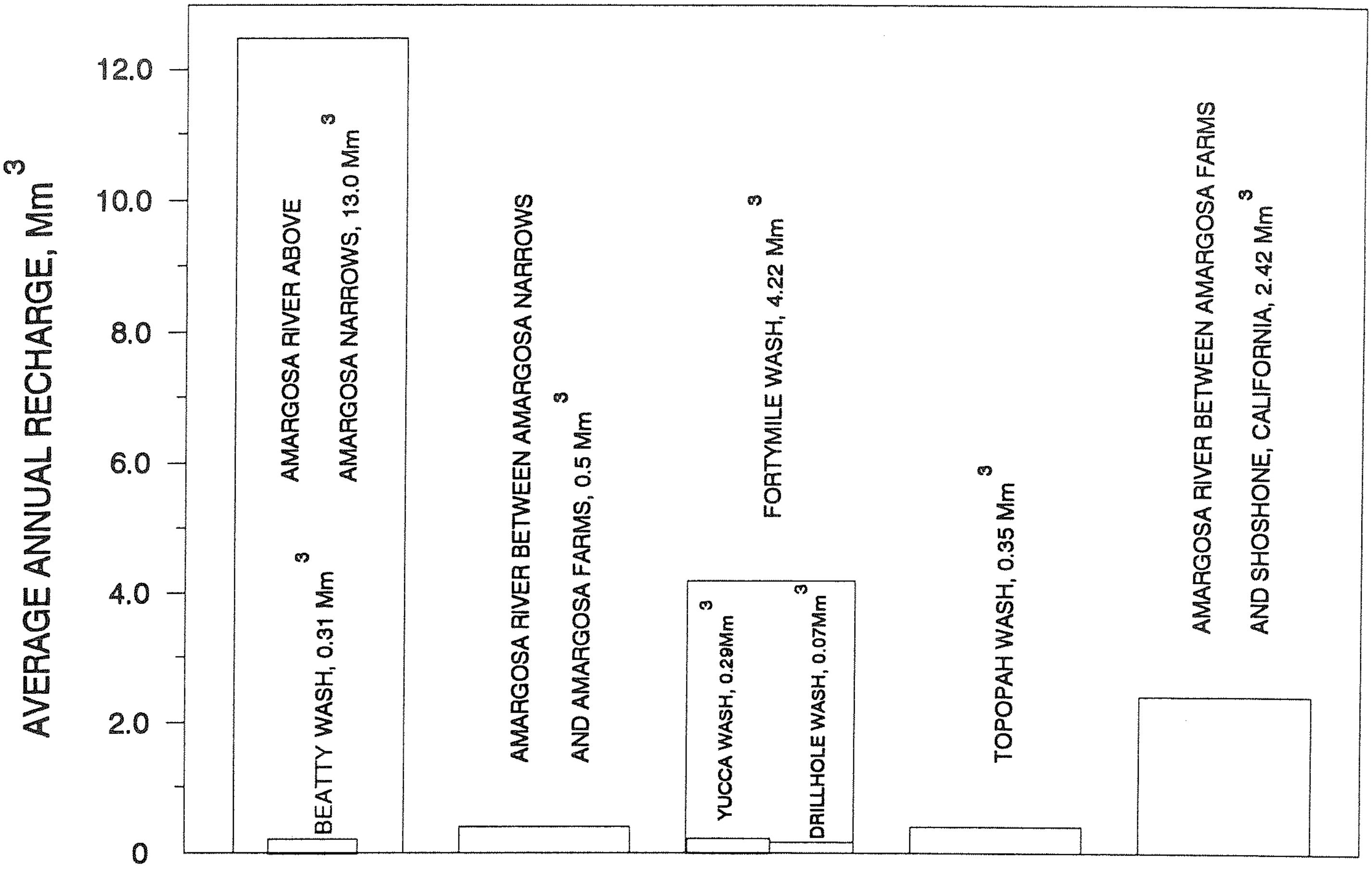

Figure 6. Bar Graph Showing Average Annual Recharge [in millions of cubic meters (Mm^3)] for Specified Parts of the Amargosa River Basin.

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