SUMMARY OF INFILTRATION RATES IN ARID AND SEMIARID REGIONS OF THE WORLD, WITH AN ANNOTATED BIBLIOGRAPHY

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CONVERSION FACTORS

Multiply	*By*	*To obtain*
square kilometers (km^2)	0.386	square mile (mi^2)
meter (m)	3.281	foot (ft)
kilometer	0.621	mile (mi)
millimeter	0.039	inch (in.)
liter	0.264	gallons (gal)
degree Celsius (°C)	F = 9/5 + 32	degree Fahrenheit

ABBREVIATIONS

mg	milligrams	mm	millimeter
L	liter	yr	year
in.	inch	s	second
m	meter	B.P.	before present

SUMMARY OF INFILTRATION RATES IN ARID AND SEMIARID REGIONS OF THE WORLD, WITH AN ANNOTATED BIBLIOGRAPHY

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ABSTRACT

Recharge is a complex function of the climatic regime, nature of the soil and substrata, depth to water, and type and extent of vegetative cover. Infiltration of water in the subsurface and recharge to the water table have been calculated by a variety of methods by hydrologists in many arid and semiarid regions of the world. Methods employed include studies using environmental and introduced tracers, lysimeter experiments, soil-moisture models, regional water budgets, areal ground-water models, and watershed models. At a site under a given climatic regime, the nature of the soil and substratum and the type of vegetative cover strongly influence infiltration rates. Recharge rates at arid sites with annual precipitation of 150 millimeters or less may range from near zero at locations with silty or clayey subsoil with a well-developed native vegetative cover to more than 25 percent of precipitation at a location with a permeable, coarse sandy soil devoid of vegetation. Precipitation is only one factor of the climatic regime, but is a useful index parameter in comparing recharge rates. Generally, other factors being equal, water availability for infiltration and recharge increases more rapidly than precipitation.

INTRODUCTION

Background

Water in arid and semiarid regions of the world is commonly referred to as the most important of the natural resources. Because of its scarcity, it is keenly recognized as vital to maintenance of life and a productive economy. Ground water is commonly the only source of water in an arid or semiarid region and if not, it commonly is an essential supplemental source. Much effort has been expended by hydrologists to determine the rate of natural replenishment of ground water. Another need for understanding the hydrologic regimen in semiarid and arid regions arises from the need to isolate hazardous wastes resulting from human activities. Arid and semiarid regions are recognized as potentially favorable for long-term disposal of solidified toxic radioactive and nonradioactive wastes (Winograd, 1981; Bedinger and others, 1984). The unsaturated zone is considered favorable for the disposal of both low- and high-level radioactive wastes. The unsaturated zone in arid and semiarid regions commonly is of sufficient thickness (up to 30 m) for disposal of solidified low-level radioactive waste and in many localities is of sufficient thickness (greater than 150 m) for disposal of high-level and solidified transuranic radioactive wastes. The low flux of water in the unsaturated zone in arid and semiarid regions greatly enhances the favorability of this zone for isolation of wastes.

Purpose and Scope

This report is a review of studies of recharge and infiltration in arid and semiarid regions of the world. An annotated bibliography was prepared of more than 40 studies with respect to rates of infiltration under various conditions of climate, geohydrology, and vegetation. The methods of calculating infiltration and the relations between infiltration and climate, geohydrology, and vegetation are discussed.

Climate, Infiltration, and Recharge

The simplest classifications of climate are based on annual precipitation. Strahler and Strahler (1978, p. 129) refer to arid climates as having 0 to 250 mm yr^{-1} (millimeters per year) precipitation, semiarid as having 250 to 500 mm yr^{-1} precipitation, and subhumid as having 500 to 1,000 mm yr^{-1} precipitation. However, a climate classification based on the relationship of general factors that affect the availability of water to plants is more useful than a classification based simply on annual precipitation. The soil-water balance of Thornthwaite (1948), provides such a classification of climate by calculating the annual cycle of soil-moisture availability or deficiency, thus providing measures of soil moisture available for plant growth. Based on the soil-water balance, Strahler and Strahler (1978) discuss the worldwide distribution of 13 climatic types based on the average annual variations of precipitation, potential evapotranspiration, and the consequent soil-moisture deficit or surplus. Soil-water balance models--very similar to the soil-moisture model for classifying worldwide climate--have been devised to estimate recharge. These models utilize more specific data such as soil type and moisture-holding capacity, vegetation type and density, surface-runoff characteristics, and spatial and temporal variations in precipitation. Soil-water balance models used in estimating recharge in arid and semiarid regions are discussed later in this report.

In this report, "flux" is the volumetric rate of moisture flow across a unit cross-sectional area. "Infiltration" is the downward flux of water from the soil-atmosphere interface through the unsaturated zone. "Recharge" is infiltration that enters the zone of saturation. Within a few meters of the soil surface, soil water is subject to loss to the atmosphere by evapotranspiration. This removal of water from the unsaturated zone and the saturated zone where the water table is near the soil surface is termed "exfiltration" by Philip (1957). Thus, the amount of water that infiltrates within the zone of exfiltration is greater than the amount of water that recharges the saturated zone. Likewise, the measured recharge rate may be greater than the long-term net recharge rate where the water table is subject to loss by exfiltration. In the annotated bibliography a distinction is made by the use of the terms "infiltration", "recharge" and "net recharge" where possible. For example, in the annotation of the report by Phillips and others (1984), infiltration rates to depths of 1 m and 5 m are reported as 2.5 mm yr^{-1} and 0.02 mm yr^{-1}, respectively. No discrepancy is perceived in these rates because the depths of 1 m are, and 5 m possibly are, subject to water loss by exfiltration.

Methods of Estimating Infiltration and Recharge

The methods for estimating infiltration and recharge discussed briefly below are those used in the reports reviewed in the annotated bibliography. The bibliography is selective and not intended to be exhaustive. Most emphasis is placed on reviewing studies of point infiltration rates, such as tracer studies, lysimeter experiments, and soil-moisture models. Fewer studies of broad-area water budgets, areal ground-water models, and watershed models are reviewed here. The reports reviewed are of studies in arid and semiarid regions of the world; some of the classical well-known methods are not represented or are represented by derivative methods or variations. For example, no studies reviewed here use the base-flow hydrograph separation method.

Soil-Water Accounting Models

An accounting of moisture flux in the unsaturated zone--the zone above the saturated zone--is used in many models to estimate recharge. A basic soil-moisture model takes into account soil-moisture storage capacity, antecedent soil moisture, precipitation, surface runoff, evapotranspiration and recharge.

Dugan and Peckenpaugh (1985) used the following formulation to estimate recharge, which they referred to as deep percolation, in the mid-continental United States:

$$R = (S + P - O - E) - C \tag{1}$$

where

R = Recharge,
S = antecedent soil moisture,
P = precipitation,
O = surface runoff,
E = actual evapotranspiration, and
C = moisture storage capacity of the soil zone.

Kafri and Asher (1978), using a soil-moisture model, examined the differences in recharge from winter and summer precipitation in a desert-mountain area of southern Arizona of varying soil characteristics. Caro and Eagleson (1981) estimated recharge in Saudi Arabia from an annual soil-moisture water-balance model that accounted for variable rainy season length and soil desiccation during the dry season.

Soil moisture models may be augmented with an array of atmospheric, soil, and saturated-zone measurements. The use of an extensive array of atmospheric and unsaturated- and saturated-zone measurements to augment an unsaturated flow model is described by Sophocleous and others (1985).

Changes in soil-moisture content in a vertical profile, both alone and with other data, have been used to estimate recharge rates (Gee and Kirkham, 1984). Lack of change in moisture content in the soil profile has been cited as evidence of lack of vertical moisture movement (Abrahams and others, 1961; Sammis and Gay, 1979). However, lack of change in soil-moisture content is not conclusive evidence of lack of flux but rather an indication of steady-state conditions. Studies in which soil-moisture measurements are augmented by measurements of other characteristics may be less equivocal. Indeed, soil-moisture measurements in conjunction with data from one or more measurement methods, such as soil-moisture tension and environmental and injected tracers, are widely used to measure infiltration and recharge rates. Lysimeters have been used by many investigators including Gee and Kirkham (1984), Holmes and Colville (1970a), and Kitching and others (1980), to measure infiltration. The infiltration measured in lysimeter experiments will be greater than recharge where the depth of the lysimeter is less than the depth to which soil moisture is lost by exfiltration.

Watershed Models

Watershed water-accounting models, such as those of Leavesley (1973) and Leavesley and others (1983), were developed primarily to model surface runoff; however, Leavesley's models include soil-moisture accounting and can be used to estimate recharge. Recharge is modeled as infiltration from a deep soil-moisture reservoir that, in turn, receives infiltration from a shallower soil-moisture reservoir in excess of its water-holding capacity. These continuous-simulation, distributed-parameter models are calibrated using streamflow. In applying the model to an area, baseflow may or may not be modeled as a component of the streamflow. Leavesley's (1973) watershed model was used by Weeks and others (1974) to estimate recharge in the Piceance basin of northwestern Colorado where recharge estimates compared favorably with those predicted by a ground-water flow model. Carey (1984) used the model of Leavesley and others (1983) to estimate recharge for a watershed in eastern Montana.

Tracer Studies

Methods of computation of infiltration employing environmental tracers rely on (1) the principle of conservation of mass using naturally introduced thermonuclear or other environmental tracers, and (2) the use of intentionally introduced thermonuclear or other tracers to calculate the rate of soil-moisture movement (tracer dating). Suitable natural environmental tracers are those that are not products of pedogenesis, do not react chemically in the soil system, are not removed substantially by exfiltration, and are highly soluble. Natural environmental tracers that have been suggested for use include chloride, sulfate, and nitrate (Kitching and others, 1980; Sharma and Pionke (1983). Chloride has been widely used as a tracer. Allison (1981) reviews the uses of natural isotopes, principally tritium, deuterium, carbon-13, carbon-14 and oxygen-18, in the qualitative and quantitative understanding of hydrologic regimes. Environmental tracers produced in significant amounts by thermonuclear explosions--namely, tritium and chlorine-36--have been used in the measurement of infiltration rates.

Studies of naturally occurring isotopes in ground water using carbon-14, deuterium, and oxygen-18 have provided insight into the paleoclimate of late Pleistocene age in an arid environment of southern Nevada (Claassen, 1986).

Mass balance of a natural environmental tracer in the soil moisture may be used to measure infiltration where the sole source of the tracer is atmospheric precipitation and where runoff is known or negligible. The relationship for a steady state mass balance is:

$$R_q = (P - R_s) \cdot C_p/C_z \; , \qquad (2)$$

where R_q, infiltration, is a function of P, precipitation, R_s, surface runoff, C_p, tracer concentration in precipitation, and C_z, the tracer concentration of the soil moisture.

In the ideal model, the tracer content of soil water increases with depth by the loss of soil water to exfiltration and conservation of tracer. The tracer content of soil water attains a maximum at the maximum depth of exfiltration. The model postulates a constant content of tracer in the soil moisture from this point to the water table. Departures from the ideal model of tracer variation with depth are common and have been ascribed to changes in land use, such as clearing of native vegetation (Allison and others, 1985), plantations of pine woodlands in place of native vegetation (Sharma and Pionke, 1983), replacement of native vegetation by cropped agriculture (Allison and Hughes, 1983), bypass mechanisms for infiltrating water through the soil profile (Allison and others, 1985; Johnston, 1983), and changes in climate (Allison and others, 1985).

Chloride is used as the tracer in the steady-state mass-balance equation (eq. 2) used by Allison and Hughes (1978; 1983), Kitching and others (1980), Sharma and others (1983), Johnston (1983), Sharma and Pionke (1983), Allison and others (1985), and Stone (1985). Peck and Hurle (1973), Eriksson (1976), Johnston (1983), Sharma and others (1983), and Sharma and Pionke (1983) use a mass-balance equation in which the chloride content of soil water that drains to the water table, C_z in equation (2), is estimated by the chloride content of ground water below the water table. Eriksson and Khunakasen (1969) used the change in chloride content of ground water along flow lines to estimate recharge from the chloride fallout for the coastal-plain aquifer of Israel.

Mass-balance equation (2) assumes that recharge occurs by piston flow. Sharma and Pionke (1983) and Johnston (1983) propose the following relation for solute mass balance with diffusion and dispersion where runoff is negligible:

$$P \cdot C_p = -D_s - \partial C/\partial Z + C_z \cdot R_q \,, \qquad (3)$$

where D_s, the diffusion-dispersion coefficient and $\partial C/\partial C_z$ is the rate of change in soil-moisture concentration with depth. P, C_z, and R_q are as defined in equation (2).

Sharma and Pionke (1983) and Johnston (1983) found that diffusion and dispersion are important components of chloride flux in the unsaturated zone.

Atmospheric fallout of chlorine-36 and tritium were at elevated levels due to atmospheric nuclear testing in the 1950's and 1960's. Thermonuclear environmental tracers can be used to date soil moisture that precipitated during a peak in fallout and can be identified in the soil-moisture profile. Thermonuclear-tracer dating methods are used to compute recharge as (1) the ratio of soil-moisture content in the dated portion of the soil column to the precipitation during the time period, or (2) as a ratio of tracer concentration in the dated column of the soil profile, accounting for decay, to the tracer concentration in precipitation for the same time period. By the first method the recharge or infiltration to the depth of the tracer peak or dated soil moisture is computed by

$$R_q = \Theta/P \tag{4}$$

where Θ is the moisture in the soil column above the depth of the peak or dated soil moisture, and P is the sum of precipitation since the time of the dated soil moisture. By the second method

$$R_q = t/T \tag{5}$$

where t is the total tritium in the soil-moisture column, adjusted for decay, above the depth of the dated soil water, and T is the tritium in precipitation for the same period. Sukhija and Rama (1973) employed both methods in India in 1967 and 1969 using tritium peak concentrations in soil moisture to date the moisture in the soil column corresponding to the maximum tritium fallout in 1963-64. Allison and Hughes (1978) used both tritium tracer dating methods in calculating recharge in the Gambier Plain, southern Australia. They were able to date the soil moisture in the profile by comparing the tritium content profile with the atmospheric tritium fallout record. Dincer and others (1974) used tritium in soil moisture to calculate infiltration through sand dunes in Saudi Arabia. Phillips and others (1984) used the soil-moisture chlorine-36 pulse in New Mexico to calculate the rate of infiltration to a depth of 1 meter. Verhagen and others (1979), using soil-moisture tritium, calculated the recharge to Kalahari sands of South Africa for two periods--one having below average precipitation and the other having above-average precipitation.

Tracers can be artificially introduced in the soil profile and used to calculate recharge by methods similar to that for thermonuclear-fallout isotopes. Datta and others (1973) discuss the injection of tritium in the soil and subsequent measurements to determine the moisture content between the injected depth and the center of gravity of tritium activity.

Ground-Water Models

Deterministic models of ground-water-flow systems commonly are used to solve for the recharge component of the mass-balance equation by simulating ground-water flow for steady-state or nonsteady-state conditions. Accuracy of the computed recharge is a function of the definition of the geohydrologic system and its representation in mathematical form. Digital models of the Ogallala aquifer of the High Plains that extends over a 451,000-km^2 (square kilometer) area in Texas, New Mexico, Oklahoma, Colorado, Kansas, Nebraska, South Dakota, and Wyoming were made using an extensive array of data from well logs, aquifer tests, and ground-water withdrawal surveys. The digital models were used to estimate recharge throughout the region for 259-km^2 units (Luckey and others, 1986).

Analysis of areal ground-water flow nets, quantitatively calculating recharge by the increase in flow between diverging flow lines, was used by Theis (1937) and Rehm (1982). Water-level changes were interpreted qualitatively to judge changes in recharge by Peck (1983). Water-level fluctuations were analyzed quantitatively to yield recharge rates by Theis (1937), and Viswanathan (1984).

Water budgets can be used to estimate ground-water recharge for ground-water flow units whose limits are defined and whose discharge can be measured or estimated. This method has been used extensively in Nevada and with modifications in Utah. The method, developed for closed basins in Nevada by Maxey and Eakin (1949), assumes that ground-water recharge within a basin equals ground-water discharge. Recharge is estimated as a percentage of average annual precipitation. The percentage is larger for zones of greater precipitation; however, the method does not assume recharge occurs wholly within the zone in which precipitation occurs. The method is discussed in more detail in the annotated bibliography (Maxey and Eakin, 1949). An analysis of recharge estimates, from studies of the basins in Nevada derived from this method, is given in Watson and others (1976).

Theis (1937) analytically simulated the water-level profile through a section of the Ogallala aquifer of Texas and New Mexico to estimate the rate of recharge. A general form of the equation for the steady-state, parabolic water-level profile under conditions of uniform recharge and transmissivity was derived by Jacob (1943) and has been widely used in areas of humid climates.

In areas of hyperaridity, such as the Sonoran Desert of the American southwest, Saudi Arabian Desert, Sahara Desert of north Africa, and the Kalahari Desert of Botswana and South Africa, and even in semiarid environments such as the Great Plains from Texas to North Dakota, controversies exist over the question of whether recharge occurs under modern climatic conditions. Several investigators have approached the problem by observing the decay of ground-water levels that are presumed to have existed during the late Pleistocene pluvial climate. Modern water levels higher than the decayed profile, assuming no recharge, would be evidence of modern recharge. Studies by Bakiewicz and others (1982), Burdon (1977), DeVries (1984), Lloyd and Farag (1978), and Luckey and others (1986) are summarized in the following annotated bibliography.

SUMMARY OF INFILTRATION RATES

A scatter diagram of infiltration as a percentage of precipitation, as a function of annual precipitation, is shown in figure 1. The references for the points are listed in table 1 and were taken from studies in the "Annotated Bibliography". Differences in methods of calculation account for part of the scatter of points, as shown by the variation in recharge at site 5 by Carey (1984) (who used two variations of a method), at site 14 by Johnston (1983) (who used two methods--one for calculating recharge and one for calculating infiltration in the unsaturated zone), site 19 by Rehm and others (1982) (who used several methods for estimating recharge), site 24 by Gee and Kirkham (1984) (who used three different methods for estimating infiltration to various depths assumed to be below the depth of water loss by exfiltration), and site 26 by Stephens and Knowlton (1986) (who used different methods and different applications of the same method for calculating infiltration to a depth below the root zone).

In addition to different methods of calculation and real differences in rates of infiltration to various depths, infiltration to the water table (equal to recharge), and net recharge (recharge minus exfiltration from the zone of saturation), the scatter is due to differences in character of the soil and substratum, vegetation, precipitation, and climatic regime. The trendlines of points for infiltration in relation to precipitation from Maxey and Eakin (1949) and Dugan and Peckenpaugh (1985) are given in figure 1. The two trendlines are for distinctively different geographical and climatic areas

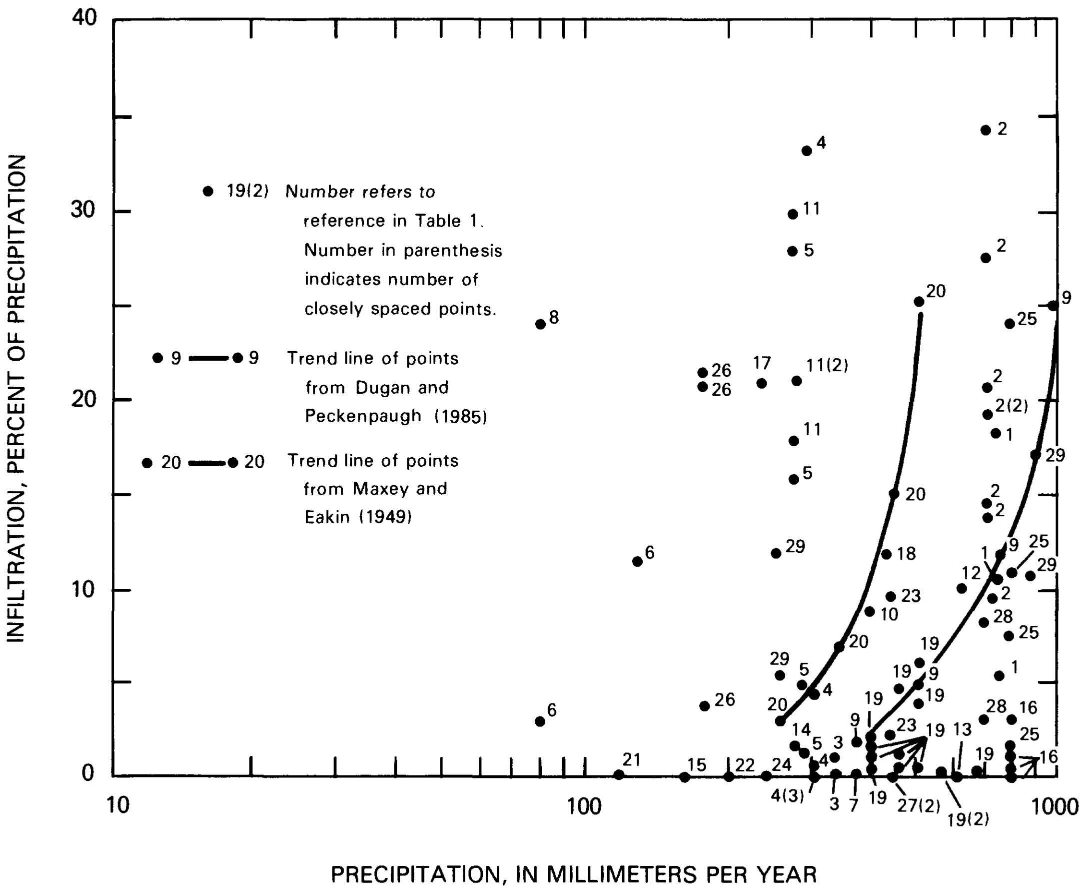

Figure 1.--Relations between infiltration and average precipitation.

and for different methods of estimating infiltration. The trend of the points from Maxey and Eakin (1949) are measurements of recharge from reconnaissance ground-water budget studies in the Basin and Range province of Nevada; the trend of the points from Dugan and Peckenpaugh are calculations of infiltration based on a soil-moisture model of the Midwestern United States. The trendlines of Maxey-Eakin and Dugan-Peckenpaugh integrate environmental difference in their respective regions and reflect the average relation between infiltration and precipitation as calculated by the investigators.

Table 1.--*Precipitation and infiltration estimates from selected references*
[mm yr^{-1}, millimeters per year]

Site no. (fig. 1)	Reference, location (method of study, notes)	Precipitation (mm yr^{-1})	Infiltration (mm yr^{-1})	Infiltration (Percentage of precipitation)
1	Allison and Hughes, 1974 (tritium tracer method in unsaturated zone) South Australia	750	40	5.3
			80	10.6
			140	18.6
2	Allison and Hughes, 1978 (chloride content of soil moisture; tritium tracer infiltration rates are similar; range is due to soil differences) South Australia	725	70	9.6
			100	13.8
			140	19.3
			105	14.5
			150	20.7
			140	19.3
			200	27.6
			250	34.5
3	Allison and Hughes, 1983 (chloride content of soil moisture; rates reflect differences in vegetation) Victoria, Australia	335	.07	.02
			3.5	1.0
4	Allison and others, 1985 (chloride mass-balance and tritium dating methods; rates reflect differences in soil type, subsoil, and vegetation) South Australia	300	.17	.057
			.1	.033
			60.0	.2
			100.0	33.3
			.06	.02
			13.5	4.5
5	Carey, 1984 (watershed model; rates reflect variations in methodology) Montana, U.S.A.	277 (1979)	45.5	16.4
			77.7	28.0
		291 (1980)	.25	.08
			13.7	4.7

Table 1.--*Precipitation and infiltration estimates from selected references*--Continued

Site no. (fig. 1)	Reference, location (method of study, notes)	Precipitation ($mm\ yr^{-1}$)	Infiltration ($mm\ yr^{-1}$)	Infiltration (Percentage of precipitation)
6	Caro and Eagleson, 1981 (water-balance model) Saudi Arabia	130 80	15 3	11.5 3.7
7	DeVries, 1984 (ground-water model) South Africa	400	.3	.08
8	Dincer and others, 1974 (tritium dating method) Saudi Arabia	82	20	24
9	Dugan and Peckenpaugh, 1985 (soil-moisture accounting model) Mid-Continent, U.S.A.	1,016 762 508 381	254 90 25 6	25 12 5 2
10	Eriksson, 1976 (chloride mass balance of unsaturated zone) India	400	35	8.8
11	Gee and Kirkham, 1984 (soil-moisture accounting model, lysimeter, and unsaturated-flow model; different rates reflect different methods) Washington, U.S.A.	283 (1983)	85 60 50 50	30 21 18 21
12	Holmes and Colville, 1970a (lysimeter; grassland) South Australia	632	63	10.0
13	Holmes and Colville, 1970b (water budget; pine plantation) South Australia	600	0	0

Table 1.--*Precipitation and infiltration estimates from selected references*--Continued

Site no. (fig. 1)	Reference, location (method of study, notes)	Precipitation ($mm\ yr^{-1}$)	Infiltration ($mm\ yr^{-1}$)	Infiltration (Percentage of precipitation)
14	Huntoon, 1977 (ground-water budget) Arizona, U.S.A.	280	2.5	.9
15	Isaacson and others, 1974 (metric potential gradient, tritium profiles, soil-moisture accounting) Washington, U.S.A.	160	0	0
16	Johnston, 1983 (method 1, mass balance of chloride in ground water and method 2, mass balance of chloride in unsaturated zone; both methods used at two locations) Western Australia	800		Method 1
			1.4	.18
			25	3.1
				Method 2
			.3	.04
			4	.5
17	Kirkham and Gee, 1983 (soil-moisture accounting model, unsaturated-flow model) Washington, U.S.A.	240 (November 1982 through October 1983)	50	21
18	Kitching and others, 1980 (tritium tracer and chloride mass balance) Cyprus	420	50	11.9
19	Luckey and others, 1986 (ground-water flow models) Southern High Plains, U.S.A.	457(Average)	3.3(Average)	.7(Average)

Table 1.--*Precipitation and infiltration estimates from selected references*--Continued

Site no. (fig. 1)	Reference, location (method of study, notes)	Precipitation (mm yr^{-1})	Infiltration (mm yr^{-1})	Infiltration (Percentage of precipitation)
19	Luckey and others, 1986--Continued			
	Central High Plains, U.S.A.	406(Average)	3.6(Average)	.9(Average)
	(different rates are for different soil types)	508(Average)	21.3	4.2
		406	9.9	2.4
		660(Average)	2.8	0.4
		510	2.8	0.6
		558(Average)	1.4	0.2
	Northern High Plains, U.S.A. (different rates are for different soil types)	508(Average)	30.5	6.0
		458(Average)	21.3	4.6
		406	7.6	1.9
		458(Average)	5.1	1.1
		406	2.8	.7
		558(Average)	1.5	.3
20	Maxey and Eakin, 1949 (ground-water budgets) Nevada, U.S.A.	254		3
		343		7
		444		15
		508		25
21	Nichols, 1986 (soil-moisture accounting model) Nevada, U.S.A.	114	.04	.04
22	Phillips and others, 1984 (chloride mass balance) New Mexico, U.S.A.	200	.02	.01
23	Rehm and others, 1982 (water level hydrograph, vertical head gradients, flow net analysis; range of recharge by the three methods) North Dakota, U.S.A.	440	10	2.3
			40	9.1
24	Sammis and Gay, 1979 (soil moisture accounting) Arizona, U.S.A.	234	0	0

Table 1.--Precipitation and infiltration estimates from selected references--Continued

Site no. (fig. 1)	Reference, location (method of study, notes)	Precipitation (mm yr^{-1})	Infiltration (mm yr^{-1})	Infiltration (Percentage of precipitation)
25	Sharma and others, 1983 (mass balance of chloride in soil moisture and ground water; both methods used for different depths to water level) Western Australia	800	86	10.8
		194	24.	
			4.6	.6
			59	7.4
26	Stephens and Knowlton, 1986 (method 1, measured metric potential gradient and unsaturated hydraulic conductivity and method 2, hydraulic conductivity assuming unit gradient) New Mexico, U.S.A.		Method 1	
		179	7.0 to 36.6	3.9 to 20.4
			Method 2	
			37	20.7
27	Stone, 1985 (chloride mass balance) Southern High Plains, U.S.A.	444	1.25	.28
			.21	.05
28	Sukhija and Rama, 1973 (tritium dating methods) India	700		3.0
				8.3
29	Verhagen and others, 1979 (tritium dating methods) South Africa	254		5.5 to 12.1
				8.8 (Average)
		875		10.6 to 17.1
				13.8 (Average)

From the studies annotated in this report, precipitation, as one component of the climatic regime appears to be a useful index of climatic factors affecting infiltration. Certainly, potential evapotranspiration also is a significant factor affecting the availability of water for infiltration, as is the temporal distribution of precipitation and potential evapotranspirtation. Generally, as precipitation increases, the availability of water for infiltration increases. As indicated from the Maxey-Eakin and Dugan-Peckenpaugh trendlines, infiltration increases more rapidly than precipitation.

Much of the vertical scatter in the graph is due to differences in character of the soil and substratum, vegetation, and climatic regime. Differences in character of the soil are shown by infiltration rates calculated by investigators at locations having different soil and substratum types at the same site. Allison and Hughes (1978) (site 2) found that infiltration, as a percentage of precipitation, ranged from 9.6 percent for a sand over a heavy clay to 34.5 percent for a permeable skeletal soil of low water-holding capacity, using chloride as a tracer. Stephens and Knowlton (1986) (site 26) calculate infiltration rates as large as 20 percent of precipitation in a coarse-grained sand having a very small percentage of silt and clay particles, whereas Phillips and others (1984) at a nearby location (site 22) calculate infiltration rates as low as 0.01 percent of precipitation in a clayey and silty sand. Several of the other points to the left of and above the Maxey-Eakin trendline represent calculations of infiltration in coarse-grained permeable soils, such as for sand dunes (site 8, Dincer and others, 1974) and coarse-grained sand (site 24, Gee and Kirkham, 1984; and site 25, Kirkham and Gee, 1983).

The effects of vegetation are clearly reflected in the work of Allison, and others (1985) who found at site 4 that recharge to a dune vegetated with native mallee was 0.02 percent of precipitation, whereas recharge to an unvegetated dune was 4.5 percent of precipitation. Other differences in infiltration at site 4 by these authors reflect largely the differences in character of the soil and substrata. Holmes and Colville (1970a) found that recharge to grassland of the Gambier Plain (site 11) was 10 percent of precipitation; in contrast, Holmes and Colville (1970b) found that no recharge occurred in the Plain at a location beneath a plantation forest of pine. Allison and Hughes (1983) (site 3) calculated that infiltration was 0.02 percent of precipitation in a location of native vegetation and 1 percent of infiltration in a cropped area of wheat-fallow rotation.

The relation of the depth of the water table to recharge is not clearly indicated in the studies annotated in this paper. Sophocleous and others (1985) calculated that recharge was greater at a location underlain by a shallow water table (2.3- to 0.2-m depth) than at a location underlain by a deeper water table (5.3- to 5.1-m depth). Sharma and others (1983) (site 20) found that infiltration was greater in areas underlain by a shallow water level (<10 m) than in areas underlain by a deep water level (>20 m). In both cases cited above the shallower water level reflects greater recharge. In a humid region, Bedinger and others (1970) found that, for different types of alluvial deposits related to grain size, recharge increased as depth to water increased. In the areas studied, recharge was calculated at many points in different depositional types, and depth to water was a function of many factors, including topography and distance to the discharging stream. Recharge rate was only one and not a dominant factor affecting depth to water.

The generally great differences in calculated infiltration and recharge rates largely reflect spatial and temporal differences in natural conditions and various differences and problems associated with the methodology. The spatial differences in infiltration rates limit the usefulness of point calculations in projecting infiltration rates over large areas. The apparent great variations in infiltration rates with time observed by (1) studies at single points over a few years (Claassen and others, 1986; Carey, 1984) and (2) by studies that indicate that recharge in arid regions may occur only during distinct periods (Claassen, 1985) or at very widely spaced time intervals (Nichols, 1986) illustrate the problem of establishing a representative long-term average infiltration rate for a region under a given climatic regime. For many regional studies requiring estimates of recharge, it would seem desirable to select several methods that integrate infiltration or recharge over a large area and over a long period of time. The resulting data may be usefully augmented by point studies that provide insight into mechanisms of infiltration and recharge under specific natural conditions.

ANNOTATED BIBLIOGRAPHY

Abrahams, J.H., Weir, J.E., Jr., and Purtymun, W.D., 1961, Distribution of moisture in soil and near-surface tuff on the Pajarito Plateau, Los Alamos County, New Mexico, *in* U.S. Geological Survey Research, 1961: U.S. Geological Survey Professional Paper 424-D, p. 142-145.

LOCATION: Pajarito Plateau, Los Alamos County, north-central New Mexico

GEO-HYDROLOGIC SETTING: Plateau is underlain by pumice deposits, ash falls, and ash flows. Soil is well developed. Water table is more than 1,000 ft below surface.

METHODS OF STUDY: Soil moisture was measured in 23 access holes with a neutron-scattering moisture probe in the spring, summer, and fall of 1960. Soil moisture was measured beneath an infiltrometer in which water was maintained for 99 days.

INFILTRATION: Authors conclude recharge was nil because soil moisture content remained constant at depths of 4 feet and greater in unweathered tuff.

Allison, G.B., and Hughes, M.W., 1972, Comparison of recharge to groundwater under pasture and forest using environmental tritium: Journal of Hydrology, v. 17, p. 81-95.

LOCATION: Gambier Plain, southeastern South Australia.

CLIMATE: Mean annual rainfall 600 to 750 mm yr^{-1}.

GEO-HYDROLOGIC SETTING: Mean depth to water was 6.0 m and 5.6 m for forest and pasture sites, respectively.

VEGETATION: Pasture and pine plantations. See Holmes and Colville (1970).

METHODS OF STUDY: Tritium concentrations in ground water within 20 cm of water table.

INFILTRATION: Authors conclude that recharge to pineland is less than one-fifth of recharge to pasture land.

Allison, G.B., and Hughes, M.W., 1974, Environmental tritium in the unsaturated zone; estimation of recharge to an unconfined aquifer, *in* Isotope techniques in groundwater hydrology, Proceedings of a Symposium, 1974, v. 1, Vienna: International Atomic Energy Agency, p. 54-72.

LOCATION: Gambier Plain, South Australia.

CLIMATE: Average annual precipitation is about 750 mm yr^{-1}. Most of the precipitation falls in winter (April-September).

VEGETATION: Land cover is improved pasture with no trees or other land use within 100 m of any sampling location.

GEO-HYDROLOGIC SETTING: Area underlain by unconfined aquifer. Soils at sampling sites include clays, sandy loam, and sand clays.

METHODS OF STUDY: Tritium content of soil moisture. The piston flow model of Smith and others (1970) and two modifications of the model were used to estimate recharge.

INFILTRATION: Annual recharge at three sites was 40 mm, 80 mm, and 140 mm. The variation was attributed to the differences in soil type.

Allison, G.B., and Hughes, M.W., 1978, The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer: Australian Journal of Soil Research, v. 16, p. 181-195.

LOCATION: Gambier Plain, South Australia.

CLIMATE: Average rainfall 700 to 750 mm yr^{-1}, mostly in winter.

GEO-HYDROLOGIC SETTING: Almost no surface runoff; underlain by a Tertiary limestone unconfined aquifer. Aquifer is overlain by soils ranging from from permeable skeletal soils of low water-holding capacity to low permeability swampy Podsols.

METHODS OF STUDY: Chloride mass balance and tritium soil-moisture dating methods. Content of tritium and chloride in soil moisture were measured at 16 sites.

INFILTRATION:

	Mean Annual Recharge (mm)	
Hydrologic Unit (Soil)	Chloride	Tritium
Sand over heavy clay	70	50
Volcanic soils	100	100
Sand over sandy clay	140	100
Sand over thin sandy clay over limestone	105	120
Terra rossa over limestone	150	130
Thin sandy loam over limestone	140	155
Aeolianite	200	195
Skeletal soils	250	270

Allison, G.B., and Hughes, M.W., 1983, The use of natural tracers as indicators of soil-water movement in a temperate semiarid region: Journal of Hydrology, v. 60, p. 157-173.

LOCATION: Mallee Research Station at Walpeup (35°7'S, 140°0'E), Victoria, Australia.

CLIMATE: Climate is semiarid; mean annual rainfall is 335 mm.

GEO-HYDROLOGIC SETTING: Surface features are a series of east-west dune systems: amplitude of dunes is about 11 m. Regional water table is about 60 m beneath swales. Authors think the regional water table plays no part in either the salt or water balance of the top 15 m of soil. Soils are sands or sandy loams overlying clay loams, sandy clays, and clays with occasional sand lenses.

VEGETATION: Areas of two vegetative types were sampled: (1) native *Eucalyptus* scrub, known as mallee. A variety of *Eucalyptus* species were present, principally *E. incrasata*, *E. calycogona* and *E. oleosa* as well as *Melaleuca pubescens*. The *Eucalyptus* species are small scrubby trees ranging in height from 2 to about 12 m. Typically, trees are 5 to 8 m apart, and (2) cropped wheat-fallow pasture rotation since 1910.

METHODS OF STUDY: Cores of material in the saturated zone were taken from depths of from 9 to 15 m beneath native and cropped land. Analyses made of water content and chloride, stable isotopes, and tritium. Cores were taken in 1977 and 1978. Recharge beneath native vegetation was calculated from data on annual precipitation and the concentration of chloride in rainfall, and in soil moisture below the root zone. A steady-state chloride profile was not reached beneath the cropped area. Estimate of recharge beneath cropped area is based on assumed change in chloride profile since cropping began.

INFILTRATION: Authors calculated recharge as 0.07 mm yr^{-1} at the site of native vegetation and 3 to 4 mm yr^{-1} beneath the cropped area.

Allison, G.B., Stone, W.J., and Hughes, M.W., 1985, Recharge in karst and dune elements of a semiarid landscape as indicated by natural isotopes and chloride: Journal of Hydrology, v. 76, p. 1-25.

LOCATION: Murray Basin, South Australia.

CLIMATE: Climate is semiarid; mean annual precipitation is about 300 mm yr^{-1}; and potential annual evaporation is about 1,800 mm yr^{-1}. Greatest precipitation occurs in winter months (June through August).

GEO-HYDROLOGIC SETTING: Two materials, calcrete and dune sand dominate the surface deposits. Calcrete, typically a layer 1- to 2-m thick, results from accumulation of authigenic calcium carbonate, lies at or near the surface and is often covered by dune sand. Depth to the water table beneath the calcrete flats is about 30 m. Sinkholes are present on many of the calcrete flats. Primary sinkholes are large shallow depressions that may have formed by dissolution of gypsum from Blanchetown clay lying beneath the calcrete. Secondary sinkholes are formed within primary sinkholes by dissolution along fractures in regional limestone aquifers at depth. Soil in sinkholes is much thicker (1.8 m) than on calcrete flats.

VEGETATION: Native vegetation is *Eucalyptus* spp. up to 10 m high with several slender trunks rising from a single lignotuber lying just below the surface. Undisturbed calcrete is vegetated by widely spaced *Eucalyptus* spp. Vegetation in the primary (older) sinkholes is almost exclusively bluebush (*Kochia sedifolia*). Vegetation in secondary sinkholes is characterized by a ring of shrubs up to 3-m high around the edge with annual grasses in the center. Dunes have (1) native mallee vegetation and (2) poorly developed pasture cleared in the 1930's.

METHODS OF STUDY: Chloride mass balance and tritium dating methods were used. Soil samples to depths of 30 m were taken for analysis of chloride and tritium in soil moisture.

INFILTRATION: Recharge rate was calculated as follows:

1. Calcrete Flats: about 0.17 mm yr^{-1}, based on chloride profile;
2. Primary sinkhole: about 0.1 mm yr^{-1}, based on chloride profile;
3. Secondary sinkhole: 60 mm yr^{-1} minimum, based on chloride, 100 mm yr^{-1} based on tritium;
4. Mallee vegetated dune: 0.06 mm yr^{-1}, based on chloride profile;
5. Unvegetated dune: 13-14 mm yr^{-1}, based on chloride profile.

Bakiewicz, W., Milne, D.M., and Noori, M., 1982, Hydrogeology of the Umm Er Radhuma aquifer, Saudi Arabia, with reference to fossil gradients: Quarterly Journal of Engineering Geology, v. 15, p. 105-126.

LOCATION: Eastern Saudi Arabia.

CLIMATE: Arid.

GEO-HYDROLOGIC SETTING: Regional aquifer is the Umm Er Radhuma aquifer, of limestone, dolomites, marls, and shales ranging in age from Cambrian to recent. The aquifer is partly under artesian conditions. Sand dunes cover a large part of the surface.

METHODS OF STUDY: (1) Analysis of carbon-14 and tritium in ground water; (2) recharge estimation from climatic and soil-moisture data; (3) analytical analysis of fossil gradients (decay of ground-water gradient upon cessation of recharge); and, (4) mathematical model simulation of aquifer.

INFILTRATION: Authors conclude that modern recharge, though erratically distributed in time and space, is sufficient to maintain a steady flow through the aquifer.

Burdon, D.J., 1977, Flow of fossil groundwater: Quarterly Journal of Engineering Geology, v. 10, no. 2, p. 97-124.

LOCATION: Sahara and Arabian Desert.

CLIMATE: Arid.

GEO-HYDROLOGIC SETTING: The ground-water basins studied are underlain by sedimentary formations in which ground water is confined.

METHODS OF STUDY: Ground water in the basins is under a hydraulic gradient moving toward discharge areas. The author investigates mechanisms that could maintain the flow of ground water in the absence of natural recharge since the pluvials of the Quaternary which ended "some 10,000 years ago". If there are no such mechanisms, there must be natural recharge. The principal mechanisms explored by the author include:

1. Residual head.
2. Tilting of the basin.
3. Compaction by sediment loading, basalt loading, and water loading.
4. Thermal drive.
5. Gas drive.
6. Lowering of discharge levels.
7. Evaporation effects on discharge.

INFILTRATION: Although the author does not reach definite conclusions as to whether or not the present-day flow of fossil ground water could have been maintained without recharge over the past 10,000 years, he states that "combinations of these mechanisms can produce heads inducing flow of fossil groundwater, but appear to be insufficient to account for present hydraulic regimes without some current surface recharge."

Carey, L.E., 1984, Application of the U.S. Geological Survey's precipitation-runoff modeling system to the Prairie Dog Creek Basin, southeastern Montana: U.S. Geological Survey Water-Resources Investigations Report 84-4178, 95 p.

LOCATION: Prairie Dog Creek Basin, southeastern Montana.

CLIMATE: Climate is semiarid continental steppe; mean precipitation is 330 mm yr^{-1}, with 60 percent occurring from April to July. Thirty to 40 percent of precipitation occurs as snow. Two years of data (1979 and 1980 water years) were used to model streamflow. Precipitation in 1979 water year was 277 mm; precipitation in 1980 water year was 291 mm.

GEO-HYDROLOGIC SETTING: The 64.8 km^2 basin is underlain by the Tongue River Member of the Fort Union Formation of Paleocene age. The Tongue River consists of lenticular layers of sandstone, siltstone, mudstone, claystone, carbonaceous shale and coal.

VEGETATION: Vegetation types consist of sagebrush steppe, sagebrush grassland, mid and short grass, ponderosa pine, riparian grassland, and mixed ponderosa pine and Rocky Mountain junipers. Land use is livestock grazing.

METHODS OF STUDY: Runoff was determined using the model developed by Leavesley and others (1983). The model is a continuous-simulation, distributed-parameter model having an optional storm mode. Recharge was modeled as accretion to a ground-water reservior which may or may not contribute to local base flow. Seepage to the ground-water reservoir is modeled by a decay function from a subsurface reservior which in turn receives seepage in excess of the water-holding capacity of the lower soil zone.

Carey, 1984--Continued

INFILTRATION: Recharge was modeled for water years 1979 and 1980 using two alternative methods of subdividing the basin, here referred to as methods A and B.

	Recharge (mm yr^{-1})
Method A	
1979	45.5
1980	0.25
Method B	
1979	77.7
1980	13.7

The greater recharge in 1979 than in 1980 may be explained by differences in the snowpack. Although total precipitation was greater in water year 1980, a larger snow pack accumulated in water year 1979. In water year 1980 the snow pack was less and melted several times during the winter.

Caro, Rodrigo, and Eagleson, P.S., 1981, Estimating aquifer recharge due to rainfall: Journal of Hydrology, v. 53, p. 185-211.

LOCATION: Central zone of Saudi Arabia.

CLIMATE: Climate is arid. Precipitation is seasonal, occurring in November through May and averaging 14.43 and 9.38 cm yr^{-1} at two stations at Riyadh and 12.18 cm yr^{-1} at Qasim. Class-A pan evaporation at three stations ranges from 1,318 to 1,912 m yr^{-1}.

GEO-HYDROLOGIC SETTING: Depth to the water table is greater than 100 m. Minjur and Wasia Formations in the presumed recharge areas are sand and sandstone.

METHODS OF STUDY: Water-balance model of Eagleson (1979) was modified to account for variable-length rainy season and soil desiccation during the dry season.

INFILTRATION:

Aquifer	Average annual (seasonal) rainfall (mm)		Probable range of median annual recharge (mm)
Minjur	130	minimum	10
		best estimate	15
		maximum	24
Wasia	80	minimum	1
		best estimate	3
		maximum	6

COMMENTS: See also comment on this paper by Dincer (1982) and reply by Caro and Eagleson (1982).

Datta, P.S., Goel, P.S., Rama, P.A., and Sengal, S.P., 1973, Groundwater recharge in western Uttar Pradesh, *in* Proceedings of the Indian Academy of Sciences, series A, v. 78, no. 1, p. 1-12.

LOCATION: Western Uttar Pradesh, India.

GEO-HYDROLOGIC SETTING: Ground water is in the deposits of the Indogangetic Plain.

METHODS OF STUDY: Water containing tritium was injected at a depth of 700 mm. Subsequently, samples were taken to determine soil-moisture content and position of the tritium spike. Recharge was estimated by the water content between the injected depth and the center of gravity of the tritium activity.

INFILTRATION: Recharge was calculated at about 50 sites. Average recharge was 215 mm yr^{-1} principally in response to rainfall during the monsoon.

COMMENTS: Precipitation is not reported; some sites may be affected by infiltration from irrigation.

De Vries, J.J., 1984, Holocene depletion and active recharge of the Kalahari groundwaters--A review and an indicative model: Journal of Hydrology, v. 70, p. 221-232.

LOCATION: Kalahari region, South Africa.

CLIMATE: Average annual precipitation ranges from 250 mm yr^{-1} in the the southwest to 550 mm in the northeast.

VEGETATION: "Most of the Kalahari is quite well vegetated and should be classified as thornbush and tree savanna with alternating grassland." "The low variability of rainfall in its lower range allows rather dense vegetation, from which deep rooted thorn scrub is likely able to utilize all temporarily stored soil moisture in areas with a thick sand-cover."

GEO-HYDROLOGIC SETTING: The Kalahari is a vast sand-covered flat land, occupying an area of 2.5 x 10^6 km^2. The Kalahari Basin is a sedimentary depression containing consolidated karoo layers, capped partially by basaltic lava and overlain by unconsolidated Kalahari beds. The area modeled by De Vries is the "....catchment of the fossil Okwa-Mmone River system, which contributed large amounts of water to the former Makgadikgadi Lake." Hydraulic head data show a decline from the divide to the discharge base of 200 m over 600 km and a decrease in ground-water depth from 125 m at the divide to the surface at the discharge area. Kalahari beds comprise Eolian sands, silicified and calcretized sands, sandstones and grits, marls, calcretes and silcretes. Karoo beds are from 10- to over 100-m thick. The Eolian sediments are moderately well sorted with median diameter between 0.125 and 0.25 mm.

METHODS OF STUDY: One-dimensional cross-sectional relaxation model simulating the decay of presumed water-table profile since the last pluvial cycle.

De Vries, 1984--Continued

INFILTRATION: Modern recharge rates of 0 to 0.3 mm yr^{-1} are compatible with the author's analysis. Allowing for uncertainty in knowledge of hydraulic properties of the system, author concludes the recharge is less than 0.5 mm yr^{-1}.

Dincer, Turgut, Al-Mugrin, A., and Zimmerman, U., 1974, Study of the infiltration and recharge through the sand dunes in arid zones with special reference to the stable isotopes and thermonuclear tritium: Journal of Hydrology, v. 23, p. 79-109.

LOCATION: Dahna sand dunes, 100 km east of Riyadh in Saudi Arabia.

CLIMATE: Mean annual atmospheric temperature, is 24.7 °C (1968-1972) and mean annual precipitation is 81.9 mm (1967-1972) at Khurais at the eastern boundary of the Dahna sand dunes east of Riyadh.

GEO-HYDROLOGIC SETTING: Sand dunes overlie Paleocene limestone. Depth to water table is about 150 m. Sand dunes are probably not more than 20- or 30-m thick.

VEGETATION: Density of vegetation is highly variable.

METHODS OF STUDY: Thermonuclear tritium was used as a tracer to identify the depth to water precipitated during the 1963-1964 high fallout of tritium. Available moisture in the soil profile was measured above the depth of the pulse.

INFILTRATION: The authors estimated an average of about 20 mm of water is infiltrating the sand dunes annually.

Dugan, J.T., and Peckenpaugh, J.M., 1985, Effects of climate, vegetation, and soils on comsumptive water use and ground-water recharge to the central Midwest regional aquifer system, mid-continent United States: U.S. Geological Survey Water-Resources Investigations Report 85-4236, 78 p.

LOCATION: An area of 712,000 km^2 in the States including Kansas and Nebraska and parts of Colorado, South Dakota, Missouri, Arkansas, Oklahoma, Texas, and New Mexico. The High Plains is excluded from the study.

CLIMATE: The climate ranges from humid to semiarid. Average precipitation ranges from 305 to 1,270 mm yr^{-1}; mean potential evapotranspiration ranges from 914 to 1,778 mm yr^{-1}.

VEGETATION: Vegetation types mapped in the region for this study include row crops, small grains, tame hay, fallow land, native grassland, and woodland.

METHODS OF STUDY: Recharge was computed using soil-moisture accounting model using input data on (1) hydrologic properties of the soil, (2) vegetation types, (3) monthly precipitation, and (4) computed monthly potential evapotranspiration. The computed evapotranspiration requires data on solar radiation and temperature.

Dugan, J.T., and Peckenpaugh, J.M., 1985--Continued

INFILTRATION: Computed recharge ranged from a minimum of 2.5 mm yr^{-1} in eastern Colorado to 380 mm yr^{-1} in Arkansas and averaged 114 mm yr^{-1}. The generalized relation between precipitation and potential recharge is shown below.

Mean annual precipitation (mm)	Mean annual recharge (mm)	Approximate proportion (percent)
1,270	381	30
1,016	254	25
762	90	12
508	25	5
381	6	2

Elzeftawy, Atef, and Mifflin, M.D., 1983, Vadose moisture migration in semiarid and arid environments, *in* Conference on Characterization and monitoring of the Vadose (unsaturated) Zone, Las Vegas, Nevada, 1983, Proceedings: Worthington Ohio, National Water Well Association p. 1-36.

LOCATION: Southern Nevada.

CLIMATE: Climate is semiarid to arid.

GEO-HYDROLOGIC SETTING: Thick basin fill deposits in Basin and Range province are underlain by a deep water table.

METHODS OF STUDY: Holes were instrumented with thermocouple psychrometers for measuring matric potential. Most holes were shallow with instruments at 1.2- and 2.4-m depth; one hole was instrumented to 45.7 m.

INFILTRATION: Majority of moisture-potential data indicated upward migration of moisture over the period of record. In response to an infrequent high intensity storm of 127 mm of rain in a few hours at the location of the deep hole, the instrumental data demonstrated a recharge pulse to a depth of 45.7 m.

Eriksson, Erik, 1976, Distribution of salinity in groundwaters of the Delhi region and recharge rates of groundwaters, *in* Interpretation of environmental isotope and hydrochemical data in groundwater hydrology, Proceedings of an Advisory Group, Vienna, 1975: Vienna, International Atomic Energy Agency, p. 235-236.

LOCATION: Delhi region, India (3,820 km^2).

CLIMATE: Average precipitation is about 400 mm yr^{-1}.

GEO-HYDROLOGIC SETTING: Alluvial deposits of the Indus-Ganga Valley.

METHODS OF STUDY: Average recharge rate was calculated by the mass balance of chloride from the estimated rate of chloride deposited as dust and in rainfall and the average chloride concentration of ground water.

Eriksson, 1976--Continued

INFILTRATION: Recharge rate was estimated to be from 30 to 40 mm yr^{-1}, somewhat less than 10 percent of precipitation.

Eriksson, Erik, and Khunakasem, Vachi, 1969, Chloride concentration in groundwater--Recharge rate and rate of deposition of chloride in the Israel coastal plain: Journal of Hydrology, v. 7, p. 178-197.

LOCATION: Coastal plain of Israel.

CLIMATE: The climate is typical for the Mediterranean region with winter rainfalls and dry, hot summers. The southern part is semiarid; precipitation increases towards the north where the climate is humid or subhumid.

GEO-HYDROLOGIC SETTING: The coastal plain aquifer consists of a sandy sequence with thin clayey strata of Pliocene and Pleistocene deposits which dip toward the Mediterranean Sea.

METHODS OF STUDY: Recharge to the coastal plain aquifer was computed based on the mass balance of chloride in ground water.

INFILTRATION: The areal distribution of recharge was computed. Calculated recharge rates were generally greater near the coast line ranging from 100 to 350 mm yr^{-1}. Inland from the coast line recharge rates increased from as low as 10 mm yr^{-1} in the southern part of the coastal plain to 75 mm yr^{-1} in the northern part of the coastal plain.

Foster, S.S.D., Bath, A.H., Farr, J.L., and Lewis, W.J., 1982, Likelihood of active groundwater recharge in the Botswana Kalahari: Journal of Hydrology, v. 55, p. 113-136.

LOCATION: Kalahari, South Africa; study area is about 5,000 km^2 near Gaborone.

CLIMATE: Desert is arid to semiarid; average annual rainfall is between 250 mm and 550 mm.

VEGETATION: The area is well vegetated except in the arid extreme southwest.

GEO-HYDROLOGIC SETTING: Study area is overlain by generally 20 to 40 m, but up to 60 m, of Kalahari beds which include sands, calcretes, marls, and gravels.

METHODS OF STUDY: Data were collected on soil-moisture content and tritium and chloride in soil moisture.

INFILTRATION: Authors conclude that diffuse recharge does not occur through a sand cover greater than about 4-m depth. On the basis of chloride in unsaturated zone, sketchy data on chloride in rainfall, the authors indicated downward movement of less than 5 mm yr^{-1} and probably less than 1 mm yr^{-1}.

Gee, G.W., and Kirkham, R.R., 1984, Arid site water balance--Evapotranspiration modeling and measurements: Richland, Washington, Pacific Northwest Laboratory, PNL-5177, UC-70, 38 p.

LOCATION: Hanford Site, south-central Washington.

CLIMATE: Average annual precipitation is 160 mm, although during the study period, average precipitation was exceeded. During 1983 the long-term average was exceeded by 177 percent and in the first half of 1984 average precipitation was exceeded by 131 percent.

GEO-HYDROLOGIC SETTING: Study area is underlain by coarse-textured well-drained soil. Depth to water table is greater than 10 m.

VEGETATION: Cheatgrass (*Bromus tectorum*) and Sandberg's bluegrass (*Poa sandbergii*) comprising 35 and 27 percent, respectively.

METHODS OF STUDY: Three methods were used to estimate soil-profile drainage:

1. Soil-moisture measurements and water balance.
2. Drainage-collecting lysimeter. Grass cover established at the beginning of the reference period.
3. One-dimensional unsaturated flow models.
   (a) Single-layer model.
   (b) Two-layer model.

INFILTRATION:

	Method			
	1	2	3	
			a	b
	More than[2]			
Infiltration	[1]85 mm/yr	60 mm/yr	[3]50 mm	[3]35 mm/yr
Reference period	March 1983 to December 1983	June 1983 to May 1984	January 1983 to October 1983	January 1983 to December 1983

[1]Drainage from 1.0 to 3.5 m.
[2]Depth of lysimeter was 1.52 m.
[3]Modeled drainage to 3.5 m.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B, 63 p.

LOCATION: High Plains, 450,700 km^2, of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming.

Guttentag, Heims, Krothe, Luckey, and Weeks, 1984--Continued

CLIMATE: Dry continental climate in most of area; central Kansas and eastern Nebraska have a humid continental climate. Average precipitation generally less than 508 mm yr^{-1}, ranging from 406 to 711 mm yr^{-1}, increasing from west to east. See also Luckey and others (1986).

GEO-HYDROLOGIC SETTING: See Luckey and others (1986) in this report.

METHODS Of STUDY: More than 30 reported estimates of recharge from studies made in the High Plains are summarized. The studies include mostly water budget and computer models of ground-water flow. Of the studies, only the study of Theis (1937) is summarized in the present report. In a companion report to Gutentag and others (1984), a report by Luckey and others (1986), summarized in this report, completed a comprehensive model study of the High Plains in which the areal distribution of predevelopment recharge is estimated for the High Plains.

INFILTRATION: Estimates of recharge for areas of the High Plains from more than 30 studies range from 0.6 to 180 mm yr^{-1}, with a medium value of about 19 mm yr^{-1}.

Holmes, J.W., and Colville, J.S., 1970a, Grassland hydrology in a karstic region of southern Australia: Journal of Hydrology, v. 10, p. 38-58.

LOCATION: Gambier Plain, southeastern South Australia.

CLIMATE: Average precipitation is 632 mm yr^{-1} and average evaporation is 588 mm yr^{-1}. May to December precipitation produced drainage to the lysimeters in the years from 1961 to 1965; January to April precipitation was ineffective in producing drainage.

GEO-HYDROLOGIC SETTING: Ground water is in limestone and other sedimentary rocks. Permeable surface materials promote recharge; there are few perennial streams. Water table is near the base of the lysimeters.

VEGETATION: Grassland area studied in this report: Subterranean clover (*Trifolium subterraneum* L.), perennial rye grass (*Lolium perenne* L.) with fewer numbers of Yorkshire fog (*Holcus lanatus* L.), soft brome grass (*Bromos mollis* L.), capeweed (*Cryptostemma calendula leporinumau* Link), and heron's bill (*Erodium botrys* Cav., Bertol).

METHODS OF STUDY: Lysimeters (2.4-m and 1.8-m deep).

INFILTRATION: Infiltration as measured by drainage to base of lysimeters averaged 63 mm yr^{-1}. Because of the shallow depth to water level, drainage to the base of the lysimeters may closely approximate infiltration to the saturated zone, but may be greater than net recharge.

Holmes, J.W., and Colville, J.S., 1970b, Forest hydrology in a karstic region of southern Australia: Journal of Hydrology, v. 10, p. 59-74.

LOCATION: Gambier Plain, southeastern South Australia.

CLIMATE: The predominantly winter precipitation is about 600 mm yr^{-1}.

GEO-HYDROLOGIC SETTING: Soil is sandy with limestone at about 5.6 to 8.5 m below surface. The depth to water is 40 m at one site and 7 m at the other.

VEGETATION: Plantation forest of Monterey pine (*Pinus radiata* D. Don).

METHODS OF STUDY: Water budget utilizing measurements of rainfall, soil-water increment, and soil-moisture tension.

INFILTRATION: From matric-potential gradients the authors conclude there was no recharge to the water table in pine forest plantations.

Huntoon, P. W., 1977, Cambrian stratigraphic nomenclature and ground-water prospecting failures on the Hualapai Plateau, Arizona: Ground Water, v. 15, no. 6, p. 426-433.

LOCATION: Hualapai Plateau, a high desert in northwestern Arizona.

CLIMATE: Average precipitation is 229 to 330 mm yr^{-1}; average potential evaporation is 1,829 to 1,930 mm yr^{-1}.

GEO-HYDROLOGIC SETTING: Strata gently tilted northeastward toward Grand Canyon of the Colorado River. The land surface, 1,400 to 1,800 m above mean sea level, is of rolling hills with incised valleys. There are no perennial streams. Surficial deposits of Tertiary sedimentary and volcanic rocks are underlain by Paleozoic sandstone, shale, limestone, and dolomite. Basement igneous and metamorphic rocks crop out on margins of plateau. Discharge of ground water occurs as springs above the Precambrian rocks.

VEGETATION: Sparse grassland in valleys with juniper and associated shrubs along ridges.

METHODS OF STUDY: Water budget was made using measurements of spring discharge around margin of plateau. Ground-water discharge was about 0.11 m^3 sec^{-1} (measured in the spring and summer of 1976).

INFILTRATION: Recharge was estimated as 2.5 mm yr^{-1}.

COMMENTS: Flow-system equilibrium was assumed. Discharge by evapotranspiration was not estimated. No deep drainage to Precambrian rocks was assumed.

Isaacson, R.E., Brownell, L.E., Nelson, R.W, and Roetman E.L., 1974, Soil moisture transport in arid site vadose zones: Richland, Washington, Atlantic Richfield Hanford Company ARH-SA-169 (SM-182/6), 23 p.

LOCATION: Hanford, Washington.

CLIMATE: Average annual precipitation is 160 mm yr^{-1}. Seventy percent of the precipitation falls during fall and winter months.

METHODS OF STUDY: Data were collected from tritium, soil-moisture, and matric-potential profiles. Geothermal temperatures, seasonal temperature cycles, and seasonal vapor-pressure fluctuations were measured. Lysimeters were installed and monitored.

INFILTRATION: "Observations to date indicate that the annual precipitation of meteoric water does not percolate to the water table but apparently moves downward only a few meters during the fall and winter months and is removed by evaporation and evaportranspiration during the summer".

COMMENTS: Using some of the same data and data from other experiments at Hanford, Gee and Heller (1985) calculate net recharge to the water table. See also Gee and Kirkham (1984) and Kirkham and Gee (1983).

Johnston, C.D., 1983, Estimation of groundwater recharge from the distribution of chloride in deeply weathered profiles from south-west Western Australia, *in* Papers of the International Conference on Groundwater and Man, v. 1, Investigation and assessment of groundwater resources, Sydney, 1983: Canberra, Australian Water Resources Council, Conference Series 8, p. 143-152.

LOCATION: Great Plateau of Western Australia.

CLIMATE: The climate is Mediterranean with cool, moist winters and dry, hot summers. Eighty percent of rainfall occurs in May through September. Average precipitation at site 1 is 800 mm yr^{-1} and at site 2 is 1,150 mm yr^{-1}.

GEO-HYDROLOGIC SETTING: The surface materials are deeply weathered (25 to 30 m) granitic and gneissic rocks of the Great Plateau of Western Australia. Depth to water is about 22.5 m at site 1 and 10 to 15 m at site 2.

VEGETATION: Native forest is dominated by *Eucalyptus* species, in particular, (*E. marginata*) in association with (*E. calophylla*). Tree roots extend to a depth of 18 m.

METHODS OF STUDY: Recharge was calculated by (1) mass balance of chloride in the ground-water system, and (2) chloride mass balance for flow in the unsaturated zone (Peck and others, 1981).

INFILTRATION: By the first method at site 1, based on average ground-water chloride in 14 bores, recharge was 1.4 mm yr^{-1}. At site 2, based on average ground-water chloride in 7 bores, recharge was 25 mm yr^{-1}. By the mass-balance method at site 1, the calculated infiltration at a depth of 7 m was 0.3 mm yr^{-1}; at site 2, the calculated infiltration at a depth of 5.5 m was 4 mm yr^{-1}. At both sites, apparent calculated recharge increased below the depths of minimum calculated infiltration cited above.

Kafri, U., and Asher, J.B., 1978, Computer estimates of natural recharge through soils in southern Arizona, U.S.A.: Journal of Hydrology, v. 38, p. 125-138.

LOCATION: Sonoita and Cienega Basins, southern Arizona.

CLIMATE: Summer rainfall varies between 176.5 and 335.8 mm yr^{-1} for elevations of 1,500 and 3,000 m, respectively. Summer rainfall, occurring as orographic, convective type, high intensity, and short storms, is related to moisture penetration from the Gulf of Mexico and amounts to 65 percent of the annual rainfall. Winter precipitation is about 160 mm yr^{-1}. The average winter precipitation event occurs over 2 days. Average annual evapotranspiration exceeds average annual precipitation.

GEOHYDROLOGIC SETTING: Fractured bedrock overlain by soil varying from 10 to 50 cm in thickness.

VEGETATION: Root densities in soil were assumed to be 60, 30, and 10 percent for the upper, middle, and lower thirds, respectively, of the soil profile.

METHODS OF STUDY: Water balance utilizing an unsaturated flow model incorporating storm intensity and duration, soil thickness and hydraulic properties, and evapotranspiration.

INFILTRATION: Though winter rainfall is smaller than summer rainfall, computed winter recharge was greater. No recharge was computed in summer through soils exceeding a 10-cm depth; no recharge was computed in winter through soils exceeding a 40-cm depth.

Kirkham, R.R., and Gee, G.W., 1983, Measurement of unsaturated flow below the root zone at an arid site, *in* Conference on Characterization and Monitoring of the Vadose (unsaturated) Zone, Las Vegas, Nevada, 1983, Proceedings: Worthington, Ohio, National Water Well Association, p. 917-935.

LOCATION: Hanford Site, south-central Washington.

CLIMATE: Average annual precipitation is 160 mm, although during the test year (November 1982 through October 1983) precipitation was greater than 240 mm with 75 percent of precipitation occurring during the 6-month period November through April.

GEOHYDROLOGIC SETTING: Depth to the water table is greater than 10 m. The soil is coarse textured and well drained.

VEGETATION: Vegetation is cheatgrass (*Bromus tectorom*) and Sandberg's bluegrass (*Poa sandbergii*); cheatgrass comprises 35 percent and Sandberg's bluegrass 27 percent of the total cover area. No roots were found below 1 m.

Kirkham and Gee, 1983--Continued

METHODS OF STUDY: Biweekly soil-moisture measurements made with neutron moisture probe at 25 access wells. Two weighing lysimeters were used to measure evapotranspiration. One lysimeter was surfaced with bare soil; one with near-natural grass cover. Recharge was estimated from (1) simulations of soil-water balance using UNSATID, a one-dimensional finite-difference computer code for liquid flow of water in soil and (2) water balance using soil-moisture data.

INFILTRATION: Recharge by both the soil-moisture simulation method and water-budget method was 5 cm during the test year.

Kitching, R., Edmunds, W.M., Shearer, T.R., Walton, N.R.G., and Jacovides, J., 1980, Assessment of recharge to aquifers: Hydrologic Sciences Bulletin, v. 25, no. 3, p. 217-235.

LOCATION: Akrotiri Peninsula, southern Cyprus.

CLIMATE: Average annual precipitation is 420 mm yr^{-1}.

GEO-HYDROLOGIC SETTING: Aquifer is relatively uniform unconsolidated Holocene dune sands. The unsaturated zone is as great as 50-m thick.

VEGETATION: Land uses are agriculture and forestry.

METHODS OF STUDY: Tritium tracer and natural chloride mass-balance methods were used in the unsaturated zone.

INFILTRATION: Recharge measured by both the tritium and chloride methods was about 50 mm yr^{-1}.

Lloyd, J.W., and Farag, M.H., 1978, Fossil ground-water gradients in arid regional sedimentary basins: Ground Water, v. 16, no. 6, p. 388-393.

LOCATION: Sahara of western Egypt.

CLIMATE: Climate is arid; precipitation is less than 50 mm yr^{-1}.

GEO-HYDROLOGIC SETTING: The principal aquifer of the region chosen for analysis is the lower Bahariya aquifer, a confined aquifer. The hydraulic gradient is from the outcrop area of the aquifer northeast to the Mediterranean.

METHODS OF STUDY: Ground water recession of hydraulic head is calculated assuming no recharge since the end of the recent pluvial (10,000 yr B.P). A nonhomogeneous hydraulic conductivity distribution and specific yield is found experimentally that yields modern observed water levels.

INFILTRATION: The authors consider that the study supports the view that present day regional gradients can in part be attributed to residual head since the Pleistocene pluvial climate, (10,000 yr. B.P.). Study methods could not dismiss the possibility of modern recharge.

Luckey, R.R., Gutentag, E.D., Heimes, F.J., and Weeks, J.B., 1986, Digital simulation of ground-water flow in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-D, 57 p.

LOCATION: High Plains, 451,000 km^2 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming.

CLIMATE: See Gutentag and others (1984).

GEO-HYDROLOGIC SETTING: The High Plains, a large plateau, is underlain by the High Plains aquifer consisting mainly of hydraulically connected units of late Tertiary and Quaternary age. The Ogallala Formation of late Tertiary age, the principal geologic unit, is a heterogeneous sequence of clays, silts, sands, and gravels. Water table ranges from near land surface to nearly 400 feet below land surface. The saturated thickness ranges from nearly zero to 1,000 ft. Natural ground-water discharge is to streams and springs and directly to the atmosphere by evapotranspiration where the water table is near the surface. Infiltration of precipitation is the principal natural source of recharge. The aquifer is intensively developed for irrigation; annual pumpage is 2 to 100 times greater than annual recharge. Soils are described in Gutentag and others (1984).

METHODS OF STUDY: Ground-water flow in the aquifer was simulated by deterministic finite-difference models incorporating aquifer thickness, hydraulic conductivity, and boundaries of the aquifer. Recharge rate and distribution was determined during calibration of the models simulating the water table for the period preceding development during which it was assumed the ground-water system was in a state of dynamic equilibrium.

INFILTRATION: Southern High Plains; an area of 75,000 km^2 in New Mexico and Texas; the average recharge rate is 3.3 mm yr^{-1}, with recharge rate over the greatest part of the area being 2.2 mm yr^{-1}. Higher rates of 22 mm yr^{-1} and 26 mm yr^{-1} were determined in areas of structural weakness along Running Water Draw and White River. Recharge rates were not found to be related to soil type or variations in precipitation and potential evapotranspiration. Soil types principally include sand, loam, and clay loam. A caliche subsoil underlies most of the area. Average annual pretation ranges from about 406 to 508 mm yr^{-1}; average Class-A pan evaporation ranges from less than 2,540 to more than 2,670 mm yr^{-1}. A ground-water recession model experiment was made to determine if predevelopment water levels were residuals from recharge during the Lubbock subpluvial ending about 10,000 yr before present. Initial water level at land surface, 10,000-yr recession simulation indicated the aquifer would be virtually drained in a few thousand years and the predevelopment water levels would be reached in less than 3,000 yr at widely distributed locations. Thus, it was concluded that the premise of no recent recharge is untenable and that significant recharge has occurred at least at regular intervals during the recent past.

INFILTRATION:
(Cont.)

Central High Plains; an area of 126,000 km^2 in Texas, Oklahoma, New Mexico, Kansas, and Colorado; the average precipitation is 406 mm yr^{-1} (western edge) to 610 mm yr^{-1} (easternmost part of area in Kansas); Class-A pan evaporation is 2,160 to 2,410 mm yr^{-1}, generally increasing from north to south. Recharge was found to be related to soil type. The long term average recharge was 3.6 mm yr^{-1}.

Soil type	Recharge (mm yr^{-1})	Approximate average precipitation (mm yr^{-1})
Sand dunes	21.3	406 to 610
Sand, southwestern part of area, New Mexico and Texas	9.9	406
Sandy loam, eastern part of area, Kansas	2.8	610 to 710
Clay loam and sandy loam in extreme southern part of area	2.8	510
Clay loam and silt loam	1.4	406 to 710

Northern High Plains; an area of about 250,000 km^{-1} in Colorado, Kansas, Nebraska, South Dakota, and Wyoming; the average precipitation is 406 to 610 mm yr^{-1}, increasing from west to east. The average Class-A pan evaporation is 1,397 to 2,159 mm yr^{-1}, decreasing from north to south. Recharge was found to be related to soil type.

Soil type	Recharge (mm yr^{-1})	Approximate average precipitation (mm yr^{-1})
Sandy, central Nebraska	30.5	406 to 610
Sandy, Colorado and southwestern Nebraska	21.3	406 to 510
Sandy, west-central Nebraska	7.6	406
Sandy loam	5.1	406 to 510
Loam soils	2.8	406
Clay loam and silt loam	1.5	406 to 710

COMMENTS: The authors point out that the recharge rates simulated by the models are net recharge rates over model nodal areas of 259 km^2. In areas such as the sand hills of central Nebraska, a nodal area may include areas of discharge by evapotranspiration and seepage to springs and streams. Recharge rates reported are based on net recharge rates for nodal areas.

Maxey, G.B., and Eakin, T.E., 1949, Ground water in the White River Valley, White Pine, Nye and Lincoln Counties, Nevada: Carson City, Nevada State Engineer, Water Resources Bulletin 8, 59 p.

LOCATION: White River Valley, White Pine, Nye, and Lincoln Counties, Nevada, about 1,620 mi^2. The valley is about 113 km long (north to south) and about 32 km wide.

CLIMATE: The climate is arid to semiarid. Precipitation ranges from about 254 mm yr^{-1} at lower elevations to more than 500 mm yr^{-1} at the highest elevations. Monthly precipitation is generally less in June through September. About 60 percent of precipitation occurs as snow between December and May.

GEOHYDROLOGIC SETTING: Indurated sedimentary and igneous rocks of Paleozoic age form the mountainous boundaries east and west of the valley. The Paleozoic rocks, except the carbonate rocks, are aquitards. The valley is underlain by alluvial deposits of gravel, sand, silt, and clay. Movement of ground water to the east and west is impeded by low permeability mountain blocks. The valley probably receives some ground water from Jakes Valley to the north.

VEGETATION: Between 1,800 and 2,700 m the highlands are covered by juniper (mostly *Juniperus utahensis*) and piñon pine (*Pinus edulis*), associated with sagebrush (*Artemisia tridentata*), blackbrush (*Coleogyne ramosissima*),and little rabbit brush (*Chrysothamnus stenogphyllus*), and other typical members of the northern desert shrub plant association. Small growths of white fir (*Abies concolor*) and other large evergreens are common in well-shaded mountain canyons between altitudes of 2,300 and 3,400 m. The alluvial apron and valley floor are commonly covered by sagebrush, little rabbit brush, and associated shrubs, except where the water table is near the land surface. Rabbit brush (*Chrysothamnus graveolens*), salt grass (*Distichlis spicatau*), greasewood (*Sarcobatus vermiculatus*), and other phreatophytes are common where the water table is near the land surface.

METHODS OF STUDY: The major assumption of the method is that ground-water recharge within a basin equals ground-water discharge; that is, the system is in a state of equilibrium. Recharge is estimated as a percentage of the average annual precipitation, taken from Hardman's (1936) map divided into zones receiving <203, 203 to 305, 305 to 381, 381 to 508, and more than 508 mm yr^{-1}. The percentages were derived from studies of 13 valleys (including White Pine Valley) in east-central Nevada in which natural discharge was estimated. Recharge was estimated for rainfall zones and balanced by trial and error with discharge estimates to derive the recharge coefficients for the Hardman precipitation zones shown below.

Maxey and Eakin, 1949--Continued

INFILTRATION: The recharge is as follows:

Hardman (1936) precipitation zone (mm yr^{-1})	Recharge coefficient (percent of precipitation)
Less than 203	0
203 to 305	3
305 to 381	7
381 to 508	15
More than 508	25

COMMENTS: This method has been widely used in Nevada and, with modifications, in Utah. The method assumes steady-state flow; it does not imply that recharge occurs within any given precipitation zone. Precipitation zones in this and other water-budget studies in Nevada by the U.S. Geological Survey, in cooperation with the State of Nevada, were taken from Hardman's (1936) precipitation map. The Maxey-Eakin method, as it has become known, was developed by Maxey and Eakin over a period of several years from water-budget studies in east central Nevada. The empirical method used by Maxey and Eakin to derive recharge coefficents was never completely described. A brief description of the development of the method, including a list of the 13 basins used as a basis for the method, is given in Watson and others (1976). Watson and others (1976) analyzed data by multiple-regression methods from water-budget studies in Nevada in examining the statistical validity of the Maxey-Eakin method. Watson's work is summarized herein.

Mazor, Emanuel, 1982, Rain recharge in the Kalahari--A note on some approaches to the problem: Journal of Hydrology, v. 55, p. 137-144.

LOCATION: Kalahari Desert, Botswana.

CLIMATE: 250 to 650 mm yr^{-1} average precipitation.

METHODS OF STUDY: Information used by the author included tritium and carbon-14 soil moisture and ground water, water-level fluctuations, and inferences from water levels in an area of ground-water withdrawal.

INFILTRATION: Author presents evidence of modern recharge to ground water in the Kalahari Desert refuting the conclusion of several investigators since 1906 that there is no modern recharge because infiltration to the sands are subsequently evapotranspired. The author suggests recharge may occur through fissures, zones of bioperturbation and other high conductance zones in the unsaturated zone. He cites as evidence of modern recharge (1) tritium and carbon-14 contents of ground water indicating recharge within the past few decades; tritium content of soil moisture at 6-m depth indicating modern recharge (at 6-m depth the author rules out the possibility of exfiltration), (2) water-level fluctuations which correlate with precipitation cycles, and (3) producing wells in flat terrain where the author believes the sustained water levels are maintained by local recharge.

Nichols, W.D., 1986, Geohydrology of the unsaturated zone at the burial site for low-level radioactive waste near Beatty, Nye County, Nevada: U.S. Geological Survey Open-File Report 85-198, 85 p.

LOCATION: Amargosa Desert, Nevada.

CLIMATE: Mean annual precipitation is 114 mm yr^{-1} at Beatty, 17.4 km north of the site, and 74 mm yr^{-1} at Lathrop Wells, 30 km southeast of the site. Annual precipitation varies considerably from year to year. During the period 1949-79 at Beatty, it ranged from 18 mm in 1953 to 263 mm in 1978. Most precipitation falls during the winter months. Pan evaporation exceeds 2,500 mm yr^{-1}.

GEO-HYDROLOGIC SETTING: The Amargosa Desert is underlain by unconsolidated to weakly indurated basin-fill deposits of Tertiary and Quanternary age. The shallow subsurface stratigraphy is relatively uniform at the study site. A thin gravel pavement on the surface is underlain by a very fine silty sand to a depth of 0.75 m. This is underlain by a coarse sandy gravel to about 2.5 m, which is in turn underlain by a dense, poorly cemented sand to silty sand, with some gravel, cobbles, and boulders, from 2.5 m to about 10 m. Depth to the water table in the area is 60 to 90 m.

METHODS OF STUDY: Measurements of soil-moisture content and soil-water potential were made from 1978 to 1980. Potential recharge was estimated using a water-balance model of precipitation, evaportranspiration, soil moisture, and recharge for bare soil conditions for the years 1961 through 1976.

INFILTRATION: Water-balance analysis indicates three recharge events could have occurred during the 16-yr period. The long-term infiltration rate below 10-m depth is estimated to be about 0.04 mm yr^{-1} under bare soil conditions.

Peck, A.J., 1983, Response of groundwater to clearing in Western Australia, *in* Papers of the International Conference on Groundwater and Man, v. 2, Groundwater and the environment, Sydney, 1983: Canberra, Australian Water Resources Council, Conference Series 8, p. 327-335.

LOCATION: Darling Range of Western Australia.

CLIMATE: Area 1, west of Collie, average precipitation 1,150 mm yr^{-1}. Area 2, east of Collie, average precipitation 800 mm yr^{-1}.

VEGETATION: Forested land and land cleared for agriculture were sampled in both areas.

METHODS OF STUDY: Measurement of potentiometric head in naturally forested areas before and after clearing.

INFILTRATION: Author concluded that clearing of native forests resulted in less evapotranspiration and an increase in recharge to aquifers.

Phillips, F.M., Trotman, K.N., Bentley, H.W., and Davis, S.N., 1984, The Bomb-36Cl pulse as a tracer for soil-water movement near Socorro, New Mexico, *in* Stone, W.J., compiler, Selected papers on water quality and pollution in New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 7, p. 271-280.

LOCATION: Sevilleta National Wildlife Refuge, 25 km north of Socorro, New Mexico.

CLIMATE: The area has a high desert climate with average precipitation of 200 mm yr^{-1} and potential evapotranspiration of about 1,800 mm yr^{-1}. Precipitation is about equally divided between late summer convective storms and midwinter snow and rain from frontal storms.

GEO-HYDROLOGIC SETTING: The site is underlain by a Pleistocene terrace with a clayey and silty sand soil.

VEGETATION: The natural vegetation is creosote bush and sparse bunch grass.

METHODS OF STUDY: Chlorine-36 tracer dating and chloride mass balance.

INFILTRATION: Calculated infiltration rates from the surface to 1-m (chlorine-36 tracer) and 5-m (chloride mass balance) depths are 2.5 and 0.02 mm yr^{-1}, respectively.

Rehm, B.W., Moran, S.R., and Groenwald, G.H., 1982, Natural groundwater recharge in an upland area of central North Dakota, U.S.A: Journal of Hydrology, v. 59, p. 293-314.

LOCATION: West-central North Dakota.

CLIMATE: The climate is semiarid with about 440 mm yr^{-1} precipitation. Seventy percent of precipitation occurs between May and September.

GEO-HYDROLOGIC SETTING: The area is underlain by nearly flat-lying coal-bearing rocks of Tertiary age consisting of silt and clay units with minor sand and thin coal beds and sand. Glacial deposits cover nearly the entire site.

METHODS OF STUDY:
1. Water-level hydrographs.
2. Vertical-head gradients in the saturated zone.
3. Ground-water flow partitioning (flow-net analysis).

INFILTRATION: All methods yielded results on the order of 10 to 40 mm yr^{-1}. These values represent 2 to 9 percent of the annual precipitation.

Sammis, T.W., and Gay, L.W., 1979, Evapotranspiration from an arid zone plant community: Journal of Arid Environments, v. 2, p. 313-321.

LOCATION: 70 km northwest of Tucson, Arizona, at elevation 730 m.

CLIMATE: Precipitation during the test year (1985-86) was 234 mm.

GEO-HYDROLOGIC SETTING: Uniform soil conditions, with gravelly sandy loam texture.

Sammis and Gay, 1979--Continued

VEGETATION: Creosote bush (*Larrea tridentata*) was the dominant shrub, with paloverde (*Cercidium microphyllum*) and bursage (*Ambrosia deltoidea*) also present.

METHODS OF STUDY: Water loss was 259 mm during the test year. Water loss was measured by a weighing lysimeter having a depth of 1 meter containing creosote bush. Water loss estimated by a budget in (1) an area vegetated with creosote bush was 242 mm and (2) in a bare soil plot was 231 mm.

INFILTRATION: Recharge was considered nil because there was no change in soil-moisture content below depth of 1 meter and water loss approximately equaled precipitation.

Sharma, M.L., Farrington, P., and Fernie, M., 1983, Localized groundwater recharge on the "Gnangara Mound", Western Australia, *in* Papers of the International Conference on Groundwater and Man, v. 1, Investigation and assessment of groundwater resources, Sydney, 1983: Canberra, Australian Water Resources Council, Conference Series 8, p. 293-302.

LOCATION: Coastal Plain, Western Australia.

CLIMATE: Annual precipitation is 800 mm yr^{-1}; Class A-pan evaporation is 1,840 mm yr^{-1}; 86 percent of precipitation falls in winter season (May to October), the cool, wet season, with warm, dry conditions between November and March (Mediterranean climate).

GEO-HYDROLOGIC SETTING: Soils and sand dunes of eolian origin (5- to 50-m deep) are relatively inert and infertile; soils do not contain chloride of pedogenic origin.

VEGETATION: Two land use types were sampled:
1. Native *Banksia-Casuarina* woodland, and
2. Pine plantation (*Pinus pinaster*).

METHODS OF STUDY: Steady-state mass balance of chloride in soil moisture of unsaturated zone.

INFILTRATION: Recharge, in mm yr^{-1}, under *Banksia* and pineland vegetation and deep and shallow depths to water level are given below:

Banksia		Pineland	
Deep water level (>20 m)	Shallow water level (<10 m)	Deep water level (>20 m)	Shallow water level (<10 m)
86	194	4.6	59

Sophocleous, Marios, Perry, C.A., and Shaukat, Nadeem, 1985, Unsaturated flow and ground-water recharge dynamics in shallow aquifers--A field-experimental approach, *in* Hydrogeology of rocks of low permeability, Tucson, Arizona, 1985: International Association of Hydrogeologist, Memoires, v. 17, pt. 1, p. 223-235.

LOCATION: Western Kansas. One site is in Equus Beds near Burrton, the other is above the Big Bend aquifer near Zenith.

CLIMATE: Subhumid continental; average annual precipitation is 738 mm, with 70 percent of precipitation falling from April to September.

VEGETATION: Mixed grass.

GEO-HYDROLOGIC SETTING: The soils at both sites are fine sandy loams with low available-water capacity. At the Burrton site the depth to water ranged from about 2.3 m to 0.2 m below land surface; at Zenith the depth to water ranged from about 5.3 m to 5.1 m below land surface.

METHODS OF STUDY: Water fluxes were calculated by Darcian approaches in combination with water-balance equations. Field sites were instrumented for collection of climatic, ground-water level, soil-moisture, and soil-moisture tension data.

INFILTRATION: Recharge at the sites occurred from February to June 1983. No summer or fall recharge was observed. Significant difference was observed in recharge at the two sites. At Burrton, 154 mm of recharge occurred; at Zenith, 2.1 mm of recharge occurred. Exfiltration from July 1983 through January 1984 was not calculated.

Stephens, D.B., and Knowlton, Robert, Jr., 1986, Soil water movement and recharge through sand at a semiarid site in New Mexico: Water Resources Research, v. 22, no. 6, p. 881-889.

LOCATION: Servilleta National Wildlife Refuge near Socorro, New Mexico.

CLIMATE: Precipitation averages 200 mm yr^{-1}; gross annual lake evaporation is about 1,780 mm yr^{-1}. Precipitation during the study period was about 179 mm yr^{-1}.

GEO-HYDROLOGIC SETTING: The study site is on a low terrace of the Rio Salado. The sediments are comprised of relatively uniform, unconsolidated, fine sand. Below 4 m the texture is coarser and includes some gravel.

VEGETATION: The area is sparsely vegetated with four-wing salt bush (*Atriplex canescens*) and a few grasses. Visual inspection of 2.5-m deep trenches showed rooting depth to be about 1.5 m.

METHODS OF STUDY: Soil moisture, soil-moisture tension, and soil temperature were measured periodically. Unsaturated hydraulic conductivity was determined by instantaneous-profile in-situ tests. Infiltration below the root zone (1.5 m) was assumed to be equal to recharge Recharge was estimated by two methods: (1) Darcy's equation using unsaturated hydraulic conductivity and hydraulic gradient, and (2) as being equal to the unsaturated conductivity correspon-ding to in-situ water content, assumming a unit hydraulic gradient.

INFILTRATION: By method 1 (above), recharge is between 7.0 and 36.6 mm yr^{-1} or 3.9 and 20.4 percent of the precipitation. The range is due to estimates of effective unsaturated hydraulic conductivity of the soil column based on a harmonic mean and a geometric mean, respectively. By method 2, recharge at the 153-cm depth was estimated as 37 mm yr^{-1} or 20.7 percent of precipitation. At the 122-cm depth, recharge was estimated as 97 mm yr^{-1} or 54 percent of precipitation.

Stone, W.J., 1985, Recharge through calcrete, *in* Hydrogeology of Rocks of Low Permeability, Tuscon, Arizona, 1985, Proceedings: International Association of Hydrogeologists, Memoires, v. 17, pt. 1, p. 335-405.

LOCATIONS: Murray Basin, South Australia; southern High Plains, New Mexico.

CLIMATE: The climate of both regions is semiarid. Annual average precipitation in the Murray Basin is 300 mm and potential evaporation is 1,800 mm yr^{-1}. Greatest precipitation occurs in June through August (winter). Average annual precipitation in the southern High Plains is 444 mm and potential evaporation is 1,156 mm yr^{-1}. Greatest precipitation occurs in May through October (late spring through mid-autumn).

GEOHYDROLOGIC SETTING: Murray Basin: Tertiary marine limestone is overlain by Quaternary fluviolacustrine and eolian deposits. Calcrete (caliche) occurs at the base of the soil complex.

Southern High Plains: Ogallala Formation (Miocene and Pliocene) overlain by Pleistocene eolian deposits. Calcrete occurs near the top of the section.

VEGETATIONS: Murray Basin: vegetation is scrub *Eucalyptus* trees (mallee), perennial shrubs, and annual grasses.

Southern High Plains: vegetation is sparse perennial shrubs, annual grasses, and various cultivated crops.

METHODS OF STUDY: The chloride mass-balance method was used to calculate recharge.

INFILTRATION:

Landscape setting	Study area	Recharge (mm yr^{-1})
Bare calcrete flats:		
old sinkhole	Murray Basin	0.10
undisturbed calcrete	Murray Basin	0.40
bare calcrete	Southern High Plains	1.25
young sinkhole	Murray Basin	60-100
Calcrete overlain by sand:		
vegetated dune sand over calcrete	Murray Basin	0.06
eolian sand sheet over calcrete	Southern High Plains	0.18, 0.24
cleared dune sand over calcrete	Murray Basin	13.0

COMMENTS: See also Stone (1984).

Sukhija, B.S., and Rama, F.A.Sc., 1973, Evaluation of groundwater recharge in semiarid region of India using environmental tritium: Proceedings of the Indian Academy of Sciences, Series A, v. 77, no. 6, p. 279-282.

LOCATION: Northern Gujarat of western India.

CLIMATE: Average annual precipitation is about 700 mm yr^{-1}. Monsoon rainfall peaks in June to September.

GEO-HYDROLOGIC SETTING: Ground water is under water-table conditions in alluvial aquifers.

METHODS OF STUDY: Environmental soil-moisture tritium dating methods were used to calculate recharge.

INFILTRATION: Average recharge by two tritium methods ranged from 3.0 to 8.3 percent of precipitation.

Theis, C.V., 1937, Amount of ground-water recharge in the southern High Plains: Transactions, American Geophysical Union, 18th Annual Meeting, p. 564-568.

LOCATION: Southern High Plains of Texas, New Mexico, Oklahoma, Kansas, and Colorado.

CLIMATE: Average precipitation ranges from 356 to 589 mm yr^{-1}, increasing from southwest to northeast, largely falling as summer thundershowers.

GEO-HYDROLOGIC SETTING: Ogallala Formation is the main aquifer. The formation consists of gravel with interbedded fine sand and silt. Near the top of the section is a caliche zone several feet thick overlain by fine sand and silt. The Ogallala rests on generally impervious shales, the surface of the shales sloping east and east-southeast about 10 feet to the mile. Natural discharge occurs largely as seeps and springs at the eastern escarpment of the plains.

METHODS OF STUDY: The methods used for calculating recharge are as follows:

1. Analysis of flow net, i.e., partitioning the flow system by flow lines enabling calculation of a tributary area and calculating the flow by Darcy's law;
2. Analysis of water-level hydrographs, (a) water level decline; (b) water level rise; and,
3. Analysis of water-table profile.

INFILTRATION: The calculated recharge by the methods described above were:

1. Near Portales, New Mexico, 13 mm yr^{-1} or less; Lea County, New Mexico, 3 to 17 mm yr^{-1}.
2. Lea County, New Mexico,
   (a) August-September 1932, 9.4 mm yr^{-1};
   May-June 1932, 6.4 mm yr^{-1};
   September-October 1933, 10.7 mm yr^{-1};
   December-January 1933-34, 6.9 mm yr^{-1}.
   (b) 6.4 mm yr^{-1}, average;
   8.4 mm yr^{-1}, in 1933.
3. Somewhat less than 13 mm yr^{-1}.

Thorweighe, U., Sonntag, C., and Klitzsch, E., 1983, Fossil groundwater reservoirs in the eastern Sahara--Case history of the Dakhla Basin, Egypt, *in* Papers of the International Conference on Goundwater and Man, v. 3, Groundwater and development, Sydney, 1983: Canberra, Australian Water Resources Council, p. 329-336.

LOCATION: Dakhla Basin, Egypt.

CLIMATE: Arid.

GEOHYDROLOGIC SETTING: Ground water occurs in fluviocontinental sandstones of the Nubia Group.

METHODS OF STUDY: Radiocarbon ages of 61 ground-water samples in the Dakhla Basin.

INFILTRATION: Authors conclude modern recharge is nil and that all ground water was recharged during the pluvial period which ended about 20,000 yr before present.

COMMENTS: Authors regard carbon-14 ages of less than 18,000 years as contaminated; they do not have information to present a description of the ground-water regimen (direction of flow, horizonal or vertical gradients, mixing, etc.).

Verhagen, B.Th., Smith, P.E., McGeorge, I., and Dziembowski, Z., 1979, Tritium profiles in Kalahari Sands as a measure of rain-water recharge, *in* Isotope hydrology, Neuherberg, 1978, Proceedings: Vienna, International Atomic Energy Agency, v. 2, p. 733-751.

LOCATION: Southern edge of the Kalahari region, South Africa.

CLIMATE: Climate is semiarid with an average rainfall about 400 mm yr^{-1}.

GEOHYDROLOGIC SETTING: Kalahari beds, which underlie the region, consist of sand underlain by clayey and calcareous sandstone and gravelly clay.

VEGETATION: Native vegetation is grassland and shrub.

METHODS OF STUDY: Infiltration was calculated using tritium dating methods with supplemental information on oxygen-18 and major chemical constituents in soil moisture.

INFILTRATION: Infiltration was calculated as a percentage of rainfall for two periods: 1962-63 to 1973-74 and 1973-74 to 1977-78, when average precipitation was 254 mm yr^{-1} and 875 mm yr^{-1}, respectively. Calculated infiltration ranged from 5.5 to 12.1 percent of precipitation (1962-63 to 1973-74) to 10.6 to 17.1 percent of precipitation (1973-74 to 1977-78).

Viswanathan, M.N., 1984, Recharge characteristics of an unconfined aquifer from the rainfall-water table relationship: Journal of Hydrology, v. 70, p. 233-250.

LOCATION: Newcastle, New South Wales, Australia.

Viswanathan, 1984--Continued

CLIMATE:	Average rainfall is about 1,100 mm yr^{-1}; during the year of the study (1979) precipitation was 775 mm.
GEO-HYDROLOGIC SETTING:	Ground water occurs in the Tomago Sandbeds, a fine- to medium-grained sand aquifer with occasional clay lenses, under water-table conditions. Depth to water varies from 2.5 to 3.5 m below land surface.
METHODS OF STUDY:	Time-series model of precipitation and water-level changes was used with time-dependent and varying dependence-rate parameters solved using a recursive least-squares method and random-walk model for variable-rate parameters.
INFILTRATION:	Recharge was estimated as about 50 percent of rainfall with model assuming parameters to be invariant with time. Recharge varied between 20 (October and November) and 90 (July) percent of incident daily rainfall, assuming time-variant rates.

Watson, Phil, Sinclair, Peter, and Waggoner, Ray, 1976, Quantitative evaluation of a method for estimating recharge to the desert basins of Nevada: Journal of Hydrology, v. 31, p. 335-357.

LOCATION:	Nevada.
CLIMATE:	Climate is arid to semiarid; precipitation ranges from less than than 127 to greater than 508 mm yr^{-1}.
GEO-HYDROLOGIC SETTING:	See "Ground-Water Resources Series" reports prepared by the the U.S. Geological Survey in cooperation with the State of of Nevada, Department of Conservation and Natural Resources, and Maxey and Eakin (1949).
METHODS OF STUDY:	The primary aim of the paper is to examine the statistical validity of the Maxey-Eakin method (Maxey and Eakin, 1949) for estimating recharge. The second aim of the paper is to develop new predictive equations for estimating recharge through the use of linear regressions. Linear-regression techniques are used to analyze data from 63 basins in Nevada for which discharge estimates exist and for which the areas of Hardman precipitation zones (Hardman, 1936) have been planimetered.
INFILTRATION:	Multiple-linear regression is used as the closest approximation to the empirical technique of Maxey and Eakin. The multiple-linear-regression equation is affected by zeros of nonexistent Hardman precipitation zones in a basin, whereas Maxey and Eakin ignored zeros in determining coefficients. A comparison of the multiple-linear-regression coefficients and the Maxey-Eakin coefficents follows:

Watson, Sinclair, and Waggoner, 1976--Continued

INFILTRATION:
(Cont.)

Hardman precipitation zone	Multiple regression Coefficient (percent)	Multiple regression 95-percent confidence intervals (percent)	Maxey-Eakin coefficient (percent)
>20 in (508 mm)	24	±15	25
15-20 in (381-508 mm)	19	±16	15
12-15 in (305-381 mm)	01	±06	07
8-12 in (203-305 mm)	04	±02	03
<8 in (203 mm)	0	±01	0

The author considers neither the multiple-linear-regression equation nor the Maxey-Eakin method reliable for predicting recharge, but indicates possibly a greater stability for the Maxey-Eakin method because they ignored zeros in establishing coefficients. The approach has utility as one practical method of estimating recharge in Nevada. Simple linear regressions were made to correlate the area of each Hardman zone with total discharge. Though these cannot be interpreted hydrologically, the recharge coefficient for total recharge is 3.4 percent with a 95-percent confidence interval of ±0.6 percent.

COMMENTS: The basic assumption of the method is that the ground-water flow system is in equilibrium, which permits estimating recharge as equal to discharge. Watson and others indicate some basins may not be in equilibrium because of agricultural development. Also, some basins may not be in equilibrium because of climatic changes in the past 10,000 to 20,000 years (Reed and Bedinger, 1985). The data used in the regression analyses do not include geologic and hydrologic characteristics of the consolidated and unconsolidated rocks, antecedent moisture, vegetation, slope, or aspect. The regressions are further limited by accuracy of discharge estimates that are themselves hampered by the sparsity of data available from the reconnaissance studies and by possible interbasin flow of ground water.

Weeks, J.B., Leavesley, G.H., Welder, F.A., and Sauliner, G.J., Jr., 1974, Simulated effects of oil-shale development on the hydrology of Piceance Basin, Colorado: U.S. Geological Survey Professional Paper 908, 84 p.

LOCATION: Piceance Basin, northwestern Colorado, an area of about 2,330 km^2.

CLIMATE: Average precipitation is 300 to 500 mm yr^{-1} between 1,680 and 2,440 m in altitude. Above 2,440-m altitude average precipitation may be as great as 640 mm yr^{-1}.

GEO-HYDROLOGIC SETTING:	Structural basin with sedimentary rocks of Cretaceous and early Tertiary age with Quaternary alluvium along stream channels. Principal aquifers in the basin are in the Great River and Uinta Formations of Eocene age, and in the alluvium. The Eocene aquifers are principally fractured marlstone, siltstone, sandstone, and oil shale with some solution of minerals. Recharge is principally from snowmelt in the spring. Recharge is most effective in areas of the basin above an altitude of 2,130 m. Water is discharged to streams through the alluvium in the stream valleys and by springs along the valley walls.
METHODS OF STUDY:	Recharge was calculated by three methods: 1. Water budget, assuming steady-state condition. 2. Watershed model of Leavesley (1973) calibrated on stream discharge. 3. Ground-water hydraulics model.
INFILTRATION:	1. Recharge rate was 1.0 m^3 s^{-1} $basin^{-1}$, calculated as the base flow (80 percent of runoff) plus evapotranspiration from the bottomlands minus precipitation. 2. Average recharge based on the watershed-simulation model for 1965 through 1973 was 16.8 mm yr^{-1}, during which time average precipitation was 323 mm yr^{-1}. Base flow as a percentage of runoff was 82 percent. Recharge from June through September was negligible; recharge was from snowmelt in the spring in areas above an altitude of 2,130 m. 3. Recharge rate based on simulating steady-state ground-water flow was 0.94 m^3 s^{-1}.

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