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REGIONAL HYDROGEOLOGY AND THE EFFECT OF STRUCTURAL CONTROL ON THE FLOW OF GROUND WATER IN THE RIO GRANDE TROUGH, NORTHERN NEW MEXICO

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INTRODUCTION

Ground-water flow in any porous medium is influenced by various hydraulic properties of the medium, together with hydrologic and hydraulic boundaries surrounding it or within it. Two rather distinct regimes of ground-water flow exist in the Rio Grande structural trough in north-central New Mexico from the Colorado border south to Espanola; the structure and stratigraphy of the Rio Grande rift effectively control the movement of shallow ground water in the area, and also the movement of a deeper ground-water body contained in saturated sediments of the Santa Fe Group. Where the cross-sectional area of Santa Fe Group sediments has been constricted or narrowed, in places like the Embudo "constriction" between Taos and Espanola near Pilar, mixing of the regimes occurs. Velocity and direction of shallow ground-water flow change and become similar to those of the deeper ground water in transient storage. The significant features of the Rio Grande rift region in north-central New Mexico are shown in Figure I.

REGIONAL GEOLOGY

Structural Setting

The Rio Grande rift is a structural feature extending the entire length of New Mexico. The dominant structural feature in the rift region is the broad sag, whose axis, in general, was followed by the Rio Grande. East of the axis, the beds dip generally westward. West of the axis, the dip of the beds is generally lower and less uniform in direction; south and east inclinations are most common. All of the faulting is normal and forms conjugate systems of fault sets dipping either cast or west. The faults are relatively steep, dipping 50-80° from horizontal (Kelley, 1978).

All of the rocks underlying the Santa Fe Group deposits are considered in this study to form the basement complex. Definite hydrologic differences between the Santa Fe deposits and the pre-Santa Fe rocks make this distinction appropriate.

The Santa Fe Group was deposited in a series of grabens and fault structures which extends roughly from Leadville, Colorado, to the vicinity of Ft. Quitman, Texas. Bryan (1938, p. 197) identified eight structural basins which comprise the Rio Grande trough. According to this nomenclature, Taos is located near the southern end of the San Luis Basin, whereas Espanola is located in the Espanola Basin. According to Kelley (1952, p. 93), these two basins are separated by the "Embudo constriction" which was formed by the Brazos uplift and the Picuris salient (Fig. 1).

Basement Rocks

There are several distinctly different basement-rock complexes in the region. The basin fill rests predominantly on Precambrian-age crystalline basement. Crystalline rocks, mostly in the Sangre de Cristo range between Penasco and Santa Fe, consist of granite, gneiss, quartzite, various schists, and greenstones (Kelley, 1978). Metamorphic rocks (schists and quartzites) occur mostly in the Picuris salient and Brazos uplift (Fig. 1). The Chama Basin forms a wedge of Paleozoic, Mesozoic, and early- to middle-age Tertiary rocks. In the vicinity of Taos the crystalline-basement rocks range in age from Precambrian to Tertiary.

Santa Fe Group and Related Deposits

The Rio Grande trough or depression was filled by sediments during Miocene and early Pliocene time. During most of the Pliocene and earliest Quaternary time, tilting, faulting, erosion, and pedimentation took place. Since then, as much as 30% of the once-accumulated maximum volume of Santa Fe Group deposits has been removed (Kelley, 1978).

The name "Santa Fe marls" was first used by Hayden (1869, p. 60) to describe a sequence of sediments which had been deposited in the Rio Grande trough. Bryan (1938, p. 205) noted that "The main body

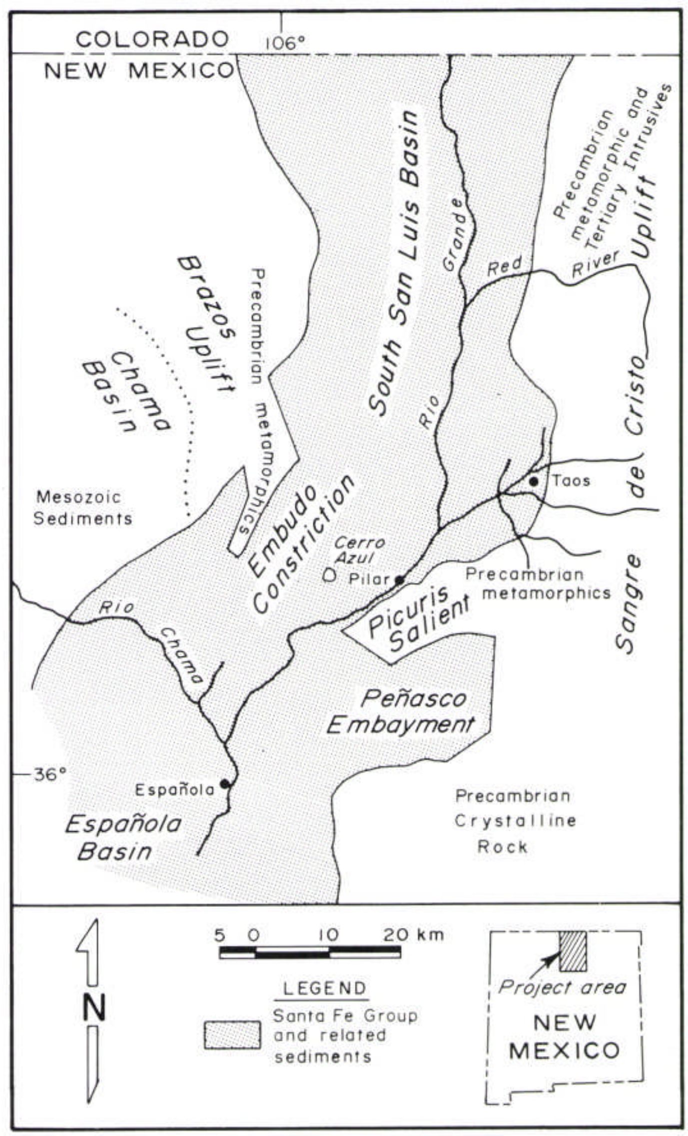

FIGURE 1. Map of north-central New Mexico showing major structural elements which form the Embudo constriction. Cerro Azul is a Precambrian block protruding through the late Tertiary Santa Fe sediments.

of sedimentary deposits of the Rio Grande depression, from the north end of the San Luis Valley, Colorado, to and beyond El Paso is considered to be the same general age and to belong to the Santa Fe Formation." Subsequently a great deal of stratigraphic nomenclature has been applied to various parts of the Santa Fe Group. In some cases the different terminology is based on lithologic characteristics (Smith, 1938; Spiegel and Baldwin, 1963; Bingler, 1968); in other instances the terminology is based on fossil content (Galusha and Blick, 1971). In other areas, different facies of the Santa Fe Group have been described without the application of additional nomenclature (Winograd, 1959; Wilson and others, 1978).

Spiegel and Baldwin (1963, pp. 34-35) first described the Tesuque Formation as a part of the Santa Fe Group. Where described south of Espanola, the formation ". . . consists of several thousand feet of pinkish-tan soft arkosic, silty sandstone and minor conglomerate and siltstone." The sorting and cementation are variable, but the beds are typically poorly sorted and unconsolidated. There are some interbedded basalt and ash deposits.

The Tesuque was deposited as a sequence of coalescing alluvial fans, and much of the material was reworked by the ancestral Rio Grande. Consequently, individual elastic beds probably are not continuous, and individual strata can seldom be traced for more than a mile or two (Miller and others, 1963. p. 50). Individual strata also are disrupted by faulting. The faults usually are less than 2 mi long (Manley, 1978, p. 12) and the displacement is usually less than 300 ft (Galusha and Blick, 1971, p. 101).

It is seldom possible to differentiate deposits of the Tesuque Formation in the subsurface. Also, it is often difficult to apply the surface nomenclature to subsurface deposits. Consequently, it has become a common practice to apply the name "Tesuque Formation" to any water-bearing strata in the Rio Grande basin which has a lithology similar to the type-Tesuque Formation.

The San Luis Basin may contain as much as 30,000 ft of sediments that are equivalent to the Santa Fe Group (Chapin, 1971, p. 191). Although this entire sequence may not be water-bearing, Emery and others (1971, p. 129) have estimated that the upper 6,000 ft are capable of producing water to wells. These thicknesses probably decrease to the south; McKinlay (1956, p. 21) estimated that the Santa Fe Group is about 3,000 ft thick in the Sunshine Valley north of Taos.

Due to the thickness of the volcanic beds on the Taos Plateau, very meager subsurface data from wells completed in the Santa Fe Group are available there. The thickness of the Santa Fe Group deposits has been estimated to be 3,000 ft or less; Kelley (1978) estimated a thickness of 8,000-9,000 ft south of Espanola.

Water-bearing Characteristics in the Southern San Luis Basin

The San Luis Basin is located in southern Colorado and extends as far south as the Embudo constriction; it includes the pediment slopes at the foot of the Sangre de Cristo Mountains and the basalt plateau west of the Rio Grande.

The four principal geologic units in the basin are the basement complex, the Santa Fe Group, the Cisneros Basalt, and fan—terrace deposits. The water-bearing characteristics of these units have been summarized by Winograd (1959) and Wilson and others (1978).

The basement complex in this area is non-water-bearing. The Precambrian and younger lithified strata of the basement complex are known to be highly fractured; however, there is very little intergranular permeability in these rocks.

According to Wilson and others (1978, pp. VI-11), drilling data from the Taos area indicated that the Santa Fe Group contains three distinct "sequences of rocks" or facies. These are: a lower sand facies, a middle facies of basalt deposits with interbedded lake and river deposits, and an upper facies of alluvial deposits. Winograd (1959, p. 15) recognized the same general sequence of strata in the Sunshine Valley; however, the basalt flows are much more prominent in that area.

Little is known of the hydrologic character of the lower facies. This is due principally to the fact that the lower unit generally is overlain by strata capable of producing adequate quantities of water for most needs. Wilson and others (1978, table 11) suggest that this lower unit may be a part of the Tesuque Formation. The maximum thickness probably does not exceed 3,000 ft and areally the unit pinches out against the mountain front. The water-bearing potential of this unit is unknown.

The middle facies of the Santa Fe Group at Taos is characterized by the presence of lake deposits and basalt flows (Cisneros Basalt of Kelley, 1978) interbedded with sediments more typical of the Santa Fe Group. The basalt flows thicken westward and interfinger with the relatively unconsolidated sand, silt, clay, and gravel of the Santa Fe Group toward the east. Ash beds are also present. Most individual basalt flows are less than 50 ft thick, but the cumulative thickness of basalt is as much as 670 ft near Taos Junction bridge (Winograd, 1959, p. 16). The basalt transmits water through the fractures and joints, as well as along bedding planes between flows. In addition, relatively thin deposits of unconsolidated sand and gravel which transmit additional water may be present between flows. Most well yields are 25 to 30 gpm (gallons per minute) (136 to 163 m'/day).

The upper facies is the principal water-bearing zone in the Taos—Sunshine area where yields as high as 3,000 gpm have been reported. This aquifer consists of poorly sorted, unconsolidated deposits of clay, silt, sand, and gravel. Due to the variability of the deposits, few of the individual beds can be traced more than a short distance. Boulders as large as eight inches in diameter are present in exposures of these deposits. In most cases it is difficult to distinguish the surficial fan and terrace deposits from the underlying upper facies of the Santa Fe Group. Spiegel and Couse (1969) suggest that these alluvial deposits may have a greater water-producing capacity than the Santa Fe Group; however, they are thin, generally not exceeding 35 ft in thickness.

The Cisneros Basalt consists of highly fractured and jointed andesitic lava flows which have reported yields of 25-30 gpm (136-163 m'/day). Most of the individual flows have zones of weathering on the upper surface. Thin deposits of alluvial and eolian sediments separate some of the flows. Owing to the fracture permeability in these basalts, there is very little runoff from the basalt plateau. Rather, the precipitation is either quickly lost by evapotranspiration or else it infiltrates the jointed Cisneros Basalt and moves laterally through joints and between individual flows. Much of this precipitation is discharged as springs along the wells of the Rio Grande gorge.

The cumulative thickness of the Cisneros Basalts is not known. On the west side of the plateau, near No Agua Mountain, a well was drilled to a depth of 700 ft without penetrating the Santa Fe deposits (Winograd, 1959, p. 14). The flows are about 670 ft thick in the gorge near Taos Junction bridge, and the total thickness decreases to less than 500 ft toward the north.

Water-bearing Characteristics in the Espatiola Basin

The geologic units of the Espanola area are present as far north as the Embudo constriction. Along the west side of the basin, these units may be present beneath the lower Rio Chama in the vicinity of Abiquiu; however, they are not known to be present in the El Rito area.

Several geologic units have been identified in the Espanola Basin. These include the Tesuque Formation, Chama—El Rito Formation, Ojo Caliente Sandstone, the Cisneros Basalt, and alluvium. Galusha and Blick (1971, p. 64) and Kelley (1978) recognized that the Chama—El Rito Formation is a facies of the Tesuque, as is the Ojo Caliente Sandstone. Because of the similarity in lithology, it would be very difficult to differentiate these individual units in the subsurface.

Because of the similarity of these units, most studies have considered the entire geologic sequence to be a single hydrologic unit (Trauger, 1967; Koopman, 1975). In a comprehensive analytical study of the Pojoaque River basin, Hearne (1980) considered all the geologic units in the middle Rio Grande trough to be part of the Tesuque aquifer system. Yields of 500 gpm (2725 m'/day) have been reported from wells drilled to sufficient depths.

The Cisneros Basalt which caps the Black Mesa north of Espanola is part of the extensive basalt-flow complex of the Taos Plateau. The basalt is highly fractured, and precipitation which falls on the Black Mesa is readily absorbed by these fractures and by unconsolidated alluvium which locally covers the flows. Much of the water is lost by evapotranspiration. When sufficient precipitation does occur, the water is discharged as intermittent springs along the edges of the mesa. Otherwise, the Cisneros Basalt is not considered to be water-bearing. Test holes drilled on top of Black Mesa are reported "dry" until they reach the level of the nearby Rio Chama and Rio Grande. This is a minimum depth of about 1,000 ft.

REGIONAL FLOW SYSTEMS

Shallow Ground Water and the Zone of Transient Storage

Emery (1971, p. 129) described two aquifer systems in the San Luis Valley of Colorado which contain at least two billion acre-feet (2.5 million cubic hectometers) of water in storage in the upper 6,000 ft. Although he described the deeper aquifer as a confined system, the discontinuity of the "clay series" resulted in varying degrees of hydraulic connection with the shallow aquifer. The shallow aquifer was found to be unconfined and therefore responsive to local conditions of recharge and discharge. The semi-confining "clay series" was generally present at depths of 50 to about 200 ft (15.2-61 m).

Underflow southward across the state line would be restricted by the San Luis Hills, a series of volcanic extrusives which form a constriction to ground-water flow approximately 5-10 mi (8.0-16.1 km) north of the state line. Nevertheless, McKinlay (1956, p. 21) estimated that there are about 3,000 ft (914 m) of saturated sediments near the state line, and the trough is approximately 21 mi (33.8 km) wide at this point. Assuming conservative aquifer parameters, there may be as much as 123 ft^3/sec (3.5 m^3/sec) of ground-water underfiow from Colorado to New Mexico across the state line. This is compared to the long-term average discharge in the Rio Grande of 325 ft^3/sec (9.2 m^3/sec) at the state line (USGS, 1977, p. 85).

Emery's concept of two aquifer systems is applicable in New Mexico as well as Colorado. Although there is no evidence of a persistent confining layer, two different flow systems probably exist. The lower zone of transient storage would represent that ground water which flows through the deeper parts of the trough without being influenced by the shallow water-table system.

The zone of transient storage extends from the bed of the Rio Grande to the bottom of the unconsolidated sediments in the trough. The cross-sectional area would vary with the structural configuration of the Rio Grande basin (Fig. 1). At the state line the width of the zone would be about 21 mi (33.8 km), but this would be reduced to only 12 mi (19.3 km) in the Embudo constriction. The upper surface of the zone of transient storage would coincide with the bed of the Rio Grande; the gradient would generally be from north to south at the rate of about 21 ft/mi (4 m/km).

The shallow-aquifer system would be that zone of saturation between the water table and the zone of transient storage. This aquifer is influenced by various components of the hydrologic cycle, such as recharge by precipitation and snowmelt, surface runoff, depletion by shallow ground-water evaporation and transpiration, pumping from wells, and various discharges from springs. North of the Embudo constriction, the shallow aquifer is a major source of recharge to the Rio Grande.

Ground-water Flow Through the Embudo Constriction

The amount of aquifer material in the Embudo constriction is considerably less than in areas north and south. Not only has the cross-sectional area been reduced, but Cerro Azul, a Precambrian outlier, is located near the middle of the constriction. Consequently, the Santa Fe deposits probably are quite thin in the middle of the structural confinement. Inasmuch as the constriction has produced a vast reduction in the amount of permeable material in the trough, the ground-water flow regime would also be affected.

In order for the same quantity of water to flow through the constriction from north to south, the velocity of flow must increase. A water-table contour map of the area shows that the predominant direction of shallow ground-water flow in the constriction is from north to south, parallel with the river channel, in order to move the required quantity of ground water through the constriction (Fig. 2). Elsewhere the flow direction is normal to the river, showing that there is ground-water discharge from the shallow aquifer to the Rio Grande.

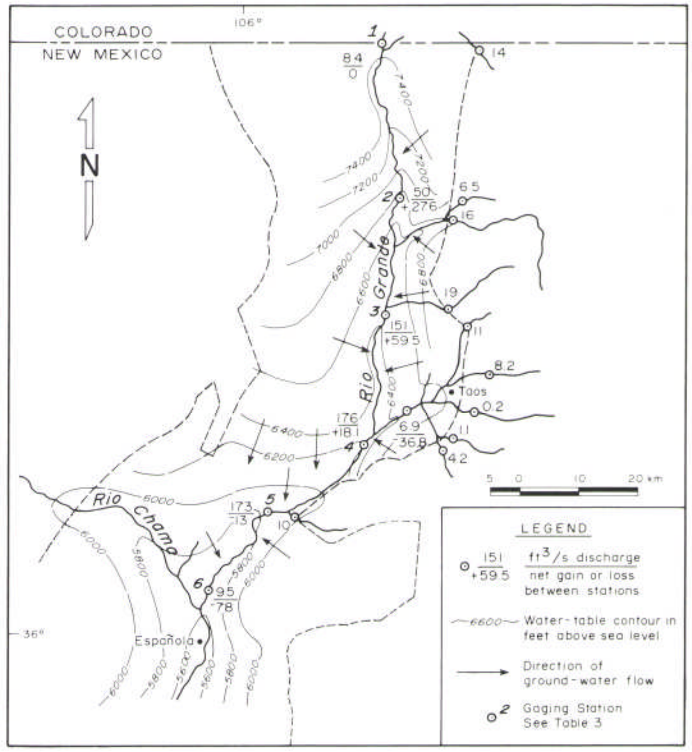

FIGURE 2. Water-table contour map and location of gaging stations in upper Rio Grande basin, New Mexico.

An evaluation of stream-flow records shows that there is a significant increase in the flow of the Rio Grande north of the Embudo constriction. Through the constriction and southward, ground-water gains are minimal.

For the purposes of analysis, the date of September 10, 1977, was selected. It was on this date that the lowest discharge was recorded by the U.S. Geological Survey at the Rio Grande above San Juan Pueblo station. This was the southernmost station used in the analysis, and therefore indicated that low-flow conditions prevailed on that date. The stations used in the analysis are listed in Table 1. Data are from U.S. Geological Survey (1977).

The flow at the state line (station 1) on September 10, 1977, was 8.3 ft^3/sec (0.24 m/sec) the amount of surface flow entering New Mexico from Colorado. At station 2, a distance of 20 river miles (32.2 km), the flow was 50 ft^3/sec (1.4 m^3/sec), or a gain of 27.6 ft^3/sec (0.78

TABLE 1. Discharge stations on the Rio Grande and its tributaries north of San Juan Pueblo.

	Name	Location		Discharge (ft^3/sec)
1.	Rio Grande at Colorado-NM State Line	37°00'03"	105°43'19"	8.4
	Costilla Creek near Costilla	36°58'01"	105°30'23"	14
2.	Rio Grande near Cerro	29.12.20		50
	Red River near Questa	29.13.32		16
	Cabresto Creek near Questa	29.13.21		6.5
	Rio Hondo near Valdez	36°32'30"	105°33'21"	19
3.	Rio Grande near Arroyo Hondo	27.12.31		151
	Rio Pueblo de Taos near Taos	26.13.36		8.2
	Rio Lucero near Arroyo Seco	36°30'30"	105°31'49"	11
	Rio Fernando de Taos near Taos	25.13.27		.24
	Rio Grande del Rancho near Talpa	36°17'52"	105°34'55"	4.2
	Rio Chiquita near Talpa	36°19'55"	105°34'42"	1.1
	Rio Pueblo de Taos below Los Cordovas	36°22'39"	105°40'05"	6.9
4.	Rio Grande below Taos Junction Bridge	24.11.15		176
	Embudo Creek at Dixon	23.10.19		10
5.	Rio Grande at Embudo	23.9.23		173
6.	Rio Grande above San Juan Pueblo	21.8.10		95

m^3/sec) when adjusted for inflow from upper Costillo Creek near Costillo. This represents a ground-water inflow of 618 gal/min (3,368 m^3/day) per river mile. The gain is even more significant between stations 2 and 3 which show an average gain of 1,666 gal/min (9,080 m7day) per river mile of channel. This reach of the Rio Grande is noted for the number of perennial springs along the channel.

The ground-water inflow diminishes to about 400 gal/min (2,180 m^3/day) per mile between stations 3 and 4, which includes the contributions from Rio Pueblo de Taos and its headwater streams. It should be noted that there is a net loss along this tributary system due to irrigation diversions in the Taos area.

Records for this date show that there was a net gain of 105.2 ft^3/sec (3.0 m^3/sec) to the Rio Grande from ground water between the state line and station 4 which is located at the upper end of the Embudo constriction. However, there was a net loss of 13 ft^3/sec (0.37 m`/sec) between stations 4 and 5, which coincides with the length of the constriction.

The significant losses which occur between stations 5 and 6 can be attributed to diversion of streamflow for irrigation between Dixon and Espafiola.

SUMMARY

Ground-water flow in the Rio Grande trough in northern New Mexico is affected by both the stratigraphy and structure of the region. Although as much as 8,000-9,000 ft (2,438-2,743 m) of basin-fill material of the Santa Fe Group fill the trough in many places, not all of this material is saturated. In the Embudo constriction, the amount of basin-till material is decreased by structural controls. Shallow ground-water flow through the constriction changes direction in order to move the required amount of flow past that location. In the constriction, shallow and deep ground-water flow share a common direction, and probably a common gradient, from north to south. Ground-water budget calculations suggest a sharp decrease in the quantity of ground water draining into the Rio Grande through the constriction, thus indicating that a relatively larger quantity of water is moving in the subsurface through the constriction that is draining into the Rio Grande and then moving through.

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