2014 Albert E. Utton Memorial Lecture

A Hydrogeologic Perspective on Groundwater Conservation in the Northern Rio Grande Basin, New Mexico, Texas, and Chihuahua

John W. Hawley, Emeritus Senior Environmental Geologist

A native of southern Indiana's Ohio River Valley, John W. Hawley graduated cum laude from Hanover College in 1954 with a B.A. degree in geology. After employment by the U.S. Geological Survey (USGS)-Ground Water Branch and overseas U.S. Army service (1954-1957), John attended graduate school at the University of Illinois, receiving a Ph.D. degree in Geology in 1962. Besides hydrogeology, academic specialties included geomorphology and Quaternary geology, stratigraphy and sedimentology, engineering geology, clay mineralogy, and soil science. Doctoral research was on the Quaternary and groundwater geology of Nevada's western Humboldt River basin. Graduate studies were supported by the GI Bill, NSF and University Fellowships, and part-time work with the Illinois Geological Survey, Nevada Department of Conservation & Natural Resources, and USGS-Water Resources Division.

Most of John's subsequent career in research, public service, and consulting has dealt with a variety of environmental-geologic problems related to natural-resource development in arid and semiarid parts of the American West. From 1962 to 1977, he led soil-geomorphology studies at Soil Conservation Service (USDA)-Soil Survey Investigations projects in New Mexico (NMSU), West Texas (Texas Tech), and the Western-States Region (Portland Technical Service Center). He then joined the Bureau of Mines [Geology] & Mineral Resources (NMBGMR) at N.M. Tech where he developed and coordinated programs in Environmental and Engineering Geology for the Office of State Geologist (Socorro and Albuquerque) until "retirement" 1997. Since then, John has been sole proprietor of HAWLEY GEOMATTERS, a consulting firm that specializes in the environmental and groundwater geology of the binational New Mexico region. Projects include pro bono hydrogeologic investigations for the U.S. Indian Health Service and several Pueblo Tribes. He also continues to serve NM Tech as a NMBGMR Emeritus Senior Environmental Geologist and an Earth & Environmental Sciences faculty adjunct; and he has adjunct appointments at the NM Water Resources Research (Senior Hydrogeologist) and NM Museum of Natural History & Science.

John has been a Certified Professional Geologist (C.P.G., American Institute of Professional Geologists) since 1971. He is a "50-Year" Fellow of the Geological Society of America (GSA) and the American Association for the Advancement of Science (AAAS), and past President and Honorary Member of the NM Geological Society. John has authored or co-authored more than 100 reports and maps on the New Mexico-West Texas-Chihuahua region, not including a large number of unpublished documents on expert-witness, consulting, and prior government-service activities. Honors for published research and public service include: AAAS Certificate of Merit "for distinguished contributions [to] arid zone research (1987)," GSA-Engineering Geology Division-Distinguished Career Award (2005), and Quaternary Geology & Geomorphology Division: Kirk Bryan and Distinguished Career Awards (1983 and 2006). John is also co-recipient of the 2005 New Mexico Earth Science Achievement Award for "outstanding contributions in areas of applied science and education;" and he has received Alumni Achievement Awards from Hanover College (2001) and the University of Illinois (Geology-2006). In 2007, the Santo Domingo Tribe honored John for "outstanding contribution to the improvement of [their] public water system." His proudest 80-yr accomplishment, however, involves 52+ years of marriage to Diane Rose Bandyk Hawley, three (Las Cruces-native) children, and three grandchildren (3, 5, and 22).

Editor's Note: This Utton Memorial Water Lecture was edited in 2020 following its original presentation in 2014, and contains references to material published since that time. The author would like to acknowledge NM WRRI employees Jeanette Torres, Tiana Gibson, Cheyenne Poyer, and Mark Sheely for their hard work in assembling this lecture for publication.

INTRODUCTION

"Now and in the years ahead, we need more than anything else the honest and uncompromising common sense of science. Science means a method of thought characterized by open-mindedness, honesty, perseverance and, above all, by an unflinching passion for knowledge and truth." —

U. S. President Harry S. Truman, Addressing the 1948 Annual Meeting of the American Association for the Advancement of Science

In Memoriam—Albert Edgar Utton
(7/6/1931 – 9/29/1998)

They received, each for his own memory, praise that will never die, and with it the grandest of all sepulchers, not that in which their mortal bones are laid, but a home in the minds of men, where their glory remains fresh to stir to speech or action as the occasion comes by. For the whole earth is the sepulcher of famous men; and their story is not graven only on stone over their native earth, but lives on far away, without visible symbol, woven into the stuff of other men's lives—Pericles Funeral Oration (*from* A Memorial Service in Thanksgiving for the Life of Albert Edgar Utton, the Cathedral Church of St. John, Albuquerque, NM, October 3, 1998)

Background

This hydrogeologic perspective on "Groundwater Conservation: Strategies, Initiatives, and Impacts on the Rio Grande" is offered as a memorial to the late Albert Edgar Utton (1931-1948), long-time UNM School of Law Professor and NM Interstate Stream Commission Chair. UNM geology major and 1953 Rhodes Scholar Al Utton (Figure 1 and Figure 2), quickly morphed into a future giant on natural-resources law at Oxford (with lots of TLC from wife Mary). We started communicating on shared interests in transboundary groundwater resources in the early 1980s when I managed the Environmental Geology program at NM Tech, Bureau of Mines & Mineral Resources (now the Bureau of Geology [NMBGMR]. However, we had no close personal interaction until NM Tech transferred me to Albuquerque in 1991. Subsequently, Al kindly allowed me to mingle with a select group of Natural Resource Center students and faculty (as long as I behaved with due respect, and assisted in his search for the "perfect Margarita"). The following passage from Michelle Minnis' "Al Utton—The Aztec Eagle" best captures the *Utton essence* (2015, p. xiv):

> Rare leaders like Al Utton remind us of what is possible. He acted passionately for the commonweal, but no less for the welfare of the person immediately in front of him. He took the long view—so long a view that present law and policy appear short-sighted in comparison. Every issue he opened is still pending, gradually rising into public consciousness. Paths to resolution may be gleaned from the foundations he laid for international networks of preventive diplomacy—*Plan and act now to avoid future catastrophe.* Al's life story may be read as an invitation to build anew on these foundations.

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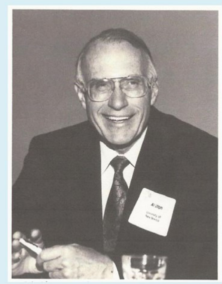


Figure 1. Aztec Eagle—Albert Edgar Utton (11/1994): UNM Geology Major and Rhodes Scholar. Chair of the NM Interstate Stream Commission and Director of the Transboundary Resources Center, UNM School of Law.

Figure 2. Two undergraduate geologists in 1952-53: one, a future Rhodes Scholar and giant in natural resources law; the other, still lost somewhere in the Rio Grande rift.

Prescient observations by Al Utton on the management of the precious aquifer systems that we share with the states of Texas and Chihuahua (Mexico) include:

"…, but as yet there is no 'comprehensive agreement on groundwater' and transboundary aquifers such as the Hueco Bolson and the Mesilla Bolson are subject to uncontrolled, unregulated withdrawals under which neither country is assured of either a secure supply or a fair share. Rather we have the law of 'he who pumps fastest', or the rule of 'we'll race you to the bottom of the aquifer' subject only to general principles of international law." —

A. E. Utton, 1983, Some International Aspects of Groundwater Development in the Mexico-United States Frontier Region; in Natural Resources Center Report to The Governor's Law Study Committee: UNM School of Law, p. 26.

Groundwater has been out of sight and out of mind. Mexico would like another 60,000 acre-feet of surface water, and if we do not reach an agreement with Mexico, what is to prevent them from taking it underground, under the table? None of us have any security in this border region. Doña Ana County, El Paso, Chihuahua—we have a game without rules. We have not been able to secure our groundwater relations. We delay reaching agreement and settling our groundwater arrangements with Mexico at our peril. We must move forward on that [,] although politically it is almost impossible.

That is all in the vein of saying that we happen to be in one of those special areas which is crisscrossed with political boundaries, and contains the transboundary situation. So we have to work extra hard at trying to seek, share, manage, cooperate, and plan together. . . . (*cf.* Székely 2010).—

A. E. Utton, 1996, WRRI 40th Annual Water Conference Proceedings, p. ix.

Al Utton was certainly not the only water-resource professional to alert public officials (as well as the general citizenry) to the approaching crisis facing unplanned groundwater development throughout arid/semiarid American Southwest. The following observations by Fred Phillips and others (2011), Steve Finch (1997), the speaker (1997), and Robert Glennon (2002) exemplify this point:

"Based on hydrogeologic studies conducted in the late 1950s, Albuquerque was thought to sit on top of a gigantic bowl of clean sand and filled with fresh water. One of the earliest sceptics was John Hawley, a curmudgeonly geologist who had worked for decades in the New Mexico Bureau of Geology and Mineral Resources. By the late 1980s and early 1990s, Hawley increasingly realized that the idealized model of the basin in vogue in the 1950s and 1960s did not correspond to the sediments he saw actually coming up the hole when new wells were drilled. In 1992 he and his colleague Steve Haase put out a report that laid the hydrogeologic evidence on the table [*cf.* Hawley and Haase 1992]. The "Lake Erie [Superior]" of fresh water under the city was a desert mirage, revealed now to be a briny sea. The coarse sands filled with, fresh, pure water were just a ribbon running down the middle of the basin; most of the rest had abundant fine sediment mixed in, and the water in these sediments was often salty." —

F.M. Phillips, G.E. Hall, and M.E. Black, 2011, Reining in the Rio Grande—People, Land, and Water: UNM Press, p. 176.

The 21st Century will force many communities to [implement] alternative water-resource management strategies; in particular the ones that can divert a nearby surface-water resource, such as Albuquerque, Las Cruces, Alamogordo, and Santa Fe. All of these cities have plans to better manage or take advantage of surface-water supplies and become less dependent on diminishing ground-water supplies. It appears that many smaller communities that do not have an existing central water distribution system or a water right for a community water supply will be left high and dry. For all of you consultants, bone up on your hydrogeology and water-resource management strategies, because every entity will be staking their claims until the last drop is gone. —

Steven Finch, AWRA-New Mexico Section Newsletter (March 1997).

As we enter the *obscene mobscene* of the Third Millennium, the lead role of hydrogeology in efficient exploitation of the limited groundwater resources in Rio Grande rift basins of the New Mexico region is gaining more attention and respect. I predict robust prospects for this field of environmental and economic geology for at least the next 50 years as communities seek out new sources of water to sustain *growth*; although interest will wane when the wells start running dry. We will obviously continue to use *politically-correct* expressions such as *conservation* and *sustainable consumptive use* when we describe development of aquifer systems in this and other arid and semiarid regions. From the perspective of 6000 years of recorded history, however, the concepts of *irreversible depletion* and *desertification* more often come to mind. —

Adapted from PPT presentation by J.W. Hawley at the 1997 Annual Meeting of the New Mexico Geological Society, Inc., NMIMT, Socorro, NM; original abstract in New Mexico Geology, v. 19, no. 2, p. 48-49 (1997).

So it is with groundwater. The doctrines of capture and reasonable use encourage exploitation of a common-pool resource. The legal rules governing groundwater use reward rational economic individuals by assuring them that the biggest pump wins. Rivers, springs, lakes, wetlands, and estuaries around the country face an uncertain future because most states have separate legal rules for regulating surface water and groundwater. For surface water, riparian law or the prior appropriation doctrine governs; but for groundwater, either a different system of prior appropriation or the doctrines of capture or reasonable use prevail.

Each proposal offers an immediate yet temporary fix to a larger problem. These alternatives are Band-Aids that may prevent an infection from getting worse, but they are not cures for the disease. They instead allow us to ignore the inescapable reality that our uses of water are not sustainable over the long term. —

Robert Glennon, Morris K. Udall Professor of Law and Public Policy, University of Arizona—From: Chapter 15 in Glennon (2002) Water follies: The Tragedy of Law and the Commons, p. 210-211 (cf. Hardin 1968; Deming 2002, p. 22-24).

SPECIAL ACKNOWLEDGEMENTS

Having the honor of being invited to present the Utton Memorial Lecture at this conference, is closely linked to so many fortuitous personal and professional contacts with the giants in the regional water-resource field starting in 1962. My hydrogeologic-research career in New Mexico was jump-started in October 1964 by an invitation to be a Charter Member of the newly established NM WRRI by its first Director, Dr. Ralph Stucky (Figure 3). Besides Ralph, early mentors included John Clark, John Hernandez, Bill King, and Bill Seager at NMSU; Frank Kottlowski, Dave Love, and Lynn Gelhar at NM Tech; Mike Kernodle and Clyde Wilson with the USGS; and State Engineer Steve Reynolds and Hydrologist Zane Spiegel with the NM OSE. Other geologist and hydrologist colleagues in the private sector and at the region's research Universities are too numerous for proper individual acknowledgement. My post-retirement (post-1997) contributions to water resource research in the New Mexico Region would never have been made without the support and mentorship of the late Dr. Bobby J. Creel (1943-1910; Figure 4). Editorial assistance and long-time support of Catherine Ortega Klett, now with OK Editorial Services, played an essential role in completion of this document. Swanson Geoscience, LLC assisted in preparation of most of the diagrams.

Figure 3. NM WRRI supporters of hydrogeologic research in New Mexico: founding director Ralph Stucky, with John Clark (director 2), Garrey Carruthers (acting director), and Tom Bahr (director 3) in right to left order. 1978 photo, courtesy of NM WRRI archives.

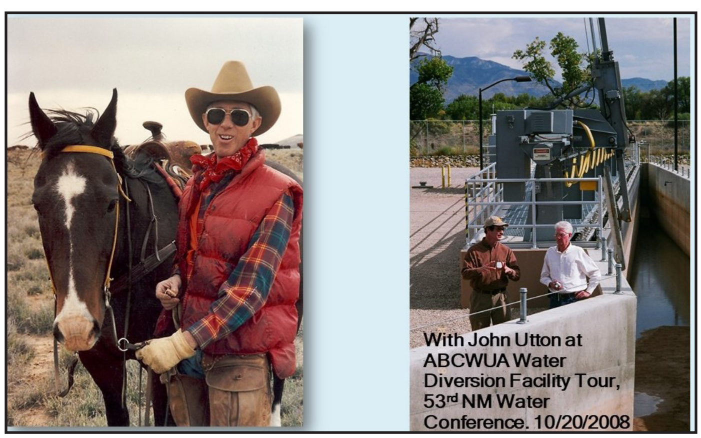


Figure 4. In Memorium; Dr. Bobby J. Creel (1943-2010).

PRESENTATION OVERVIEW

From my octogenarian and somewhat *curmudgeonly* perspective, thorough knowledge of any entity is needed before it can be effectively conserved (or exploited). Because our dryland-culture's contacts with water-realities can be a bit depressing, however, I'll try to keep this presentation as optimistic and moist as possible. Since human history reminds us that bad-news bearers almost always meet very bad ends, it's prudent for me to avoid doom and gloom scenarios whenever possible. Accordingly, I'll be pointing out *opportunity areas* that are ideally suited for desalination projects or where de-watered spaces in former or dwindling basin-fill aquifers can be refilled with state-of-the-art "managed aquifer recharge (MAR)" science and technology (e.g., Wolf et al. 2020).

In an attempt to find the right mix of *enlightenment* and *delightenment,* this presentation has a three-part organization: In **PART 1,** I'll review **s**ome basic principles of the earth-science discipline of hydrogeology as applied to long-term development of this region's large, but still-finite groundwater (GW) reserves. The somewhat *fuzzy* concepts of "GW sustainability" and GW-mining are described here in the context of arid/semiarid-region aquifer systems in Rio Grande-rift basins where replenishment of "mined-out" aquifers is economically and environmentally viable. **PART 2** comprises a brief overview of the historic, geomorphic, and hydrogeologic setting of the Santa Fe metro-area, the site of the 59th Annual NM Water Conference. In **PART 3**, we'll visit areas of three intermontane basins in the Rio Grande rift province that have a substantial GW-resource development future, but where large-scale GW pumping could easily evolve into GW-mining operations without immediate implementation of prudent resource-management strategies: the Albuquerque-Rio Rancho metro-area of the Albuquerque Basin, the Palomas-Rincon [Hatch] Basin, and the binational/tristate Mesilla Basin.

PART 1. BASIC CONCEPTS AND TERMINOLOGY

This paper is designed as a background document for a short PowerPoint® (PPT) presentation, with Figures and cited references selected to illustrate concepts and/or feature of specific hydrogeologic relevance. Emphasis is on intermontane-basin deposits of the Rio Grande rift geologic province that form the primary Santa Fe Group (SFG) groundwater reservoirs (aquifer systems) in the Rio Grande corridor that extends from south-central Colorado to the Texas-Chihuahua border region. An abbreviated glossary (Table 1) is included at the end because I feel that it is essential to provide standard definitions of some common terms used in any water-resource assessment. *Groundwater [GW],* for example, is defined by David Deming (2002, p. 433) in the term's broadest terrestrial context as any "subsurface aqueous fluid, either saline or fresh."

> *USGS Conceptual Model of Groundwater Sustainability (Alley and others, 1999, p. 3)*
> Perhaps the most important attribute of the concept of ground-water sustainability is that it fosters a long-term perspective to management of ground-water resources. Several factors reinforce the need for a long-term perspective. First, ground water is not a nonrenewable resource, such as a mineral or petroleum deposit, nor is it completely renewable in the same manner and time frame as solar energy. Recharge of ground water from precipitation continually replenishes the ground-water resource but may do so at much smaller rates than the rates of ground-water withdrawals. Second, ground-water development may take place over many years; thus, the effects of both current and future development must be considered in any water-management strategy. Third, the effects of ground-water pumping tend to manifest themselves slowly over time. For example, the full effects of pumping on surface-water resources may not be evident for many years after pumping begins. Finally, losses from ground-water

> storage must be placed in the context of the period over which sustainability needs to be achieved. Ground-water withdrawals and replenishment by recharge usually are variable both seasonally and from year to year. Viewing the ground-water system through time, a long-term approach to sustainability may involve frequent temporary withdrawals from ground-water storage that are balanced by intervening additions to ground-water storage.

Note that *subjective* terms like *sustainability*, *opportunities*, and *challenges* only suggest conceptual starting points in the complex iterative processes involved in 1) hydrogeologic-framework characterization; and 2) evaluation of the anthropogenic factors now involved in all contemporary water-resource development activity. Accordingly, credible positive or negative outcomes are best described qualitatively as belonging to one of three broad event categories: 1) possible to probable, 2) possible to improbable, and 3) possible but highly improbable (*aka* "Black Swan" events [like climate change or the current COVID-19 pandemic]; *cf.* Taleb 2010).

Dating back to the observations of John Wesley Powell (1885), problems related to the management of both surface-water and groundwater resources remain pressing issues throughout the Colorado River and Rio Grande basins and adjacent areas of the American West (e.g., Glennon 2002, Phillips et al. 2011, Fleck 2016, and Alley and Alley 2017). Absence of enforceable rules for governing groundwater overuse is evident in above-cited observations by Glennon and Utton, and the following example of current conditions in south-central Arizona:

> Associated Press Report raises alarms over Arizona's water supply— Albuquerque Journal-NATION, Sunday, October 27, 2019 [*cf.* Davis 2019a]:
>
> TUCSON, Ariz.—A new report by an Arizona State University think tank [Kyl Center for Water Policy] says its questionable whether Arizona can find enough water to replenish aquifers for pumping to new homes in fast-growing suburban areas without access to the Colorado River. . . .
>
> The report warns that some suburbs of Tucson and Phoenix will struggle to find enough water to keep growing without damaging aquifers by overpumping groundwater.
>
> According to the report, the result could be land subsidence, including ground fissures, lower water quality and even the possibility of wells drying up.
>
> And it said there's a prospect of further hiked water rates for homeowners and financial problems for a three-county agency responsible for finding renewable water supplies for further development in Pinal County located between the two metro areas.
>
> The report suggest that the landmark 1980 Groundwater Management Act is environmentally unsustainable and requires an overhaul. . . .
>
> University of Arizona law professor Robert Glennon [2002], who has written two books about water supply issues, said the new report's authors 'convincingly demonstrate that it's a broken system that will cause great economic and personal hardship if the legislature and DWR [AZ Department of Water Resources] don't act to implement their recommendations."

Groundwater Mining

The intended or unintended consequences of "Groundwater mining" are key factors in development of aquifer-systems in almost all arid and semiarid regions. According to Dr. David Deming (2002, p. 19): "Groundwater is a renewable resource, but not necessarily on a human time scale. **Mining groundwater** refers to extraction groundwater faster than it can be recharged. . . . [The] classic example is the High Plains Aquifer, also known as the Ogallala Aquifer after it chief water-bearing formation."

Dr. Samuel Mandel of the Center for Groundwater Research at the Hebrew University, Jerusalem provides a global perspective on GW mining (1979, p. 439):

> In 1975 the late G.B. Maxey* and the author were engaged in studies of groundwater mining. A collection of case histories revealed that overexploitation of groundwater is a very common practice, especially, though not exclusively, in dry areas. Generally, with very few exceptions, overexploitation develops unintentionally and is only belatedly recognized. Available data refer to areas where attempts are being made to rationalize groundwater mining and to plan rescue schemes. Data from areas where groundwater mining "just happens," or where it has run its full destructive course, generally, remain inaccessible. Thus the available data are probably indicative of a problem that will become acute, on a global scale, within the next two or three decades, unless the present trends in groundwater development are reversed.
>
> The respective merits of sustained yield exploitation versus mining may be arguable in each particular area. <u>The wide-spread uncontrolled development of irreplaceable water resources is certainly an undesirable state of affairs.</u>

**Note: Dr. George Burke Maxey was my Ph.D. research advisor at the University of Illinois from 1959 to 1962 (cf. Hawley 1962, Hawley and W.E. Wilson 1965). He established Nevada's Desert Research Institute's Hydrology Program (e.g., Maxey and Shamberger 1961), and was the recipient of the 1971 Geological Society of America O.E. Meinzer Award for his paper "Hydrogeology of Desert Basins (Maxey 1968)."*

In their seminal 1979 report on "International groundwater management: The case for the Mexico-United States frontier," A.E. Utton and C.E. Atkinson cite prescient observations by (then) New Mexico State Engineer, Steve Reynolds on "the mining of water" that definitely apply to many parts of New Mexico outside the Lea County-Southern High Plains region:

> As Steve Reynolds points out, it must not be overlooked that in some situations as a matter of policy 'the mining of water can be justified as readily as the mining of any of our other mineral resources such as uranium, oil or coal. It is not practical to operate a groundwater basin on a continuous-yield basis when the amount of water in storage is very large compared with the average annual recharge.'[89]
> *[89] *Excerpt from Statement of S.E. Reynolds, State Engineer, Santa Fe, N.M.—Sept. 30, 1959, p. 113-114:*
>
> While it is possible to justify the mining of groundwater resources, the practice will make it necessary to face serious water supply problems in the future. In some instances it will be possible to meet these problems only by complete adjustment of the economy of the area. While long range predictions of the value of water in various uses are dangerous, it appears likely that it will not be, in general, economically feasible to import water over appreciable distances for agricultural purposes when the local groundwater resources have been mined out. However, when reduced well yields or excessive lifts make pumping for agricultural purposes uneconomic, the residual water may well supply the municipal and industrial needs of a vigorous non-agricultural economy for many years.
>
> In Lea County [and many other places that rely on the Ogallala Aquifer System] pumping for irrigation will probably be uneconomic when about two thirds of the aquifer is dewatered. At that time there will probably remain substantial valuable reserves of oil and gas in the area. To produce and process those reserves it will be necessary to use numerous

low-production wells to pump the residual fresh water, and it may also be necessary to desalinize the abundant brackish waters and brines that occur in the area.

PART 2. HISTORIC, GEOMORPHIC, AND HYDROGEOLOGIC SETTING OF THE CITY OF SANTA FE AREA

It is quite appropriate that the 59th Annual New Mexico Water Conference is located in the *Historic* nucleus of the City of Santa Fe, *La Villa de Santa Fé*, which was founded as a Spanish colonial-provincial capital on the banks of *El Río de Santa Fé* in 1609 (Snow 2015, Figure 5 and Figure 6). This place ranks high, not only in North American history but also in pioneering developments in classic geology. Of special regional significance is the city's piedmont plain location at the base of the Santa Fe (SF) Range in the southeastern Española Basin of the Rio Grande (RG) rift tectonic province, and in a transition zone between the semi-arid Basin and Range and sub-humid Southern Rocky Mountain physiographic provinces (Figure 6). The rift is a continental-scale product of Earth crustal extension (Hawley 1978, Keller and Cather 1994, Hudson and Grauch 2013). This tectonic feature comprises a series of deep structural basins and flanking fault-block ranges or volcanic highlands. Its general north-south trend is marked by valleys and canyons of the Rio Grande that extend across New Mexico from Colorado's San Luis Basin headwaters area to the lower end of the Hueco Bolson in western Trans-Pecos Texas (Figure 7).

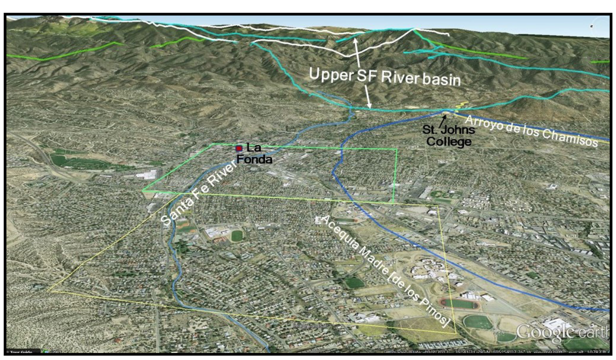


Figure 5. Welcome to Santa Fe—The City Different: Okapoge (1250-1450-TEWA): La Villa De Santa Fe (1609-1846) (Google Earth-Base).

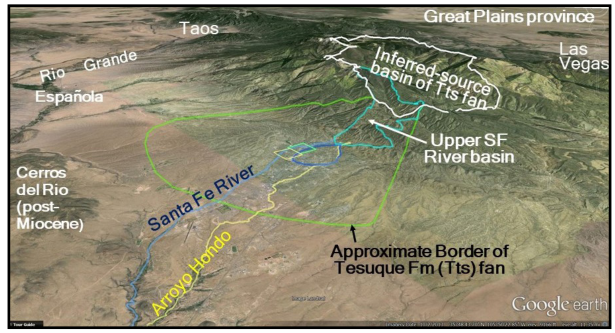


Figure 6. Major elements of an early Miocene geologic terrane superimposed on 10/2/13 Google Earth—image of the Rio Grande rift-Espanola Basin and Southern Sangre De Cristo mountain region.

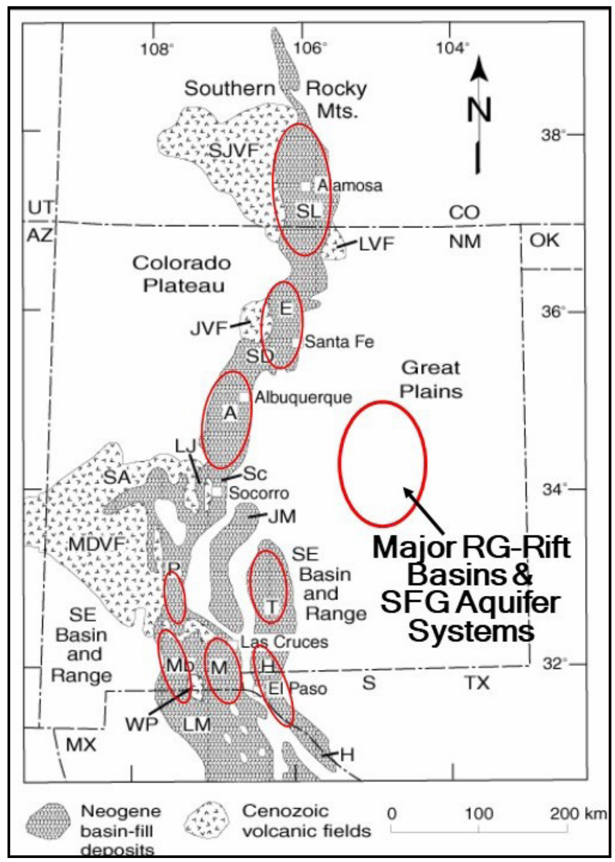
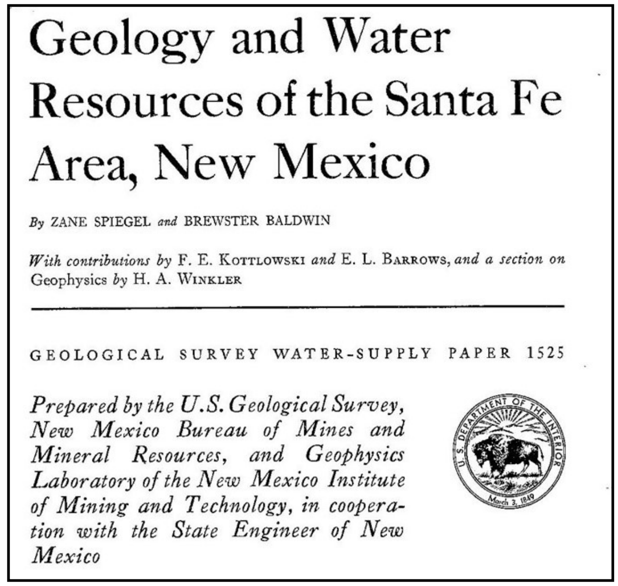


Figure 7. Index map showing major basins/aquifer systems and volcanic field (VF) locations in the Rio Grande rift tectonic provice (adapted from Keller and Cather 1993). From north to south: San Juan volcanic field (SJVF), San Luis Basin (SL), Latir VF (LVF), Española Basin (E), Jemez VF (JVF), Santo Domingo Basin (SD), Albuquerque Basin (A), Socorro (Sc), La Jencia Basin (LJ), San Agustín Plains (SA), Jornada del Muerto Basin (JM), Mogollon-Datil VF (MDVF), Palomas-Rincon Basin (P), Tularosa Basin (T), Mimbres Basin (Mb), Mesilla Basin (M), Bolson de los Muertos (LM), and West Potrillo VF (WP).

Dominant terrain features of the local urban landscape are 1) the Santa Fe River Valley, which cuts through remnants of a Late Tertiary-Age alluvial-fan piedmont, and 2) the river's headwaters area in the Santa Fe Range of the southwestern Sangre de Cristo Mountains (Figure 6). Maximum elevation of the upper-river basin is 12,408 ft amsl, and the average elevation of central unban area is about 7,200 ft. The vital roles that the terraced river valley and its interlinked acequia-irrigation systems have played in surface-water supply, aquifer recharge, and environmental concerns still resonate (Spiegel and Baldwin 1963). Accelerated population growth, and associated environmental and water-supply problems started with arrival of trans-continental railroads in the 1880s, and automobile-based tourism in the 1920s. However, things got really rolling in late 1942 when the AT&SF Railyards became the staging area for Manhattan Project construction of the "Secret City on the Hill" at Los Alamos.


Geology and Water Resources of the Santa Fe Area, New Mexico

By ZANE SPIEGEL and BREWSTER BALDWIN

With contributions by F. E. KOTTLOWSKI and E. L. BARROWS, and a section on Geophysics by H. A. WINKLER

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1525

Prepared by the U.S. Geological Survey, New Mexico Bureau of Mines and Mineral Resources, and Geophysics Laboratory of the New Mexico Institute of Mining and Technology, in cooperation with the State Engineer of New Mexico

Figure 8. Cover of USGS water-supply paper 1525- Spiegel and Baldwin (1963).

The beginning of a post WWII era of federal and state collaboration in water-resources investigations was marked by the "Geology and Water Resources of the Santa Fe Area, New Mexico," published in 1963 as US Geological Survey Water-Supply Paper-1525 (Figure 8 and Figure 9). This seminal, multi-disciplinary assessment of ground- and surface-water resources was conceived and headed by Zane Spiegel (USGS hydrologist) and Brewster Baldwin (NM Bureau Mines geologist). Perhaps the major contribution to regional hydro-science was establishing the Española Basin as the type area of the Santa Fe Group, the primary basin-fill stratigraphic unit in the RG-rift. While hydrogeologic and geohydrologic concepts have been improved at local scales by subsequent geological, geophysical and hydrochemical studies, the basic interpretations recorded in WSP-1525 have stood the test of time (*cf.* Hudson and Grauch 2013).

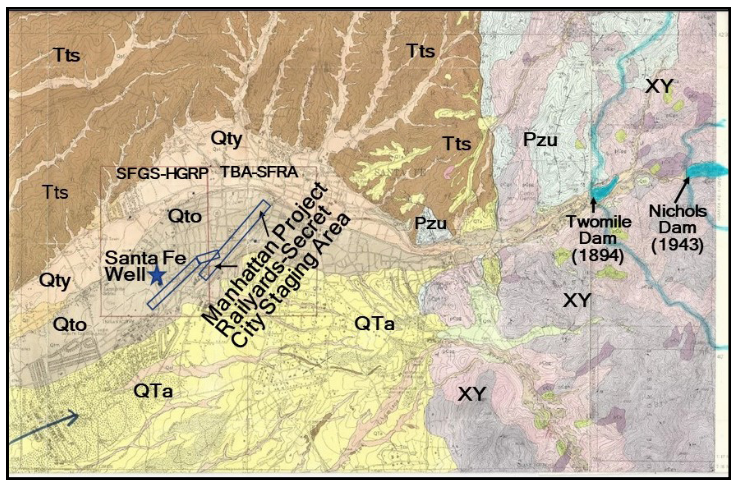


Figure 9. Santa Fe quadrangle geology (Kottlowski and Baldwin, 1952). From USGS water-supply paper 1525 (Spiegel and Baldwin 1963).

PART 3. HYDROGEOLOGIC FRAMEWORK OF THREE RIO GRANDE RIFT AQUIFER SYSTEMS

Albuquerque Basin

The present era of detailed hydrogeologic-framework characterization and groundwater-flow system modeling in the Albuquerque Basin began in 1991; but it was proceeded by decades of pioneering geohydrologic/hydrogeologic investigations, which were initiated by Kirk Bryan and Charles Vernon Theis in the 1930s (Bryan 1938; Theis 1938, 1941; Hawley and Kernodle 2000, 2008). The early 1990s studies were an inter-agency/multi-disciplinary effort, with the NM Bureau of Mines [now Geology] & Mineral Resources (NMBMMR) at NM Tech and the USGS NM Water Resources Division having leadership roles (Hawley and Haase 1992, Thorn et al. 1993). Basic funding support was provided by the City of Albuquerque Public Works Department. The conceptual model of the basin-scale hydrogeologic framework, which was completed between 1992 and 1995, included identification of three hydrostratigraphic-unit (HSU) subdivisions of the Santa Fe Group: Lower (LSF), Middle (MSF), and (Upper), with the latter including the primary aquifer system formed by Ancestral Rio Grande (ARG) channel deposits (Hawley et al. 1995, Kernodle et al. 1995). Each HSU also included subunits based on 1) depositional environment (e.g., piedmont-slope vs. basin floor) and 2) textural and induration variations in sedimentary materials (lithofacies) that form the primary controls on water-transmitting properties in both the saturated and vadose zones. This framework was used immediately in initiating the present generation of groundwater-flow and hydrochemical models that form the basis for water-resource management (e.g., McAda and Barrow 2002; Plummer et al. 2004).

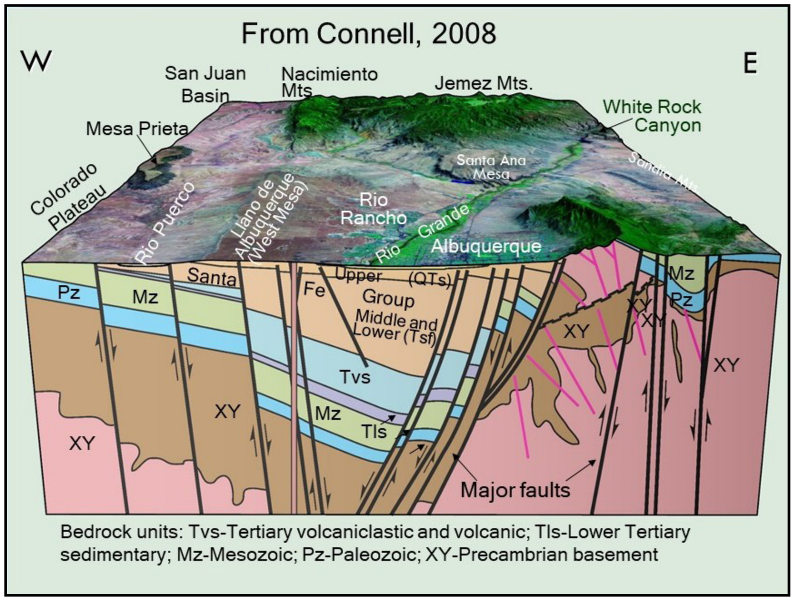


Figure 10. Block model of the northern Albuquerque basin.

In simplest geologic terms, the northern part of the Albuquerque Basin is an east-tilted structural depression (half graben) formed during the past 25 million years (Ma) by extension of the Earth's crust (Figure 10). It is one of the deepest segments of the Rio Grande rift. Most of the basin fill is sedimentary, but igneous-intrusive and interbedded-volcanic rocks are locally present (Connell 2008, Hudson and Grauch 2013). Almost all units are included in the Santa Fe Group (SFG). The only exception are Late Quaternary sediments and volcanics in valleys of the present Rio Grande fluvial system. Basin-flanking structural uplifts include the Sandia-Manzano Mountains to the east and the Colorado Plateau to the west. One of the places of maximum basin subsidence is located in the Albuquerque "East Heights" (fan-piedmont) area just west of basin-boundary-fault zone at the foot of Sandia Mountains. Thousands of feet of aggregate displacement has occurred in the past 15 Ma, and at least 10,000 feet of SFG basin fill have accumulated.

During early stages of Albuquerque Basin filling (25 to about 10 Ma), closed-topographic basin (bolson) conditions existed. As a result, alluvial flats and ephemeral-lake plains (playas) formed the dominant basin-floor depositional environments, and lower Santa Fe Group deposits are typically fine-grained sediments, which form *aquitards* or *aquicludes*, but never significant *aquifers* in terms

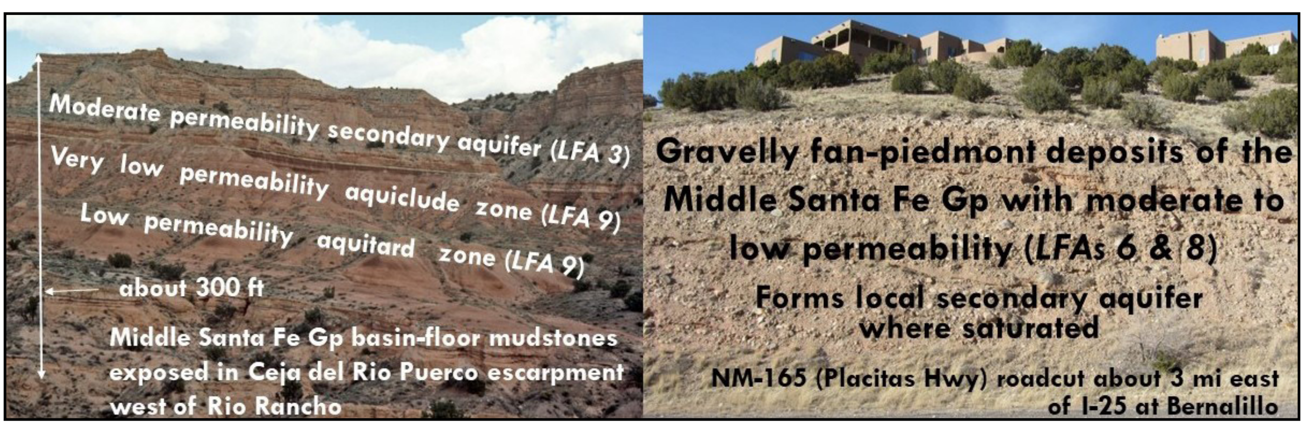


Figure 11. (L and R) Representative exposures of Middle Santa Fe Group basin-floor and piedmont slope facies (LFAs 3, 9, and 8, respectively) that underlie and include primary and secondary aquifer zones of the Albuquerque basin.

of either produced-groundwater quantity or quality (Figure 11L). Correlative SFG piedmont-slope deposits, coarse-or medium-grained, are of relatively low permeability due to moderate to strong cementation (Figure 11R). During the past 8 million years, however, much of the basin floor was occupied by a large fluvial system, the Ancestral Rio Grande (ARG), which included the ancestral upper Rio Puerco as a major tributary. The ARG system ultimately contributed as much as 3,000 ft of sand-dominated fluvial sediment to the most actively subsiding parts of basin between the boundary-fault zone underlying Albuquerque's "East Heights" and the inner Rio Grande Valley. Much of this material has high permeability and forms the basin's major aquifer unit (Figure 12, Figure 13, and Figure 14).

Between about 5 and 1 million years ago, the ancestral-river system expanded to one of regional extent that connected all Rio Grande rift basins between the San Luis Basin and the Hueco Bolson (Figure 7). The ARG and its major tributaries, however, continued as the major contributor to basin aggradation and the source of sediments that comprise our primary aquifer systems until initial entrenchment of present river valley (Figure 13 and Figure 14). That latter feature, which now separates Albuquerque's "East Heights" and "West Mesa," has existed as an erosional river-valley landform only for the relatively short span geologic time (probably less than 800,000 yrs). This interval was marked by the culmination of the Pleistocene Ice Ages, and expansion of the Rio Grande-Pecos drainage basin from southern Colorado to the Gulf of Mexico (Hawley 2005; Connell et al. 2005, 2007).

The major complicating factors in this fluvial-geomorphic history involve millions of years of differential uplift/subsidence between mountain and basin structural blocks, construction of the Jemez volcanic field, and continental-scale climate change. For example: 1) Rio Grande-rift basins were not nearly as deep, nor mountains as high 8 Ma; 2) upper Rio Grande drainage terminated in the Socorro area until about 5 Ma; 3) the onset of alpine glaciation in Southern Rocky Mountains and large pluvial-lake expansion started about 2.6 Ma; 4) the first extensive of basaltic-volcanic fields in the Albuquerque Basin formed at about the time; and 5) highlands of the Jemez Mountain caldera complex only appeared on the Basin's northern horizon about 1.8 Ma (Figure 10). Major fault displacements of SFG deposits, both at the edges and within the basin, have continued throughout the Pleistocene; and fault-zone features locally form significant subsurface-flow boundaries (Figure 13 and Figure 14).

The floor of the Rio Grande Valley throughout its RG rift course is underlain by as much as 100 ft of sand and gravel-dominant channel and floodplain deposits of the fluvial system that excavated and then backfilled the inner valley starting in last glacial cycle of the Pleistocene 15 to 25 thousand years (ka) ago. This is the main site of river/aquifer interaction and groundwater recharge throughout the RG rift region (Figure 15). So love it and protect it, or move away!

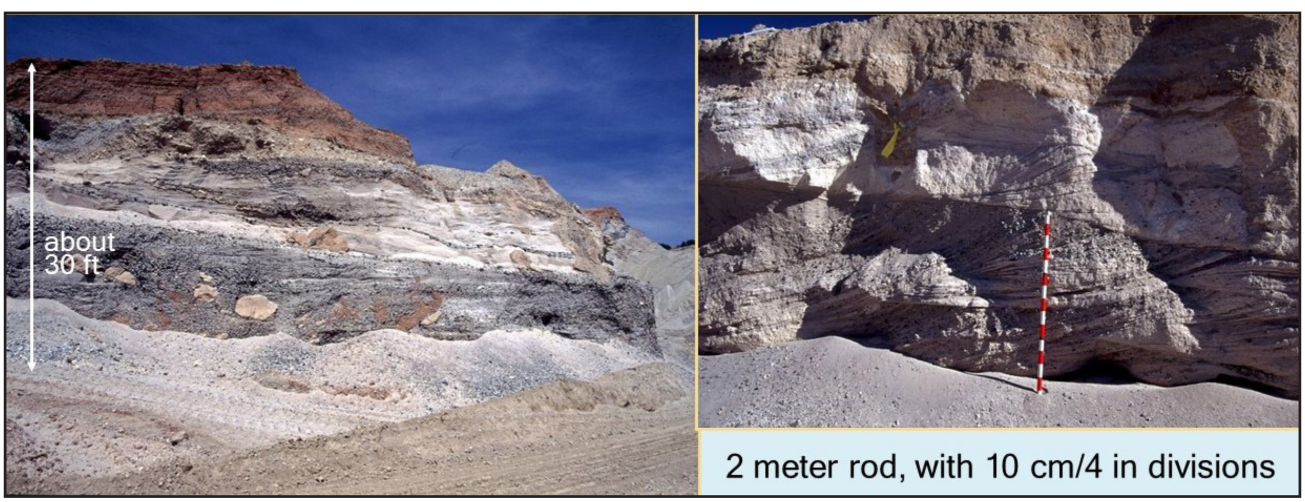


Figure 12. Representative exposures of high-permeability ancestral-Rio Grande channel deposits (LFA 1) in the upper Santa GP that form primary aquifer zones of the central Albuqueque basin and parts of other Rio Grande rift basins in New Mexico (Connell, 2008).

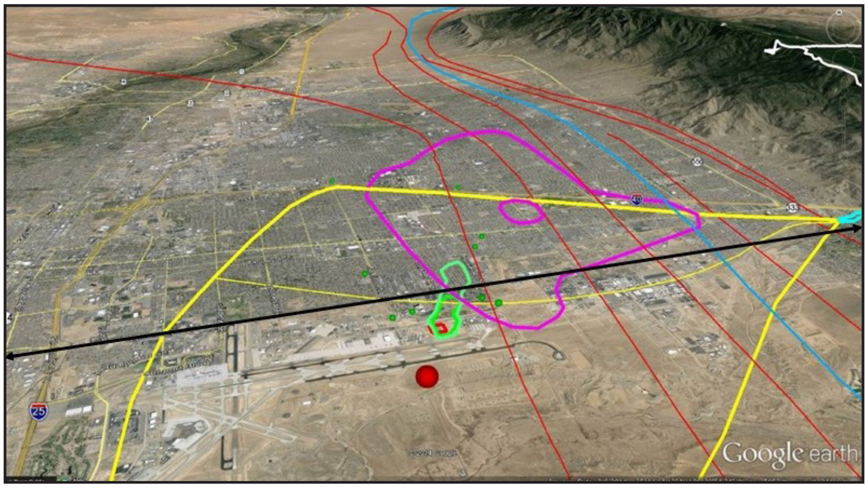


Figure 13. Google Earth® view of NE Albuquerque basin between the Rio Grande valley and the Sandia Mountains: Tijeras Canyon fan (yellow); inferred faults offsetting Santa Fe Group basin fill (red); East edge of ancestral river-channel deposits (Blue); Outline and centroid of deep potentiometric-surface depression in aquifer system (violet); KAFB fuel-spill plume w / edb (green).

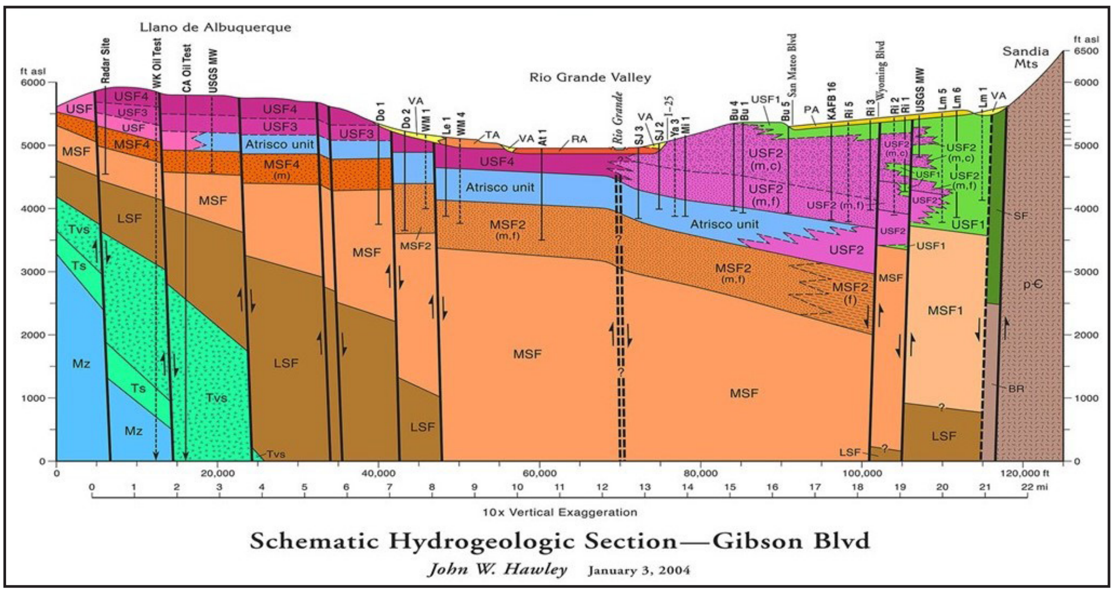


Figure 14. Schematic hydrogeologic cross-section of the North-Central Albuquerque basin (Gibson Blvd. alignment).

Figure 15. Very high permeability late Pleistocene Rio Grande channel deposits (HSU-RA / LFAa1) exposed in ABCWUA flood basin west of Menaul School and Broadway (1994). Primary component of the river valley's shallow-aquifer system, and a great Managed Aquifer Recharge (MAR) site!

Palomas Basin, Rincon (Hatch) Valley, and Selden Canyon

Geologic/hydrogeologic field investigations in the southern Palomas and Jornada [del Muerto] Basin area, and contiguous parts of the Rincon Valley and Selden Canyon were initiated in the mid-1960s. Work was done primarily by geologists and their students at NMSU, with primary funding support provided by the US Soil Conservation Service (now NRCS), and research grants from the NM Water Resources Research Institute (WRRI) and the NMBMMR at NM Tech (e.g., Seager et al. 1971, 1982, 1987). Detailed geohydrologic studies by a USGS-WRD team headed by Clyde Wilson were not started until 1972, when a USGS Sub-district Office was established on the NMSU campus (Wilson et al. 1981). Nearly all of these studies, however, were restricted to the area south of Caballo Reservoir, and primarily in Doña Ana County (Figure 16-22). The 1980 death of Clyde Wilson (at 45) was a major setback to all hydrogeologic/geohydrologic efforts in the Mesilla-Palomas Basin region; and additional detailed studies in the Palomas Basin area have only be initiated in the past decade, again with major NMSU and NM Tech-based, and USGS involvement.

The structural-high geologic setting of much of the Rincon (Hatch) Valley corridor between Caballo Dam and Selden Canyon provides excellent exposures of the entire Santa Fe Group (SFG) stratigraphic sequence (Figure 18 and Figure 19). However, in downstream Mesilla Basin and Hueco Bolson areas (Figure 17 and Figure 20), older parts of the SFG are deeply buried by Upper SFG basin fill. For example, at least 3,500 of Lower and Middle SFG deposits at exposed at the Tonuco-San Diego Mountain uplift in the boundary zone between the Jornada Basin and the southernmost Rincon Valley. As in the analogous geologic setting of the western Albuquerque Basin's Rio Puerco Valley (Figure 10 and Figure 11L), aquiclude and aquitard geohydrologic conditions prevail in the middle and lower parts of the SFG (Figure 14).

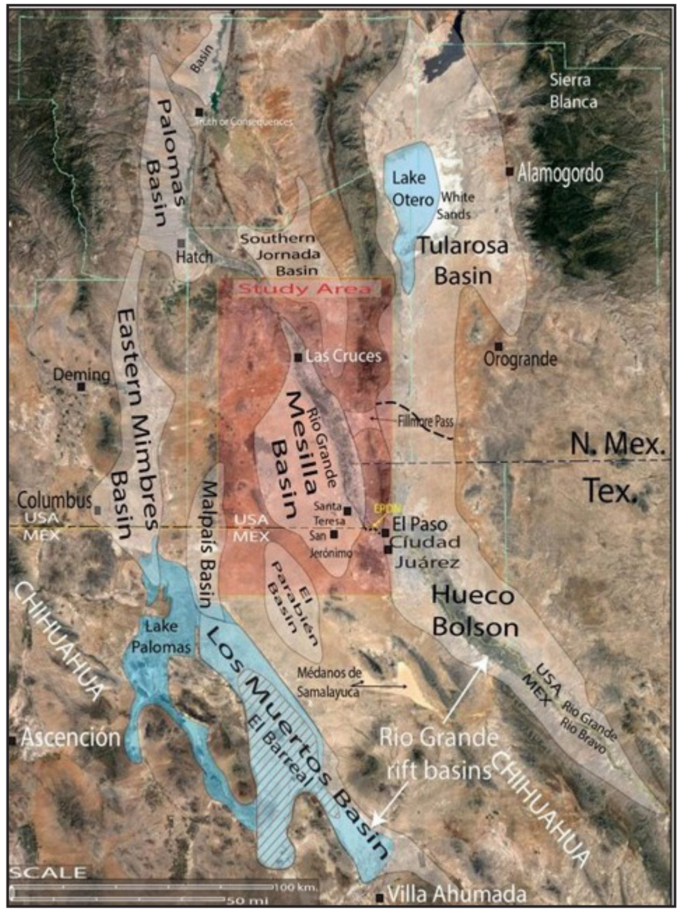


Figure 16. Index map showing major landscape features of the southern RG-Rift and SE Basin & Range provinces. Basin-floor areas occupied by High stands of Late-Pleistocene pluvial Lakes Otero and Palomas are shown in light blue. The beige rectangle covers the area of ongoing NM WRRI hydrogeologic studies that includes post-2006 federal Transboundary Aquifer Assessment Program (TAAP) activities (see Figure 27).

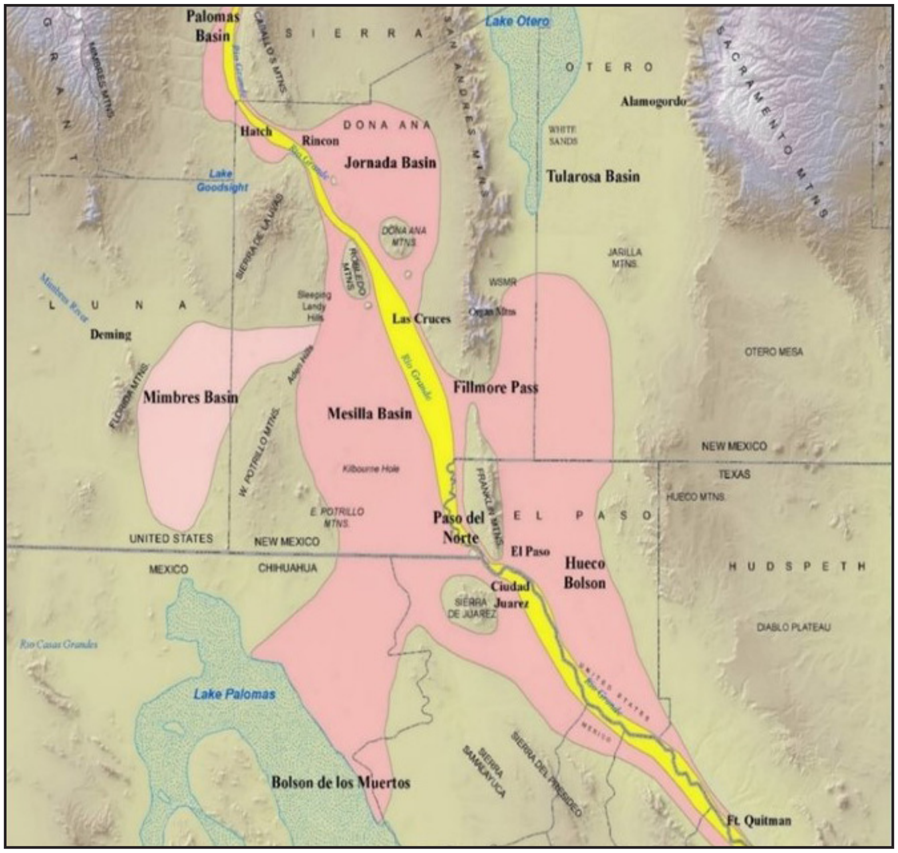


Figure 17. Major landscape features of the Mesilla Basin region of the southern RG-rift province (Hawley et al. 2009, FIG. 10). Approximate area covered by the Ancestral Rio Grande (ARG) distributary drainage network that spread out from a trunk-ARG channel system in the Palomas Basin is in pink. Entrenched valley and canyon reaches of the Rio Grande are in yellow. Stipple patterns cover basin-floor areas occupied by deep stages of Lakes Otero (Tularosa Bsn.) and Palomas (Los Muertos Bsn.) during Late Pleistocene glacial/pluvial stages.

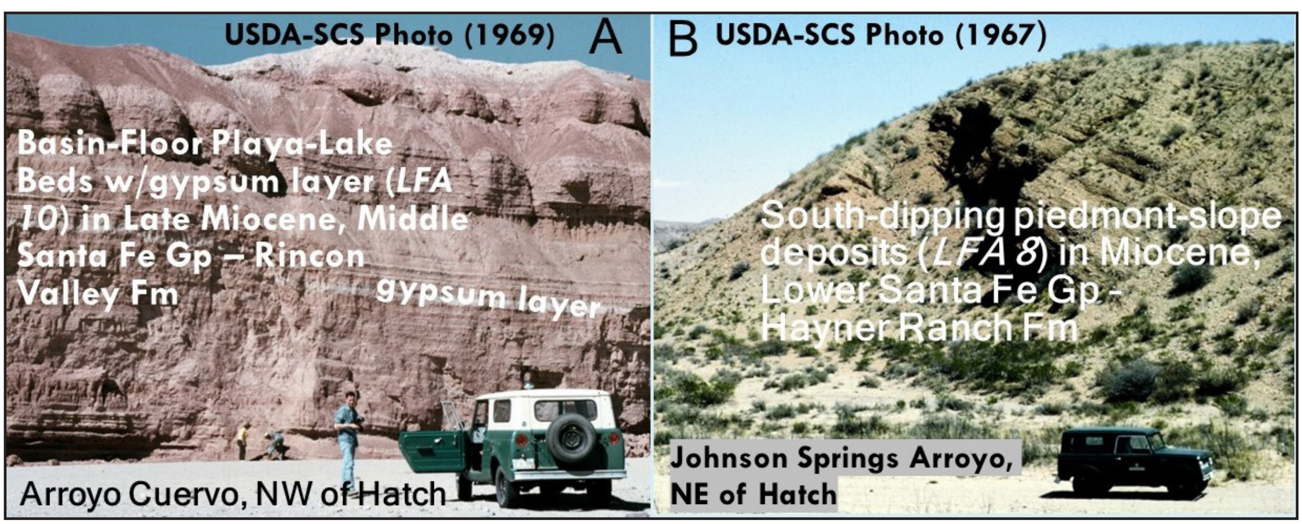


Figure 18. Middle Santa Fe Gp Hydrostratigraphic-Unit (HSU) and Lithofacies Assemblage (LFA) Classes: A. HSU-MSF2: LFA 10 (fine-grained playa-lake plain [barreal-salina] facies); B. HSU-LSF: LFA 8 (piedmont-slope fanglomerate facies).

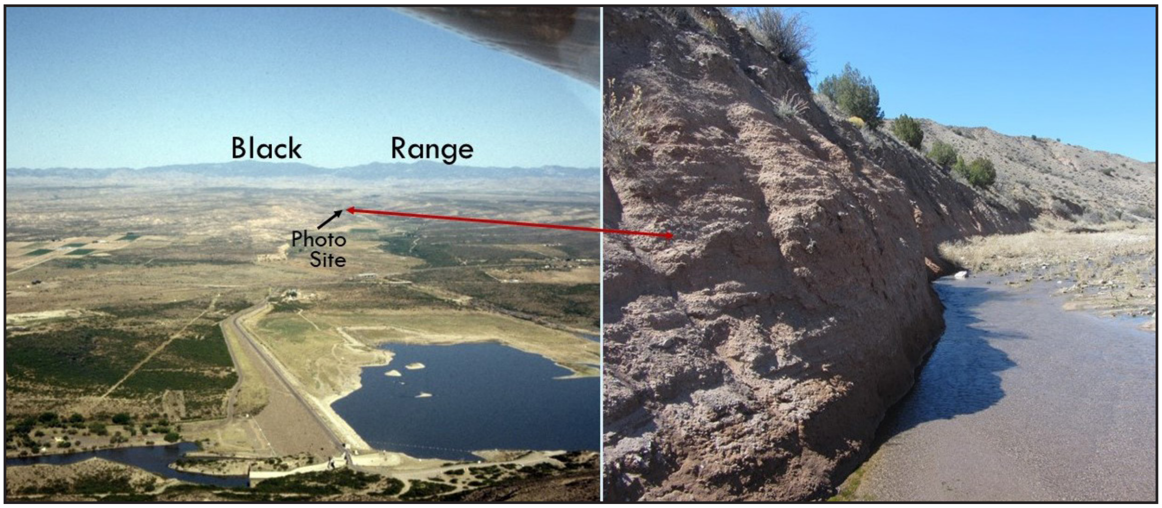


Figure 19. Left: Caballo Dam / Reservoir at Rio Grande-Percha Creek confluence in the upper Rincon Valley, Palomas Basin (9/1991). Right: Percha Creek recharging Black Range-sourced Upper Santa Fe Group (Palomas fm) fan-piedmont deposits (HSU-Usf 1 / lfa 5) (3/2016).

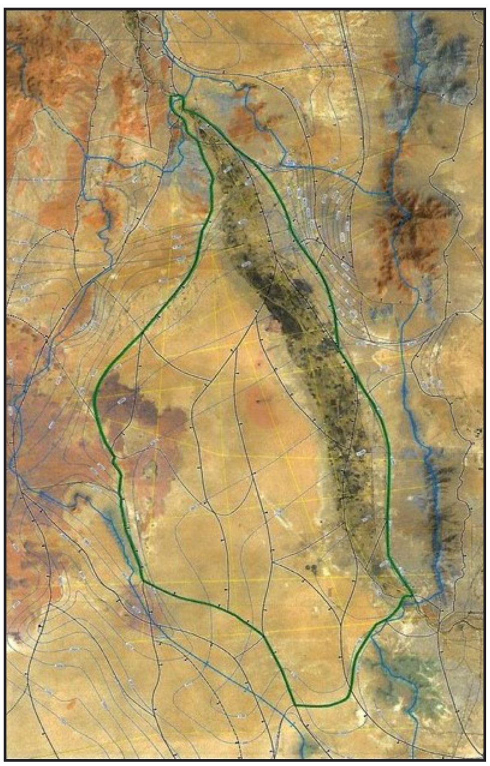


Figure 20. Index map to major geohydrologic features of the Mesilla GW Basin (MeB) Study Area, with MeB boundary in green. thick, solid and dashed blue lines show primary hydrographic boundaries (watershed divides). An approximation of the pre-development potentiometric-surface altitude is shown with thin, dark-blue lines (20 and 100-ft [~6 to 30-m] contour interval). 2017 Google Earth® image base.

The structural setting of the central Palomas Basin, which lies between the Black Range and Caballo Reservoir, is much different than the immediately downstream river-valley and canyon corridor (Figure 19). Here, the eastward-tilted basin structure is much like that of the metro-area section of the Albuquerque Basin (Figure 10 and Figure 14). Upper SFG deposits are as much as 1,000 ft thick in the deepest known part of the basin that is located within 5 miles of the southern Caballo reservoir. Much of the Upper Santa Fe hydrostratigraphic unit (HSU-USF) comprises alluvial-fan-piedmont and axial-stream deposits with demonstrated great potential for increased groundwater production and future MAR projects (Figure 19).

The basin-bordering Black Range is of special hydrologic importance, particularly because of its geographic/hydrographic location and elevation. With summit elevations locally exceeding 10,000 ft, it is the southernmost high-mountain mass that is an integral part of the Rio Grande watershed. Surface and subsurface flow systems in the valley-reservoir reach between Elephant Butte and Caballo Dams is already the beneficiary (or occasional unhappy recipient) of highland-sourced warm-season precipitation/flood-runoff events that can and do produce large discharges of water and sediment. Watershed health is therefore of major importance in both surface- and subsurface-water conservation.

Mesilla Basin and Valley

Hydrogeologic characterization of SFG basin fill and Rio Grande alluvial deposits of the Mesilla Basin is of excellent quality (Figure 20-24). Much of this work is based on public-sector funded research (Federal, State, university, and local water-utilities) dating to the 1940s (e.g., Conover 1954, Leggat et al. 1962, Hawley et al. 1969, King et al. 1971, Gile et al. 1981, Wilson et al. 1981, Peterson et al. 1984, Hawley and Lozinsky 1992, Frenzel and Kaehler 1992, Nickerson and Myers 1993, Hawley and Kennedy 2004, Creel et al. 2006, Hawley et al. 2009). Private-sector contributions (e.g., irrigation agriculture, and oil & gas-exploration and livestock/ diary industries) have also been very substantial. The *almost* perennial Rio Grande runs down the Mesilla Valley corridor and serves as the primary recharge source for basin- and valley-fill aquifer systems (Figure 24). With the exception of recharge from the river, irrigation-agriculture and a few mountain highlands, groundwater resources in this semiarid, binational region are primarily replenished by underflow from basin-boundary sources that are predominantly brackish.

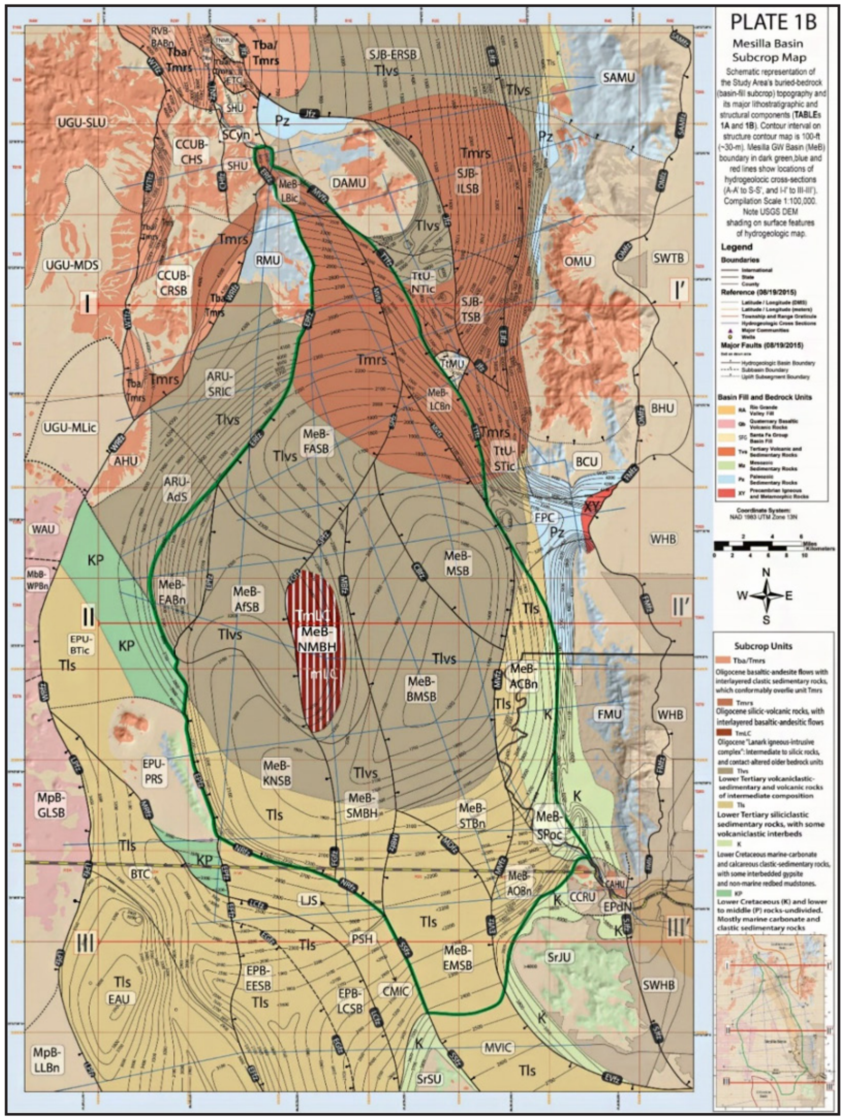


Figure 21. Primary topographic, lithostratigraphic and structural components of the Bedrock surface buried by SFG basin fill in the Binational Mesilla Basin region. Bedrock-map units are defined in Table 3. The Mesilla GW Basin is outlined in green; and W-E red lines show locations of geologic cross-sections I-I' to III-III' on Figure 25.

Primarily because of the aquifer's great depth (with *vadose-zone* thicknesses in the 300 to 400-ft range), most of Mesilla Basin floor ("West Mesa)" west of the irrigated and urban/suburban lands of the inner Mesilla Valley has not been utilized except for livestock grazing and wildlife management. The "West Mesa" surface and Rio Grande alluvium of the inner-river valley are immediately underlain by the Upper Santa Fe hydrostratigraphic unit (HSU-USF, Figure 17). It consists mostly of permeable sand and gravelly sand deposited by the ancestral Rio Grande (Figure 23A), and ranges from 500 to 1000 ft in thickness in central basin floor and valley areas north of the International Boundary. Conservative estimates of the amount of recoverable fresh to moderately brackish groundwater in storage exceeds 30 million acre-feet (Figure 25). Sand-dominant texture, high permeability, and the relatively compact structure of the bulk of these sediments indicates that: 1) groundwater-pumping yields will be high (1,000 gpm range); 2) land-subsidence potential low; and 3) suitability for post-/co-development MAR is excellent. National Monument designation in 2014 and 2019 Border Wall construction, both without consideration of water-resource management concerns, however, now complicates groundwater-conservation planning in the binational part of the "West Mesa" area.

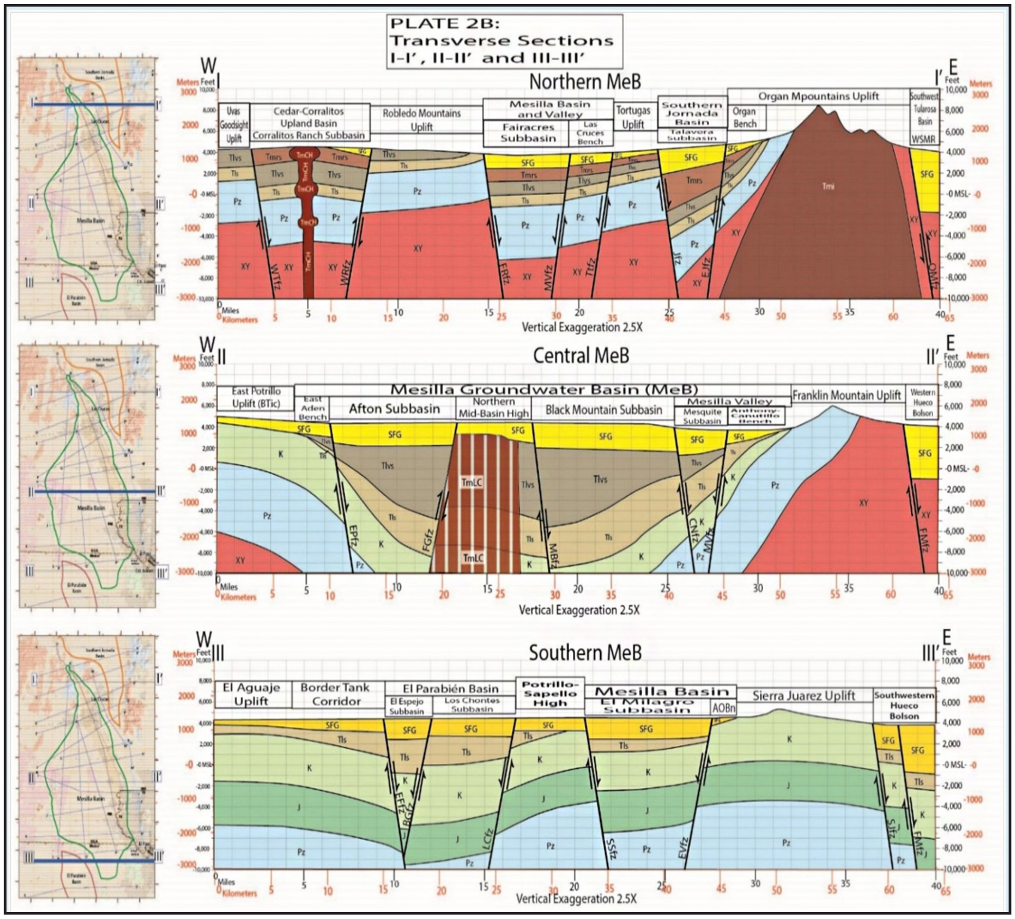


Figure 22. Schematic geologic cross sections I-I' to III-III' that show basic RG-rift structural relationships in the binational Mesilla Basin region. Section locations shown on Figure 24, and Bedrock-map units defined in Table 3.

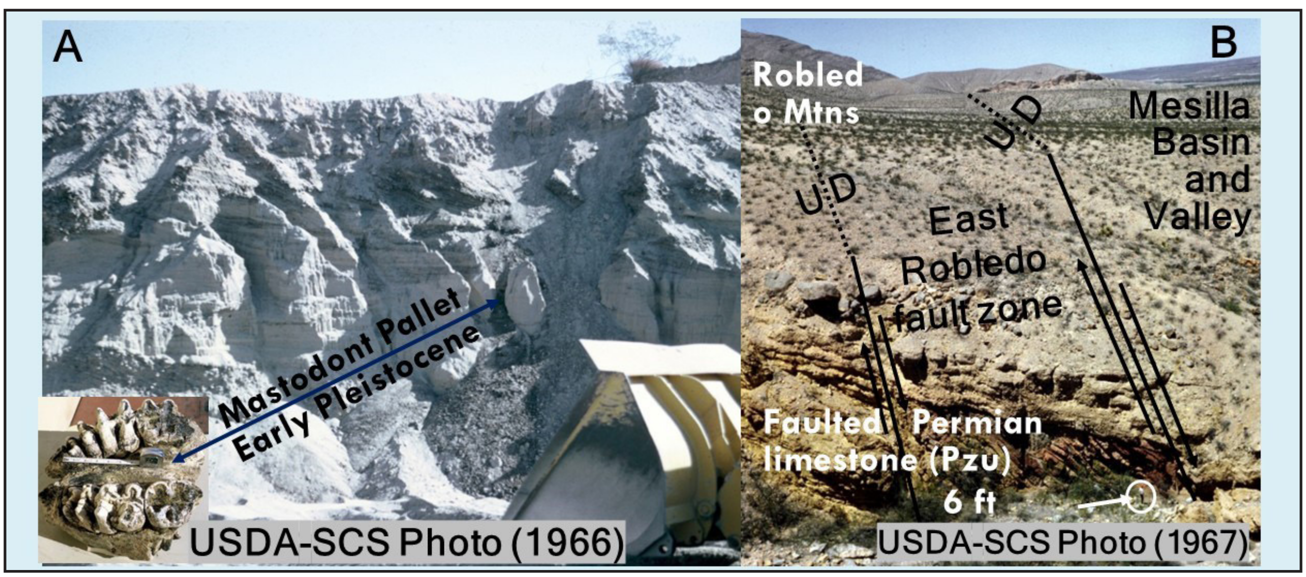


Figure 23. Upper Santa Fe Gp HSU-USF and Lithofacies Assemblage (LFA) Classes: A. HSU-USF2: Ancestral Rio Grande (ARG) channel deposits (LFAs 1 & 2); B. HSU-USF1: faulted bouldery fan-piedmont alluvium (LFA 6); on Permian carbonate bedrock.

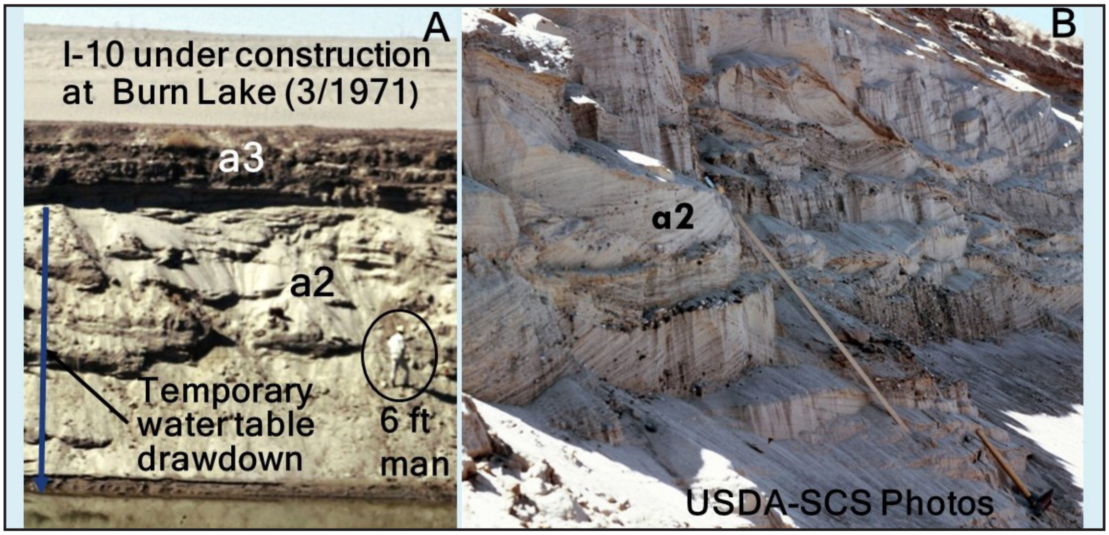


Figure 24. 36-ft (11-m) Section of Historic Rio Grande Channel and Floodplain Deposits (HSU-RA) at Burn Lake I-10 Borrow Pit NE of Old Mesilla. A. General: HSU-RA and LFAs a3/a2 ; B. Detail of HSU-RA (LFA a2) exposure.

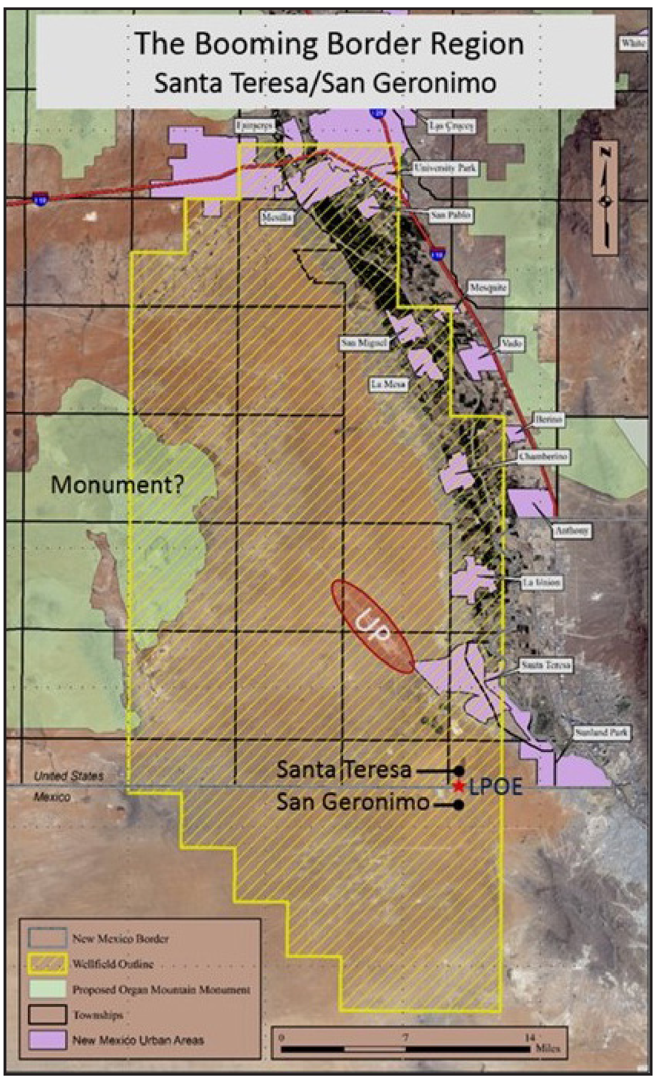


Figure 25. Map of Mesilla Basin area (yellow outline) that is underlain by as much as 1,000 ft of saturated Upper and Middle SFG basin fill with at least 50 million ac-ft of <5,000 mg/L tds economically minable groundwater (Esslinger, 2014, unpublished).

Opportunities for both surface and subsurface disposal of desalination-produced concentrate are excellent, provided that binational/tristate (NM, TX, and Chihuahua) cooperative agreements can be reached concerning development of shared groundwater resources and managed aquifer-recharge (MAR) projects (Figure 26 and Figure 27). Natural-gas powered electric-energy generation is already locally available; and prospects of future solar-energy generations are unlimited. Design and implementation of large-scale (mg/d) desalination operations can begin immediately, provided that the existing 27 mg/d desalination facility operated by the El Paso Water Utility in the nearby western Hueco Bolson is used as a state-of-practice working model (e.g., Archuleta 2010).

Now a few caveats: Doña Ana (NM) and El Paso (TX) Counties, and contiguous parts of Chihuahua share many of the pitfalls of adverse environmental impacts on aquifer integrity that are associated with a very large urban/suburban population. For example, a major locale of potential groundwater contamination is the bi-state area of concentrated irrigation-agriculture, and feedlot and industrial operations that is located in and along the east edge of the Mesilla Valley (e.g., Hibbs et al. 1997, Macías-Corral et al. 2006, Mumme 2010, Walker et al. 2015). One of the new environmental-impact areas involves occurrences of anthropogenic “Contaminants of Emerging Concern (CECs)” that are now appearing on groundwater-contamination maps of “1,4-dioxane MRL exceedances” at M&I sites in El Paso-Ciudad Juárez and Santa Teresa-San Jerónimo (e.g., Suthersan et al. 2016; USEPA 2015; cf. Alley and Alley 2020, Chapts. 9 and 10).

Plausible future climate scenarios suggest that the regional precipitation-distribution pattern in the Upper Rio Grande basin could shift from the present winter-snow dominant in the basin’s Rocky Mountain highlands to the summer-monsoon storm conditions already prevalent in the Basin

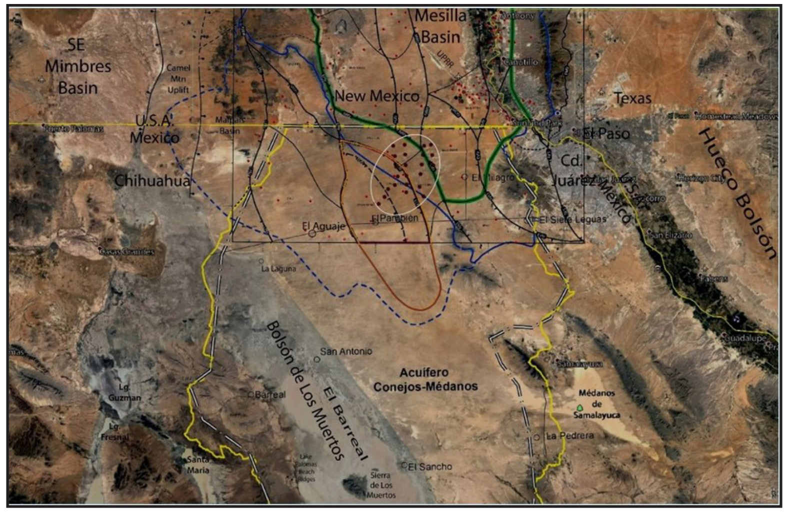


Figure 26. “International-Boundary Zone (IBZ)”.

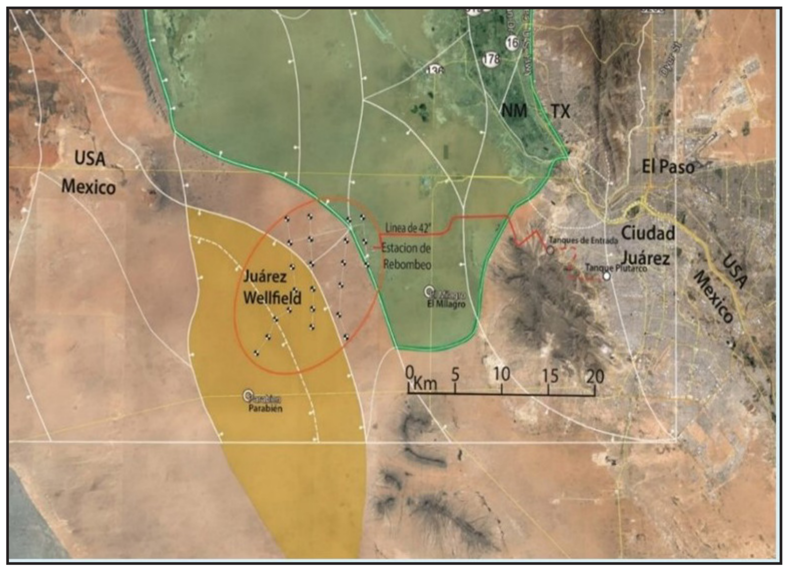


Figure 27. Index map showing locations of the new Ciudad Juárez (JMASCJ) well field and the 42-in transmission line (red) that connects it with the central part of the city. Mesilla and El Parabién gw basin in green and beige, respectively.

and Range-Chihuahuan Desert landscape of the region. For example: Most of the Mesilla Basin floor is a flat dune-covered fluvial plain (long since abandoned by the ancestral Rio Grande) with no inter-connected surface drainage and numerous shallow closed depressions (Gile et al. 1981, Seager et al. 1987). As such, it now serves as a marginal ephemeral source of groundwater recharge, but only after extreme warm-season rainstorm events.

HYDROGEOLOGY MEETS “THE LAW OF THE RIO GRANDE

In conclusion, it is fitting to refer to one more of Al Utton’s seminal contributions to groundwater-resource management in the Trans-International Boundary region of the American West. With grant support from the NM WRRI, Al Utton and Clifford K. Atkinson prepared a report titled "International Groundwater Management: The Case of the Mexico-United States Frontier. The theme of this seminal document still resonates, and the geohydrologic information it contains is applicable in all stream/alluvial aquifer-corridors of this arid/semiarid region, no matter what type political-boundary condition exists (*cf*. Utton and Atkinson 1979, 1981, 1983; Hibbs et al. 1997; Granados-Olivas et al. 2012; INEGI 2012):

> In view of the agreed upon allocations of surface waters for the Rio Grande and Colorado and the example of the Santa Cruz River upon which both Nogales, Sonora and Nogales, Arizona depend, it is absolutely essential that the interrelationship between surface and groundwaters be recognized.

As [Harold] Thomas and Luna [Leopold] [1964] point out,

> We have been discussing ground water more or less as if it were separate and distinct from the rest of the hydrologic cycle. Such segregation has been common among hydrologists as well as the general public, and is reflected in legislation, in the division of responsibility among government agencies, in development and regulation. Yet it is clear that this isolation can be maintained only when and where water is being mined from underground storage. Any water pumped from wells under equilibrium conditions is necessarily diverted into the aquifer from somewhere else, perhaps from other aquifers, perhaps from streams or lakes, perhaps from wetlands—ideally, but not necessarily, from places where it was of no use to anyone. There are enough examples of streamflow depletion by ground water development, and of ground water pollution from wastes released into surface waters, to attest to the close though variable relation between surface water and ground water.

Thus, the IBWC [International Boundary & Water Commission] will undoubtedly have to treat differently two major classifications of groundwaters: those that are tributary to surface water flows and those which are not tributary, or more precisely, those which are interrelated to surface water flows (which would include, for example, the Santa Cruz, which is tributary to the groundwater supply) and those which are not connected hydrologically with any identifiable surface stream or lake.

In fact, the Rio Grande itself already has provided extensive hydrologic and institutional experience concerning the interrelationships between surface flows and the associated alluvial groundwater system. Hydrologic studies have shown "an intimate hydraulic relationship between the Rio Grande and adjacent groundwater reservoirs. There are extensive sedimentary rocks adjacent to the river . . . which form the principal aquifer adjacent to the river. This aquifer is recharged directly by precipitation, by lateral flow of water from adjacent formations, by seepage from Rio Grande tributaries, and in some areas from seepage from the Rio Grande mainstream."

Pumping from groundwater flows thus can have direct effects on surface water flows which can be calculated, once the characteristics of the aquifer are known [*cf.* Spiegel 1962]. Using the formula devised by C.V. Theis [1938, 1941], the State Engineer of New Mexico [Steve Reynolds] has devised a system of administration which allows new appropriations of groundwater in the Rio Grande basin in New Mexico only "under the condition that the appropriator acquire and retire from usage surface water rights in amounts sufficient at each point in time to compensate for the increasing effects of his pumping on the stream." This conjunctive administration of surface and groundwaters protects prior users of both, and has been upheld by the courts.

Table 1. Glossary of Some Basic Terms Used in a Hydrogeologic Context

Aquiclude: A saturated geologic formation [of very low permeability] that contains water but does not transmit significant quantities (Hornberger et al. 1998, p. 277).

Aquifer: A saturated geologic formation that contains and transmits significant quantities of water under normal field conditions (Hornberger et al. 1998, p. 277).

Aquitard: A saturated geologic formation that is of relatively low permeability (Hornberger et al. 1998, p. 277).

Confined Aquifer: A permeable formation whose upper boundary is an *aquitard*; water in a well within a *confined aquifer* will rise above the top of the *aquifer* (Hornberger et al. 1998, p. 279; *cf. potentiometric surface*).

Conservation: A careful preservation and protection of something; *especially* planned management of a natural resource to prevent exploitation, destruction, or neglect, e.g., *water conservation.* https://www.merriam-webster.com/dictionary/coservation

Geology: The study of the planet Earth, the materials of which it is made, the processes that act on these materials, the products formed, and the history of the planet and its life forms since its origin (Neuendorf et al. 2005, p. 267).

Groundwater: (1) (a) That part of the *subsurface water* that is in the saturated zone . . . . (b) loosely, all *subsurface water* as distinct from *surface water* (Neuendorf et al. 2005, p. 286). **(2)** Any *subsurface* aqueous fluid, either saline or fresh (Deming 2002, p. 433).

Hydrogeology: **(1)** The science that deals with *subsurface waters* and related geologic aspects of surface waters. Also used in the more restricted sense of groundwater geology only. (Neuendorf et al. 2005, p. 311). **(2)** The branch of *hydrology* which studies underground fluids and their interaction with solid geologic materials (Deming 2002, p. 433).

Hydrology: The study of the occurrence and movement of water on and beneath the surface of the Earth, the properties of water, and its relationship with living and material components of the environment (Hornberger et al. 1998, p. 282).

Potentiometric Surface: **(1)** A surface that depicts the distribution of hydraulic heads in a *confined aquifer*; the water [level] in a well or piezometer penetrating the *confined aquifer* defines that surface (Hornberger et al. 1998, p. 286). **(2)** Commonly defined more broadly to include the *water table*.

Quaternary (Ice Age) **Period:** The youngest geologic time-rock unit with a span of about 2.6 million years (Ma; Walker and Geissman 2009). It comprises the **Holocene** (past 10-12 thousand years [ka]) and **Pleistocene Epochs**, and is preceded by the **Tertiary Period**. **Quaternary** and **Tertiary** are subdivisions of the **Cenozoic Era**.

Saturated Zone: A region of the subsurface where pores are completely filled with water; it is bounded at the top by the water table (Hornberger et al. 1998, p. 287).

Tertiary Period: The geologic time-rock unit that extends from about 2.6 to 65.5 Ma. It is subdivided into the **Pliocene** (2.6-5.3 Ma), **Miocene** (5.3-23 Ma), **Oligocene** (23-34.9 Ma), **Eocene** (34.9-55.8 Ma), and **Paleocene** (55.8-65.5 Ma) **Epochs**, which are preceded by the **Cretaceous Period** of the **Mesozoic Era** (65.5-251 Ma). Informal **Upper**, **Middle**, **Lower Tertiary** units, respectively comprise the Pliocene/Miocene, Oligocene, and Eocene/Paleocene Epochs.

Unconfined Aquifer: A permeable formation whose upper boundary is the *water table* (Hornberger et al. 1998, p. 291).

Vadose Zone (preferred here) **or Unsaturated Zone:** The zone in soils or rocks between the Earth's surface and the *water table*; pores are partly filled with water and partly filled with air (Hornberger et al. 1998, p. 291).

Water Table: A surface separating the *saturated* and *unsaturated* zones of the subsurface, [that is] defined as a surface at which the fluid pressure is atmospheric (Hornberger et al. 1998, p. 292).

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