



Hydrostratigraphy, hydrodynamics, and hydrochemistry--Geologic controls of ground-water phenomena in the San Juan Basin

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HYDROSTRATIGRAPHY, HYDRODYNAMICS, AND HYDROCHEMISTRY— GEOLOGIC CONTROLS OF GROUND-WATER PHENOMENA IN THE SAN JUAN BASIN

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ABSTRACT.— The San Juan Basin is a Laramide depression containing approximately 15,000 ft of sedimentary deposits. This general geologic framework, a thick and varied stratigraphic section together with a basin structure, exerts a strong influence on the occurrence, movement, and quality of ground water in the region. The depositional history of the region produced limestone, sandstone and alluvium aquifers separated by mudrock aquitards. This complex stratigraphic sequence and the basin structure result in confined hydraulic conditions. Hydrodynamically, the basin has evolved through the compaction (discharge) stage to the equilibrium (recharge) stage. Recharge occurs where aquifers crop out or subcrop beneath alluvium and colluvium. The rate of recharge varies with aquifer type and landscape setting. Flow direction is generally basinward, controlled by dip. Rates of movement are greatest in the permeable sandstones and limestone. Discharge areas are associated with topographic lows, principally stream valleys. Total-dissolved-solids content of water in the sandstone aquifers varies with associated rock type, grain size of the water-bearing unit, and distance from recharge areas.

INTRODUCTION

The San Juan Basin is a Laramide depression occupying most of northwestern New Mexico as well as adjacent parts of Colorado and Arizona. It contains approximately 15,000 ft of sedimentary deposits ranging in age from Paleozoic through Quaternary. This diverse assemblage of strata includes marine sandstone and limestone of Paleozoic age overlying the Precambrian basement and cropping out around the basin margin. Rocks of Cretaceous age, displaying the full spectrum of marine margin, shore-zone, and deep-water facies, overlie and are exposed basinward of these deposits. Capping these, and lying at the surface in the basin center, are various nonmarine deposits making up the Tertiary section.

The complex stratigraphic sequence and structure have a strong influence on the regional hydrology. The conceptual hydrogeologic model of a regional saturated system not only includes the occurrence, movement, and quality of the ground water but also the geologic controls of these phenomena (Stone, 1999). The San Juan Basin contains excellent examples of geologic controls of ground-water phenomena. The purpose of this paper is to illustrate some of these. The undertaking is facilitated by the large amount of previous work in the basin. Stone et al. (1983) formulated and documented the basic conceptual hydrogeologic model for the basin and gave a comprehensive list of previous geologic and hydrologic studies, some of which are cited in support of controls discussed below.

HYDROSTRATIGRAPHY

The geologic column of an area is often redrawn in terms of the hydraulic behavior of the stratigraphic units to depict the distribution of aquifers and aquitards throughout the rock record. The depositional history of the region controls the type and stratigraphic distribution of aquifers and aquitards.

Significant ground-water production in the San Juan Basin is associated with three aquifer types, in order of increasing depth, as they would be encountered in drilling (Fig. 1): alluvium, sandstone, and limestone. Alluvium is the aquifer along major canyons

and stream valleys. Fluvial sandstones are the aquifers in the Tertiary section (San Jose Formation, Nacimiento Formation, Ojo Alamo Sandstone), the upper part of the Jurassic section (Morrison Formation), and the Triassic section (Chinle Group). Eolian sandstone is the aquifer in the lower part of the Jurassic section (Zuni-Bluff-Cow Springs and Entrada Sandstones). Marine shoreline sandstones are the aquifers in the Cretaceous section (Pictured Cliffs Sandstone, Mesaverde Group) whereas marine limestone is the aquifer in the Permian section (San Andres Limestone).

Intergranular porosity provides for water storage in the alluvium and poor- to moderately-cemented sandstone aquifers, whereas fracture porosity provides for most storage in the limestone and densely-cemented sandstone aquifers. Grain-size sorting controls porosity and permeability in the alluvium and sandstones. Fracturing and fracture widening by dissolution control porosity and permeability in the limestone.

Water also occurs in, but is not generally produced from, aquitards interbedded with the sandstone aquifers. These aquitards consist of various mudrocks (shale, silty shale, siltstone, etc.). Examples include, in descending order: the mudrocks in the San Jose and Nacimiento Formations, the Lewis Shale, the Mancos Shale, the Brushy Basin Member of the Morrison Formation, the Recapture Member of the Bluff Sandstone, the Summerville Formation, and the Chinle Group.

Another aspect of ground-water occurrence is hydraulic condition: whether the contained water is confined or unconfined. The hydraulic condition under which ground water occurs in the San Juan Basin is strongly controlled by the basin structure and stratigraphy. Ground water typically occurs under confined or artesian hydraulic conditions. The general basinward dip of the strata provides the pressure (hydraulic head), and alternating coarse- and fine-grained sedimentary deposits (aquifers and aquitards) provide confinement. For example, water is confined within sandstone aquifers by overlying and underlying mudrock aquitards in both the Cenozoic and Mesozoic sequences.

Scale of ground-water occurrence also depends on geologic conditions. The extent of ground-water is either local, in the case of perched saturation; or regional, in the case of the deep zone

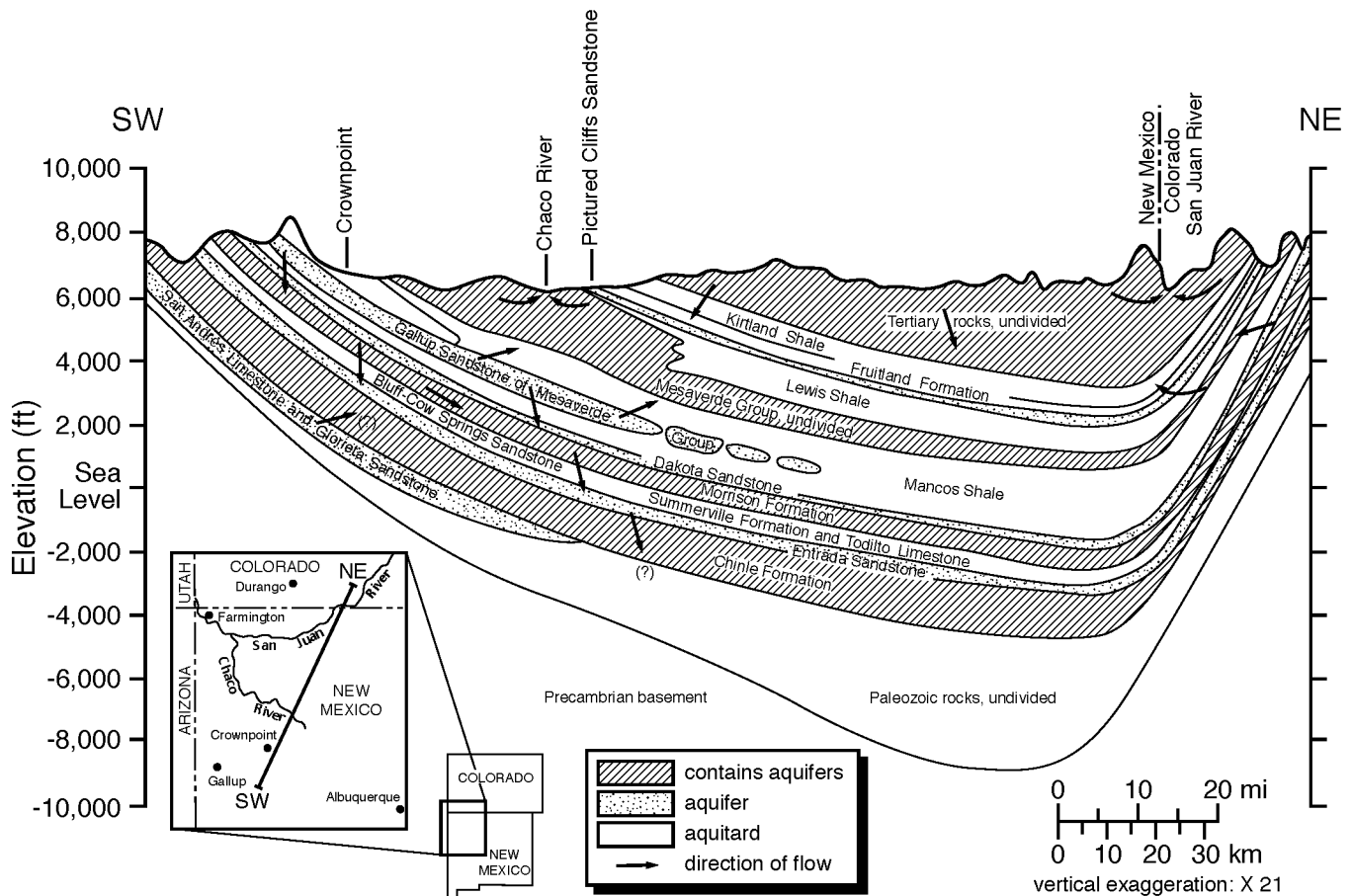


FIGURE 1. Conceptual hydrogeologic cross section of the San Juan Basin (modified from Stone, 2002, fig. 1).

of saturation. Most ground-water in the San Juan Basin occurs extensively throughout the basin, as it is associated with the deep, regional zone of saturation. For example, saturation in the Cretaceous or Jurassic sandstones is continuous from recharge areas to discharge areas associated with major streams, such as the San Juan or Puerco Rivers. However, limited local occurrences of perched ground water also exist where saturation builds up in sandstones atop mudrock aquitards.

HYDRODYNAMICS

Where petroleum and groundwater coexist, oil typically occurs above water. However, near the margin of the San Juan Basin, water can occur above oil. This can be attributed to the hydrodynamic history of the basin.

It has long been recognized that hydrodynamic conditions are important in the entrapment of oil (Hubbert, 1953; North, 1985). For example, oil accumulation in the Gallup Sandstone of the Bisti field is controlled by permeability and hydrodynamics, with no structural trap (McNeal, 1961). Furthermore, hydrodynamic conditions vary predictably throughout the history of a sedimentary basin (Pirson, 1970; Coustau, 1977). Initially, as the deposits undergo compaction, water is squeezed out of aquitards (for example, mudrocks) and into aquifers (for example, sandstones).

Within the aquifers, ground water flow is centrifugal or updip toward the basin margins (Fig. 2a). Whitney and Northrup (1987) concluded from mineral zonation in the Westwater Canyon Member of the Morrison Formation that warm “oilfield” fluid migrated updip as late as Tertiary time. When compaction is complete, there is a change in flow direction. Once the updip edges of aquifers are exposed at the surface, the input of meteoric water and, ultimately, recharge are enhanced. In contrast to the compaction stage, water flow in the equilibrium stage is centripetal or downdip toward the basin center (Fig. 2b). If oil has formed by then, it is driven ahead of the water toward the basin center. Thus, wells in basin margins could encounter water above oil. As the water in the latter case is confined by interbedded aquitards, it is under pressure to move upward to its potentiometric surface (the “U-tube” scenario), but can do so easily only in wells or where geologic conditions permit (for example, along faults or dikes). As shown in Figure 1, there is some upward leakage into and even through the confining beds (aquitards). Water is not discharged in some giant fountain in the basin center but rather at topographic lows associated mainly with river valleys. Multiple flow directions can occur in the period of transition between the compaction or discharge and equilibrium or recharge hydrodynamic phases. For example, one model for the precipitation of uranium in the Mesozoic section across the Colorado Plateau

involves a mixture of upwelling brine and descending meteoric water (Sanford, 1982).

Recharge is the addition of water to a perched or regional zone of saturation. It depends on the amount of water available at the surface, and is thus controlled by the mean annual precipitation and microclimate. These, in turn, are influenced to some extent by topography. However, the geologic setting determines the ease with which available water can enter and move through the ground.

Recharge may be characterized as to area and rate. Most recharge of the sandstone aquifers is believed to occur in areas of bare outcrop, especially in hogbacks where the edges of dipping strata are exposed at the surface with little vegetative cover to capture precipitation before it percolates to depth (especially along stream beds), and where aquifers subcrop beneath alluvium and colluvium adjacent to hogbacks and uplifts. Similarly, the limestone aquifer is recharged on dip slopes in and adjacent to uplifts, such as on the north flank of the Zuni Mountains.

Geologic factors not only control the rate of infiltration of precipitation and runoff into the ground, but also the subsequent percolation of soil water through the unsaturated zone. These factors include geomorphic setting, extent of bare aquifer outcrop, porosity type, dip of strata, and soil texture where the aquifer is covered. Long-term ground-water recharge rates were estimated by the chloride mass-balance method for the Fruitland Formation (Cretaceous) at Navajo mine (Stone, 1990). Values vary distinctly with setting: 0.002 in/y for badlands and 0.09 in/y for ephemeral stream terraces. (Recharge along stream beds was not evaluated by the chloride method, as it assumes precipitation, not runoff, is the source of recharge.) These low rates are not surprising in view of the low precipitation in the area (<6 in/y at the mine) and high potential evaporation rate (72 in/y at Gallup; Stone et al., 1983). However, considering the large area of the San Juan Basin, such recharge rates are sufficient to sustain ground-water flow and discharge.

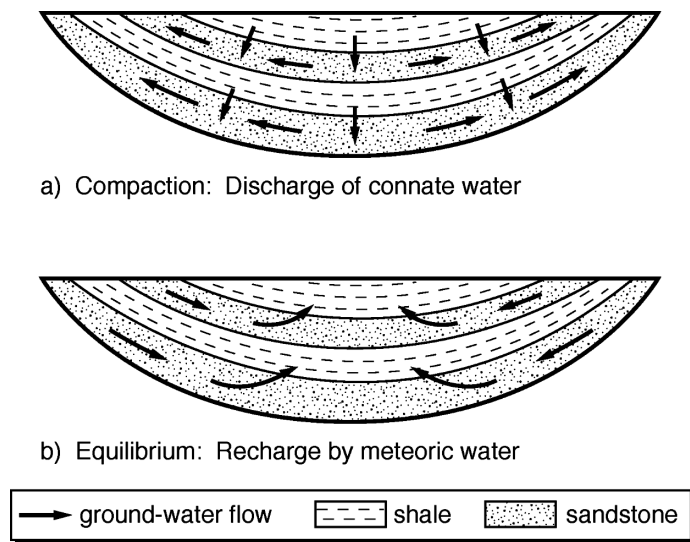


FIGURE 2. Generalized ground-water flow during two major phases in the hydrodynamic history of a sedimentary basin (modified from Cous-tau, 1977, fig. 8).

Ground-water flow may be characterized by direction and rate. In the recharge hydrodynamic phase, ground-water flows from recharge areas to the basin center and thence to discharge areas. More specifically, the direction of ground-water flow is controlled by the slope of the water table in unconfined aquifers and the slope of the potentiometric surface for confined aquifers. Slope of the water table and location of flow boundaries are related to topography (Hubbert, 1940), whereas the slope of the potentiometric surface depends on the dip of the aquifer. Flow direction changes where strata pinch out as a result of nondeposition or truncation along paleo-erosion surfaces. For example, ground water in the Gallup Sandstone flows basinward until encountering the eroded pinchout of this unit (Stone, 1981). From there it turns to the north and flows toward the San Juan River, where it discharges. The abundant dikes in the San Juan Basin act as barriers to ground-water flow and cause local changes in flow direction as well as upward leakage. Faults may or may not interfere with ground-water flow direction, depending on the amount of displacement, nature of materials offset, and degree of fracture fill. For example, some faults in the Ambrosia Lake area seem to have little impact on flow and water table (Brod and Stone, 1981).

The rate of ground-water flow is derived from Darcy's law as

$$v = KI,$$

where v = Darcy velocity, K = hydraulic conductivity, and I = hydraulic gradient.

K varies with grain size and sorting, and gradient varies with topography or structure. Thus, the ground-water flow rate is controlled by the depositional origin and dip of an aquifer. Transmissivity (T) is the volume of water per unit time (gal/d/ft of width or, converting gallons to cubic feet, ft²/d) that would flow from a vertical section of aquifer having a width of 1 ft and a height equal to the total aquifer thickness, under a unit hydraulic gradient. T not only varies between but also within aquifer types (Stone et al., 1983). In the case of sandstones, for example, T for the Tertiary sandstones is generally less than 250 ft²/d; that for the Cretaceous sandstones is generally less than 100 ft²/d (except for the Gallup Sandstone, for which T may be as high as 400 ft²/d); and Jurassic sandstones are generally characterized by T values of less than 50 ft²/d (except in the Morrison Formation, for which T may be up to 500 ft²/d).

Discharge is the loss of ground water from a saturated system. This occurs naturally at springs or low-lying areas such as along river valleys, or artificially at wells. Like recharge, discharge is usually described in terms of area and rate. Most discharge occurs along the major streams or stream valleys. This includes the San Juan River and its tributaries in the northern part of the basin and the Rio Puerco and Rio San Jose in the southern part of the basin. Minor discharge occurs at springs. Some of these occur where shallow, perched ground water spills over the edge of a perching layer in the sides of buttes and mesas or in canyon walls. Other springs are the surface manifestation of deep ground water rising along fracture zones or dikes. Craigg and Stone (1983) reported springs associated with dikes in the east-central part of the basin. Although it has seldom been quantified, what goes in must come out. Thus, ideally, discharge equals recharge. However, differ-

ences between the two may result because of a lagged response to climate change.

HYDROCHEMISTRY

Water is a universal solvent. Consequently, depending on chemical conditions, ground water dissolves minerals to release major ions, metals, and radioactive constituents from the geologic section through which it flows. Salinity is a common measure of water chemistry or quality, and is usually characterized by total-dissolved-solids (TDS) content or specific conductance, an electrical measure of salinity. TDS content of water in the sandstone aquifers varies with associated rock type, grain size of the water-bearing unit, and distance from outcrop recharge areas.

As for hydraulic condition, the stratigraphic section dictates the lithology of units with which the aquifers are in contact. Interbedded shales are the major source of dissolved solids in the Tertiary and Cretaceous sandstone aquifers. Water moving along sandstone–shale interfaces or vertically through the shales picks up dissolved solids from the clay minerals present. For example, ground water does not have to travel very far in sandstones adjacent to the Lewis or Mancos Shale before it becomes saline. The shale is a medium for ion exchange: calcium in the ground water is exchanged for sodium in the clay. Thus, a common ground-water classification in the basin is sodium-sulfate. By contrast, gypsum is the source of salinity in the deeper Jurassic sandstone aquifers. For example, elevated amounts of dissolved solids in ground water in the Entrada Sandstone is related to the solution of gypsum in the overlying Todilto Formation.

The rate of ground-water flow determines the opportunity for dissolution of mineral matter. Elevated ground-water salinity in the Cow Springs-Bluff aquifer is due to the low hydraulic conductivity of these fine-grained sandstones. Conversely, the freshness of the water in the sandstones of the Morrison Formation is a result of their higher hydraulic conductivities associated with their coarser textures.

Length of flow path or residence time is a further control on hydrochemistry. The longer water flows through an aquifer, the more solids it is able to dissolve. Thus, water quality varies with the distance from outcrop recharge areas. For example, specific conductance of ground water in the Ojo Alamo Sandstone ranges from less than 1000 $\mu\text{mhos/cm}$ in and near outcrop areas to much greater than 2000 $\mu\text{mhos/cm}$ in the basin center (Fig. 3). A similar pattern is exhibited by water in the Gallup Sandstone: less than 1000 $\mu\text{mhos/cm}$ in and near outcrop to as much as 5,000 $\mu\text{mhos/cm}$ at its downdip pinchout (Stone, 1981). Other Tertiary and Cretaceous sandstones exhibit similar patterns (Stone et al., 1983). Residence time also controls the variation in TDS content of ground water with depth (Freeze and Cherry, 1979).

It may be argued that the downdip saline water is actually connate water, that trapped in pores at the time of deposition. However, because hydrologic systems are dynamic, such water is usually flushed from the aquifer by recharging meteoric water. Given the ages of strata in the San Juan Basin, such water has probably been flushed out several times over.

In large sedimentary basins, ground water tends to evolve chemically toward the composition of seawater (Chebotarev, 1955). The dominant anion in the water changes along flow path. Ground water is bicarbonate-rich in recharge areas and sulfate- or chloride-rich in discharge areas. Flow paths are long for most of the aquifers in the San Juan Basin. As the sandstone beds dip deep into the basin before rising to discharge areas, the water flowing in them has had a long time to dissolve mineral matter and the Chebotarev sequence is observed.

Ground water is also responsible for deposition. When chemical conditions are favorable, calcium carbonate or silica are precipitated in the pores of sandstone aquifers from the water flowing through them. This cement reduces both porosity and permeability of the aquifer. Given enough time, aquifers can become completely plugged and behave hydraulically as aquitards. Ironically, the most transmissive strata may eventually become the least transmissive, simply because more water with the potential for precipitating solids moves through them.

SUMMARY

In short, the San Juan Basin is a natural demonstration of geologic controls of hydrologic phenomena. The depositional and structural history of the region exerts considerable control on the hydrostratigraphy, hydrodynamics, and hydrochemistry of the basin. Deposition determined the type and distribution of aquifers and aquitards, hydraulic condition and scale of ground

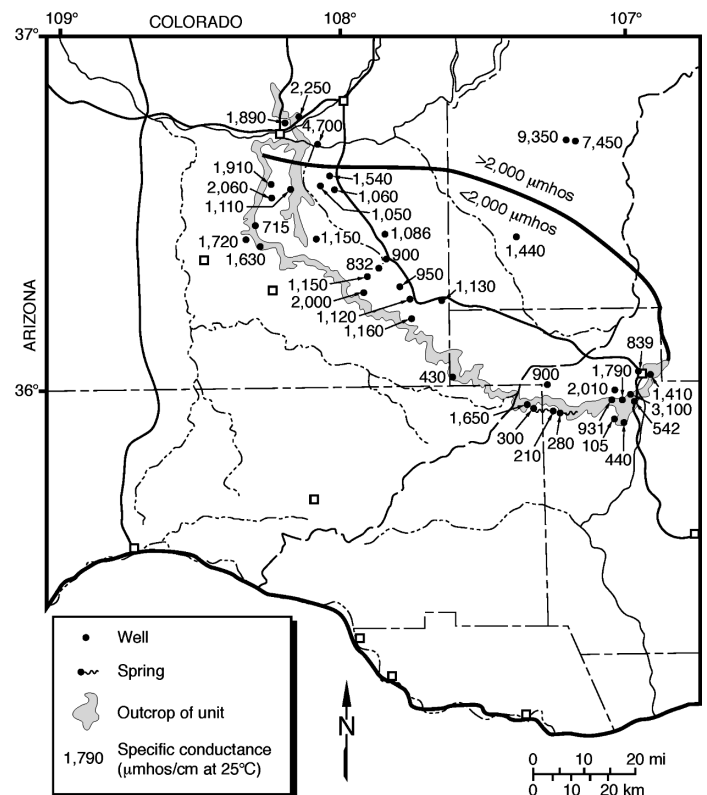


FIGURE 3. Degradation of water quality with distance from outcrop, Ojo Alamo Sandstone, San Juan Basin (modified from Stone et al., 1983, fig. 30).

water occurrence, rate and direction of ground-water flow, as well as water quality. Structure contributes to hydraulic condition of occurrence, location of recharge and discharge areas as well as length of flow paths.

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Dutton's (1885, fig. 2) woodcut photograph of the Wingate Sandstone, described as "Wingate sandstone, with many bands and partings; the same horizon as that shown in Fig. 1."