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RECHARGE IN SEMIARID MOUNTAIN ENVIRONMENTS

Technical Completion Report

Project No. B-059-NMEX

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by

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ABSTRACT

A systematic investigation of tritium activity in precipitation, surface water, springs, and groundwater of the Roswell artesian basin in New Mexico has been supplemented by hydrogeologic reconnaissance of spring systems; by various statistical correlations and spectral analysis of streamflow and water level records of observation wells; by spring discharge measurements; by stable isotope determinations (oxygen 18 and deuterium); and by numerical modeling of part of the basin. Two recharge contributions to the Principal or Carbonate Aquifer have been distinguished principally on the basis of their tritium label and aquifer response characteristics. A 'fast' recharge component, of relatively high tritium activity, consists of snowmelt and storm runoff and enters the groundwater system mostly as leakage from surface drainages where these cross the karstic San Andres Formation. A 'slow' recharge component, low in tritium, is transmitted from the western mountains through formations underlying the San Andres. Near the western basin edge, this 'slow' component, in the form of springs and shallow groundwater, also feeds effluent streams which, in turn, lose most of it to the San Andres aquifer where they cross karstic zones. Almost all basin waters (including deep groundwater) fall close to the meteoric line of hydrogen/oxygen isotopic composition, and this rules out a juvenile origin or appreciable bedrock interaction.

Keywords: groundwater, recharge, isotope hydrology, hydrologic modeling, springflow, groundwater/surface water interaction, tritium, oxygen 18, deuterium

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ACKNOWLEDGEMENT

This work would not have been possible without the generous cooperation of many individuals and governmental agencies. Specific recognition is expressed in Partial Technical Completion Reports listed later in this report.

Much of the work summarized in this report was performed by students as part of the requirement for the M.S. degree in Hydrology or Geology. The author is pleased to acknowledge the very important contributions to this work made by P. Davis, C. J. Duffy, R. N. Hoy, K. Rehfeldt, and R. Wilcox.

PROJECT JUSTIFICATION AND OBJECTIVES

The Roswell Basin (Figs. 1, 2) is one of New Mexico's major economic regions both from the standpoint of agriculture and of energy production (SUMMERS and KOTTLOWSKI, 1969; SALEEM and JACOB, 1971). Serious problems of progressive water level or piezometric decline, salt water intrusion and deterioration of water quality have plagued the region and have grown progressively worse during the last twenty years. These problems require an ever increasing expenditure of energy for pumpage and water purification. Its magnitude can be appreciated by traveling through the region during the irrigation season and observing the many powerful pumps (1,500-2,000 estimated total) running continuously, or by inspecting the statistics given by SALEEM and JACOB (1971). The concern aroused by these problems is reflected in administrative measures by the New Mexico State Engineer, court-ordered restrictions on water consumption, a pilot water purification plant operated in Roswell by the Department of the Interior's Office of Water Research and Technology, and technical studies sponsored by a number of State and Federal agencies.

A quantitative investigation was undertaken by Prof. M.S. HANTUSH of New Mexico Institute of Mining and Technology (1957), performed at the request and under the auspices of the Pecos Valley Artesian Conservancy District. Among other recommendations, Hantush's report called for the drilling of observation wells in the recharge

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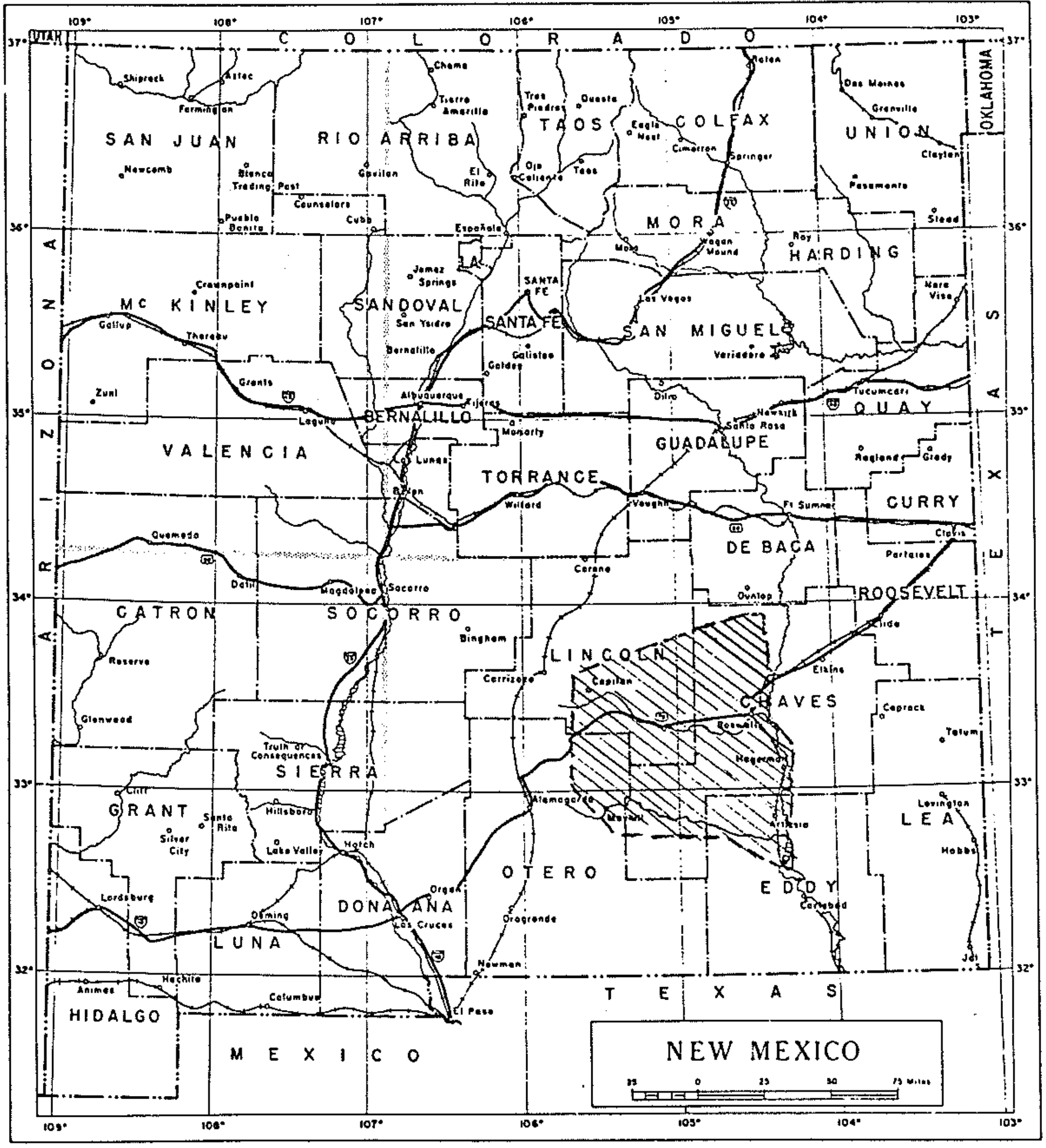

Figure 1: The study area and its location.

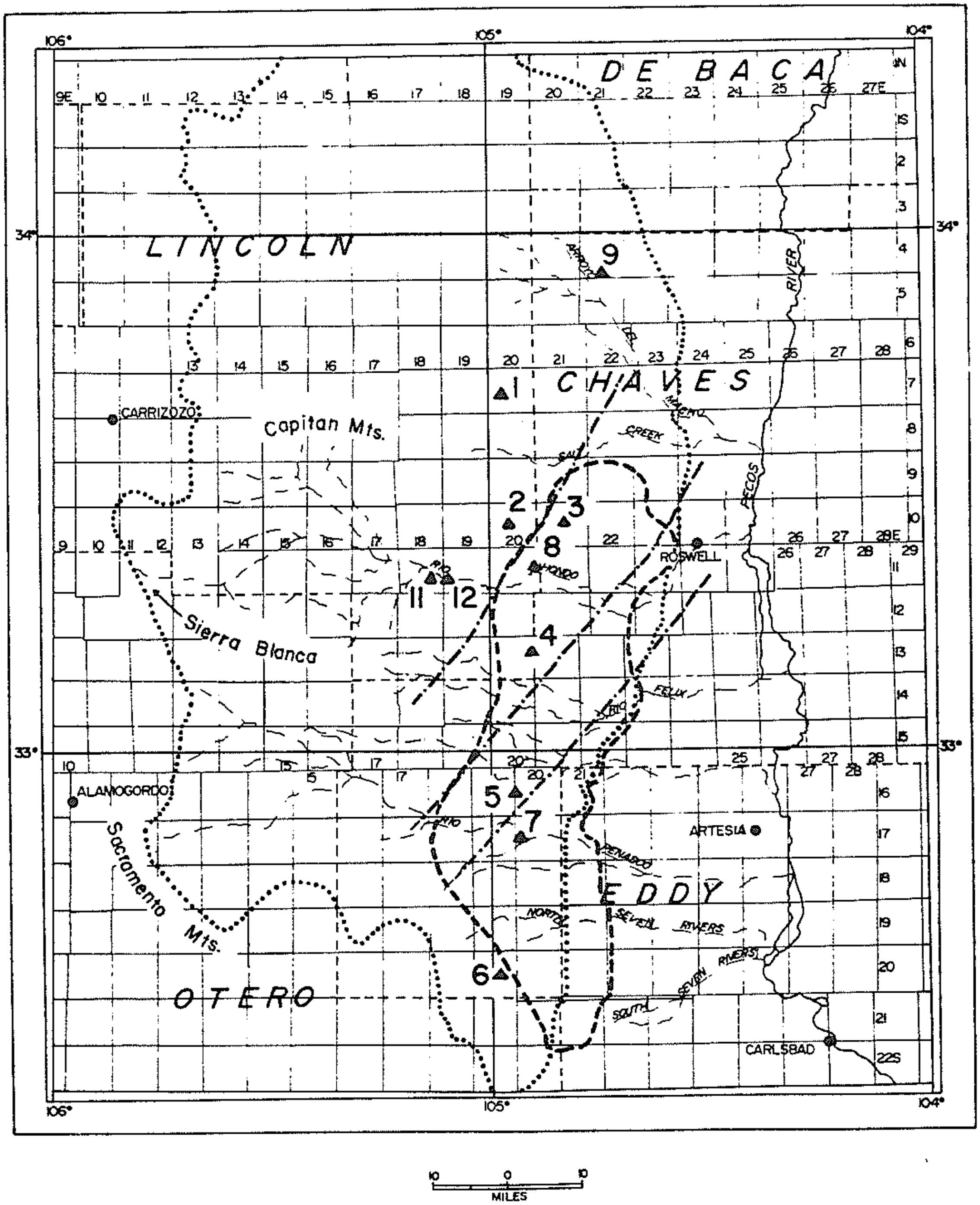

Figure 2: The Roswell Basin. Hydrologic and geographic boundaries. Dotted: total intake area (after Bean, 1949). Dashed: Principal Intake Area (after Fiedler and Nye, 1933, Plate 2). Dash dot: Structure zones (from north to south: Border Hill, Six-Mile Hill, Y-O). Triangles: observation wells, numbered 1-12 (Duffy et al., 1978). Obs. well 10 (drilled in the Macho drainage at T.8, R.24) no longer exists. Wells 5 and 6 were not used for this study.

area of the Basin, in locations selected for their specific geological and hydrological characteristics and unaffected by pumping activity in the Basin.

Following Hantush's recommendation, ten such wells, from 400 ft. to 1100 ft. deep, were drilled by the Conservancy District in cooperation with the State Engineer Office and the United States Geological Survey, Water Resources Div. They were carefully logged, cased, and equipped with water level recorders and rain gauges (CRAWFORD and BORTON, 1958). Continuous records have been kept since 1957. The location of these wells is shown in Fig. 2.

In conjunction with systematic measurements of environmental tritium, these records were analyzed under an Annual Allotment grant from the New Mexico Water Resources Research Institute (A-055-NMEX, 3109-066).

Spectral analysis techniques were used to model the aquifer's response to recharge from streamflow. The results shed new light on sources of recharge to the Basin and the processes by which water is introduced into the Basin's groundwater system (DUFFY et al., 1978; GELHAR et al., 1979).

The specific purpose of the present work was to explore further questions raised by these results, v.gr: What is the size, location, and geohydrological structure of the area or areas most responsible for groundwater recharge to the Basin. What is the relative importance of winter and summer precipitation for groundwater recharge.

What is the connection between groundwater and stream runoff in different sections of rivers Hondo, Felix, and Peñasco. What is the role of Glorieta Sandstone and Yeso Formation in the recharge and transmission of groundwater to the Basin. The findings would ultimately be useful for quantifying the several recharge contributions and total groundwater resources, for tracing groundwater flowpaths and for modeling Basin response to recharge fluctuations caused by climatic or man-made factors.

To this end, it became desirable to measure deuterium and oxygen 18 in addition to tritium. Representative springs, their flow regimes, their geological and geochemical characteristics were investigated. The geological conditions favoring recharge and transmission of groundwater were defined and mapped. The piezometric surface in a representative strip across the Basin, oriented east-west along the Hondo River, was modeled numerically to clarify the roles of surface and deep recharge.

Beyond its immediate and local usefulness, this work should lead to a better understanding of recharge processes in semiarid regions generally.

Results are summarized in this Final Technical Completion Report. The detailed documentation is available in five Partial Technical Completion Reports and one Final Technical Completion Report of a previous project, all published by the New Mexico Water Resources Research Institute and listed in the next section.

PUBLICATION

Duffy, C.J., L.W. Gelhar, and G.W. Gross (1978): Recharge and Groundwater Conditions in the Western Region of the Roswell Basin. Report 100. (111 pp.).

Gross, G.W., P. Davis, and K.R. Rehfeldt (1979): Paul Spring. An Investigation of Recharge in the Roswell (N.M.) Artesian Basin. Report 113. (135 pp.).

Davis, P., R. Wilcox, and G.W. Gross (1980): Spring Characteristics of the Western Roswell Artesian Basin. Report 116. (93 pp.).

Gross, G.W., and R.N. Hoy (1980): A Geochemical and Hydrological Investigation of Groundwater Recharge in the Roswell Basin of New Mexico: Summary of Results and Updated Listing of Tritium Determinations. Report 122. (141 pp.).

Rehfeldt, K.R., and G.W. Gross (1981): The Carbonate Aquifer of the Central Roswell Basin. Recharge Estimation by Numerical Modeling. Report 142. (136 pp.).

Hoy, R.N., and G.W. Gross (1982): A Baseline Study of Oxygen 18 and Deuterium in the Roswell, N.M. Groundwater Basin. Report 144. (94 pp.).

In addition, two papers have been published.

Gelhar, L.W., G.W. Gross, and C.J. Duffy (1979): Stochastic methods of analysing groundwater recharge. In *The Hydrology of Areas of Low Precipitation*. Proceedings of the Canberra Symposium, December 1979. IAHS-AISH Publication No. 128, pp. 313-321.

Gross, G.W., R.N. Hoy, C.J. Duffy, and K.R. Rehfeldt (1982): Isotope studies of recharge in the Roswell Basin. In: Isotope Studies of Hydrologic Processes (E.C. Perry, Jr., and C.W. Montgomery, editors). Northern Illinois University Press, DeKalb, IL. (118 pp.).

ISOTOPE TERMS DEFINED

Tritium (^3H, T)

Radioactive isotope of hydrogen of mass 3. Decays with a half life of 12.3 years. Forms part of the water molecule as HTO. Activities (concentrations) are reported as tritium units (TU):

1 TU = 1 tritium atom per 10^{18} hydrogen atoms.

Cosmic-ray produced tritium is present in atmospheric water in concentrations of $\sim$10 TU. Large quantities of tritium were introduced into the environment by atmospheric nuclear tests. This raised the environmental tritium count to a peak of several 1000 TU in 1963. Following the Nuclear Test Ban Treaty (1963), the activity has been steadily declining and over the North American continent is presently of the order of 100 TU (in rain). Tritium is an emitter of soft beta rays. It is measured by means of internal gas counters (Geiger or proportional) or with scintillation counters, after it has been electrolytically enriched. Because tritium decays radioactively, it can be used for dating groundwater. For details see RABINOWITZ and GROSS, 1972.

Deuterium (^2H, D)

Stable isotope of hydrogen of mass 2. Present in water as HDO. Concentration in natural water is of the order of 0.015 mole percent. A strong isotope altitude effect makes it valuable for hydrologic studies. Deuterium concentrations are measured by conversion to hydrogen gas and mass spectrometry. The deuterium content of a water sample is expressed as the per mil deviation of the ratio D/H measured in the sample, relative to the D/H ratio measured in Standard Mean Ocean Water (SMOW).

Oxygen 18 (^{18}O)

Stable isotope of oxygen, forming part of natural waters (as $H_2{}^{18}O$). Like deuterium, it shows a pronounced isotopic altitude effect, but with characteristics different from those of deuterium. Hence the two isotopes complement each other for the purpose of hydrologic studies. Measurement: equilibration of a water sample with CO_2 - gas, and mass spectrometry. The oxygen 18 content of a water sample is expressed as the per mil deviation of the ratio $^{18}O/^{16}O$ in the sample relative to SMOW. For a more detailed discussion of deuterium and oxygen 18, and their behavior in the environment, the reader is referred to HOY and GROSS (1982).

BRIEF DESCRIPTION OF THE BASIN

The Roswell basin, located in east central New Mexico (Fig. 1), is one of the most important and extensive artesian basins in the USA. The basin slopes eastward from the Capitan-Sierra Blanca-Sacramento Mountains (max. elev. is Sierra Blanca, 11,977 ft. a.m.s.l.) to its outlet, the Pecos River (Roswell, 3570 ft.). The study area is of the order of 9,000 sq. mi. The climate is semiarid, with large temperature contrasts. Annual mean temperature is 15°C. Winters are short and mild, summers are long and hot. Precipitation falls mainly from May to September as intense, brief, and localized thundershowers. However, winter snows accumulate in the highest mountains (especially Sierra Blanca) and enter the basin as spring runoff. Presently only three major streams (Hondo, Felix, and Peñasco), tributaries to the Pecos River, cross the basin in an easterly direction. These streams are perennial in their upper reaches, ephemeral in the center section, and they rarely flow near the outlet (Fig. 2).

A simplified structural section is shown in Fig. 3. The most prominent hydrologic unit is the Permian San Andres Formation, a karstic limestone and evaporite complex. It crops out on the dip-slope that connects the eastern flank of the mountains with the alluvium-covered floodplain of the Pecos River.

Agriculture, concentrated in a 20-mile wide strip along the

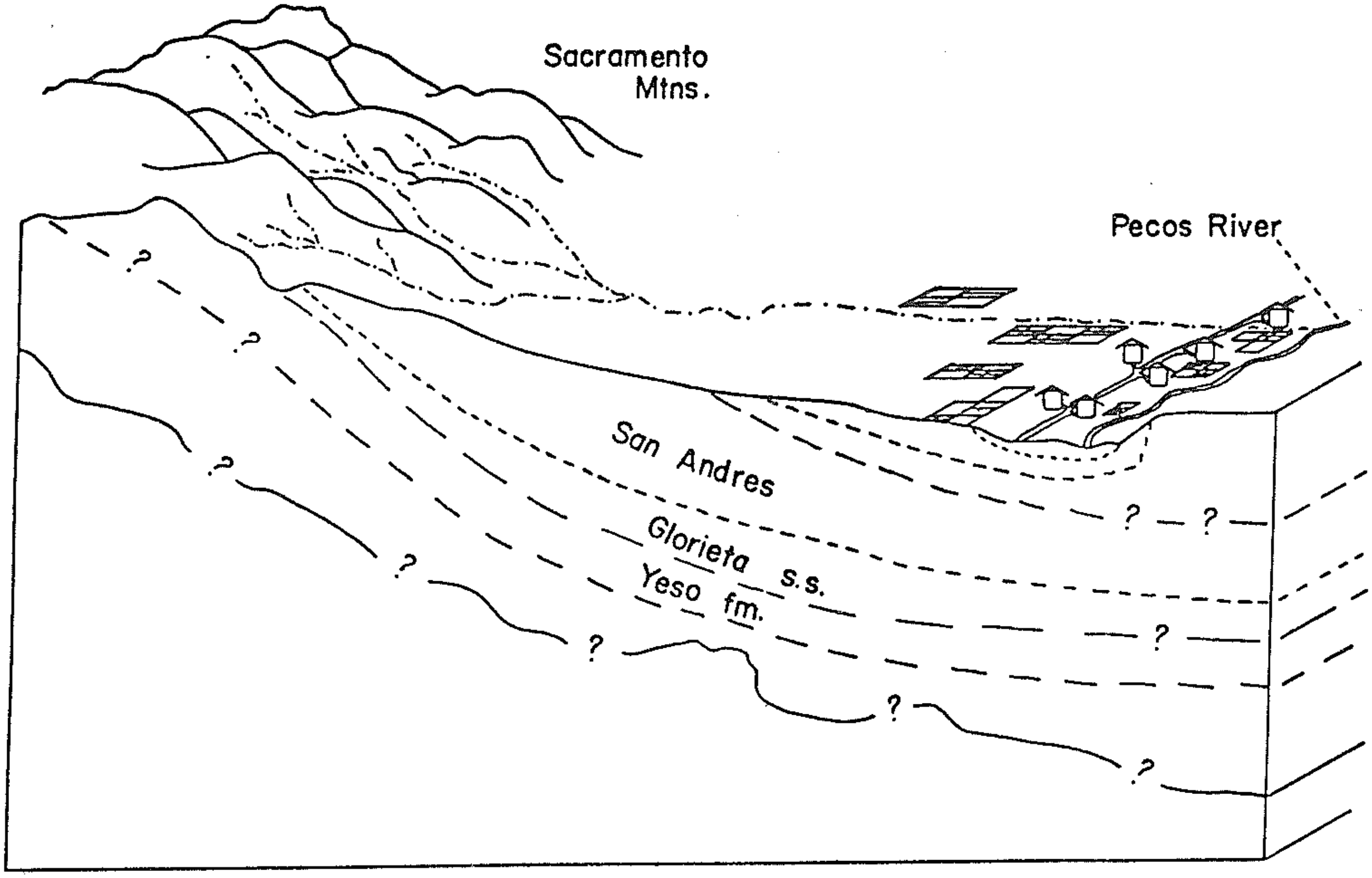

Figure 3: Schematic cross section of the Basin.

west bank of the Pecos River, makes heavy use of surface and groundwater, and this has led to large declines of water levels and water quality. A saltwater intrusion from the northeast is menacing the municipal water supply of Roswell, the region's principal population center (pop. about 42,000).

HYDROLOGY

The region's Principal, also called the Carbonate, Aquifer is the San Andres Formation. It is unconfined on the dipslope and becomes confined along R.21 to 23E.

The dipslope is steeper than the regional hydraulic gradient and the water table rises stratigraphically toward the east. Beneath the Hondo drainage, its gradient flattens abruptly where it enters the San Andres Formation approximately along R.21E (Figure 2). This is inside FIEDLER and NYE's (1933) Principal Intake or Recharge Area (PRA). East of R.23, the Principal Aquifer is confined by the Artesia Group (Permian) and/or the Gatuna Formation (Plio-pleistocene), overlain by the Alluvium. The Alluvium contains an unconfined aquifer (Shallow Aquifer). During the pumping season, leakage may occur from the Shallow to the Principal Aquifer. At other times, the Principal Aquifer discharges into the Shallow Aquifer.

Northeasterly trending "structural zones" (HAVENOR, 1968; KELLEY, 1971) of narrow overturned folds and faults subdivide the Basin, and notably the dipslope, into a series of tilted fault blocks (Fig. 2). They are believed to control groundwater flow patterns in the basin (HAVENOR, 1968). In the PRA, they are believed to facilitate infiltration and recharge, as do the abundant solution (karst) features in the San Andres. According to the classical view (FIEDLER and NYE, 1933) the Principal Aquifer receives most of its recharge in this region, where precipitation and runoff are readily absorbed into the groundwater system. Appreciable recharge from deeper aquifers to the west or underlying the San Andres*was discounted because of unfavorable transmissivity values and because poor water quality was encountered in certain wells penetrating the deeper aquifers. These locally unfavorable characteristics were assumed to be indicative of the entire Yeso-Glorieta aquifers, in spite of the fact that spring data and some well information show that a good deal of usable groundwater also is found in these aquifers.

For the discussion to follow we divide the study area into three longitudinal zones from west to east (Figs. 2,3): the mountainous western zone; the Principal Recharge Area on the dipslope, and the discharge zone which is a strip of about 20 miles adjacent to the Pecos River (on its west bank) where the Principal Aquifer is confined. The first two zones comprise the (total) intake area.

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* Three formations below the San Andres are important as known or potential aquifers: the Glorieta Sandstone (<100 ft) is commonly considered the basal unit of the San Andres. Because of its distinctive lithology and hydrologic role it is treated as a separate aquifer in this and related reports. The Yeso Formation (<1400 ft) underlies the San Andres (<1400 ft) throughout the study region. The Yeso consists typically of thinly bedded variegated shales, sandstones, limestone beds, and evaporites. In the southern part of the study area, the Yeso is underlain by the predominantly brownish to reddish sandstones of the Abo Formation. Nothing is known at present about the hydrologic properties and role of the Abo in the study area. Members of the Artesia Formation, which overlies the San Andres, form part of the Principal, or Carbonate, Aquifer in parts of the Basin, whereas other Artesia members act as confining layers.

MODEL BASED ON TRITIUM MEASUREMENTS IN THE DISCHARGE ZONE

Close to 3,000 tritium determinations of ground and surface waters have been completed since 1957. Initially, the emphasis was on samples taken from irrigation wells in the Shallow and Principal Aquifers along the Pecos River. An early model attempted to correlate tritium activity peaks in groundwater with peaks in atmospheric water (RABINOWITZ et al., 1977). Assuming a line source of "instantaneous" recharge along the PRA (about 20 miles from and paralleling the Pecos River), it arrived at a residence time of about 4 years for groundwater in the northern part of the Roswell basin. This amounts to a particle flow velocity of the order of 70 ft/day (RABINOWITZ et al., 1977, p. 43). No peaks were observed in the southern part of the basin (Artesia), and this was attributed to a much lower transmissivity. Residence time in that area was estimated at 7 years or more. According to this interpretation, tritium peaks should have appeared during the decade 1970/80, but a systematic rise of tritium activity in deep irrigation wells, consistent with this interpretation, has not materialized thus far.

TRITIUM ACTIVITY IN THE PRINCIPAL RECHARGE AREA AND THE MOUNTAINS

All tritium results are tabulated in a report by GROSS and HOY (1980). The model implied that tritium activity in groundwater of the PRA should be that of precipitation over the area, (perhaps averaged over a number of years). But this remained to be verified.

Observation wells in the PRA

Nine observation wells, equipped with water level recorders, were available in the PRA (Fig. 2). They are described in GROSS et al. (1976) and DUFFY et al. (1978). Four of these wells, located within 2,000 ft. or less of major streams (Hondo and Peñasco, respectively) showed high (>20 TU) or intermediate (>10 TU) tritium levels and rapid water level fluctuations in response to major runoff events in the streams (Figs. 4,5). Five wells in the interfluvial highlands showed low tritium activity (<10 TU) and little short-term response attributable to rainfall and recharge. Slow monotonic water level changes in these wells are believed to respond to basinwide climatic changes over a period of 16 years. Tritium samples from wells along the Felix and Peñasco reflect the low tritium activities in these streams (see below).

Spectral analysis was used to compute the recharge contribution of Rio Hondo from water level and stream runoff data (DUFFY et al., 1978; GELHAR et al., 1979). A reasonable estimate was obtained which

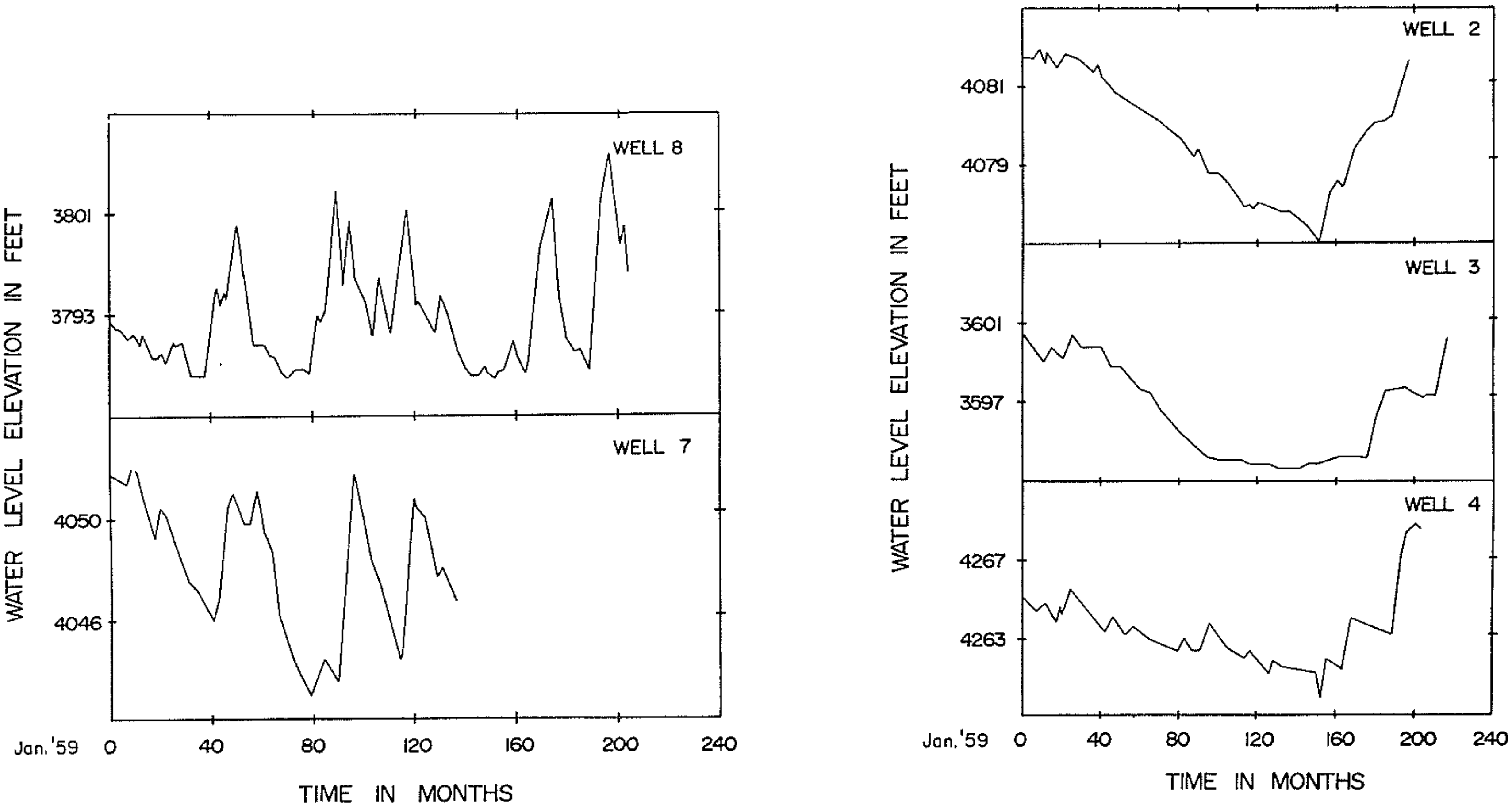


Figure: 4. Observation well hydrographs. From DUFFY et al. (1978). Left: wells 7 and 8; rapid fluctuations are related to runoff events in nearby stream channels. Right: wells 2, 3, 4 of the interfluvial regions; slow monotonic variations predominate.

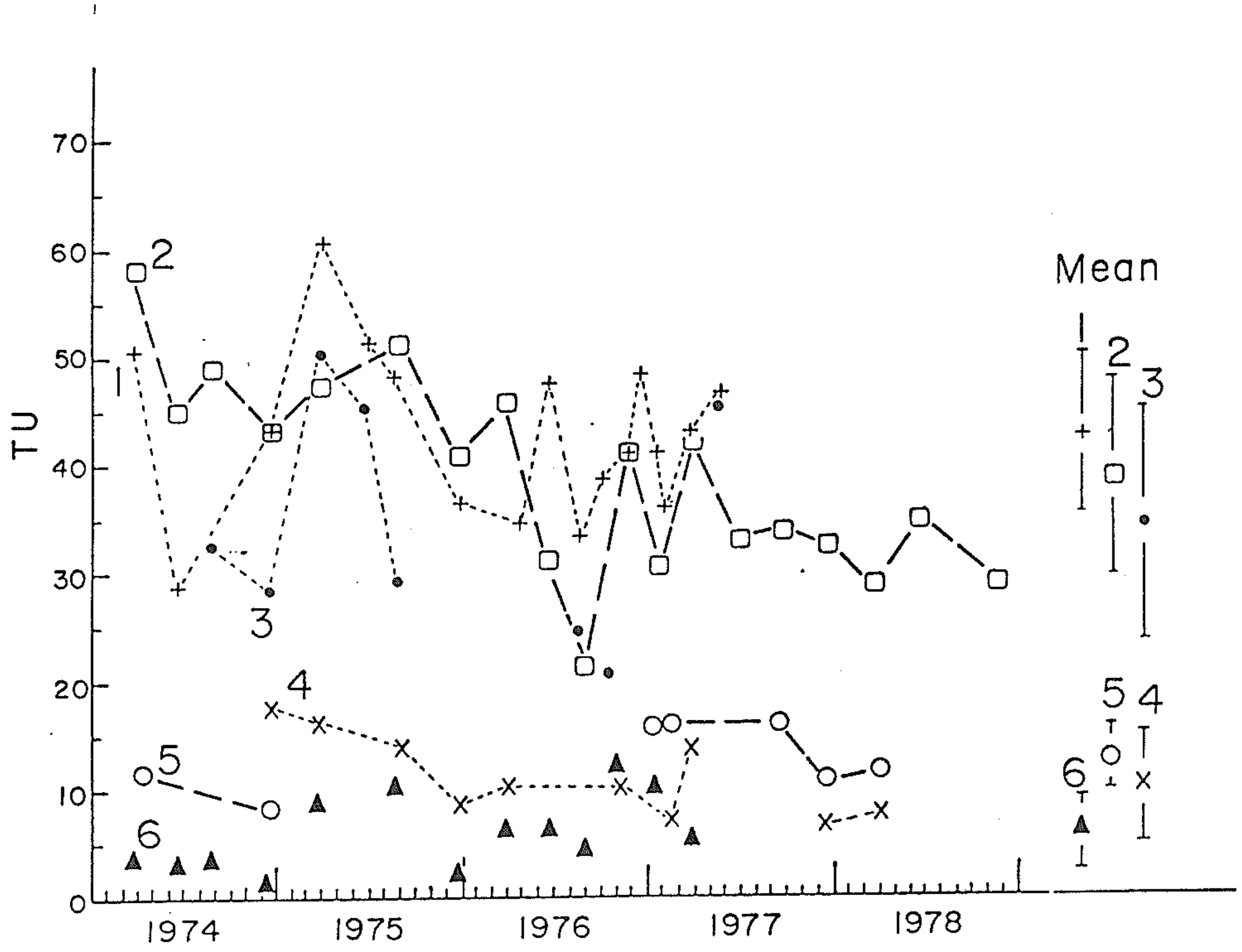


Figure 5: Groupings of natural waters according to tritium activity. Principal Recharge Area. Typical counting standard deviation of individual data points is ±1 TU. For individual samples, see Gross and Hoy, 1980. 1 = Rio Ruidoso at Hondo; 2 = Observation well 8; 3 = Rio Bonito at Hondo; 4 = Rio Peñasco at Observation well 7; 5 = Observation well 7 (no data for 1975/76 because of cave-in); 6 = Observation well 2.

agreed well with earlier estimates by BEAN (1949), based on channel losses between stream gauges. The recharge contributions of the Felix and Peñasco were estimated by extrapolation. The total recharge due to channel losses from all three drainages thus obtained was 36,000 to 38,000 acre-feet per year, whereas the total yearly basin recharge is estimated at 250,000 acre-feet (FIEDLER and NYE, 1933). Even though the inclusion of effects from smaller drainages would increase the surface recharge estimate somewhat, it would still fall substantially short of the total recharge.

The distribution of tritium in observation wells and their water level fluctuations seemed to indicate that surface recharge in the PRA occurs primarily in the major drainages, and this is consistent with the deep water table (250-1000 ft).

In conclusion, a deep recharge component seemed more important than had been assumed heretofore, since surface recharge in the PRA apparently cannot account for the total basin recharge. To test this hypothesis, further hydrogeological and tritium studies were made in the PRA and west of it; the results are summarized below.

Stream water

Water from the Rio Hondo drainage (sampled throughout its course and at different seasons) consistently shows tritium values somewhat below the weighted average tritium activity of rain and snow (Fig. 5). Rio Hondo derives most of its flow from surficial runoff.

Rios Felix and Peñasco, by contrast, have much lower tritium activity (Fig. 5). A major fraction of their flow is derived from springs in their upper courses (west of R.18). A mixture of surface runoff with groundwater is indicated. Observation Well #7 near the Peñasco, shows rapid water level changes correlatable with major runoff events (DUFFY et al., 1978) like the wells near the Hondo (8, 11, 12), but tritium activity is much lower than in the latter. The rivers Felix and Peñasco contribute, like the Hondo, a surficial recharge component in the PRA. The lower tritium activity of this water may be a contributing factor (together with the lower transmissivity of the Principal Aquifer in this region) to why tritium peaks have not been observed in deep irrigation wells around Artesia.

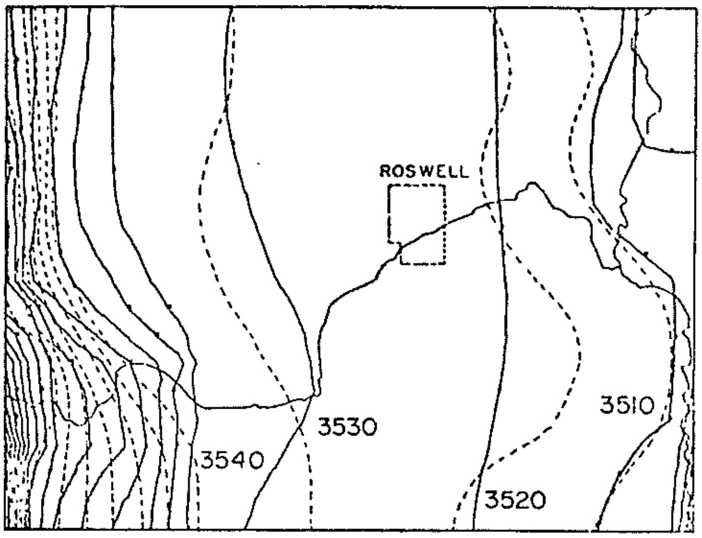
Hydrogeologic survey of springs west of PRA

Many of these springs contribute to the upper courses of the three major drainages, especially of the Felix and Peñasco (GROSS et al., 1979; DAVIS et al., 1980). Most of them issue from perched aquifers located at the contact of the Glorieta Sandstone with the underlying Yeso Fm. Where it outcrops, this contact is characterized by prominent slump and solution features. It is believed to play a major role in the transmission of groundwater into the basin.

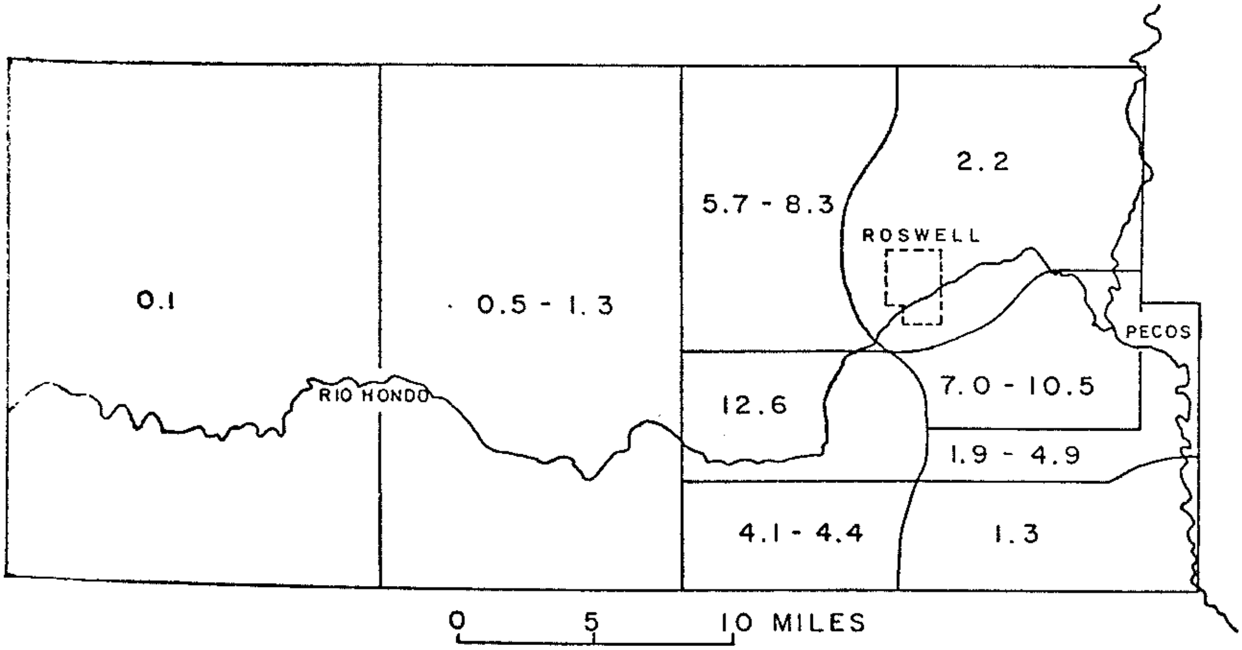
Tritium values of springwater are much lower than in precipitation. A detailed study of Paul Spring (GROSS et al., 1979) which is considered typical, indicates that no more than 20% of its flow is supplied by direct surface infiltration in its surrounding recharge area, the remainder being supplied by deep flow.

HYDROLOGIC MODELING OF THE PRA

A narrow east-west strip of aquifer across the PRA (Fig. 6) was modeled with a two-dimensional finite-difference model (TRESCOTT et al., 1976). The model area included the transition zone from a steep to a very shallow hydraulic gradient in the PRA. The model was calibrated with water level data corresponding to the period January 1967 to January 1968 and verified with data for the period January 1967 to January 1975 (REHFELDT and GROSS, 1982). The reconstruction of the hydraulic head distribution required recharge over the PRA surface of the equivalent of 50% to 100% of the mean annual precipitation (12") falling over the area (Fig. 6). Under the climatic and soil conditions prevailing in the area, a recharge fraction of even 10% seems to be high (GROSS et al., 1979). All the other parameters in the model, such as transmissivity, leakage, pumpage, etc., were consistent with measured values in the Basin. This result seems to support the conclusion, based on the tritium data, of a very substantial deep recharge component supplied by upward leakage from the Glorieta and/or the Yeso Formation. A test well in the vicinity of Roswell showed a higher piezometric head in the combined Yeso-Glorieta-San Andres formations than in the San Andres alone (HAVENOR, 1968), also indicating upward leakage.



HYDRAULIC HEAD, 1975



RECHARGE

(INCHES / YEAR)

Figure 6: Modeling of hydraulic head and recharge. Top: hydraulic head, 1975. Solid lines: computed; dashed lines: observed. Bottom: computed model recharge. From REHFELDT and GROSS (1982).

OXYGEN 18 AND DEUTERIUM

187 determinations of ^{18}O and 76 of D were made. The numerical data are available in a report by HOY and GROSS (1980). The preliminary study had the twofold purpose of (a) obtaining baseline values for a region where nothing of this sort had been done; and (b) to formulate additional criteria for characterizing sources and flowpaths of groundwater recharge. In particular, we hoped to differentiate recharge contributions by winter precipitation (summits of Sierra Blanca and Sacramento Mts.) from those of summer thunderstorms predominant in the PRA.

Precipitation

Weighted mean $\delta^{18}O$ values (with respect to SMOW) were determined for systematic precipitation samples collected from 1976 to 1978 at two NOAA weather reporting stations, Roswell (3669 ft. a.m.s.l., east of the PRA) and Elk (5700 ft., west of the PRA). The results are:

Roswell. . . . . -6.0 ±0.3 ‰

Elk. . . . . -7.1 ±0.3 ‰

This amounts to an altitude effect of only -0.18‰ / +100m. The correlation of $\delta^{18}O$ with mean "condensation temperature" is shown in Fig. 7. As expected, the resultant straight line is steeper than the DANSGAARD (1964) line.

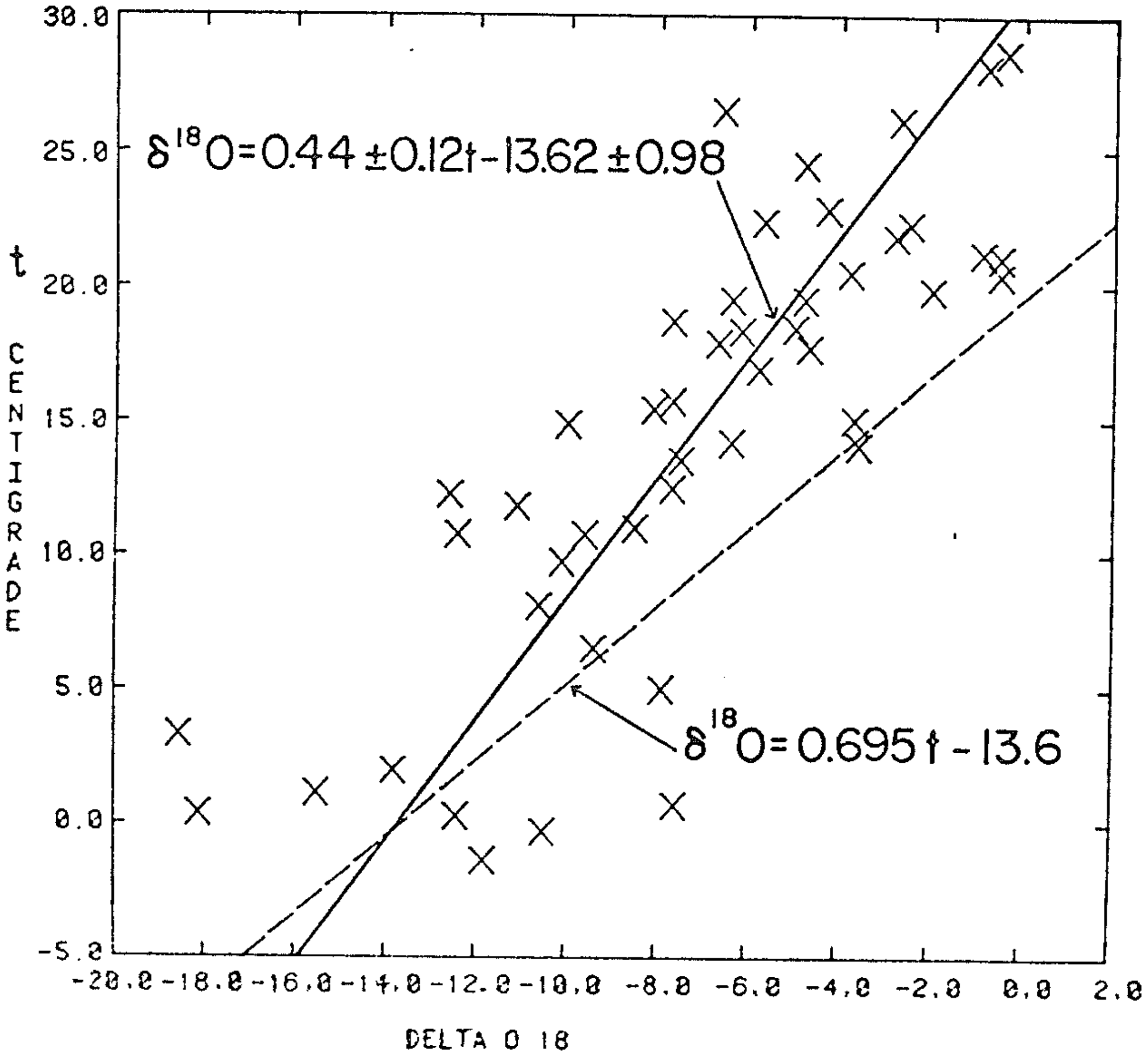


Figure 7: Correlation of $\delta^{18}O$ with mean condensation temperature. Roswell and Elk. Standard deviation of individual data points is $\pm$ 0.2°/∘∘. Full trace: best straightline through data points. Dashed: Dansgaard's (1964) line.

Unfortunately, few deuterium determinations are available for this set of samples.

The plot of δD vs. $\delta^{18}O$ for selected precipitation samples from these two stations plus additional surface water samples is shown in Fig. 8. They fall close to CRAIG's (1961) meteoric line. Evaporation effects are discernible near the upper extreme (Bitter Lakes, a series of closed saltwater lagunes at 3,500 ft. elev.).

Major drainages

Water in the rivers Hondo, Felix, and Peñasco is slightly lighter in ^{18}O (-9‰) than precipitation at Elk (-7.1‰). This reflects the contribution of recharge from higher elevations.

Springs and wells

While the δD-$\delta^{18}O$ data for precipitation are spread out over the whole usual range of CRAIG's meteoric line, reflecting climatic or orographic diversity of the study area, the values for springs and wells fall within surprisingly narrow limits (Fig. 8). Two exceptions were observed. Boiling Spring (T.20, R.26) issues from the San Andres Fm. into the Pecos River and may show an oxygen shift due to interaction with the limestone aquifer or evaporation. A hand-dug well in the Shallow Aquifer of the Pecos floodplain east of Artesia exhibits evaporation effects (H on Fig. 8).

Based on ^{18}O alone, groundwater in the northern part of the study area (Arroyo del Macho and Rio Hondo drainages) is perhaps

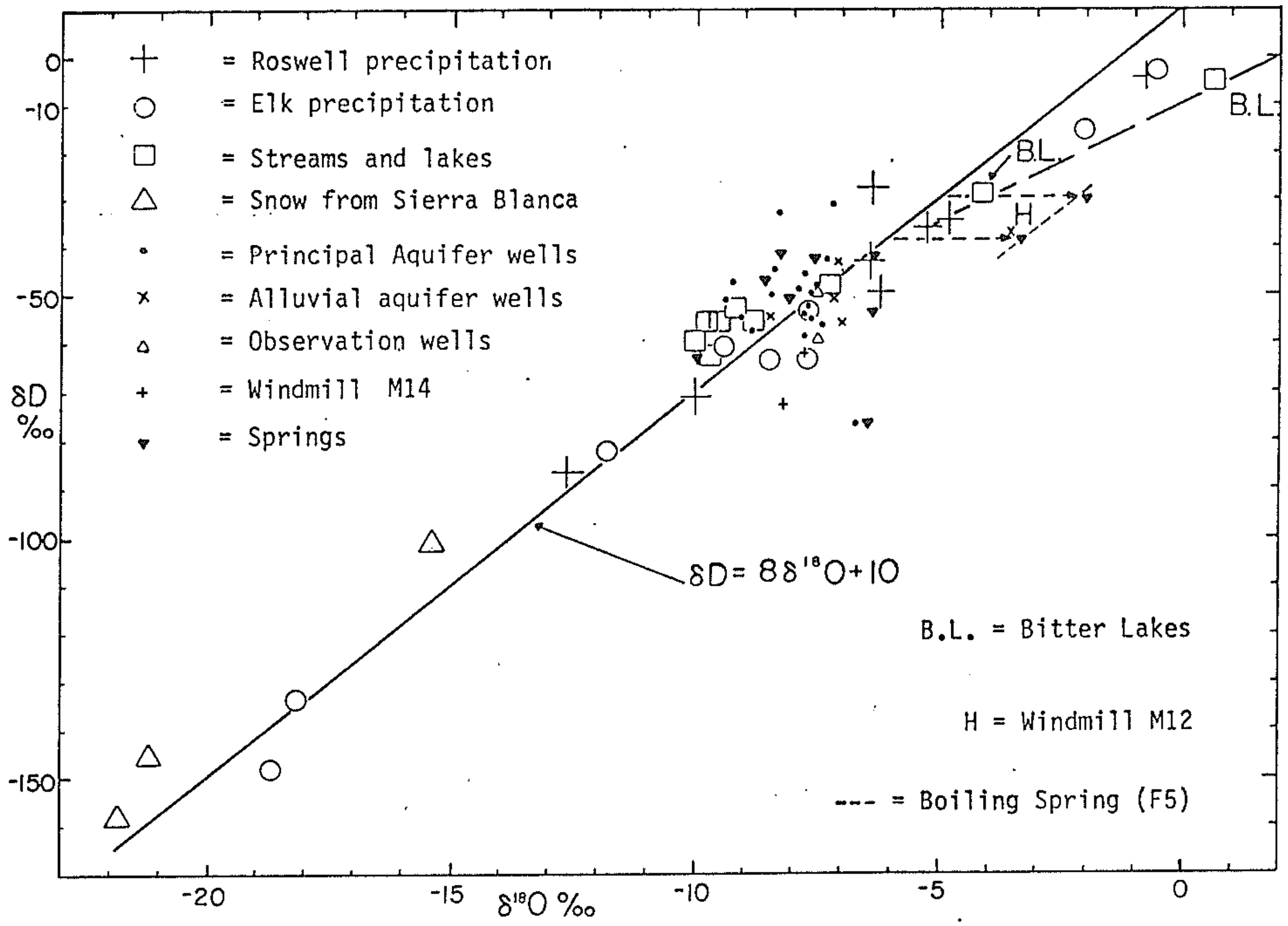


Figure 8: δD vs. $\delta^{18}O$ plot. Standard deviation for individual data points ±0.2°/∘∘ for $\delta^{18}O$, and ±1.5°/∘∘ for δD.

slightly lighter than groundwater from the Peñasco drainage. The difference is of the order of a per mil. There are numerous exceptions, however, and a firm interpretation should not be placed on our limited number of determinations.

A homogeneous δD-$\delta^{18}O$ distribution in groundwater, such as observed in the present case, is usually considered evidence of thorough mixing in the aquifer (CONRAD et al., 1978) or of a very localized recharge source (GALLO, 1978). In our case, mixing is reasonable because the flowpaths are long. There are two possible additional factors contributing to this effect: (1) in this semiarid continental environment, the altitude effect may be overshadowed by large temperature fluctuations that occur at all elevations. (2) moisture is supplied from two sources, the Gulf of Mexico and the Pacific, although the former predominates in summer (RABINOWITZ et al., 1977).

SUMMARY OF CONCLUSIONS

Tritium measurements give evidence for two principal recharge components. A fast surface component consists of snowmelt and summer storm runoff through the Hondo drainage. It is characterized by high tritium values (>20 TU). A slow deep component consists of groundwater recharged to the Yeso and Glorieta aquifers in the western mountains; it enters the Principal Aquifer by upward leakage beneath the Principal Recharge Area. It has low tritium activity (<10 TU). The Felix and Peñasco drainages short-circuit water of this second component into the PRA. The deep component makes up 50% or more of the reservoir.

Stochastic modeling of the interaction of surface runoff with water level fluctuations in observation wells, and numerical modeling of a portion of the basin have substantiated these conclusions.

Differentiation of recharge components on the basis of stable isotopes (D, ^{18}O) is not clearcut. This in spite of the large elevation contrast in the basin. This may be due to groundwater mixing, to atmospheric mixing of two moisture sources, climatic effects, or a combination of these factors.

RECOMMENDATIONS

Detailed recommendations have been presented in several Partial Technical Completion Reports. They are here summarized. The several approaches used in this work, - tritium measurements, hydrogeologic characterization of springs in the recharge zone, stochastic modeling, numerical modeling, stable-isotope determinations - , have supplied evidence for 'slow' and 'fast' recharge contributions to the groundwater basin. It also appears that a deep recharge component (or components) is considerably more important than had been recognized heretofore. Management of this (and any other) groundwater basin involves optimal allocation, conservation, and forecasting of availability of water resources in function of climatic and cultural variables (e.g.: population expansion, agricultural or industrial developments, diversions). Successful forecasting depends on a reliable knowledge and understanding of the hydrologic budget (inflows and outflows) and how it is affected by these several variables singly or in combination. This, in turn, requires a quantitative understanding of recharge/discharge processes and of their variation in time. The most immediate need for this basin is the study of the mechanisms, the paths, and the travel times by which different recharge components reach the principal user zone along the Pecos River, as well as the relative contributions of these different components to total recharge. Specifically, the hydrologic properties of the Yeso

Formation and perhaps of the underlying Abo should be investigated. This is difficult because not much subsurface information is available. Nonetheless, something can be done. All available subsurface information should be assembled, the formations should be mapped in detail where they outcrop in the Basin and on the basis of well logs where they do not. Hydrologic properties should be inferred on the basis of lithology, and correlations in different parts of the Basin should be attempted because it appears that the transmissivity is linked to specific, relatively thin sections of sandy lithology in the Yeso Formation.

The establishment of observation wells (equipped with water level recorders) and execution of pumping tests in the western, or recharge, zone of the Basin would be highly desirable.

The numerical model, with explicit inclusion of 'fast' and 'slow' recharge sources, should be extended to other parts of the Basin, including the western recharge belt.

In the course of this study, the relation of surface runoff to groundwater was studied especially in the lower Rio Hondo drainage basin. Springs were also investigated in the upper Peñasco. A comprehensive study of recharge/discharge relationships of major streams, upper Rio Hondo (with its tributaries Bonito and Ruidoso), Rio Felix, and Rio Peñasco should be completed.

How and where does deep leakage enter the Principal or Carbonate Aquifer? Are there preferred zones of leakage, perhaps controlled by structure, or is the leakage distributed relatively uniformly over the contact between Principal (Carbonate) Aquifer and underlying formations. Much drilling has taken place in recent years, and perhaps it is time to compile new and detailed subsurface maps of the top and bottom surfaces of the San Andres Formation.

Several observation wells show long-term fluctuations suggesting climatic effects. These should be further investigated; they might give useful information about response time of the aquifer system.

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