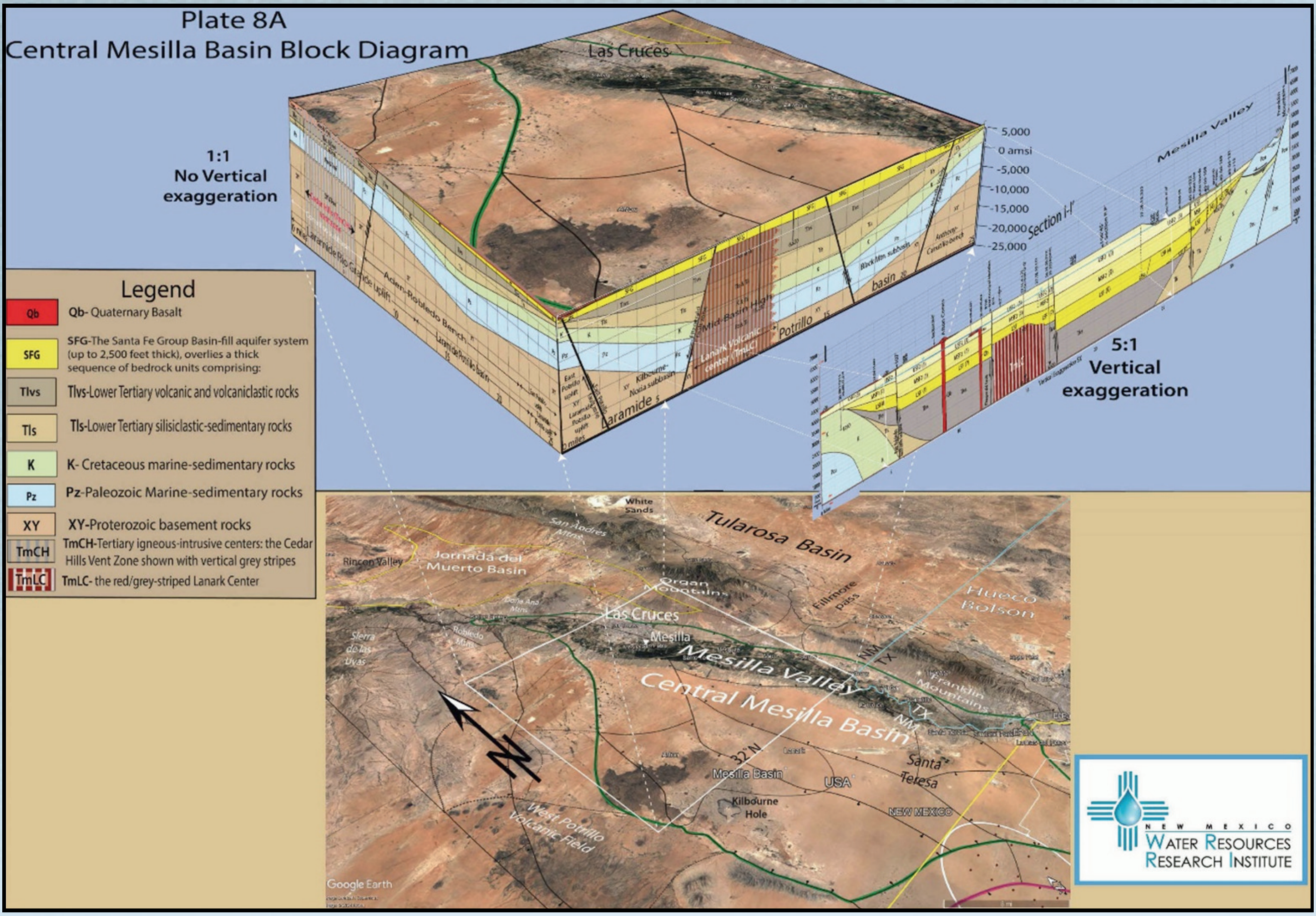
Hydrogeologic Framework of the Mesilla Basin Region of New Mexico, Texas, and Chihuahua (Mexico)—Advances in Conceptual and Digital-Model Development

Appendix E

Conservation of Groundwater Resources in the United States Part of the Mesilla Basin Region

John W. Hawley

J. Steven Walker



Northeast-facing schematic-block diagram of the central Mesilla Basin region, with the southern panel (Section I-I') at latitude 32° north.

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APPENDIX E[1]

CONSERVATION OF GROUNDWATER RESOURCES IN THE UNITED STATES PART OF THE MESILLA BASIN REGION (MBR – FIG. E9-1)

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[1] APPENDIX E *in* Hawley, J.W., Swanson, B.H., Walker, J.S., Glaze, S.H., and Ortega Klett, C.T., 2025, Hydrogeologic Framework of the Mesilla Basin Region of New Mexico, Texas, and Chihuahua (Mexico)—Advances in Conceptual and Digital Model Development: NM Water Resources Research Institute, NMSU, Technical Completion Report No. 363, 359 p., 8 Appendices.

APPENDIX E
CONSERVATION OF GROUNDWATER RESOURCES IN THE UNITED STATES PART OF THE MESILLA BASIN REGION (MBR – FIG. E9-1)

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/conservation

E1. CHALLENGES FACING WATER-RESOURCES CONSERVATION IN THE AMERICAN SOUTHWEST

John Wesley Powell (1885) and William W. Follett (1898) were among the first water scientists and engineers to recognize that prospects for long-term water-resource development was a pressing issue throughout the American Southwest, and especially in the Colorado River and Rio Grande basins (*cf.* Reisner 1993, Glennon 2002, Phillips et al. 2011, Fleck 2016, Alley and Alley 2017, Paskus 2020, Fleck and Udall 2021). To say the least, accepting the reality of the limited amount of fresh (<1,000 mg/L tds) groundwater (GW) resources has proven to be a major challenge in a development-obsessed culture.

E1.1. Twentieth Century Past

E1.1.1. "Rio Grande: 'Country'" (Harvey Fergusson, 1933, p. 10)

Above all, it is a land where water has always been scarce and therefore precious, a thing to be fought for, prayed for and cherished in beautiful vessels—a land where thunder is sacred and rain is a god.

E1.1.2. "New Mexico-A pageant of Three Peoples: 'Water'" (Erna Fergusson, 1973, p. 381)

It is easiest to disregard nature when unseen water is in question. Pump irrigation has pointed up the struggle between advocates of conservation of natural resources for a distant future and of unthinking people who would heedlessly exhaust them to satisfy present greed. Grandsons of men whose windmills watered a few head of stock observed that motor pumps would bring up water in artesian-like flow. Why not tap "underground lakes and streams" and go into farming? The answer is that subterranean water does not always stand in vast pools or flow in dark rivers; it often inches slowly along through beds of gravel; ultimately it depends upon rainfall for renewal. And New Mexico's rainfall still averages only fifteen inches annually. Water, even hidden water, is not an inexhaustible resource. Engineers not hired by exploiting companies or chambers of commerce agree on this, and their judgment is confirmed by what has happened and is happening daily.

E1.1.3. "Lazy B – Growing up on a cattle ranch in the American Southwest" (SCOTUS Justice Sandra Day O'Connor [1930-2015], and [brother] H. Allen Day, 2002)

The problem in the Arizona—New Mexico area was water. Water was scarce and limited the use of the land. Wells could be dug, but often they had to be several hundred feet deep to reach water. Even at that depth, a well was apt to produce a small stream of four gallons per minute or so. Windmills produced the power to pump water out of the wells. The deeper the well, the larger the windmill required to fit the sucker rod and pump out the water (**Preface, p. ix**).

Water was scarce and hard to find. Every drop counted. We built catchment basins and dirt tanks to catch and store it. We pumped from underground. We measured it and used it sparingly. Life depended on it (**Early Memories, p. 7**).

E1.2. Twenty-first Century and Future

Groundwater is a renewable resource, but not necessarily on a human time scale (Deming 2002, p. 19).

It's time state leaders started a real dialogue about how we're going to survive diminishing stream flows in the face of a drought that shows no signs of ending soon. We're already 20 years behind the curve (September 27, 2022 Albuquerque Journal Editorial, p. A10).

E1.2.1. The Tragedy of the Commons (Deming 2002, p. 22, 24)

The **tragedy of the commons** is the tendency to deplete and ultimately destroy a resource that has a common ownership. The concept was first developed by Garrett Hardin in his 1968 article, *The Tragedy of the Commons [Science, v. 162].* Hardin used the example of a pasture that is shared by herdsmen. Each herdsman will graze as many cows as possible, as each added cow enriches him further. This system works so long as the load imposed by the cumulative burden of all herdsmen does not exceed the carrying capacity of the pasture. At that point, Hardin (1968) wrote, "the inherent logic of the commons remorselessly generates tragedy." The logic of the commons is that each individual is logically compelled to add further to the exploitation of the pasture, because altruistic sacrifice is not rewarded. If a herdsman were to withdraw cows from the common pasture, it would still be overwhelmed by other individuals less altruistic moving further cows onto the pasture. The only logical course for each herdsman to follow is to add still more cows to the pasture, and ultimately the common resource is ruined for all. The lesson of the tragedy of the commons is that a shared or common resource such as groundwater or surface water must be regulated by law or it may be destroyed. Alternatively, resources held in common may be sold to individuals. Individual ownership provides an economic motivation for the preservation of a resource.

E1.2.2. The Colorado River Compact at 100: "Groundwater is Plan B for Arizona—Farmers, urban users have no idea how much river water use they'll have to cut" (Tony Davis 2022, p. A1, A6)

In Tucson, officials of the Tucson Water utility are optimistic about their ability to survive major CAP [Central Arizona Project] cuts. The utility about 40 years ago signed up to take almost a third more CAP water than it needs today to serve the 735,610 customers living inside and outside city limits.

That's allowed it to store nearly five and a half years' worth of CAP in large, recharge basins — water that can be pumped when needed during CAP shortages later. The utility also has access to a huge aquifer lying under a large expanse of former farmland northwest of the city that it bought and retired in the 1970s. It also is regularly recharging and storing underground large amounts of partially treated effluent that can be pumped later for drinking.

Ultimately, the story of CAP water in Arizona is a story about groundwater, said Kathryn Sorensen, a researcher for Arizona State University's Kyl Center for Water Policy.

"We are very blessed to have plentiful aquifers in central Arizona we can fall back on," Sorensen said while noting they are fossil aquifers, meaning water entered them thousands of years ago and they are not easily replaced.

"If we pump them and are unable to replenish the pumping, the aquifers will pay the price," she said.

The Associated Press, Albuquerque Journal, The Colorado Sun, The Salt Lake Tribune, The Arizona Daily Star and The Nevada Independent are exploring the pressures on the Colorado River in 2022 [*cf.* Theresa Davis, 2022d].

E2. CONTENT AND ORGANIZATION

E3. REALITIES FACING CONSERVATION OF LIMITED WATER RESOURCES IN A TWENTY-FIRST CENTURY CONTEXT

E3.1. Realities of Uncertainty and Human Nature

"Uncertainty is an uncomfortable position. But certainty is an absurd one (François-Marie d'Arouet ['Voltaire']" https://www.britannica.com/biography/Voltaire. *From* **C.M. Hester, and J. Coleman (2014) Between an uncomfortable position and an absurd one: Groundwater, v. 52, no. 5, p. 645-646** (*cf.* Lewis 2016, Chpt. 4: Errors; Miller and Gelman 2020; Laplace 1825; **APPENDIX G**: heuristics)

"Humankind cannot bear very much reality." **Thomas Stearns (T.S.) Eliot (1888-1965)** https://en.wikipedia.org/wiki/T._S._Eliot

"Reality is that which, when you stop believing in it, doesn't go away." **Philip K. Dick (1928-1982)** https://en.wikipedia.org/wiki/Philip_K._Dick

"IN THE END, a writer survives only if there is wisdom in their work. A hundred years later, a reader has to recognize the emotional patterns as their own, no matter what the social circumstances of the writer was." **Vivian Gornick (1935-)** https://en.wikipedia.org/wiki/Vivian_Gornick

As a writer, it seems to me that the most baleful development in our collective contemporary life is the preponderance of a practice derived from digital technology that treats knowledge and information as synonymous. For while the way to wisdom leads through knowledge, there is no path to wisdom from information. Especially when that information is being used as a training treat in what has come to feel like a wholesale attempt at permanent reeducation.

Having one's bias confirmed endlessly by a curated cascade of information reflecting back to you, your preferences and opinions, second after second, understandably breeds an illusion of certainty. But certainty is nothing like wisdom; it might in fact be something closer to wisdom's opposite. Wisdom: a kind of knowing ever-riven with contradiction, a knowing intimate with the inevitability of uncertainty. *From* **Ayad Akhtar (2021) Singularity is here: The Atlantic, v. 328, no. 5, p. 21**. https://en.wikipedia.org/wiki/Ayad_Akhtar

Humanity

Humanity is the primary reason we need humility; it doesn't matter how well we understand the machinery if we misunderstand people.

Technology continually changes. Human nature doesn't.

AI [Artificial Intelligence] and the metaverse won't make humanity better; they will augment and intensify what we all already are, for good and for ill. People can be good. People can be bad. People can be kind. People can be cruel. People can build. People can destroy.

And people will always need meaning in their lives. As real as the metaverse may seem, the only human thing about it will be the humans in and around it. No matter how well an artificial intelligence mimics a relationship, it can't have one.

Only people can. Sentience matters. Soul is real.

This is an early opinion and I'm certain time will reveal how naive it is. There's so much we still don't understand. But you can never go wrong with humility, and things won't always go right with humanity.

Keeping those two things in mind will help us navigate whatever lies ahead. *From* **Steve McKee (2022), As AI progresses, keep humanity in mind: Albuquerque Journal–BUSINESS OUTLOOK, January 24, 2022, p. 5** (*cf.* Garber 2023)

> **Reality and AI**
>
> But the reality of my profession, and most others, is shaped by language more than numbers. Language who we are as people. A culture is defined by its language. AI is, by definition, not alive. It does not experience the world as you and I do. It communicates as it is told to. *From* **Jim Hamill (2023) On artificial intelligence, and mice and men: Albuquerque Journal – BUSINESS OUTLOOK, June 5, 2023, p. 14** (*cf.* McKee 2022).

E3.2. "The Black Swan – The Impact of the Highly Improbable," a seminal work by Prof. Nassim Nichols Taleb (2010)*

> **"The Black Swan changed my view of how the world works." – Daniel Kahneman –2002 Nobel Laureate: for "for having integrated insights from psychological research into economic science, especially concerning human judgment and decision-making under uncertainty." (cf. Kahneman and Tversky 1996; E4.1)."*

> **PROLOGUE (p. xxi-xxii)**
>
> Before the discovery of Australia, people in the Old World were convinced that *all* swans were white, an unassailable belief as it seemed completely confirmed by empirical evidence. The sighting of the first black swan might have been an interesting surprise for a few ornithologists (. . .), but that is not where the significance of the story lies. It illustrates the severe limitation to our learning from observations and experience and the fragility of our knowledge. One single observation can invalidate a general statement derived from millennia of confirmed sightings of millions of white swans. All you need is one single (and, I am told, quite ugly) black bird.
>
> I push one step beyond this philosophical-logical question into an empirical reality, and one that has obsessed me since childhood. What we call here a Back Swan (. . .) is an event with the following three attributes.
>
> First, it is an *outlier*, as it lies outside the realm of regular expectations, because nothing of the past can point to its possibility. Second, it carries an *extreme impact* (unlike the bird). Third, in spite of its outlier status, human nature makes us concoct explanations for its occurrence *after* the fact, making it explainable and predictable.
>
> I stop and summarize the triplet: rarity, extreme impact, and retrospective (though not prospective) predictability. A small number of Black Swans explain almost everything in our world, from the success of ideas and religions, to the dynamic of historical events, to the elements of our personal lives. Since we left the Pleistocene, some ten millennia ago, the effect of Black Swans has been increasing. It started accelerating during the industrial revolution, as the world started getting more complicated, while ordinary event, the ones we study and discuss and try to predict from reading the newspapers [or gleaning from cyberspace] have become increasingly inconsequential.

Examples of *extreme impacts* of Black Swan-type *outliers* in the Rio Grande basin include:

1. Unknown long-term effects of projected Global and regional climate change that include major shifts in seasonality, type, and intensity of precipitation (Székely 1991, Gutzler 2005, Rango 2006, Creel 2010, Meixner et al. 2016, Overpeck and Udall 2020, Paskus 2020, Siegel 2020, Williams et al. 2020a, Brannen 2021, Davis 2021 a-h&j; *cf.* **Part E2.3**).
2. Unknown future global environmental conditions of an Anthropocene Epoch of Geologic Time, which quite possibly started in about 1950 CE (*cf.* Zalasiewicz et al. 2019 and 2021).
3. Pending legal/institutional restrictions on Rio Grande Project deliveries in terms of both water quantity and quality (Davis 2020a-i, 2021; Pacheco 2020c, ABQ Jrnl. 2021).
4. The Border Wall, and COVID-19 (*cf.* Rpt. **Part 8.2.4**; Banerjee et al. 2018, Bixby and Smith 2020, McKay et al. 2020, Robinson-Avila 2020d, Pacheco 2020a to 2020d, Spencer and Crawford 2020).
5. Uncertainties of the ongoing war on environmental science (e.g., Lewis 2018, Alley and Alley 2020).

E4. CLIMATE CHANGE AND THE GLOBAL WARMING WILD CARD

E4.1. Nassim Taleb, 2010, The Black Swan – Postscript Essay: On robustness and fragility, deeper philosophical and empirical reflections*

*"*I owe the idea of this . . essay to Danny Kahneman, toward whom I (and my ideas) more debt than toward anyone else on this planet (**p. 309**).*"*

I have been asked frequently on how to deal with climate change in connection with the Black Swan idea and my work on decision making under opacity. The position I suggest should be based both on ignorance and on deference to the wisdom of Mother Nature, since it is older than us, hence wiser than us, and has been proven much smarter than scientists. We do not understand enough about Mother Nature to mess with her— and I do not trust the models used to forecast climate change. Simply, we are facing nonlinearities and magnifications of errors coming from the so-called butterfly effects** we saw in Chapter 11 actually discovered by [Edward] Lorenz using weather-forecasting models [*cf.* Lorenz 1963 and 1976]. Small changes in input, coming from measurement error, can lead to massively divergent projections, and that generously assumes that we have the right equations (**p. 315**).

"The butterfly effect – an underlying principle of chaos theory – holds that tiny, apparently inconsequential changes can produce enormous, globally felt repercussions. The butterfly effect was formalized by the meteorologist Edward Lorenz [1963], who noticed, while running data through his weather models, that even the seemingly insignificant rounding up or down of initial inputs would create a big difference in outcomes: A flap of a wing, as he once put it, would be 'enough to alter the course of the weather forever (Jordan Kisner 2022, p. 87***).'"*

Consider the *wild card* possibility of a "Black Swan – Butterfly Effect," collapse of the oceanic-circulation system (e.g., the Gulf Stream) triggered by Global Warming, and a temporary return to continental and oceanic deep-freeze conditions in the northern hemisphere (*cf.* Broecker 2010, Keigwin et al. 2018, Wang et al. 2018).

E4.2. "The Future for Geoscience in the Context of Emerging Climate Disruption" (*Excerpt from* the 2019 Geological Society of America Presidential Address by Donald Siegel, 2020, p. 4)

I speak to climate disruption, the result of the most sweeping tragedy of the commons, when nations use a resource owned by none, in this case the atmosphere, and then individually degrade it to achieve individual advantage [*cf.* Hardin (1968]. The tragedy of the commons originally referred to common pastures where farmers would graze their animal stock. When each farmer incrementally added more animals-thinking nothing bad would happen-the pasture failed. Much as humanity has incrementally added greenhouse gases to our collective atmosphere [*cf.* Brannen 2021, Zalasiewicz et al. 2021].

Sadly, I see no evidence that most nations releasing greenhouse gases will make the necessary economic and political decisions to prevent at least a two-degree increase in average tropospheric temperature-a temperature beyond which severe climate disruption will almost certainly affect our way of life and the survival of many, if not most, current ecosystems (e.g., Knutti et al., 2016). Large swaths of our planet will suffer hell or high water or both.

Hypothetically, of course, humanity could scale up and generate sufficient green energy by covering hundreds of thousands of square miles in the world's major deserts with solar panels and then retooling up our electric grids. Landscapes would be created filled with solar panels and turbines as far as the eye could see, like cornfields in Iowa [*cf.* Robinson-Avila 2020h, 2021a, 2021b]. Here in the United States, we'd cover an area equivalent to at least two states and globally, the area of a medium-sized country. You just have to look at the figure at https://ourworldindata.org/energy-production-and-changing-energy-sources to see how far we have to go. Historically, it takes about three decades for a new energy to replace even 20% of

> what was used prior. How can we possibly go renewable globally (the operative word to make a difference) given this historical reality?
>
> In addition, humanity will also have to develop orders-of-magnitude more electrical storage capacity and find and mine up to ten times more rare elements than we now get from open pits or playa lakes to do the green energy. Humanity already has mined out the easy elements to find. Where will the rest come from?

E4.3. Past and Future Climates in Western North America and New Mexico

The following prescient inferences on regional hydrologic impacts of climate change and global warming in western North America is based on early computer modeling of Earth-atmospheric conditions by David S. Gutzler, Ph.D. (2005, p. 277):

> A computer model simulation of atmospheric conditions 18,000 years ago, during the last ice age, is compared with an ensemble of simulations of future climate warmed by increasing greenhouse gases. We consider whether the ice age simulation and the future "global warming" simulation present opposite climate anomalies in New Mexico compared to current climatic conditions. Not surprisingly, this turns out to be the case for temperatures in both winter and summer (colder 18,000 BP, warmer in the 21st Century). Simulated winter precipitation also exhibits opposite departures relative to current conditions: the ice age simulation shows more precipitation, consistent with a larger meridional temperature gradient across North America, whereas the global warming simulation is drier. Summer precipitation, however, is decreased relative to the current climate in both the ice age and the warmer climate. The combination of wet winters and cold summers in the Pleistocene is consistent with the existence of large lakes in Southwest North America at that time. If the future climate simulation holds true, with drier conditions in both winter and summer, then New Mexico could face quite difficult hydrological conditions that herald persistent drought [*cf.* Gutzler and Robbins 2011, Chavarria and Gutzler 2018, Gutzler 2020, Paskus 2020].

E4.4. "Climate Change and Aridification of North America" (*Excerpt from* Johnathan Overpeck and Bradley Udall, PNAS 2020)

> In the southwest United States and adjacent Mexico, the implications [of climate change] are dire for water security and ecosystems. More severe extreme heatwaves and dust storms are also already occurring, and these and other impacts of aridity will only increase until the cause is halted. Across North America, greater aridity is being offset with increased groundwater use, but this strategy has limits in the many places, such as the Southwest and the High Plains, where groundwater use exceeds recharge and is thus unsustainable [*cf.* Konikow and Leake 2014, Bryan 2020 and 2021, Davis 2020a-h, Paskus 2020, Williams et al. 2020a, Bennett et al. 2021].

E4.5. Climatologist: Dry Areas in Southwest getting drier – Precipitation declines as temperatures rise (Susan M. Bryan, ABQ Journal, September 27, 2020)

> It's another sign of dry times in the American Southwest, [when] New Mexico State Climatologist Dave DuBois said the fingerprints of climate change have become more evident as drought intensifies and temperatures rise. . . . DuBois said that part of the blame rests on a semipermanent high-pressure system over the West that has become stronger over time. The system has been keeping weather patterns from bringing moisture into the Southwest.
>
> 'We're actually seeing this pan out in our monsoons,' he said, noting it's a pattern shift that has been developing for more than a decade.
>
> 'There are other things that go on with the Pacific Ocean, but in general it's this longer term, big-scale change that we're seeing,' he said. 'The dry areas get drier and it's more erratic.'

From the Colorado River to the Rio Grande, water managers in the West are being forced to reconsider contingency plans as winter snowpack, spring runoff and summer monsoons become less consistent [*cf.* Fleck 2016, Fleck and Udall 2021].

Federal officials and local governments had to strike leasing agreements again this year to keep the Rio Grande flowing for an endangered minnow, and state officials reported this week that every reservoir in New Mexico is far below historical averages. The largest – Elephant Butte – is at 4% capacity, officials said.

Forecasters with National Weather Service offices in the Southwest and experts with [the] National Climate Prediction Center say there's little relief expected in the coming months as chances are better for below-average precipitation, continued drought and higher temperatures [Davis 2019a, Davis 2020a-i; Bryan 2021; Davis 2021a-c, e-h&j; Tebor 2021; Polich 2023a,b].

E4.6. In 50 Years: Hotter, Drier – New Mexico's changing climate spells uncertainty for water (Theresa Davis, ABQ Journal, Monday, July 23, 2021)

New Mexico temperatures will likely continue to climb over the next 50 years, state geologist Nelia Dunbar said this week — a change with major consequences for regional water supplies and landscapes.

Dunbar, the New Mexico Bureau of Geology and Mineral Resources Director, serves on the eight-member advisory panel crafting a "leap-ahead climate analysis" for the Interstate Stream Commission of what water supplies could look like in 2070.

"The question is not so much will (temperatures) increase, but by how much," Dunbar said during a video update on the state's long-term water plan.

New Mexico models show that annual average statewide temperatures could rise between 5 and 7 degrees Fahrenheit over the next 50 years, regardless of whether global carbon dioxide emissions rise or fall.

A warmer climate could impact nearly every aspect of New Mexico's water and land.

- Decreased aquifer recharge, more common and hotter drought periods, earlier winter runoff, greater groundwater demands and stress on plant life [*cf.* Meixner et al. 2016].
- Dry vegetation and catastrophic wildfires that could affect runoff and floodplain ecosystems.
- Warmer streams and rivers that could mean changing oxygen levels, which can disturb fish habitat [*cf.* Naishadham 2022].

"Likely the dominant impact on water quality going forward is going to be related to temperature increase," Dunbar said.

State law requires that the Office of the State Engineer update a water plan every five years. Gov. Michelle Lujan Grisham tasked the agency with creating a 50-year water plan with proposed adaptation strategies.

The advisory panel compiled climate and water data and projections into an 11-chapter report that is under review by other New Mexico and Arizona scientists.

Dunbar said the "science-based foundation" will help inform the water plan, and should be publicly available by the end of August.

The team found precipitation changes more difficult to predict than temperature, but concluded that New Mexico could see gradual declines in streamflow and snowpack as the state becomes more arid [*cf.* Davis 2021a-j, 2022a-d; Naishadham 2022]..

Temperature changes may not be uniform across the Land of Enchantment.

"The bottom line is that the northwest part of the state in the San Juan Basin area may experience the highest temperature increases over the next 50 years, whereas the Bootheel, the southwest part of the state, will experience some of the lower temperature increases," Dunbar said.

E4.7. Snowmelt and Upper Rio Grande Watershed Hydrology (Albert Rango, 2006)

Albert Rango, Research Hydrologist at the USDA, Agriculture Research Service (ARS) Jornada Experimental Range addressed water supply and conservation concerns from a source-watershed snowmelt perspective (2006, p. 99):

> The Rio Grande basin in Colorado, New Mexico, Texas, and Mexico is an important drainage in southwestern North America, vital for water consumption by a rapidly growing population, irrigated agriculture, economic development, preservation of endangered species, and energy generation. The most important source of water in the Rio Grande drainage results from snowmelt in the mountains of the upper basin. The gap between water supply and water demand is continually increasing as the population increases, and long term climate change further will affect the amount and timing of streamflow. The criticality of these problems will continue unabated through the 21st Century. Planning to cope with these water management problems needs to move now from relying on projections derived from current storage in reservoirs to additionally incorporating new technologies for measurements and hydrological modeling to allow the development of likely scenarios in both the short and long term. Models that can accept and integrate all types of measurements need to be utilized. Such models exist and are ready to be used operationally. Examples are given of both daily flow forecasts for an entire snowmelt season in the basin as well as predictions of future changes in streamflow to be expected under conditions of climate change. These types of data are vital in deciding among various future options which include the determination of the cost of water, controls on industrial and domestic development, new water distribution and storage systems, and the implementation of water conservation measures [*cf.* Western Water Assessment (WWA) 2008, Elias, Rango, et al. 2015, Lehner et al. 2017, Davis 2019a, Davis 2021a-c, e, g-i].

E4.8. Climate Change and Upper Rio Grande Watershed Hydrology (Creel, 2010)

Bobby J. Creel, Ph.D. (1943-2010), Associate Director of the NM WRRI, made these observations on "Research Needs in the U.S. Portion of the Rio Grande Watershed" (p. 33):

> Climate change is also likely to affect the availability of water in the future. Although existing climate models are an uncertain tool for estimating change, there is a growing consensus among researchers that precipitation will increase at higher latitudes and decrease in the subtropics as warming occurs [*cf.* Gutzler 2005, 2020]. As mean temperature increases, the volume of snowpack will decrease at higher elevations and snowmelt will occur earlier than in the past, causing an earlier release of water and greater losses (Seager et al. 2007 [2009]). Because the bulk of water supplies in the upper [RG] basin are obtained from snowmelt, any change in the timing of releases will have serious repercussions for management [*cf.* **Part E3.5.3**]. Despite the uncertainty associated with the results of climate forecasting models, simulations made from different assumptions have led to a consensus on several characteristics of the impact of climate change. There is widespread agreement that precipitation will become more variable and will create amplified variations in runoff and streamflow (Houghton 2004, Seager et al. 2007, Christensen et al. 2007). Associated with this increased variability will be an increase in the frequency of extreme events such as floods and droughts (Seager et al. 2007 [2009]*).*
>
> Climate modeling is an emerging science, and varying degrees of reliability characterize the forecasts of future change that are derived from climate models. The prognosis that there will be greater variability in precipitation leading to more floods and droughts is also reliable, and it is predicted with some confidence that rainfall will increase at higher latitudes and decline in the subtropical regions. However, accurate estimates of changes in the amount of precipitation in different regions and in different locales within regions are more difficult to forecast (Seager et al. 2007). New developments in hydrologic modeling will also be important. The response of

aquifers to changes in snowmelt and runoff patterns cannot be assessed with precision, although it is known that recharge is higher from snowmelt than from rainfall-generated runoff. Much remains to be learned about large-scale hydrologic processes and about the interrelationships between hydrologic and climatological processes. Advances in the physical sciences that underlie and explain the behavior of water resources will be critically important in the future [*cf.* Seager et al 2009].

E4.9. Where's the Snow? Rockies Winter Starts with a Whimper (Thomas Peipert and Brittany Peterson-ASSOCIATED PRESS, ABQ Journal, December 4, 2021)

DENVER — Denver's winter has started with a whimper, and the parched mountains to the west aren't faring much better.

The Mile High City has already shattered its 87-year-old record for the latest measurable snowfall set on Nov. 21, 1934, and it's a little more than a week away from breaking an 1887 record of 235 consecutive days without snow.

The scenario is playing out across much of the Rocky Mountains, as far north as Montana and in the broader Western United States, which is experiencing a megadrought that studies link to human-caused climate change. It's only the second time since 1976 that Salt Lake City has gone snowless through November, and amid the unseasonably warm weather in Montana, a late-season wildfire fueled by strong winds ripped through a tiny central Montana farming town this week.

The warm and dry weather has drawn crowds to restaurant and bar patios in Denver, and the city's parks and trails have been bustling with people basking in the sunshine in shorts, short sleeves and occasionally flip flops.

As enjoyable as the weather is, climate scientists and meteorologists are warning that prolonged drought could threaten the region's water supply and agriculture industry. It also could hurt tourism, which relies heavily on skiers, snowboarders, rafters and anglers.

"Every day that goes by that we don't see precipitation show up and we see this year-to-year persistence of drought conditions, it just adds to a deficit. And we continue to add to this deficit year after year, particularly in the Colorado River Basin," said Keith Musselman, a hydrologist at the University of Colorado-Boulder.

E4.10. Meeting the Challenges of Changing Climatic Conditions with "Resilience"

Architect and urban planner Jon Penndorf* offers a contemporary view on "Resilience" *in* "Adapting for the effects of climate change:" Urban Land (2018), v. 77, no. 3, p. 78:

> The prospect of a changing climate and the natural impacts that accompany it must be met by each of us. Resilience means working with—instead of fortifying against—nature and the greater community. Resilience requires us to understand the patterns of how the natural environment works. And it demands that we design a built environment that aligns with those mechanisms for the long-term viability of humanity's investment [*cf.* McHarg 1969, McPhee 1989].
>
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E5. AN ENVIRONMENTAL-GEOLOGIC PERSPECTIVE ON GROUNDWATER-RESOURCE CONSERVATION IN "DRY" REGIONS

Environmental geology: A specialty of geology concerned with Earth processes, Earth resources, and engineering properties of Earth materials and relevant to (1) protection of human health and natural ecosystems from adverse biochemical and/or geochemical reactions to naturally occurring chemicals or to chemicals or chemical compounds released into the environment by human activities, and (2) the protection of life, safety, and well-being of humans from natural processes, . . ., through land-use planning (Neuendorf et al. 2005, p. 212).

E5.1. The Nebulous Concept of Groundwater-Resource Sustainability (W.M. Alley, T.M. Reilly, and O.L. Franke, 1999, U.S. Geological Survey Circular 1186, p. 3)

Perhaps the most important attribute of the concept of ground-water [groundwater] 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 [*cf.* Alley and Leake 2004, Alley and Alley 2017].

E5.2. Arizona Perspectives on Groundwater-Resource Sustainability

E5.2.1. Robert Glennon (J.D., Morris K. Udall Professor of Law and Public Policy at the University of Arizona): Chapter 15 *in* Water Follies – Glennon 2002, p. 210-211; *cf.* E3.2

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.

E5.2.2. "Report raises alarms over Arizona's water supply" (Associated Press –ABQ Journal, Sunday, October 27, 2019 [*cf.* Part E1.1.3])

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 [*cf.* **Part 8.2.6**].
>
> 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], . . ., 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 [*cf.* **Part E2.1.2**]."

E5.3. Background on Groundwater Mining in Arid and Semiarid Regions

> **Groundwater Mining:** The process, deliberate or inadvertent, of extracting groundwater at a rate so in excess of the replenishment that the water level declines persistently, threatening exhaustion of the supply or at least the decline of pumping levels to uneconomic depths (Neuendorf et al. 2005, p. 286).

E5.3.1. Groundwater Mining – A Global Dry-Lands Perspective

Dr. Shmuel Mandel (1919-1995) of the Center for Groundwater Research at the Hebrew University, Jerusalem provides a global perspective on groundwater 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. . . [PI underlining for emphasis].</u>*
>
> **Dr. George Burke Maxey was the PI's Ph.D. research advisor at the University of Illinois from 1959 to 1962 (cf. Hawley et al. 1961, Hawley 1962, Hawley and Wilson 1965). He established the State of Nevada's Desert Research Institute's Hydrology Program in 1961 (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, Hackett 1972)."*

E5.3.2. Groundwater Mining – Southern New Mexico Perspective

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 observations by (then) New Mexico State Engineer, Steve Reynolds on "the mining of water" that apply to many parts of the southern New Mexico region beyond the Southern High Plains area (p. 91 and Footnote [89]):

> 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] *From 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 . . . 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 other areas 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.

E6. A WATER LAW PERSPECTIVE ON SURFACE-WATER AND GROUNDWATER INTERRELATIONSHIPS

Utton and Atkinson (1979) also provide a detailed Water Law perspective on surface-water/groundwater interrelationships in the US-Mexico border region (p. 91):

The Interrelationship of Surface [-waters] and Groundwaters

In the management of international groundwaters, it is essential to recognize the interrelationships between surface [-waters] and groundwaters which frequently are interconnected. Contrary to hydrologic reality, the law frequently has made distinctions which separate surface waters from underground waters and "percolating waters" from definite underground channels. These distinctions fail to recognize the interrelationships between surface and underground waters and have been characterized as attempts to restate the "physical universe [Thomas and Leopold 1964, Hayton 1978a, b]."

Scientists have criticized themselves and the law on this subject:

Man has coped with the complexity of water by trying to compartmentalize it. The partition committed by hydrologists--is as nothing compared with that which has been promulgated by the legal profession, which has on occasion borrowed from the criminal code to term some waters "fugitive" and others "a common enemy." The legal classification of water includes "percolating waters," "defined underground streams," "underflow of surface streams," "water-courses," and "diffuse surface waters;" all these waters actually are interrelated and interdependent, yet in many jurisdictions unrelated water rights rest upon this classification.

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 [R.E. Clark 1965 and 1978]. As [Harold] Thomas and Luna [Leopold] 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 [Thomas and Leopold 1964].

Thus, the [International Boundary and Water Commission] IBWC 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 [*cf.* Spiegel 1962]. 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 [1941], the State Engineer of New Mexico 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.

E7. NEW MEXICO WATER LAW AND WATER-RESOURCE MANAGEMENT

E7.1. New Mexico State Constitution

Water as a Unique Category (Tessa T. Davidson, J.D., 1998, p. 35)

. . . Water was placed in a unique category in our Constitution - something that cannot be said of lumbering, coal mining, or any other element or industry. The reason for this is of course too apparent to require elaboration. Our entire state has only enough water to supply its most urgent needs. Water conservation and preservation is of utmost importance. Its utilization for maximum benefits is a requirement second to none, not only for progress, but for survival.

E7.1.1. Water Rights Transfers (T.G. Bahr, Ph.D., Former NM WRRI Director, 1998, p. 34)

New Mexico is rapidly approaching the time when any new water uses will have to be accommodated by water transfers from existing uses. With well over 80 percent of current water use being consumed by the agricultural sector, there are increasing pressures for water transfers to occur from irrigated agriculture to municipal and industrial uses. New Mexico has enacted and administered a comprehensive body of water law which has served the state well for many years. There appear to be opportunities, through agricultural water conservation, to accommodate increasing municipal and industrial demands, but changes in policy are needed as incentives to do so. Developing more in-depth scientific information about the nature and extent of our water resources will continue to be a vitally important ingredient for the wise management of this important resource.

E7.1.2. Artificial Recharge and Prior Appropriation Doctrine (Tessa Davidson, J.D., 1998, p. 53)

For [GW] recharge to become a reality in New Mexico, state policy makers must examine the goals of groundwater replenishment within the context of the prior appropriation doctrine. In doing so, they must consider the appropriate balance of potential water savings against possible reductions in surface-flow requirements. To encourage using existing water rights for recharge activities, state law must explicitly recognize recharge as a beneficial use of water entitled to constitutional protection. Without such recognition, there is little incentive for widespread support of groundwater replenishment projects in New Mexico.

E7.2. Excerpts *from* "100 Years of Water Wars in New Mexico—1912-2012 (Catherine Ortega Klett, ed. 2012)"

E7.2.1. "Water Wars During Our Territorial Years;" John W. Hernandez (2012, p. 19-20)

Is Our Hispanic Ancestry a Root Source of Our Water Wars?

While not the fundamental problem, the answer is probably, yes. Our heritage of Iberian customs, in the management of scarce water resources, is certainly a contributing factor in our apparent tendency toward water conflicts. One look at the snow-capped mountains and arid, fruitless plains of Andalucía is enough to convince a New Mexican that, yes, this is where many of us came from, followed by an unvoiced certainty that water practices that were used in Spain came with us to New Mexico.

It should be noted that some parts of Spain followed slightly different water codes than others. Some regional differences prevailed. As southern Spain was the last stronghold of the Moors, we probably also inherited some of their customs and technology in designing and managing the early community ditches in New Mexico, the acequias, that were the backbone of much of the farming in our territorial days.

Elements of Spanish and Moorish practices that made it into New World water codes included: the ownership of water in a river belonged to the general public for their free use; the rights of existing water users to divert water from a stream were protected; the rights to use water were tied to the land where application was made; canal systems belonged to those who built them, and right-of-way to ditch for construction and maintenance was guaranteed; these ditch owners annually prescribed their own rules for scheduling cleaning and maintenance of the ditch and the times, amounts, and methods of water diversions from the acequia to farm fields; water use was limited to beneficial purposes; and limits were placed on upstream diversions to that which was absolutely needed. In some areas, constraints were probably imposed on developments of springs, seeps, and shallow groundwater.

E7.2.2. "Ready to Fight: Steve Reynolds-Institution-Engineer-Litigator;" John W. Hernandez (2012, p. 52-53)

At Statehood, Were the People of New Mexico the Problem?

Maybe. You might make the case that our relatively recent background as pioneers was responsible for at least a part of our proclivity to "fight" over water in those early years. Is it fair to say that we are different and more likely to be involved in a fight over the right to use water, than are our other western neighbors? Arizona, Colorado, and Texas don't seem to have their supreme courts involved in as many water conflicts as we do.

And what state, other than a "ready to fight over water" bunch would include the heart of their water code in the state constitution? Other states may have done it, too, but our grandfathers thought it important enough to put the core of our water law in our 1912 constitution:

Article XVI Irrigation and Water Rights:

Section 1. All existing rights to the use of any waters in this state for any useful or beneficial purpose are hereby recognized and confirmed.

Section 2. The unappropriated water of every natural stream, perennial or torrential [i.e. intermittent and ephemeral], is hereby declared to belong to the public and be subject to appropriation for beneficial use... Priority of appropriation shall give the better right.

Section 3. Beneficial use shall be the basis, the measure and the limit to the right to the use of water.

Water wars are still going on in New Mexico even though the words in the state constitution seem straightforward and easy to understand. But the record says something different. After 90 years of statehood, the state's higher courts had already rendered 160 opinions in water cases, almost two a year. That's just the state court cases; interstate conflicts go to the federal courts where we also have had more than our share. Some federal water rights adjudication cases in New Mexico have gone on and on. These cases did not just involve legal conflicts among water users; other factors seemed to have been involved. The folks that came to New Mexico were by nature a scrappy bunch, particularly those charged with the protection of the little water that we do have. . . .

E7.2.3. Adjudications: Managing Water Wars in New Mexico (Judge Gerald A. Valentine, 2012, p. 30-31)

When precipitation returns liquid water to the land surface of the earth, or snow and ice melt at elevations above the oceans, the water takes the path of least resistance as it flows downhill. If the geologic condition of the land on which the precipitation flows is impermeable, the path of least resistance will be primarily on the surface. If the geologic condition of the land is permeable, some of the water ordinarily will result in surface runoff with some water sinking beneath the surface and continuing underground as part of the entire stream system. . . . Groundwater that flows underground as a part of a stream system is hydrologically connected to the part of the stream that is flowing on the surface.

Reduction of the surface water by diversion to farmlands or other beneficial uses may, over time, impact the groundwater, and reduction of the supporting groundwater underlying a stream by pumping wells may, over time, impact the surface water. The amount of time it takes for reduction in one to affect the other depends on the amount of water removed from the stream system, the slope of the terrain, the permeability of the soil (the resistance of the soil to flow), the distance from the location of the sites where the water is diverted, and loss of water from the stream through evapotranspiration. Evapotranspiration is the water lost to the atmosphere by two processes: evaporation and transpiration. Evaporation is the loss of moisture from open bodies, such as lakes and reservoirs, wetlands, bare soil, and snow cover. Transpiration is the loss of moisture from living plant and animal surfaces. . . .

Groundwater may be trapped in basins created over geologic time that are not connected to any stream flow, and hence are neither naturally part of the hydrologic cycle nor recharged. Taking water from a basin that is not recharged through the hydrologic cycle is similar to mining a mineral: once it is depleted, it may be gone forever [*cf.* **E1.2**].

Water is substantially different from any other natural resource in that use for one purpose at a given time and location does not necessarily displace its use elsewhere, or at a later time, for the same or another purpose. Water can be used many times as it moves downstream. After water has been used for one purpose, irrigation for example, the same water can return to the stream either as surface or hydrologically connected groundwater. The return flow contributes to recharge the stream. It could conceivably irrigate several crops before it reaches the oceans and begins the hydrologic cycle anew.

E7.2.4. Future Water Wars in New Mexico (M. Karl Wood, Ph.D., Former NM WRRI Director, 2012, p. 264-265)

It appears in water meetings in this region that local water engineers, hydrologists, economists, and lawyers are as well informed and competent as those from state agencies in Santa Fe. The major Lower Rio Grande water providers are linked in an organization called the Lower Rio Grande Water Users Organization. One of the group's functions is to serve as a watchdog on dealings in this region by outside interests. The organization is always suspicious of divide-and-conquer tactics, such as the state engineer making generous offerings-of-judgment to the City of Las Cruces and New Mexico State University in the adjudication before offerings to Elephant Butte Irrigation District are completed. Other suspicious tactics include offerings-of-judgment to pecan growers that are much greater per acre of farmland than to farmers of other crops. This creates great consternation within the region.

Some of the climate change models predict long and severe droughts for New Mexico. With or without human influence, droughts invariably will happen, always sooner than we would like. Drought could result in a priority call on the Lower Rio Grande that could cause turmoil, as the junior water rights holders are often the most affluent, which means they can hire the lawyers. The 1906 treaty with Mexico contains a provision where Mexico's allotment is reduced in times of extraordinary drought. This term "extraordinary drought" has never been defined. It could bring pressure to adjust the treaty. Long and severe drought could also make it difficult to deliver water to Texas, as groundwater pumping could severely affect the flow of the river. . . .

E8. BINATIONAL AND INTERSTATE CONVENTIONS AND COMPACTS

E8.1. "A Grand River" *from* "Whose water is it anyway? Anatomy of the water war between El Paso, Texas and New Mexico" (Linda Harris, 2012, p. 229-230)

The very nature of water makes it an elusive subject at best. Because it honors only geologic boundaries and the laws of hydrology, water can complicate man's most reasoned attempts at regulation. That is particularly true in this corner of the Southwest where El Paso and New Mexico share common hydrological resources. The region receives some 8 inches of precipitation a year, mostly during July and August. Early on, farmers had laid claim to the surface waters of the Rio Grande for irrigation, leaving cities like El Paso and Las Cruces forced to depend upon groundwater aquifers for their municipal needs. When the river runs low, farmers also tap into the aquifers for supplemental irrigation [*cf.* Bryan 2023].

Although El Paso's legal battle was over rights to groundwater in New Mexico, the Rio Grande and its underflow dominate the overall water supply picture. The river, which begins as snowmelt, winds its way through the San Luis Valley in southern Colorado, pure and blue as the sky. . . . At El Paso it angles southeast until it reaches the Gulf of Mexico, a meandering 1,800-some miles from its headwaters in Colorado. While today's Rio Grande hardly lives up to its "grand river" title (the flow of the Colorado River is 17 times greater), it reigns as the region's only renewable water supply.

For most of its history the region's most important river also has been most unpredictable. Historically the Rio Grande was a shallow meandering river during the winter. But heavy spring snowmelt and summer storms could quickly send the river overflowing its low banks, creating a floodplain as much as five miles wide in parts of the Mesilla Valley. During the flood of 1865, the Rio Grande dramatically altered its course through the valley. During the flood, the river cut a new course west of Mesilla, leaving the village situated on the river's east bank. El Paso experienced a similar boundary shift in 1867 when the flooding Rio Grande changed its course and moved south into Mexico. The new channel created an island, known as the Chamizal, between the old river border and Mexico. The Chamizal boundary dispute was finally settled in

> 1963 when both nations signed an agreement dividing the land between them (*cf.* **APPENDIX H, Part 3.6**).
>
> Every ten summers or so, the river also ran dry, with droughts sometimes lasting several months. The drought of 1879 was so severe that farmers in Las Cruces abandoned some 2,500 acres of farmland for lack of irrigation water. Demands on the river had increased so much following the Civil War that by 1880, farmers were irrigating nearly every piece of farmland along the Rio Grande in Colorado and New Mexico. By the 1890s, upstream irrigators were taking so much water from the river that farmers downstream in the Mesilla and El Paso valleys as well as in Mexico sued for a guaranteed share of the Rio Grande. In order to allocate the shares, the U.S. Bureau of Reclamation started the Rio Grande Project, which furnishes irrigation water for about 178,000 acres of land. Part of the project included Elephant Butte Dam, which was completed in 1916 to store water for downstream users. Below Elephant Butte and Caballo dams, the Rio Grande now follows a course laid out by the Bureau to control flooding. Also, because of its importance to the region's economy and the number who share its supply, the water is released from the reservoirs according to treaty obligations to Mexico, provisions of contracts entered into between the irrigation districts in the Rio Grande Project, and other legal and legislative mandates.

E8.2. Convention between the United States and Mexico on Equitable Distribution of the Waters of the Rio Grande – Proclaimed, January 16, 1907 (United States and Mexico, 1907, Washington, DC; U.S. Government Printing Office, 3 p.)

> **PROCLAMATION by the President of the United States of America (p. 1)**
>
> Whereas a Convention between the United States of America and the United States of Mexico, providing for the equitable distribution of the waters of the Rio Grande for irrigation purposes, and to remove all causes of controversy between them in respect thereto, was concluded and signed by their respective Plenipotentiaries at Washington on the twenty-first day of May, one thousand nine hundred and six, the original of which Convention being in the English and Spanish languages, is word for word as follows:
>
> The United States of America and the United States of Mexico being desirous to provide for the equitable distribution of the waters of the Rio Grande for irrigation purposes, and to remove all causes of controversy between them in respect thereto, and being moved by considerations of international comity, have resolved to conclude a Convention for these purposes . . .
> [*cf.* Hundley 1966, Littlefield 2000].

Article I of the "Convention" also specified that: "After the completion of the proposed storage dam near Engle, New Mexico (**Part E7.3**), and the distributing system auxiliary thereto, and as soon as water shall be available in said system for the purpose, the United States shall deliver to Mexico a total of 60,000 acre-feet of water annually in the bed of the Rio Grande at the point where the head works of the Acequia Madre, known as the Old Mexican Canal, now exist above the city of Juárez, Mexico (*cf.* Kelley et al. 2007, p. 538)."

E8.3. Elephant Butte Dam and Reservoir

Elephant Butte Dam, as it was formally named, was completed on May 13, 1916. In an address at the dam's dedication on October 19, 1916, Arthur P. Davis, Director and Chief Engineer of the Reclamation Service, reviewed the reasons for its size and great storage capacity (Kelley et al. 2007, p. 539):

> There were evidences in the records - which were of considerable extent - that some years only about 200,000 acre-feet of water were discharged in this river and that in other years more

than 2,000,000 acre-feet were discharged. Sometimes a series of those dry years occurred together, and at other times more than one of those wet years occurred in a series; and, looking over the ground and having studied that water supply, I made up my mind that the full utilization of this water supply could not be obtained without a reservoir of immense dimensions - one large enough, first, to hold the waters of those great years when 2,000,000 acre-feet were discharged, and to provide for evaporation and hold that water here until a dry year should come. . . [*cf.* Davis 2021e-f].

E8.4. The Rio Grande Project (Clyde Conover 1954, p. 17)

The Rio Grande Project (RGP) of the Bureau of Reclamation includes most of the valley lands of the Rio Grande in New Mexico and Texas from Caballo Dam southward to a point about 40 miles below El Paso, a distance of about 130 miles (**Fig. E8-1**). From Caballo Dam to Selden Canyon, a distance of about 30 miles, the Rio Grande flows in the Rincon Valley, which has a maximum width of about 2 miles. Below Selden Canyon the valley floor widens into the Mesilla Valley, which extends about 55 miles southeastward to "The Pass [EPdN]," 4 miles above El Paso. The Mesilla Valley is one of the larger widened areas along the Rio Grande and has a width of about 5 miles near Las Cruces. The El Paso Valley extends about 90 miles south[east]ward from El Paso and ranges in width from 4 to 6 miles, but only the upper 40 miles is included in the Rio Grande Project.

The water for the Rio Grande Project is stored in Elephant Butte Reservoir, which has a capacity of 2,197,600 acre-feet, and in Caballo Reservoir, which has a capacity of 345,870 acre-feet, about 28 miles below Elephant Butte Dam. Water released from Caballo Reservoir is diverted into canals in the Rincon Valley by Percha Dam, about 2 miles below Caballo Dam; in the Mesilla Valley at the head of the valley and by Mesilla Dam, about 5 miles southwest of Las Cruces; and in the El Paso Valley by the American Dam, about 3 miles northwest of El Paso. Water for the Mexican side of the El Paso Valley, generally referred to as the Valle de Juárez, is diverted at the International Dam, about 2 miles below the American Dam.

E8.5. The IBWC Rio Grande Canalization Project (Andrea Glover, IBWC, 2018, p. 63)

The levees [between Caballo Dam and El Paso] are owned, constructed, and maintained by the United States Section of the International Boundary and Water Commission (originally named International Boundary Commission (IBC) but name was changed to International Boundary and Water Commission with the Treaty of 1944 [*cf.* Sandoval Solis, 2011]. The levees, river, and floodplain fall under International Boundary and Water Commission's (IBWC) Rio Grande Canalization Project. The project extends along the Rio Grande from Percha Dam, just south of Caballo Dam in Sierra County, to American Dam and Canal in El Paso, TX [**Fig. E8-1**]. These levees exist because of a treaty with Mexico [**Part E7.2**]. The Convention of 1906 (34 Stat. 2953) requires that the United States (US) deliver an annual appropriation of water to Mexico at their Acequia Madre headgates in El Paso, TX (IBC, 1936, p. 2) and while the US Government owns Elephant Butte and Caballo Dams, prior to the Canalization Project they did not own the river channel. Measuring treaty water deliveries was almost impossible because of private water diversions along the 125 river mi (201 km) in the US. The unregulated flows also allowed Mexico to sometimes exceed their allotment (IBC, 1936, p. 3). Public Resolution No. 648, Act of June 4, 1936, authorized the canalizing of the Rio Grande from Caballo Dam, NM, to El Paso, TX. Construction began on January 15, 1938 and was completed in February 1943 (History and Development of the International Boundary and Water Commission, unpubl. report, revised 1954). The project was meant to establish a normal flow and flood channel confined between parallel levees sized to carry the estimated maximum flood flows (IBC, 1935, p. 5). When the initial project was complete, 125.92 mi (202.6 km) of levee were constructed, almost 3300 ac

(1334 ha) of floodway were leveled, the river was shortened by approximately 10 mi (16 km), and 7395 ac (2993 ha).

E8.6. The 1938-39 Rio Grande Compact (Kevin Flannigan 2007, p. 518-519)

The Rio Grande Compact, an interstate agreement that apportions waters of the Rio Grande between the states of Colorado, New Mexico, and Texas, was executed in 1938 and became effective in 1939. Under the Compact, New Mexico is allowed to consume on average roughly twice as much water as Colorado and three times as much as Texas. New Mexico's share includes the amount of water it is entitled to consume between the Colorado-New Mexico state line and the Otowi gage, the amount in the Middle Rio Grande valley between Otowi gage and Elephant Butte Reservoir (including all tributary inflow and San Juan-Chama Project water), and the amount in the Elephant Butte Irrigation District below Elephant Butte in the Lower Rio Grande [*cf.* Littlefield 2000 (p. 21-28), Ortega Klett 2000, Theresa Davis 2022d, and Tony Davis 2022].

There are a number of Compact restrictions that have an impact on reservoir operations and surface water management in the Middle Rio Grande valley. The most important is Article VII, which prohibits increasing storage of native Rio Grande water in any upstream reservoir constructed after 1929 when the combined storage in Elephant Butte and Caballo reservoirs, not including credit and San Juan-Chama Project water, is below 400,000 acre-feet. . . .

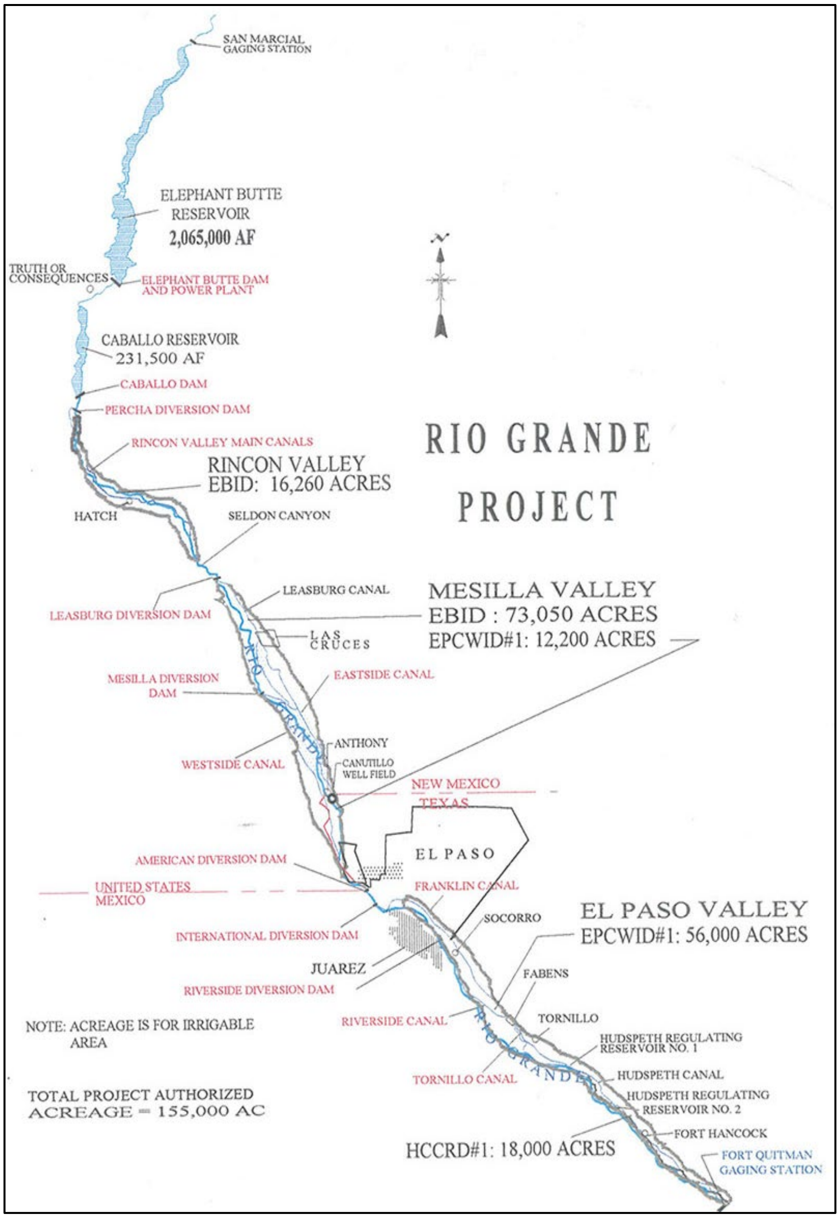

Figure E8-1. U.S. Bureau of Reclamation Map showing locations of major components of the Rio Grande Project between the San Marcial (removed 1964) and Fort Quitman Gaging Stations. EBID: Elephant Butte Irrigation District (map courtesy of Rhea Graham; *cf.* USBOR 2011).

E8.7. Water Politics in Southern New Mexico—Gary L. Esslinger (1998, p. 101-102)

> On June 15, 1918, the Elephant Butte Water Users Association entered into an agreement with the United States and the Elephant Butte Irrigation District where the Water Users Association dissolved and the irrigation district assumed the liability for distribution and drainage works. In addition, the District received an assignment of all of the association's assets and rights.
>
> The United States agreed to release the individual shareholders and the lands of the shareholders of the association from liens on their property as security for the repayment of the construction obligation once the District assumed the obligation for repayment of the construction of the Rio Grande Project [**Fig. E8-1**; Esslinger 1996].

> Congress contemplated under the Reclamation Act, that when the District completed repayment of its allocated construction costs for the Project in 1973 the United States should no longer be the record holder of the Project water rights. Their rights in the water rights were extinguished with payout. The priority dates for the Project water supply relate back to the dates in filings by the United States in 1906 and 1908. The River Alluvium which underlies the Rio Grande and which forms the supply for many shallow wells located within the District is part of the Project supply. The full irrigation of the Project lands within this region was the intent and purpose of the appropriations.
>
> Throughout the history of the Project, there has been an increasing use of groundwater to supplement the supply of surface water available from the Rio Grande. This use of groundwater commenced at least as early as 1940s and probably earlier. In the early and mid-1950s, the Rio Grande Project in New Mexico suffered water shortages because of a series of droughts in the watershed of the upper Rio Grande in Colorado and New Mexico and because of the up-stream use of water in excess of Rio Grande Compact entitlements. This severely impaired the ability of the members of the irrigation district to continue to grow crops with surface water, and led to increased groundwater pumping in the early and mid-1950s. Most of these wells have been drilled into the shallow aquifer which constitutes the Rio Grande alluvium, and others have been drilled into the underlying aquifer known as the Santa Fe Formation [Group]. These wells have been used, replaced, and supplemented by additional wells for the same purposes over the years [*cf.* Bryan 2023].
>
> The surface water delivery within the District contributes tremendously to the recharge of the River Alluvium and Santa Fe Formation [Group] in the Lower Rio Grande. Each owner of water-righted land of the District is entitled to water the acreage listed in their contract based on available Project water supply. . . .
>
> The District will defend the right of its Water users to have delivered and use all of the Project water supply that the 90,640 acres of water-righted land within the District is entitled to use. Additionally, the District will defend any and all attempts by federal or state agencies to obtain or use the District's share of Project water for purposes that do not benefit its water users.

E8.8. Management of Shared, Interstate-Water Resources—Progress and Pitfalls after 1980

A second excerpt from "Whose water is it anyway?" (Harris 2012, p. 249) provides an appropriate introduction to the discussions in **Parts E8.8.1** and **E8.8.2**:

> On Sept. 5, 1980, El Paso took the first step along a legal route it hoped would lead to a plentiful and free water supply from New Mexico. On that Friday after Labor Day, the city of El Paso, through the Public Service Board, filed suit in US District Court in Albuquerque against Steve Reynolds individually as the New Mexico state engineer, and also New Mexico Attorney General Jeff Bingaman and the New Mexico district attorney for Doña Ana County. The city sought to overturn New Mexico's embargo statute as violating the Commerce Clause of the US Constitution. The embargo statute, enacted in 1953, prevents anyone from drilling wells in New Mexico and transporting the water outside the state.
>
> By September 12, New Mexico State Engineer Steve Reynolds declared both the Mesilla Basin and the Hueco Bolson under state authority. El Paso responded quickly by filing well applications for 246,000 acre-feet a year in the Mesilla Basin***** and for 50,000 acre-feet a year in the Hueco Bolson.
>
> ********USGS hydrologist Clyde A. Wilson, the leading expert on Mesilla Basin and Lower Rio Grande Valley water-resource matters, died unexpectedly on October 11, 1980 at an age of 48!** . . . .*
>
> The state engineer denied all of El Paso's applications on grounds that New Mexico statute

prohibited the transfer of water across the state line. El Paso took its case before US District Court Judge Howard Bratton in January 1982. In July of that year the US Supreme Court ruled that groundwater was to be considered an article of commerce and as such its transfer across state lines could not be restricted. In January 1983, Bratton ruled in favor of El Paso on all accounts, writing that New Mexico's embargo violated the Commerce Clause of the US Constitution because it promoted New Mexico's economic advantage.

E8.8.1. Feedbacks of irrigator decisions, hydrologic change, and long-term water planning, Mesilla Valley—Beene and others (2020)

Facing a cacophony of environmental, social and economic changes, many Mesilla Basin farmers have transitioned over the last 20 years away from traditional crops and irrigation to large-scale pecan farming. We synthesize the drivers of the decisions leading to – and the physical hydrologic feedbacks caused by – these changes. As legally-binding interstate and international delivery requirements were complicated by megadrought, the availability of usable river water has declined and groundwater use has increased. Simultaneously, market demand and perceived benefits from achieving a higher adjudicated water right have led to an increase in water-intensive irrigated crop acreage. An analysis of basin-scale groundwater levels estimates that 0.5 Maf of groundwater was removed from storage during this period. The falling groundwater levels induced by groundwater extraction and reduced recharge stressed the connectivity of river-groundwater interaction, decreasing the efficiency of delivering available surface flows in the river. In response to these unintended feedbacks, community organizations, such as EBID, have worked to help find a resilient path forward. Moving forward, short-to-mid-term decisions by irrigators that center on economic and legal realities may be supported by long-term planning by community organizations focusing on physical hydrology and the legal system, leading to stable water tables [*cf.* Davis 2021a-c, g-j].

E8.8.2. Confronting water shortages on the Lower Rio Grande—Gary Esslinger (2021)

State Representative Dow called a meeting on May 7th in Truth or Consequences, NM. It was a hybrid zoom meeting where Federal, State and local businesses met to discuss the crisis building up at Elephant Butte (EB) reservoir as the summer progresses and storage levels drop to record lows, maybe as low as 10,000 ac/ft. and heaven forbid a fish kill. In attendance were the [Rio Grande] Compact Commissioners from NM and Texas, Bureau of Reclamation and State Parks officials, MRGCD and EBID were present along with the Marina owners and local business operations. Staffers from the Congressional offices also listened to the discussion.

The meeting was centered around the historic operations of the Compact and how the debit and credit accounting could play a factor in help keeping a minimum pool if the three Compact states could agree. Everyone’s input was focused on their needs and certainly it all boiled down to there is no water available anywhere on the river for anyone to give up to help what could appear as a crisis situation unless the upcoming monsoon season provided some relief.

History has a tendency to repeat itself and it was pointed out that in the early 50’s and even in the 70’s, lake levels dropped even lower than anticipated for this coming year.

It was clear to everyone that more long-term planning had to be initiated to prevent levels to drop to such a low and it would take a tremendous amount of negotiating under the Rio Grande Compact accounting methods as well as with upstream and downstream users to coordinate a workable plan.

Representative Dow suggested that each agency in attendance provide a list of recommendation to stabilize storage levels in all the NM reservoirs and the cost benefits that could be presented to the State Legislators as well as the Congressional Delegation in DC to provide for Water infrastructure funding being contemplated in Congress and the next NM legislative session.

The uncertainty of spring runoff and current minimum inflows into EB presents a problem to predict the final level of storage at EB reservoir at the end of the summer, but it was the consensus of the group that as much water as possible should remain tin EB rather than spread out in Caballo reservoir below.

FYI: EBID is forecasting a 4" inch/acre allotment to its farmers this year and that spells out about a 35 day irrigation season and we are finished for the season. We will start up on June 1st and probably run out of our surface water allotment the first week of July. Pray for Rain!

E8.8.3. Importing water to NM? Challenges are stunning (Bruce Thomson, Ph.D., P.E., 2023)

We must recognize that multistate interbasin transfers quickly become impractical when factoring in the water demands for all participants.

The volumes of water in the Missouri River, Atchafalaya River and other North American rivers are large, but they are nowhere near sufficient to meet the demands of the arid West. We simply need to learn to live with what we've got, accept the fact that future shortages are inevitable, and then manage this most precious resource wisely and equitably (p. A3)

E9. POTENTIAL FOR LONG-TERM GROUNDWATER-RESOURCE DEVELOPMENT IN THE UNITED STATES PART OF THE MESILLA BASIN REGION

E9.1. Background

Figures E9-1 to **E9-3** illustrate major water resource-related features in the tristate-binational Mesilla Basin region (MBR). All were compiled by Swanson Geoscience, LLC, with the first two on a 2017 Google Earth® image-base, and the third on a **PLATE 1** (DEM) hydrogeologic-map base. Water resource-related issues in Chihuahua, Mexico are discussed in detail in **APPENDIX H**.

Figure E9-1 is an index map of the MBR that shows locations of the NM WRRI Study Area (beige rectangle), major landscape features in the northern Mexican Highland section of the Basin and Range province, and basins of the southern Rio Grande (RG) rift tectonic province (*cf.* Hawley 2005, 2020). Blue shading shows the approximate extent of the areas inundated by pluvial-Lakes Palomas and Otero at their respective Late Pleistocene high stands between 29,000 and 12,000 years ago in the "Los Muertos (El Barreal)" and Tularosa Basins of Chihuahua and New Mexico.

Figure E9-2 (page-size **PL. 8A**) is a northeast-facing block diagram of the southern Mesilla Basin, with its southern panel at 32˚ North Latitude. It schematically portrays major RG-rift stratigraphic and structural features to a base elevation of 25,000 ft (~7.6 km) below mean sea level (msl). Inset cross-section I-I′ is one of 19 hydrogeologic sections that show lithofacies, hydrostratigraphic, and structural relationships to a base elevation of mean sea level. It also depicts major components of the deeply buried Mid-Basin High in the area of the Lanark igneous-intrusive complex of Oligocene age. 2017 Google Earth® image base.

Figure E9-3 (page-size **PL. 4A**) is an index map for major geohydrologic features of the Study Area. The respective Mesilla, southern Jornada, and El Parabien GW Basin boundaries are in green, orange and violet. The approximate pre-development (1976) potentiometric-surface altitude (amsl) is shown with thin-blue 20- and 100-ft contour lines (U.S. database from Wilson et al, 1981). Major surface-watershed divides are shown by solid and dashed thick blue lines. The dashed blue line with arrows in the map's SW corner shows the approximate position of the regional GW-flow divide between El Paso del Norte-directed and "Los Muertos (El Barreal)"-directed underflow (*cf.* Rpt. **Part 7.6.2**).

E9.2. Sustainable Groundwater-Resource Development in a Mesilla Basin Regional Context

Predicting impacts of long-term groundwater (GW) development of the Mesilla Basin region (MBR) remains problematic, particularly since river-sourced aquifer recharge is dependent on the presence of a relatively small perennial "post-dam" Rio Grande (*cf.* Rpt. **Part 7.4.1**—Conover 1954, Wilson et al. 1981, Ackerly 1999). Circumstances contributing to uncertainty in predictions of future GW-resource availability include:

1. A physiographic setting in an arid region where the finite surface- and subsurface-water resources are subject to increasing anthropogenic and climatic stresses (**Parts E3** to **E5**; *cf.* Phillips et al. 2011, Paskus 2020).
2. The myriad impediments associated with binational and tristate issues of a legal, political, and socio-economic nature in a region with an urban-suburban population approaching 2 million…
3. Present lack of flexibility in management of Rio Grande Project (RGP—**Fig. E8-1**) irrigation water in terms of maximum GW- recharge efficiency (Esslinger 1998, 2021).
4. Current absence of realistic assessment of the enormous costs (monetary and temporal) that will be required for successful implementation of any plans for large-scale groundwater-resource development in the near future (e.g., Archuleta 2010).

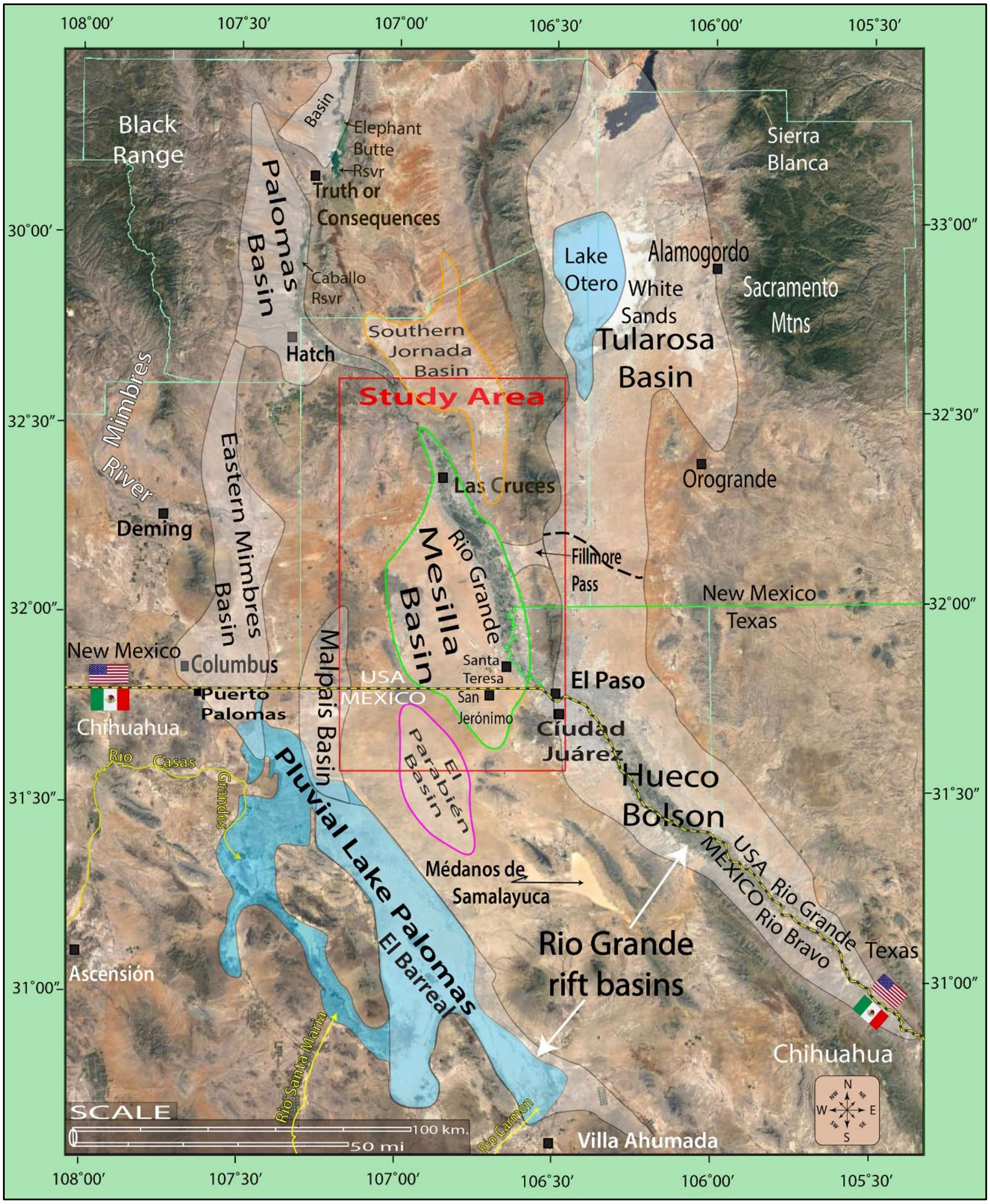

Figure E9-1. Index map of the Mesilla Basin region (MBR) showing locations of the NM Water Resource Research Institute Study Area (beige rectangle), major landscape features in the northern Mexican Highland section of the Basin and Range province, and basins of the southern Rio Grande (RG) rift tectonic province (Hawley 2005, 2020). The Mesilla Valley (MeV) of the Rio Grande occupies much of the eastern Mesilla Basin. Blue shading shows the approximate extent of the areas inundated by pluvial-Lakes Palomas and Otero at their respective Late Pleistocene high stands in the "Los Muertos (El Barreal)" (Chih.) and central Tularosa (NM) Basins. Swanson Geoscience LLC compilation on 2017 Google Earth® image base.

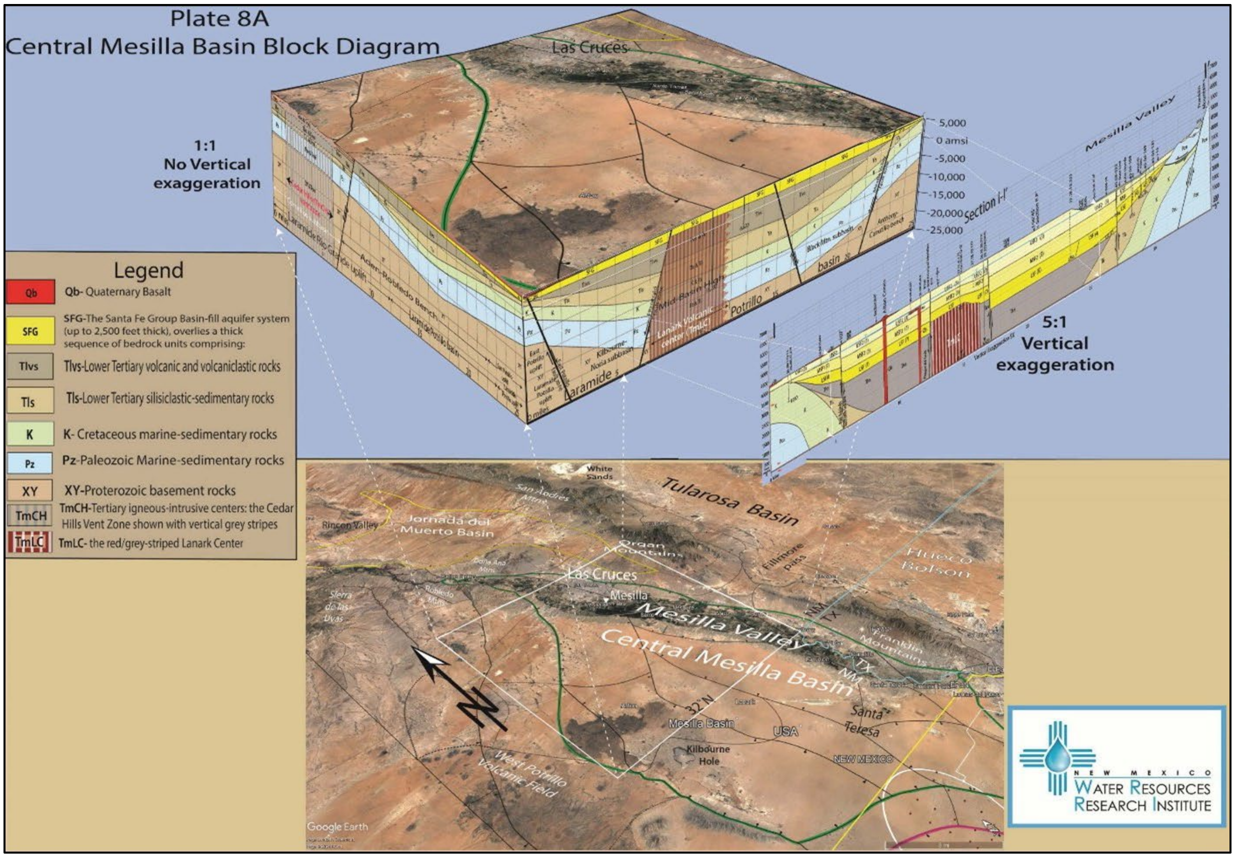

Figure E9-2. (page-size **PLATE 8A**) Northeast-facing block diagram of the southern Mesilla Basin, with its southern panel at 32˚ North Latitude. It schematically portrays major RG-rift stratigraphic and structural features to a base elevation of 25,000 ft (~7.6 km) below mean sea level (msl). Inset cross-section I-I′ is one of 19 hydrogeologic sections that show lithofacies, hydrostratigraphic, and structural relationships to a base elevation of mean sea level. It also depicts major components of the deeply buried Mid-Basin High in the area of the Lanark igneous-intrusive complex of Oligocene age. 2017 Google Earth® image base.

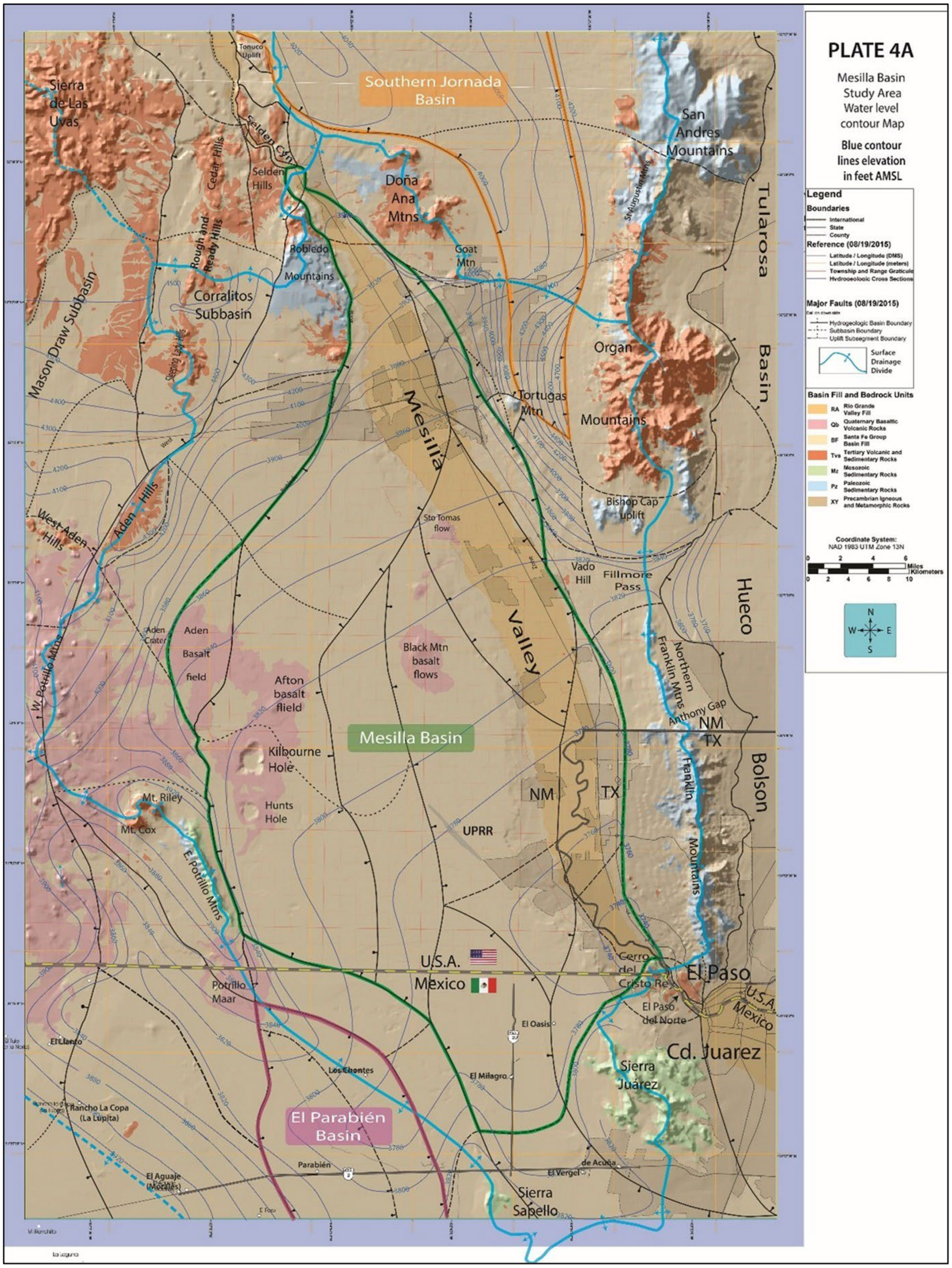

Figure E9-3. (page-size **PL. 4A**) Index map to major geohydrologic features of the binational NM WRRI Study Area. Major surface-watershed divides are shown by thick blue lines; and thin blue lines show the ~1976 potentiometric-surface altitude in feet amsl (20- and 100-ft contour intervals). Swanson Geoscience LLC compilation.

Application of the conceptual models of groundwater (GW) *sustainability* and *conservation* throughout the upper Rio Grande basin is obviously a *subjective* process, especially in the MBR. *Opportunities* for and *challenges* to effective water-resource management in this Chihuahuan Desert terrain involve: (1) the complex iterative process of hydrogeologic-framework characterization; and (2) evaluation of an ever-increasing number of anthropogenic factors that influence GW flow and chemistry. Nonetheless, economically and environmentally viable opportunities for prudent long-term GW-resource development remain available (*cf.* Rpt. **CHAPTER 8**). For example:

1. The large extent and great thickness and Santa Fe Group (SFG) basin-fill deposits.
2. The very large quantity of fresh to moderately brackish water (~500 to 5,000 mg/L TDS) that is stored in the SFG aquifer system.
3. The major aquifer-recharge role played by Rio Grande Project (RGP) waters.
4. The readily-available material infrastructure involved in RGP and agricultural-irrigation activity.
5. Many optimum locations for managed aquifer-recharge (MAR) activity.
6. Many optimum locations for desalination-plant and concentrate-management facilities.
7. Many optimum locations for a) solar energy development, b) additional use of natural gas electric-power generation; c) potential wind- and geothermal-energy projects; and d) possible hydrogen-fuel generation facilities.
8. With respect to the region's long history irrigation agriculture and water-resource conservation, moreover, a rarely mentioned non-material resource continues to be available for meeting many future water-related challenges—namely the multi-generational Human infrastructure that has existed in the MBR since establishment of the *Brazito [Bracito] Land Grant* (south of Las Cruces) in the early 19th Century, and the founding of *El Ancón de Doña Ana* Colony in 1839 (Julyan 1996, p. 49 and p. 112-113; Dailey 2021, p. 4-5; *cf.* **Parts E8.8** and **E8.9**).
9. New (2024) Department of Interior $60 million investment "to address drought resiliency in the Rio Grande south of Elephant Butte" Reservoir (Cook 2924; *cf.* **Fig. E 8-1**).

Beyond the inner valley of Rio Grande, the primary source of aquifer replenishment is water stored in Santa Fe Group (SFG) basin-fill deposits and a few subjacent bedrock units. As such, much of the GW is brackish (*cf.* Stanton et al. 2017), and only effectively recharged with fresh (<1,000 mg/L tds) water, during glacial/pluvial cycles with multi-millennial periodicity. For example, most of the recharge to the aquifer systems of the MBR occurred more than 12,000 years ago during Late Pleistocene high stands of pluvial-Lake Palomas *(***Figs. E9-1** and **E9-2**). Sand-dominant, Ancestral Rio Grande (ARG) channel deposits in upper part of the SFG comprise the primary aquifer component that stores and transmits this "Ice-Age" GW in the MBR (Garcia-Vasquez et al. 2022, Hawley and Swanson 2022).

E9.3. Conjunctive Management of Surface-Water and Groundwater Resources in the MBR

The Rio Grande in the Mesilla Basin region (MBR) is now subject to a large number of dams and diversions (**Fig. E8-1**); but even in an era of major urban/suburban expansion, this somewhat diminished fluvial *umbilical cord* continues to sustain the surface-flow and GW-recharge systems in all river-valley reaches downstream from Elephant Butte Reservoir (*cf.* Rpt. **Parts 3.2.3** and **8.5**). For example, the extensive network of canals, ditches, laterals, and drains that occupies much of the Mesilla Valley floor still serves as an effective replacement for the river's initial hydrologic function in terms of recharge to, storage in, and discharge from the shallow-aquifer system (**Fig. E9-4** [Nickerson and Myers 1993, Fig. 10]; *cf.* Rpt. **Part 3.2.3b**, Teeple 2017a). Note also that terms like "seepage loss" or *losing reach of a stream* commonly have a positive context when considered from a GW-recharge perspective.

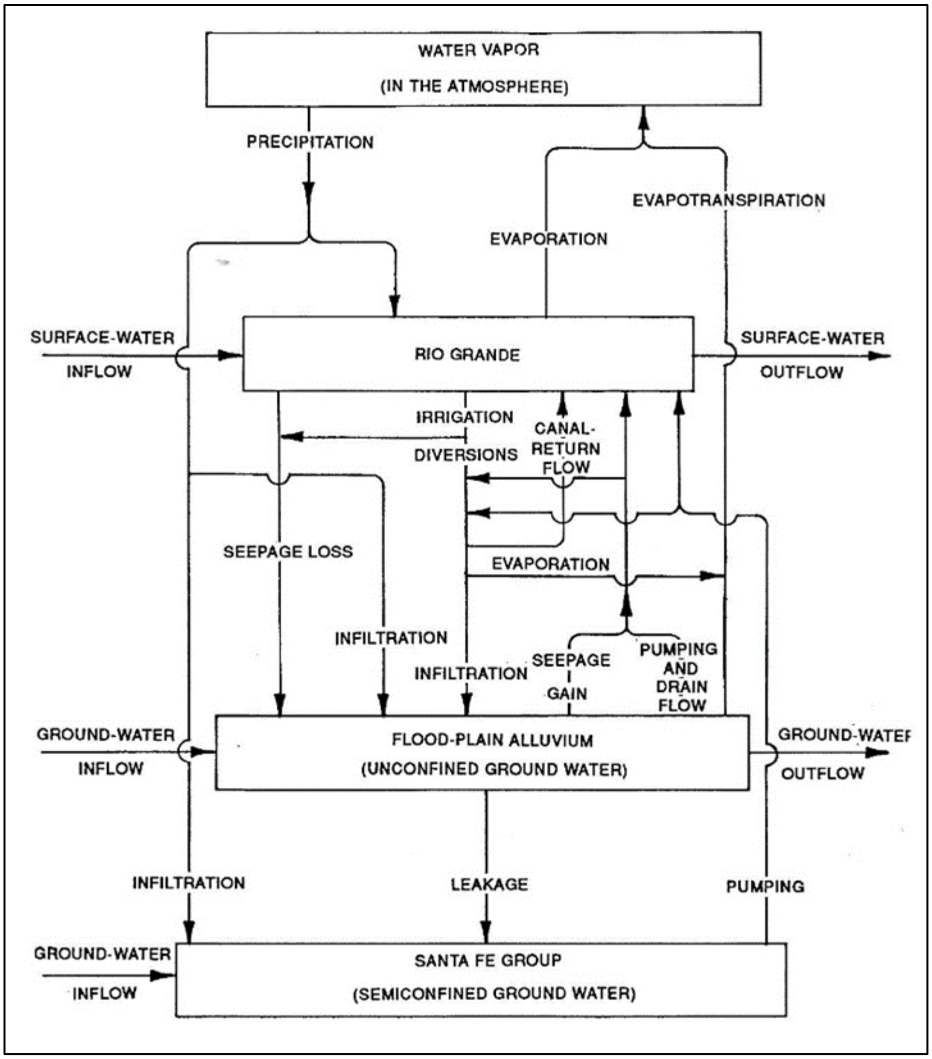

Figure E9-4. (FIG. 10 *in* Nickerson and Myers 1993) Generalized surface and shallow-subsurface circulation of water in the Rio Grande channel and floodplain area.

As noted in Report **Parts 3.2.3** and **8.5**, two key factors in long-term sustainability of both surface- and subsurface water-resource in GW basins downstream from Caballo Dam involve (1) the enormous scale of Rio Grande Project modifications of river-channel and floodplain environments, and (2) the essential role played by efficient reservoir-management practices in terms of storage in and deliveries from the Elephant Butte and Caballo Reservoirs (e.g., **Fig. E8-1**; *cf.* Baker 1943, Glover 2018 [p. 63], Esslinger 1996 and 1998, SSURGO 2002/2003). While the material and human infrastructure remains in place, the major challenge facing future generations of Project managers involves finding an optimum balance between competing reservoir uses that (1) minimize evaporative losses and maximize downstream deliveries, versus (2) permit at least seasonal recreational activity and maximize evaporative losses. When placed in the context of 1938 Rio Grande Compact delivery obligations, strategies for water-resource management throughout the RG-Basin north of Caballo Dam will also be faced with similar or even greater challenges (e.g., Littlefield 2000, Ortega Klett 2000, Hernandez 2012b-c, Davis 2019a-b, S. Bryan 2020, Davis 2020a-h, Land 2020, Pacheco 2020c, ABQ Jrnl. 2021, Crawley 2021, Davis 2021a-h&j, Davis 2022a-d, Tony Davis 2022, Naishadham 2022, Bryan 2023).

Watershed-management strategies throughout the Upper Rio Grande basin will continue to have a major impact on river discharge and aquifer recharge. Significant modifications in operation of the large reservoirs on the Rio Grande-Chama system, for example, will probably be needed to ensure that all Rio Grande Compact delivery obligations are fulfilled (e.g., Haynes 2020, Land 2020, Paskus 2020). Essential ingredients in river-through-flow sustainability include maintaining (1) the integrity of existing flood- and sediment-control impoundments on major tributary arroyos, (2) the health of upland watersheds bordering the Rio Grande between Leasburg Dam and Elephant Butte Reservoir (**Fig. 8-1**), (3) reservoir-water level for management of surface-evaporation losses, and (4) basin-wide vigilance in any area with wildfire vulnerability (e.g., Davis 2021d, Tebor 2021). As emphasized by Jerry Pacheco, Executive Director of the Santa Teresa-based International Business Accelerator: "Every citizen of the Southwest has to become a good steward of each fresh drop of water that we have. Working together, we can lay out a plan in which the development sector, the agricultural sector, and various levels of government can ensure smart water management in the future" (Pacheco 2020c, p. A8).

E10. AQUIFER AND VADOSE-ZONE VULNERABILITY TO CONTAMINATION

E10.1. Background

> Contamination (water)—The addition to water of any substance or property that changes the physical and/or chemical characteristics of the water, and prevents the use or reduces its usability for ordinary purposes such as drinking, preparing food, bathing, washing, recreation, and cooling. Sometimes arbitrarily defined differently from *pollution*, but generally considered synonymous (Neuendorf et al. 2005, p. 139).

One of the greatest challenges facing groundwater-resource managers in any region relates to the vulnerability of some of the most-productive aquifers and overlying vadose-zone material to contamination (Longmire et al. 1981, L. Wilson 1981, Hawley and Longmire 1992, Creel et al. 1998, Mumme 2010, Walker et al. 2015). Such problems are exacerbated by the ever-increasing amounts of toxic chemicals in the general environment and major recent shifts in environmental-protection policies at a federal level (e.g., USEPA 2015c, Suthersan et al. 2016a [Fig. 1] and 2016b, Lim 2019, Alley and Alley 2020 [Chapt. 9]). Of special concern, is the expanding presence of the fluorinated class of poly- and perfluoroalkyl substances (PFAS), or "forever chemicals" (Hu et al. 2016, Davis 2019b, NGWA 2019a-c, Ross et al. 2019, USEPA 2019, Alley and Alley 2020 [Chapt. 10], Horst et al. 2020, and Bryan and Daly 2022, Prokop 2023c, Boetel 2024b). In addition, microplastics are an important emerging class of groundwater contaminants in urban, suburban, and industrial areas of the Mesilla Basin region (Divine et al. 2024, Polich 2024).

Addressing the ever-increasing problems related to subsurface-water contamination requires detailed hydrogeologic-framework characterization and GIS coverage at a site-specific scale, which is beyond the scope of this study. Emphasis here is on to parts of the Mesilla GW Basin (MeB) where urban/suburban populations, and agricultural and M&I activities are concentrated. While much of the inner Mesilla Valley (MeV) remains dominated by irrigation-agricultural activity, it now includes expanding areas of urbanization near Las Cruces, Anthony, and El Paso. MeV-border areas adjacent to Interstate Highways 25 and 10 are also sites of large feedlot operations, several pecan orchards, a variety of relatively small-scale manufacturing activities, a steel mill and scrap-metal recycling facility near Vinton (TX), a stone quarry near Vado (NM), several natural-gas and liquid-fuel pipeline crossings, and the large area impacted by 29th-Century American Smelting and Refining Corporation (ASARCO) operations in EPdN. The toxic legacy of ASARCO-related soil and shallow-GW contamination is described in detail in **APPENDIX H, Part 9.3** (e.g., high levels of lead, zinc, cadmium and arsenic; *cf.* U.S. CDC, 1997, p. 871-877, https://www.cdc.gov/mmwr/preview/mmwrhtml/00049347.htm).

E10.2. Potential for Groundwater Pollution in New Mexico: Lee Wilson, Ph.D.; N.M. Geological Society, Special Publication No. 10

> Significant contamination of ground water requires, in combination, a source of pollutants, an aquifer which is susceptible to pollution, and geological pathways capable of conveying contaminants to the aquifer. In New Mexico major sources include pumping-induced saline intrusion, mill wastewater, septic tank effluent, and brine disposal. Leaks, spills, municipal wastewater, animal-confinement facilities, mine drainage, and industrial wastewater are locally important. Significant pathways reflect a highly permeable and/or thin vadose zone, or presence of improperly constructed wells, which bypass vadose zone protection. . . . (Wilson, 1981, p. 47)

The first comprehensive "Program for the statewide monitoring of ground-water quality in New Mexico" is described by Lee Wilson and others (1979), and it is as relevant today as it was then. Wilson (1981, p. 47-48) identified seven significant "Pollution Sources and Pathways" in parts of southern New Mexico that include the Mesilla Basin region:

1. Irrigation—salinity, nutrients, and pesticides in return flows (e.g., McQuillan 1982, Thomson and McQuillan 1984, Creel et al. 1998).
2. Saline intrusion—overpumping of fresh water, which is adjoined or overlain by saline water (*cf.* Rpt. **Part 7.7.2**).
3. Septic tanks and cesspools—nutrients and pathogens in discharges, especially where systems are poorly constructed (e.g., McQuillan 1982 and 2004, Walker et al. 2015).
4. Leaks and spills—accidental releases of hydrocarbons or chemicals from pipelines, tanks, and vehicle accidents.
5. Municipal wastewater—nutrients and pathogens in discharges to arroyos and fields, and in pond seepage (e.g., McQuillan 1982, Thomson and McQuillan 1984).
6. Industrial wastewater—salinity and chemicals in seepage from cooling ponds, refinery wastewater ponds, and septic tanks (e.g., McQuillan 1982, Thomson and McQuillan 1984, Alley and Alley 2020 [Chapts. 9 and 10]).
7. Animal-confinement facilities—nutrients and organics in dairy wastewater and seepage from feedlots (e.g., Macías-Corral et al. 2006).

The initial groundwater-vulnerability assessments by Lee Wilson and associates were completed when the population of New Mexico was about 1.3 million; while it now exceeds 2.1 million, or about the same as the binational population of the MBR! The major increase in urban and suburban residents is also reflected in the number of municipal sanitary landfills and potential sites for hazardous-waste disposal (*cf.* McQuillan and Keller 1988, and 1982, Hawley and Longmire 1992). In addition, the number of "identified potential-groundwater contaminants" has increased exponentially. Still unregulated "emerging contaminants" now include "forever chemicals" such as anthropogenic per- and polyfluoroalkyl substances that have toxic properties at parts/trillion levels (*cf.* Suthersan et al. 2016a-b, Davis 2019b, NGWA 2019a-c, Alley and Alley 2020).

E10.3. Assessing Groundwater-Contamination Potential with the *DRASTIC* Model

Several GIS-based models have be developed for assessing groundwater-contamination potential at a GW-basin/subbasin-scale (Walker et al. 2015, p. 5). Most were designed to use data that is readily available, and have relatively simple formulas compared to the processes being modeled. The *DRASTIC* model of Aller and others (1987) has performed well enough to attract many users simply because it provides a "standardized" platform for dealing with the complexities of the hydrogeologic environment while keeping modeling parameters as concise and manageable as possible. *DRASTIC* is an acronym for a seven-factor "standardized system for evaluating the groundwater contamination potential using hydrogeologic settings." In combination with state-of-practice GIS methodology, the *DRASTIC* has two major portions: (1) designated mappable units, termed *hydrogeologic settings* for different regions of the United States, and (2) a superimposed relative-rating subsystem that in many areas can involve a wide range of subjective interpretation. Each *setting* incorporates seven hydrogeologic factors that affect and control groundwater movement in the context of groundwater-contamination potential: (*D*) depth to water table, (*R*) net recharge, (*A*) aquifer media, (*S*) soil media, (*T*) topography, (*I*) impact of the vadose zone, and (*C*) hydraulic conductivity of the aquifer material.

The *DRASTIC INDEX*, a relative ranking scheme of the above-listed factors, uses a combination of weights and ratings to produce a numerical value that facilitates prioritization of areas with respect to groundwater contamination potential. The "ground-water aquifer sensitivity assessment and management practices evaluation for pesticides in the Mesilla Valley" by Creel and six others (1998) represents the first detailed application of the *DRASTIC* model in the Study Area (*cf.* Hibbs et al. 1997, p. 38-45; Kennedy 1999; Hawley et al. 2000, p. 12). In their adaption "of the *DRASTIC* model to evaluate groundwater pollution sensitivity from on-site wastewater systems in the MeB," Walker and others (2015, p. 6) found that the *DRASTIC* method was well suited for their subbasin-scale evaluation of the "pollution sensitivity" of relatively shallow GW-flow systems in MeB because of the following advantageous features:

> The use of the Delphi consensus method (a structured, iterative, questionnaire process…) to obtain hydrogeologic factors and ratings and weights, provides the system with expert backing and structure (Aller et al. 1987). The number of hydrogeologic factors and their interrelationships reduces the probability of overlooking important parameters, increases statistical accuracy, and provides a relatively good representation of the hydrogeologic setting (Rosen 1994). The system also provides estimates for large regions with complex geologic structures without the need for specialized methods, equipment, or data (Kalinski et al. 1994, McLay et al. 2001). Finally, the system is specifically designed to be a management tool that is inexpensive, simple to use, easy to understand, uses existing data, and is employable by a diverse collection of individuals with differing levels of expertise (Aller et al. 1987).
>
> Walker and others (2015, p. 5), on the other hand, also note that:
>
> Despite the number of users, the *DRASTIC* model does have a number of disadvantages. The major problem [involves] the subjectivity of the rating determinations and scales it employs. Since many factors are chosen, as opposed to being measured, this system is much more qualitative than quantitative (. . . , Worrall and Kolpin 2004, Panagopoulos et al. 2006, Yang and Wang 2010).

Major drawbacks to application of the *DRASTIC* model outside the Mesilla Valley also includes: (1) vadose-zone thicknesses that are commonly in the 300 to 500 ft (90-150 m) range; and (2) general absence of closely spaced well control (*cf.* **Figs. 1-7** and **2-2** [**PLS. 3** and **4**]; Rpt. **Parts 6.3, 8.4** to **8.6**; *cf.* McQuillan 2004).

E11. CONCLUDING REMARKS

> By the end of the 20th century humanity has developed powerful processes that transport masses of Earth materials equal to about half that transported by natural transport processes and three times that created by mountain building; consume and intercept about 72% of continental runoff; has removed between 26% and 46% of global forests; and may have intervened in the biosphere in a way that has created an extinction rate of mammalian species about 40 times the 'natural' background rate. Moreover, by burning fossil fuel, humanity has released enough carbon from natural storage in 60 years or so to increase atmospheric carbon dioxide concentration to levels not experienced through the whole of the Quaternary, and which

> are maybe responsible for the dramatic rise in northern hemisphere temperatures shown during the last 60 years [*cf.* Mann et al. 1999]. It is possible, as a result of such human impacts, that the future geological environment of Scotland [and globally] will be very different from those of the Quaternary (Boulton, Peacock, and Sutherland, 2002, p. 430).

In October 1992, Marc Reisner closed his final edition of *Cadillac Desert* with a more optimistic statement (1993, p. 518): "At some point, perhaps within my lifetime, the American West will go back to the future rather than forward to the past." He didn't live to see that dream fulfilled; but many earth historians still cherish it as one of their most worthy "lifetime" goals (*cf.* Hawley 2005, p. 49). On the other hand, it is now quite possible that contemporary geochronologists may actually have to concede that the Quaternary "Ice Age" Period is over, and that the Earth and its inhabitants are entering the uncharted territory of an "Anthropocene" Epoch (e.g., Zalasiewicz et al. 2021). With respect to the Earth's near future, science journalists, Pulitzer Prize Recipient Elizabeth Kolbert and Peter Brannen paints the darkest pictures of all. In Kolbert's "The sixth extinction – An unnatural history (2014)," she suggests that:

> Obviously, the fate of our own species concerns us disproportionately. But at the risk of sounding anti-human — some of my best friends are humans! — I will say that it is not, in the end, what's most worth attending to. Right now, in the amazing moment that to us counts as the present, we are deciding, without quite meaning to, which evolutionary pathways will remain open and which will forever be closed. No other creature has ever managed this, and it will, unfortunately, be our most enduring legacy. The Sixth Extinction will continue to determine the course of life long after everything people have written and painted and built has been ground into dust and giant rats have—-or have not-inherited the earth [p. 288-289].

In an article in the March-April 2021 issue of *The Atlantic*," titled "The dark secrets of the Earth's deep past – The geologic record suggests that climate models are missing something truly frightening," Brannen states that:

> When he coined the term *mass extinction* in a 1963 paper, "Crises in the History of Life," the American paleontologist Norman Newell posited that this was what happened when the environment changed faster than evolution could accommodate. Life has speed limits. And in fact, life today is still trying to catch up with the thaw-out of the last ice age, about 12,000 years ago. Meanwhile, our familiar seasons are growing ever more strange: Flycatchers arrive weeks after their caterpillar prey hatches; orchids bloom when there are no bees willing to pollinate them. The early melting of sea ice has driven polar bears ashore, shifting their diet from seals to goose eggs. And that's after just 1 degree of warming.
>
> Subtropical life may have been happy in a warmer Eocene Arctic, but there's no reason to think such an intimately adapted ecosystem, evolved on a greenhouse planet over millions of years, could be reestablished in a few centuries or millennia. Drown the Florida Everglades, and its crocodilians wouldn't have an easy time moving north into their old Miocene stomping grounds in New Jersey, much less migrating all the way to the unspoiled Arctic bayous if humans re-create the world of the Eocene. They will run into the levees and fortifications of drowning Florida exurbs. We are imposing a rate of change on the planet that has almost never happened before in geologic history, while largely preventing life on Earth from adjusting to that change.
>
> Taking in the whole sweep of Earth's history, now we see how unnatural, nightmarish, and profound our current experiment on the planet really is. A small population of our particular species of primate has, in only a few decades, unlocked a massive reservoir of old carbon slumbering in the Earth, gathering since the dawn of life, and set off on a global immolation of Earth's history to power the modern world. As a result, up to half of the tropical coral reefs on Earth have died, 10 trillion tons of ice have melted, the ocean has grown 30 percent more acidic,

> and global temperatures have spiked. If we keep going down this path for a geologic nanosecond longer, who knows what will happen? The next few fleeting moments are ours, but they will echo for hundreds of thousands, even millions, of years. This is one of the most important times to be alive in the history of life [p. 75].

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Topic/Subtopic Categories, with Alphanumeric Cross-Reference Codes (Appendix B)

A. Bibliographies, Dictionaries, Glossaries, Biographies, Reviews, and News Items
    A1. Bibliographies, Dictionaries, and Glossaries
    A2. Biographies and Reviews
    A3. News Items
B. Time: Geologic, Prehistoric, and Historic
    B1. Geologic and Prehistoric Time
    B2. Prehistoric Perspective: US Southwest and Northern Mexico
    B3. Historic Perspective: US Southwest and Northern Mexico
C. Environmental, Physiographic, and Geologic Setting
    C1. Climatic, Hydrographic, Ecologic, and Paleoenvironmental Setting
    C2. Geologic and Geomorphic Setting
        C2a. Geologic and Geomorphic Setting: Pre-1990
        C2b. Geologic and Geomorphic Setting: Post-1989
    C3. Soil-Geomorphic Relationships and Soil Surveys
    C4. Geophysical/Geochemical Data and Interpretations
D. Basic Hydrogeologic Concepts
    D1. Conceptual Models, Definitions, and Regional Overviews
    D2. Groundwater-Flow Systems, Including Recharge
E. GIS/Remote Sensing and GW-Resource Management/Planning
    E1. GIS/Remote Sensing
    E2. Resource Management/Planning
        E2a. Desalination
        E2b. Recharge and Recovery
        E2c. Groundwater-Quality Projection and Waste Management
    E3. Legal and Environmental Issues and Constraints
F. Transboundary Regional Hydrogeology and Geohydrology
    F1. Binational
    F2. USA
    F3. México
G. Early Documents on Mesilla Basin Regional Aquifer Systems (1858-1970)
    G1. 1858 to 1935
    G2. 1935 to 1970
H. Contemporary Documents on Mesilla Basin Regional Aquifer Systems
    H1. Hydrogeology
    H2. Hydrochemistry
    H3. Flow Models
I. Paleohydrology: Ancestral Fluvial and Pluvial Lake Systems
    I1. Regional Overviews
    I2. Transboundary Region Paleohydrologic Systems
    I3. Evolution of the Rio Grande Fluvial System

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