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**HYDROGEOLOGIC FRAMEWORK OF THE MESILLA BASIN REGION  
OF NEW MEXICO, TEXAS, AND CHIHUAHUA (MEXICO)—  
ADVANCES IN CONCEPTUAL AND DIGITAL-MODEL DEVELOPMENT**

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## ABSTRACT

This Report describes the results of the latest of a series of NM Water Resources Research Institute investigations that provide state-of-practice information on the hydrogeologic-framework of intermontane basins of the Mesilla Basin region (MBR) that are linked by the valleys and canyons of the Rio Grande, and includes parts of New Mexico, Trans-Pecos Texas, and Chihuahua (MEX). Work in a 3,350 mi<sup>2</sup> (8,675 km<sup>2</sup>) binational/tristate Study Area gets special emphasis. Effective conservation of the region's large, but still finite low-salinity groundwater resources, requires detailed hydrogeologic characterization of basin- and valley-fill deposits. Major advances in geographic information systems science and technology during the past two decades have permitted substantial progress in this research area. Of special note are the advances in the conceptual- and digital-model development that have occurred since publication of work completed prior to 2005.

The Mesilla Basin and the Mesilla Valley of the Rio Grande are located near the southern end of the Rio Grande rift tectonic province and in the southeastern part of the Basin and Range (B&R) physiographic province. Parts of the MBR below an altitude of about 5,000 ft (1,525 m) amsl are also in the arid to semiarid Chihuahuan Desert ecoregion. The Study Area, as defined herein, includes the Mesilla Basin and hydrologically linked parts of three other large RG-rift basins: (1) the Southern Jornada [del Muerto], New Mexico, (2) the western Hueco Bolson, mostly in Texas and Chihuahua, and (3) the recently identified El Parabién Basin, Chihuahua, Mexico. Rift-basin fill of the Upper Cenozoic Santa Fe Group, and Quaternary alluvium in the inner valleys of Rio Grande/Bravo fluvial system comprise the only significant aquifer systems throughout the MBR.

Three-dimensional portrayal of the basin-scale (~1:1,000,000) hydrogeologic framework has been the primary contribution of this investigation. Many illustrations had to be initially designed and manually compiled by the Principal Investigator (PI), and reflect his field-based experience in the MBR that dates back to the 1960s. From this perspective, conceptual design and preparation of the Report's maps (8), cross-sections (19), and block diagrams (2) has been a mind-expanding iterative process. It has involved the input of dozens of individuals, including highly skilled cartographers. Concepts and assumptions in map, cross-section, and block-diagram preparation are derived from the large body of public-domain information, most of which is adequate for basin-scale hydrogeologic-framework characterization (Appendices A and C to E). Major components of this database include information on (1) surficial geomorphic and geologic relationships, (2) subsurface stratigraphy and structure, and (3) geophysical and hydrochemical conditions. The body of the Report and its eight Appendices, for example, are supported by almost 1,000 source documents in the compilation of Cited References, and an expanded Glossary of geoscientific terms (Appendix G) has nearly 240 entries. With respect to the interpretation of geomorphic processes and landscape features alone, the current generation of Google Earth® image products, and space-platform imagery in general have played an essential role in map preparation, particularly in the Mexican part of the Study Area (*cf.* Appendices F and H).

**Keywords:** Mesilla Basin, Hydrogeologic Framework, Transboundary Aquifers, Geographic Information Systems (GIS), Conejos-Médanos Aquifer, Brackish Groundwater, and Aquifer Storage and Recovery.

## DISCLAIMERS

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Special—The views and conclusions presented herein are those of the Principal Investigator (PI), and do not necessarily reflect views and policies of the NM WRRI or any other local, state or federal governmental entity.\* The binational and tristate scope of the Report’s hydrogeologic information and interpretations has required special attention to a number of potentially sensitive issues (technical, legal, and political). Hydrogeologic-framework interpretation are based on (1) thorough review of hundreds of published documents, most accessed between 1968 and 2000, and (2) field investigations in the study region that were initiated in 1962 and continue to the present (*See Parts 1.1 and 1.2*). No surface or subsurface databases acquired after 2006 were used in characterization of hydrogeologic-framework conditions in La “Zona Hidrogeológica de Conejos Médanos (INEGI 2012).”

\*Primary entities: City of Las Cruces (CLC), El Paso Water Utility (EPWU), Junta Municipal de Agua y Saneamiento de Ciudad Juárez (JMASCJ), Elephant Butte Irrigation District (EBID), Lower Rio Grande Water Users Organization (LRGWUO), N.M. Interstate Stream Commission (NMISC), N.M. Office of State Engineer (NM OSE), N.M. Bureau of Geology & Mineral Resources (NMBGMR), Texas Water Development Board (TWDB), University of Texas Bureau of Economic Geology (UT BEG), University of Texas El Paso (UTEP), Texas A & M University (TAMU), Universidad Autónoma de Ciudad Juárez (UACJ), U.S. Environmental Protection Agency (USEPA), U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (USBOR), Comisión Nacional de Aguas (CONAGUA), Servicio Geológico de México (SGM), International Boundary and Water Commission-U.S. Section (IBWC), and Comisión Internacional de Límites y Aguas (CILA).

## **SPECIAL NOTE ON REPORT AUTHORSHIP**

The PI has had sole responsibility for Report content and initial design of all maps, illustrations, tables, and appendices. His co-authors provided the scientific and technical support essential for (1) preparation of Report illustrations (maps, cross-sections, and block-diagrams) in digital formats, and (2) electronic-file creation for Report-related documents in text and graphic formats. Detailed background information on their work is presented in Chapter 2–METHODS. Because of the variety of co-author responsibilities, the Report is presented in third-person. Individual author names are used only in the context of specified Project contributions.

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The many constructive contributions by participants in the final peer-review process deserve special acknowledgement. Finally, the thorough editorial review of the Report and Appendix drafts by former NM WRRRI Program Manager Jeanette Torres played an essential role in successful project completion.

## IN MEMORIAM

During the past six decades, the many now-deceased geologists, soil and water scientists, biologists, and civil engineers have made major contributions to hydrogeologic investigations in the Mesilla Basin region (*cf.* **CITED REFERENCES**). Notable among them are: Dr. Thomas (Tom) G. Bahr (d. 2025), Dr. John W. Clark (d. 1978), Dr. Russell E. Clemons (d. 1994), Thomas E. Cliett (d. 2015, *cf.* **APNDX. C2**), Charles Crowder (d. 2018), Leland H. Gile, Jr. (d. 2009), Dr. Narendra Gunaji (d. 2010), Dr. John Whitlock Hernandez (d. 2018), Walter G. Hines, P.E. (d. 2021), Dr. William E. King (d. 2014), Dr. Frank E. Kottowski (d. 2001), Dr. Earl M.P. Lovejoy (d. 1981), Dr. Artie L. Metcalf (d. 2016), Gary L. Richardson, P.E. (d. 2011), Dr. Dean L. Stoneman (d. 2015), Clyde A. Wilson (d. 1980, *cf.* **APNDX. C3**), Francis West, P.E. (d. 2015), and Dr. Robert R. White (d. 2014).

## **DEDICATION**

This Report is dedicated to the memory of Dr. Bobby J. Creel, who was Associate Director of the NM Water Resources Research Institute in the decade prior to his untimely death in February 2010. This investigation would not have been initiated and definitely not completed without his early support and continuing inspiration. A southeastern New Mexico native (b. 9/30/1943), Bobby Creel was a visionary natural-resources economist who never stopped growing in intellectual and professional stature. Throughout his long career as Assistant, Acting, and Associate Institute Director, he always tried to ensure that public funds were most appropriately distributed and utilized in a wide variety of peer-reviewed water-resources research projects. His great success as a consensus builder on complex water-resource issues in this part of the North American West was underpinned by unwavering respect for the dynamic environmental and multi-cultural boundaries inherent in its long historical record, from both human- and geological-time perspectives.

## EXECUTIVE SUMMARY

### Background

Major advances in geographic information science (GISc) and geographic information systems (GIS) software during the past two decades have permitted substantial progress in characterization of the hydrogeologic-framework\* of aquifer systems in a group of intermontane basins in the south-central New Mexico (NM) border region that are linked by the valleys and canyons of the Rio Grande (RG). The area of interest includes parts of New Mexico, Trans-Pecos Texas, and Chihuahua, Mexico (MEX) that are here informally named the Mesilla Basin region (MBR) (**Frontispiece**). This Report describes the results of the latest of a series of NM Water Resources Research Institute (NM WRRI) supported hydrogeologic investigations that have been designed to provide state-of-practice information on the finite groundwater (GW) resources of the MBR. Investigations in a 3,350 mi<sup>2</sup> (8,675 km<sup>2</sup>), binational/tristate Study Area receive special emphasis (**Frontispiece**). Of special note are the advances in the conceptual- and digital-model development that have occurred since the publication of studies by Hawley and Kennedy (2004), and Hawley and others (2000 and 2009). More than 980 source documents on the geoscientific principles that comprise the basic-framework foundation are cited in the body of the Report and its eight Appendices. The current phase of the investigation was initiated in 2007 and completed in 2022.

The intermontane Mesilla Basin and the Mesilla Valley of the Rio Grande are located near the southern end of the Rio Grande (RG) rift tectonic province. The basin and surrounding parts of the southeastern Basin and Range (B&R) physiographic province are designated the Mesilla Basin Region (MBR) herein (**Frontispiece, Part 3.2**). Parts of the MBR below an altitude of about 5,000 ft (1,525 m) amsl are in the arid to semiarid Chihuahuan Desert ecoregion (**Part. 3.3**). The “Study Area,” as defined in this Report, includes the Mesilla Basin and hydrologically linked parts of three other large rift basins: (1) the Southern Jornada [del Muerto], New Mexico, (2) the western Hueco Bolson, mostly in Texas and Chihuahua, and (3) the recently identified El Parabién Basin, Chihuahua (**Frontispiece**). RG-rift basin fill of the Upper Cenozoic Santa Fe Group (SFG), and Quaternary alluvium in the inner valleys of Rio Grande/Bravo fluvial system comprise the only significant aquifer systems throughout the MBR (**Parts 3.2.3 and 3.4**). Effective conservation of the large, but still finite low-salinity GW resources of the MBR requires detailed, state-of-practice hydrogeologic characterization of basin- and valley-fill deposits.

Prior to Elephant Butte Dam construction and initial “Rio Grande Project” deliveries in 1916, MBR aquifer systems were recharged by Rio Grande/Bravo-channel seepage (historically intermittent), with a smaller component derived from local ephemeral streams (arroyos) with large-upland watersheds. Much of the GW-reservoir in and near the Rincon, Mesilla and El Paso Valleys is now used conjunctively

with “Rio Grande Project” surface water for irrigation-agriculture (I-Ag). Near river-valley floors, upper parts of the basin-fill aquifers currently receive intermittent to perennial recharge from three primary sources: (1) Rio Grande Project irrigation return flow, (2) treated municipal wastewater, and (3) inflow from GW in basin-fill storage. “Project water” deliveries through canals, laterals, and increasingly efficient field-application practices are here considered to be essential for the long-term GW-resource availability. However, the reliability of these deliveries is now affected by: (1) the “2020” realities of global climate change, (2) ever increasing water-user demands on the entire Upper Rio Grande watershed, and (3) competition between I-Ag, and municipal and industrial (M&I) users of the limited fresh-GW reserves in a binational/tristate area with an urban/suburban population that now exceeds 2 million (**APNDX. E**).

At increasing distances away from the inner Mesilla Valley, the percentage of the underflow contribution of older water stored in SFG basin fill and subjacent bedrock units also increases. Much of it is brackish (>1,000 mg/L TDS), and only effectively recharged during glacial/pluvial cycles with multi-millennial periodicity. For example, all of the effective recharge to the US-Mexico Transboundary aquifer system occurred more than 11,000 years ago (11 ka) during Late Pleistocene high stands of pluvial-Lake Palomas in the Los Muertos Basin region (**Frontispiece**). Thick, high-permeability Ancestral Rio Grande (ARG) channel deposits in the upper SFG form the primary aquifer unit that stores and transmits this “Ice-Age” GW.

### **Advances in Conceptual- and Digital-Model Development**

State-of-practice, three-dimensional portrayal of the Study Area’s hydrogeologic framework, has been the primary contribution of this investigation. Geologic processes and their lithologic-material and structural products are inherently deterministic in nature, and sampled populations of representative types are relatively small in many cases. As such, many Report illustrations had to be initially designed and manually compiled by the PI, and reflect his field-based experience that dates back to the mid-1950s. From this perspective, conceptual design and preparation of the Report’s maps (8), cross-sections (19), and block diagrams (2) has been a mind-expanding iterative process (**PLS. 1 to 9**). It has required the scientific and technical input of dozens of individuals, including highly skilled cartographers, over a span of many years. It is therefore essential to recognize that all geology-based modeling efforts remain “works in progress” simply because of the limits imposed by the uneven distribution and inconsistent quality of information on the earth’s subsurface environment.

Concepts and assumptions in map, cross-section, and derivative block-diagram preparation are derived from the large body of public-domain information, most of which is adequate for basin-scale hydrogeologic-framework characterization (*see APNDS. B to E*). Major components of this database

include information on (1) surficial geomorphic and geologic relationships, (2) subsurface stratigraphy and structure, and (3) geophysical and hydrochemical conditions. With respect to the interpretation of geomorphic processes and landscape features alone, the current generation of Google Earth® image products, and space-platform imagery in general have played an essential role in map preparation, particularly in the Mexican part of the Study Area (**APNDX. F**).

**PLATES 1 to 4, and 6 to 8** were initially compiled at a scale of 1:100,000, and each is designed for electronic-file access available online, as well as 11 x 17-inch format printing. The 10,000 m (100 km<sup>2</sup>) UTM-SI grid system is used in combination with latitude/longitude-degree and township-range (USA) coordinates for feature location. An especially challenging task involved compilation of the robust well database in **TABLE 1** (395 key wells) that is essential for portrayal of aquifer hydrostratigraphy, lithofacies composition, and groundwater-flow boundaries in this binational-tristate region (*cf.* **Parts 2.4 and 4.2**). Published and unpublished sources used in **TABLE 1** (Excel® spreadsheet-format) compilation are listed in **TABLE 1A**, and **TABLE 1B** includes an explanation of ID acronyms for the hydrogeologic-map subdivisions in which the wells are located. Areal distribution of key well locations in the Study Area is shown on **PLATE 3**. **PLATES 4A and 4B** illustrate the primary components of the groundwater-flow system, as well as the position of the major surface-watershed divides. Pre-development (~1976) potentiometric-surface altitude contours are shown in both feet and meters (20, 50 and 100 ft intervals in **PL. 4A**, and 10 and 30 m intervals in **PL. 4B**).

**TABLES 2 and 3** provide explanations of feature-location, hydrostratigraphic, and boundary-fault zone categories on the **PLATES 1- and 5-series** hydrogeologic maps and cross-sections. The heavy lines (solid and dashed) with displacement-direction symbols on **PLATE 1-series** maps and their derivative products also show positions of basin- and subbasin-boundary fault zones (names and acronyms on **TBL. 3**). Their locations are based on state-of-practice interpretation of surface/subsurface geological-map and geophysical-survey data for optimum use in GW-flow and hydrochemical model development. Because of differences in compilation scales, some structural-boundary features on more detailed geologic maps are merged or omitted on **PLATE 1-derivative** cartographic products (e.g., closely spaced or small-displacement faults).

Major RG-rift structural subdivisions include: (1) groundwater (GW) basins, (2) GW-basin subdivisions, (3) basin-bounding bedrock uplifts (U) and their lithostratigraphic composition, (4) inter-basin/intrabasin GW-flow corridors (C), and (5) boundary-fault zones (**TBL. 3**). Basin-boundary bedrock uplifts are grouped primarily on the basis of lithologic and geohydrologic properties. As shown on the Study Area index map (**PL. 1A**), the 19 hydrogeologic cross-sections (**5a to 5s**) in the **PLATE 5** electronic folio have a fence-diagram format, in which 13 sections (A-A' to L-L' and S-S') have a general

transverse-basin (W-E) orientation, and the other 6 (M-M' to R-R' ) are aligned approximately parallel to dominant NNW to SSE rift-basin trends.

The new hydrogeologic map and cross-section compilations (**PLS. 1A to 1C and 5a-5s**) now show major framework components (lithologic, stratigraphic, and structural) on digital terrain-model or Google Earth® image backgrounds. More detailed explanations of map-unit stratigraphic and lithofacies categories and their hydrogeologic-framework properties are included in **TABLE 2**. A mean sea level (msl) base altitude allows full-depth display of most of the 395 borehole records used in cross-section compilation (**TBL. 1, PL. 3**). This facilitates 3-D graphic portrayal of the primary hydrogeologic-framework controls on groundwater-flow and chemistry at levels of detail more amenable to numerical modeling than was heretofore possible.

The updated hydrogeologic-framework template represents an important advance over previous work because it is designed for continued refinement as additional baseline information on subsurface conditions is acquired. These refinements in mapping-unit definition are especially important in parts of the Study Area where GW-basin boundaries do not coincide with the positions of surface- and/or subsurface-watershed divides (**PLS. 2 and 4**). The above outlined innovations in framework characterization, however, have not required significant changes in the basic definitions of lithofacies, hydrostratigraphic, and basin-boundary components, all of which were developed for ongoing GW-flow model development throughout the “Southwest Alluvial Basins Regional Aquifer-System” region (*cf.* **CHPTS. 4 to 6**).

### **Chapter Content Summaries**

**CHAPTER 1** provides general background information about the investigation, while the emphasis of much of the rest of the Report is on specific details of hydrogeologic-framework controls on groundwater-flow and hydrochemistry at various spatial and temporal scales. Brief Chapter summaries follow:

**CHAPTER 2. METHODS.** It includes (1) an explanation of well numbering systems, (2) GIS-related sections on feature location, and digital hydrogeologic-framework map and cross-section compilation, and (3) information on data compilation, analysis, and interpretation. Supplemental material is included in **APPENDIX A**.

**CHAPTER 3. PHYSIOGRAPHIC AND GEOLOGIC SETTING OF THE MESILLA BASIN REGION—A HYDROGEOLOGIC PERSPECTIVE.** Detailed geological- and geophysical-based information on the basic hydrogeologic framework components is presented in seven parts: (1) Basin and Range physiographic-province, (2) Chihuahuan Desert ecoregion, (3) Rio Grande rift tectonic province

and Santa Fe Group rift-basin fill, (4) Ancestral Rio Grande (ARG) and La Mesa surface, (5) Major rift-basin components, (6) Stages of rift-basin evolution and SFG deposition, and (7) Mid-to-Late Quaternary evolution of Rio Grande valleys and canyons, and endorheic rift-basin areas. Deep-seated bedrock- and structural-boundary controls on both basin-fill composition and aquifer-system properties are illustrated with maps, cross-sections, and block diagrams (e.g., **PLS. 1A, 1B, 1C, and 5**). The Chapter concludes with an introduction to the paleohydrology of an interlinked pluvial-Lake Palomas—Paso del Norte GW-flow system.

#### **CHAPTER 4. BASIC CONCEPTS OF HYDROGEOLOGIC-FRAMEWORK CONTROLS ON GW-FLOW AND CHEMISTRY IN BASIN AND RANGE, AND RIO GRANDE-RIFT PROVINCE AQUIFER SYSTEMS.**

Basic concepts on hydrogeologic-framework controls on basin-fill aquifer composition, and groundwater flow and chemistry are presented in two map-scale contexts: Basin & Range provincial and Study Area. Framework controls are first discussed in terms of conceptual models of GW-flow systems in basin-fill deposits of intermontane structural basins. Basic concepts of basin *closure* in a topographic sense, and intra-basin/extra-basin GW flow classes are introduced. Rift-basin and RG-valley fills are defined in terms of both lithofacies-assemblages (LFAs) and hydrostratigraphic units (HSUs) at 1:100,000 map scale.

#### **CHAPTER 5. BEDROCK- AND STRUCTURAL-BOUNDARY COMPONENTS OF INTERBASIN UPLIFTS.**

This part of the Report, and the following chapter (6) form its core sections. Emphasis is on the major lithostratigraphic- and structural-framework elements that are exposed in the basin-bounding highlands or are buried at shallow depths beneath the RG-rift basin fill. They comprise: (1) Uplifts—exposed highland and shallowly buried bedrock terranes, (2) Benches—areas of structural transition between basins and bordering uplifts that are covered in Chapter 6, and (3) Corridors—large gaps in basin-bounding Uplifts with potential for significant amounts of interbasin underflow exchange.

#### **CHAPTER 6. GROUNDWATER BASINS OF THE STUDY AREA AND THEIR PRIMARY HYDROGEOLOGIC SUBDIVISIONS.**

Emphasis here is on the internal hydrostratigraphic and structural composition of the Study Area's three major groundwater (GW) basins (Mesilla, El Parabién, and Southern Jornada) and their respective hydrogeologic subdivisions (**PLS. 1 to 7, TBLS. 1 to 5**). How to best characterize the complex lithofacies, stratigraphic, and structural framework components in the three GW basins is a recurring theme in **CHAPTERS 5 and 6**. This is especially true for Mesilla Basin (MeB) with its 15 distinctive hydrogeologic map-unit subdivisions (**Fig. 1-10**).

#### **CHAPTER 7. HYDROGEOLOGIC CONTROLS ON GROUNDWATER FLOW**

**AND CHEMISTRY IN AQUIFER SYSTEMS OF THE MESILLA BASIN REGION.** Emphasis is on known and inferred hydrogeologic controls on components of the regional GW-flow system

throughout the Study Area. Special attention is given to flow regimes in the “International Boundary Zone (IBZ)” that are directed toward the southeastern MeB-Lower MeV area (**Fig. 1-9, PL. 4**).

**CHAPTER 8. PROGRESS IN HYDROGEOLOGIC-FRAMEWORK CHARACTERIZATION, AND OPTIONS FOR LONG-TERM GROUNDWATER-RESOURCE DEVELOPMENT IN THE MESILLA BASIN REGION.** Study purpose and scope, and Report content are summarized in **Part 8.2**, and the history of RG-rift evolution, SFG basin-fill deposition, and river-valley/canyon development is outlined in **Parts 8.3 and 8.4**. The latter includes overviews of (1) the GW-flow system evolution that followed initial development of the through-going Rio Grande/Bravo fluvial system, and (2) the Late Quaternary history of pluvial lakes that formed in hydraulically linked endorheic rift basins. **Part 8.5** offers a contemporary perspective on GW-resource management concerns in the Mesilla Basin region. It includes reviews of the rather nebulous concepts of “resilience” and GW “sustainability” in the context of climate-change and resource-management realities. Prospects for long-term GW-resource in the United States part of the Mesilla GW Basin (MeB) aquifer systems are reviewed in **Part 8.6**, with emphasis on areas of the MeV and MeB-West Mesa where viable opportunities for long-term GW-resource development exist, especially those related to (1) brackish-GW (BGW) desalination and concentrate disposal, and (2) managed-aquifer recharge (MAR) operations. **Part 8.7** comprises short “Concluding Remarks.”

### **Appendix Content Summaries**

The scope and format of the body of the Report did not permit inclusion of large amounts of relevant background information. The addition of the below listed **APPENDICES (A to H)** addresses the need to recognize the significant contributions to hydrogeology-related research in the binational Mesilla Basin region by many agencies and individuals. Each, with cited references, has been compiled in a separate electronic-file folder that is available online at <https://nmwri.nmsu.edu/publications/technical-reports/tr-reports/tr-363.html>.

**APPENDIX A** is primarily a **CHAPTER 4** addenda that includes background material on development of conceptual models and digital methods for hydrogeologic-framework characterization. Much of its content was extracted from the following NMBG&MR and NM WRRI publications: King et al. 1971, Gile et al. 1981, Hawley and Lozinsky 1992, Hawley and Kernodle 2000, Hawley et al. 2000, Hawley and Kennedy 2004, and Hawley et al. 2009.

**APPENDIX B** is an expanded bibliography of more than 2,200 publications on topics related to hydrogeologic controls on groundwater-flow and hydrochemical systems in the western US-Mexico Boundary region. The 9 major topic and 31 subtopic alphanumeric codes assigned to each entry are designed to facilitate cross-referencing and EndNote® compilation. Its compilation was initiated in 2007

in collaboration with the Universidad Autónoma de Ciudad Juárez as part of the Transboundary Aquifer Assessment Program (TAAP).

**APPENDIX C** reviews major contributions to the hydrogeology, geohydrology, and hydrochemistry of the MBR (1890-2010), with emphasis on collaborative investigations by federal, state, and local agencies and organizations.

**APPENDIX D** includes facsimile reproductions of selections from published work on the Cenozoic geology, hydrogeology, geomorphology, and physical and cultural geography of the New Mexico-Chihuahua border region.

**APPENDIX E** is a **CHAPTER 8** addenda that provides background information on conservation of GW resources in the United States part of the MBR. Topics covered include: (1) “Sustainable” GW Development, (2) the rather nebulous concept of “resilience” in a groundwater-resource-management context, (3) GW mining, (4) Rio Grande Project water management, (5) potential impacts of climate change on water-resource availability, (6) vulnerability to aquifer and vadose-zone contamination, and (7) challenges facing future GW-resource conservation.

**APPENDIX F** is a compilation of selected images and photographs (satellite, aerial, and ground) of the New Mexico-Texas-Chihuahua border region: (1) Apollo, Gemini, and Landsat photographs and images, (2) aerial-photo views of Study Area landscapes, and (3) ground-photos of major Hydrostratigraphic Units and Lithofacies Assemblages in Santa Fe Group basin fill and alluvial deposits of the Rio Grande Valley.

**APPENDIX G** is a glossary of more than 250 scientific and technical terms. The compilation is designed to provide ready access to definitions of a large number of specialized geologic and hydrologic terms, most of which are in common usage in reports on basin-fill aquifer systems in the Basin and Range physiographic province.

**APPENDIX H** includes more-detailed background information on (1) the 1680 to present history of water-resource development, and (2) the conservation of shared GW resources in Transboundary aquifer systems of the Paso del Norte region. Binational research collaborations, many of which have had NM WRRRI support since 1964, get special attention. The most recent of these postdate 1994 implementation of EPA-La Paz Agreement Title XXI. It also includes a UACJ translation of selections on the geohydrology of northern Chihuahua from Estudio Hidrológico del Estado de Chihuahua (INEGI 1999).

## Major Take-Away Points

Among the major conclusions presented in this Report, the following “Take-Away Points” deserve special note:

1. Groundwater (GW) in most areas outside the valleys of the Rio Grande/Bravo fluvial system is a nonrenewable resource on a Human time scale in this Chihuahuan Desert ecoregion.
2. All surface and subsurface water in the fresh to moderately brackish range (<3,000 mg/L TDS) is here considered to be an asset rather than a liability.
3. The amount of economically recoverable water in the 500 to 3,000 mg/L TDS range in the upper basin-fill aquifer system beneath the MeB’s West Mesa (Fig. 1-6) is estimated to be at least 30 million ac-ft (37,000 hm<sup>3</sup>).
4. Economically and environmentally viable locations for desalination plant operations and concentrate disposal are readily available in the Mesilla GW Basin-West Mesa area.
5. Many areas of ongoing and projected future aquifer depletion are also ideal places for managed aquifer recharge (MAR) operations.
6. Opportunities for future development of solar-energy resources are unlimited, and natural gas supplies for electric-power generation are readily available.
7. Optimal hydrogeologic conditions for GW production and recharge commonly occur in areas most susceptible to GW contamination.
8. Effective binational/tristate cooperation is essential for long-term transboundary aquifer-system development.

## TABLE OF CONTENTS

**Frontispiece.** Index map of the Mesilla Basin region (MBR) showing locations of the Study Area (Fig. 1-3, red outline), major landscape features in the northern Mexican Highland section of the B&R province, and basins of the southern RG-rift province (Fig. 1-1). 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 Zona Hidrogeológica de Conejos Médanos/El Barreal basin complex, and the Tularosa Basin. Swanson Geoscience, LLC compilation on a 2017 Google Earth® image-base..... ii

TITLE PAGE ..... iii

ABSTRACT..... v

DISCLAIMERS ..... vi

SPECIAL NOTE ON REPORT AUTHORSHIP ..... vii

ACKNOWLEDGEMENTS ..... viii

IN MEMORIAM ..... x

DEDICATION ..... xi

EXECUTIVE SUMMARY ..... xii

Background ..... xii

Advances in Conceptual- and Digital-Model Development..... xiii

Chapter Content Summaries..... xv

Appendix Content Summaries..... xvii

Major Take-Away Points ..... xix

CHAPTER CONTENTS ..... xxi

TABLES AND FIGURES IN BODY OF REPORT ..... xxviii

List of Tables..... xxviii

List of Figures ..... xxx

TABLES STORED IN DIGITAL FORMAT ON NM WRRI WEBSITE ..... xli

PLATES STORED IN DIGITAL FORMAT ON NM WRRI WEBSITE..... xli

APPENDICES STORED IN DIGITAL FORMAT ON NM WRRI WEBSITE ..... xlvi

ABBREVIATIONS AND ACRONYMS–GENERAL USAGE ..... xlvii

**CHAPTER CONTENTS**

**CHAPTER 1. INTRODUCTION**..... 1

1.1. PURPOSE, LOCATION, AND MAJOR PHYSIOGRAPHIC AND GEOLOGIC FEATURES ... 1

    1.1.1. Purpose..... 1

    1.1.2. Location ..... 1

    1.1.3. Major Physiographic and Geologic Features ..... 5

1.2. GROUNDWATER BASINS: HYDROGEOLOGIC AND NM OFFICE OF THE STATE  
ENGINEER ADMINISTRATIVE ..... 5

    1.2.1. Groundwater (GW) Basins Defined in a Hydrogeologic Context ..... 5

    1.2.2. “Declared Groundwater Basin”–NM Office of State Engineer Definition..... 9

1.3. MAJOR HYDROGEOLOGIC AND CULTURAL FEATURES OF THE MESILLA  
BASIN REGION ..... 10

1.4. SCOPE OF WORK ..... 11

1.5. REPORT ORGANIZATION ..... 14

    1.5.1. Chapter Content Summaries ..... 14

    1.5.2. Appendix Content Summaries ..... 16

1.6. INTRODUCTION TO ILLUSTRATION PREPARATION AND CONTENT ..... 18

1.7. INTRODUCTION TO HYDROGEOLOGIC-FRAMEWORK CHARACTERIZATION ..... 20

    1.7.1. Basic Hydrogeologic Concepts and Terminology ..... 20

    1.7.2. Framework Characterization in a RG-Rift Provincial Context..... 23

    1.7.3. Major Geohydrologic Features in the Study Area ..... 28

1.8. INTRODUCTION TO INVESTIGATIONS IN THE SOUTHERN MESILLA  
BASIN REGION ..... 31

    1.8.1. The Transboundary Aquifer Assessment Program (TAAP)..... 31

    1.8.2. Introduction to Hydrogeologic Investigations in the “International Boundary Zone”..... 34

    1.8.3. Border-Wall Construction and Infrastructure-Operation Concerns ..... 36

**CHAPTER 2. METHODS**..... 39

2.1. OVERVIEW..... 39

2.2. FEATURE-LOCATION CLASSIFICATIONS..... 41

2.3. PREPARATION AND CONTENT OF TABLES AND PLATES ..... 44

    2.3.1. Background on the Tradition of Merging Art with Science ..... 44

    2.3.2. Background on the Compilation and Content of TABLES 1 to 3 ..... 44

    2.3.3. Background on the Compilation and Content of PLATES 1 to 8..... 45

2.3.4. PLATE-Content Summaries .....	48
2.4. PROGRESS IN DEVELOPMENT OF DIGITAL PLATFORMS FOR DISTANCE EDUCATION AND TELECONFERENCING .....	55
<b>CHAPTER 3. PHYSIOGRAPHIC AND GEOLOGIC SETTING OF THE MESILLA</b>	
<b>BASIN REGION—A HYDROGEOLOGIC PERSPECTIVE</b> .....	56
3.1. OVERVIEW .....	56
3.2. BASIN AND RANGE (B&R) PHYSIOGRAPHIC PROVINCE .....	60
3.2.1. B&R-Mexican Highland Section.....	60
3.2.2. Major Landscape Features and Geomorphic Processes .....	62
3.2.3. Valleys and Canyons of the Rio Grande.....	64
3.2.3a. Selden Canyon (SCyn) .....	65
3.2.3b. Mesilla Valley (MeV) .....	65
3.2.3c. El Paso del Norte (EPdN).....	66
3.3. CHIHUAHUAN DESERT ECOREGION .....	66
3.3.1. Background on the “Regiones Hidráulicas-Cuencas Cerradas del Norte” of Chihuahua.....	68
3.3.2. Bolsón de los Muertos (BdLM) .....	71
3.3.3. Pluvial-Lake Palomas .....	72
3.4. INTRODUCTION TO THE RIO GRANDE RIFT TECTONIC PROVINCE AND SANTA FE GROUP (SFG) RIFT-BASIN FILL .....	74
3.5. UPPER SFG BASIN FILL, THE ANCESTRAL UPPER RIO GRANDE (ARG), AND LA MESA GEOMORPHIC SURFACE .....	77
3.6. MAJOR STRUCTURAL COMPONENTS OF RG-RIFT BASINS AND UPLIFTS.....	80
3.6.1. Background.....	80
3.6.2. Basin-Scale Characterization of Buried Bedrock Terrane .....	83
3.7. STAGES OF RIFT-BASIN EVOLUTION AND SANTA FE GROUP DEPOSITION.....	91
3.7.1. Early and Middle Stages of Basin Formation and SFG Deposition.....	91
3.7.2. Late-Stage Rift-Basin Development and Culmination of SFG Deposition .....	92
3.7.2a. Evolution of the ARG Fluvial-Deltaic System.....	92
3.7.2b. Fort Hancock and Camp Rice Formations, and Paleo-Lake Cabeza de Vaca.....	93
3.7.3. Background on the Distributive Fluvial System (DFS) Model.....	94
3.8. QUATERNARY EVOLUTION OF RIO GRANDE/BRAVO VALLEYS AND CANYONS, AND CONTIGUOUS ENDORHEIC RIFT-BASINS.....	102
3.9. INTRODUCTION TO THE PALEOHYDROLOGY OF AN INTERLINKED PLUVIAL- LAKE PALOMAS—EL PASO DEL NORTE GW-FLOW SYSTEM.....	108

<b>CHAPTER 4. BASIC CONCEPTS OF HYDROGEOLOGIC-FRAMEWORK CONTROLS ON GW-FLOW AND CHEMISTRY IN BASIN AND RANGE, AND RIO GRANDE-RIFT PROVINCE AQUIFER SYSTEMS .....</b>	<b>110</b>
4.1. CONCEPTUAL MODELS OF HYDROGEOLOGIC CONTROLS ON GW-FLOW IN A BASIN AND RANGE PROVINCIAL SETTING .....	110
4.1.1. Adaptions of the Eakin, Price, and Harrill (1976) Conceptual Model .....	110
4.1.2. Anning and Konieczki (2005) Hydrogeologic Area and Flow System Classification....	113
4.2. LITHOFACIES AND HYDROSTRATIGRAPHIC COMPONENTS OF THE BASIN- SCALE HYDROGEOLOGIC FRAMEWORK .....	116
4.2.1. Lithofacies Assemblages (LFAs) .....	116
4.2.2. Hydrostratigraphic Units (HSUs).....	122
 <b>CHAPTER 5. BEDROCK- AND STRUCTURAL-BOUNDARY COMPONENTS OF INTERBASIN UPLIFTS .....</b>	 <b>124</b>
5.1. UPLIFTS AND CORRIDORS BETWEEN THE SOUTHERN JORNADA AND MESILLA BASINS, AND THE TULAROSA BASIN AND HUECO BOLSON .....	125
5.1.1. Organ Mountains and Bishop Cap Uplifts (OMU and BCU) .....	126
5.1.2. Fillmore Pass Corridor (FPC).....	126
5.1.3. Franklin Mountains Uplift (FMU) .....	127
5.1.4. Campus Andesite Hills and Cerro de Cristo Rey Uplifts .....	127
5.1.5. Sierra Juárez and Sierra Sapello Uplifts .....	128
5.1.6. Méndez-Vergel Inflow Corridor .....	129
5.2. UPLIFTS BETWEEN THE LOWER RINCON VALLEY, SELDEN CANYON AND MESILLA BASIN, AND THE SOUTHERN JORNADA BASIN .....	130
5.2.1. Doña Ana Mountains Uplift .....	130
5.2.2. Selden Hills and Tonuco Mountains Uplifts .....	130
5.2.3. Tortugas and Tortugas Mountain Uplifts .....	132
5.3. UPLIFTS NORTHWEST OF THE MESILLA GW BASIN .....	133
5.3.1. Northwestern MeB-Boundary Uplifts .....	133
5.3.1a. Robledo Mountains Uplift.....	133
5.3.1b. Aden Hills and Aden-Robledo Uplift .....	134
5.3.2. East and West Robledo Fault Zones.....	134
5.4. UVAS-GOODSIGHT UPLIFT AND CEDAR-CORRALITOS BASIN .....	135
5.4.1. Uvas-Goodsight Uplift (UGU).....	135
5.4.2. Cedar-Corralitos Upland Basin (CCUB).....	135

5.4.2a. Cedar Hills Subbasin.....	136
5.4.2b. Corralitos Ranch Subbasin.....	137
5.5. UPLIFTS BETWEEN THE MESILLA GW BASIN, AND THE EASTERN MIMBRES AND MALPAIS BASINS .....	137
5.5.1. East Potrillo Uplift (EPU) .....	137
5.5.1a. Potrillo-Riley Sector .....	138
5.5.1b. Brock Tank Inflow Corridor .....	139
5.5.2. East Potrillo Fault Zone (EPfz) .....	139
5.6. WEST POTRILLO VOLCANIC FIELD .....	141
5.7. BASIN-BOUNDARY SUBDIVISIONS OF THE SOUTHWESTERN STUDY AREA.....	141
5.7.1. West Aden Uplift and West Potrillo Bench .....	142
5.7.2. Malpais Basin.....	142
5.7.3. Border Tank Corridor.....	143
5.7.4. Uplift-Boundary Fault Systems of the Southwestern Study Area.....	144
5.7.5. El Aguaje Uplift and PEMEX No. 1–Moyotes Exploration Well.....	145

**CHAPTER 6. GROUNDWATER BASINS OF THE STUDY AREA AND THEIR PRIMARY**

<b>HYDROGEOLOGIC SUBDIVISIONS.....</b>	<b>146</b>
6.1. SOUTHERN JORNADA GW BASIN (SJB).....	155
6.1.1. Experimental Range Subbasin (ERSB).....	155
6.1.2. Isaacks Lake Subbasin (ILSB) .....	156
6.1.3. Talavera Subbasin (TvSB) .....	156
6.2. LOWER RINCON VALLEY GW BASIN (RVB).....	157
6.3. MESILLA GW BASIN (MeB).....	158
6.3.1. Mesilla Valley of the Rio Grande (MeV) and the Mesilla Valley Fault Zone (MVfz)...	160
6.3.1a. Inner Mesilla Valley.....	162
6.3.1b. Mesilla Valley Fault Zone (MVfz) .....	162
6.3.2. Mid-Basin High (MeB-MbH) .....	163
6.3.2a. North Mid-Basin High (NMbH) .....	164
6.3.2b. South Mid-Basin High (SMbH).....	168
6.3.3. Hydrogeologic Subdivisions North and West of the Mid-Basin High.....	169
6.3.3a. Leasburg Inflow Corridor (LBic).....	169
6.3.3b. Fairacres Subbasin (FASB).....	172
6.3.3c. Afton Subbasin (AfSB).....	177
6.3.3d. East Aden Bench (EABn).....	179

6.3.3e. Kilbourne-Noria Subbasin (KNSB) .....	180
6.3.4. Hydrogeologic Subdivisions between Mid-Basin High and Mesilla Valley Fault Zone ...	184
6.3.4a. Mesquite Subbasin (MSB) .....	184
6.3.4b. Black Mountain Subbasin (BMSB) .....	190
6.3.4c. Santa Teresa High (STH) .....	198
6.3.4d. El Milagro Subbasin (EMSB).....	200
6.3.5. Hydrogeologic Subdivisions East of the Mesilla Valley fault zone (MVfz).....	203
6.3.5a. Las Cruces Bench (LCBn) .....	203
6.3.5b. Anthony-Canutillo Bench (ACBn) .....	204
6.3.5c. Anapra-Oasis Bench (AOBn) .....	208
6.3.5d. Sunland Park Outflow Corridor (SPoc) .....	209
6.4. EL PARABIÉN GW BASIN AND THE POTRILLO-SAPELLO HIGH.....	210
6.4.1. El Parabién GW Basin (EPB).....	211
6.4.2. Potrillo-Sapello High (PSH).....	215

**CHAPTER 7. HYDROGEOLOGIC CONTROLS ON GROUNDWATER FLOW**

<b>AND CHEMISTRY IN AQUIFER SYSTEMS OF THE MESILLA BASIN REGION .....</b>	<b>217</b>
7.1. INTRODUCTION .....	217
7.2. REVIEW OF SANTA FE GROUP DEPOSITION AND ANCESTRAL RIO GRANDE DEVELOPMENT FROM A GW-FLOW SYSTEM PERSPECTIVE.....	227
7.2.1. Deposition of Lower and Middle Santa Fe Hydrostratigraphic Units.....	228
7.2.2. Late Stages of Rift-Basin Filling and Initial SFG Aquifer System Development.....	228
7.2.3. River-Valley and Canyon Entrenchment, Paleo-Lakes in Post-SFG Endorheic Basins, and Early-Stage GW-Flow System Evolution.....	231
7.3. INTERACTION OF THE RIO GRANDE AND SHALLOW GW-FLOW SYSTEMS IN THE PAST 6,000 YEARS.....	233
7.3.1. Impacts of Elephant Butte Dam and the Rio Grande Project on the Hydrologic System ..	233
7.3.2. Background on Hydrogeologic-Framework Characterization in the MBR.....	236
7.3.3. “Paleohydrology” of an “Exotic” River—Inferences from Historic Accounts, Gaging-Station Records and Tree-Ring Proxies .....	239
7.3.4. Use of Stable-Isotope Data to Identify Groundwater “Types” in Basin-Fill Aquifers the Pre-Dam River-Recharge Processes .....	241
7.4. ADVANCES IN GW-FLOW SYSTEM CHARACTERIZATION—1946 to 2021 .....	242
7.4.1. Early-Stage USGS and NM WRI Investigations—1946 to 2007 .....	242
7.4.2. Transboundary Aquifer Assessment Program (TAAP) Contributions.....	246

7.4.2a. Teeple 2017a (p. 81; <i>cf.</i> Fig. 7-14) .....	249
7.4.2b. Teeple 2017b (p. 95) .....	249
7.5. HYDROGEOLOGIC CONTROLS ON INTERBASIN GW FLOW IN THE UNITED STATES	
PART OF THE STUDY AREA .....	250
7.5.1. GW-flow Contributions from the Southern Jornada GW Basin to the MeB.....	251
7.5.2. GW-Flow Relationships between the MeB and Western Hueco Bolson .....	253
7.5.3. GW-Flow Contributions from the Cedar-Corralitos Upland Basin	
to the Northwestern MeB.....	255
7.5.4. GW-Flow Contributions to the MeB from Western Basin-Boundary Areas.....	257
7.5.5. Indirect GW-Flow Contributions from the Malpais Basin to the Southern MeB.....	259
7.6. HYDROGEOLOGIC CONTROLS ON INTERBASIN GW-FLOW IN THE	
INTERNATIONAL BOUNDARY ZONE.....	260
7.6.1. Background on Early-Stage Trans-International Boundary Aquifer Investigations.....	260
7.6.2. Provisional Assessment of Pluvial-Lake Palomas GW-Outflow Contributions to the	
Transboundary Aquifer System of the Southern Mesilla Basin Area .....	264
7.7. CONCLUDING REMARKS ON THE TRANSBOUNDARY GW-FLOW SYSTEM.....	265
<b>CHAPTER 8. PROGRESS IN HYDROGEOLOGIC-FRAMEWORK CHARACTERIZATION,</b>	
<b>AND OPTIONS FOR LONG-TERM GROUNDWATER-RESOURCE DEVELOPMENT</b>	
<b>IN THE MESILLA BASIN REGION.....</b>	<b>267</b>
8.1. OVERVIEW .....	267
8.1.1. Geographic Setting .....	270
8.1.2. Chapter Content Summary .....	270
8.2. REPORT CONTENT SUMMARY .....	271
8.2.1. Purpose, Scope of Work, and Chapter Content .....	271
8.2.2. APPENDIX-Content Summary .....	273
8.2.3. Preparation and Content of Illustrations and Tables.....	274
8.3. MAJOR GEOLOGIC FEATURES OF THE MESILLA BASIN REGION .....	277
8.3.1. Regional Geologic Setting.....	277
8.3.2. Hydrogeologic Subdivisions.....	277
8.4. SUMMARY OF HYDROGEOLOGIC-FRAMEWORK DEVELOPMENT	
AND GROUNDWATER FLOW-SYSTEM EVOLUTION .....	286
8.4.1. Major Middle-to-Late Cenozoic Stages of Hydrogeologic-Framework Development ...	286
8.4.2. Quaternary Groundwater-Flow System Evolution .....	286

8.5. CHALLENGES TO LONG-TERM GW-RESOURCE DEVELOPMENT IN THE U.S. PART OF THE MESILLA BASIN REGION.....	291
8.5.1. The Rather Nebulous Concepts of Resilience and Groundwater Sustainability in the Context of Climate-Change and Resource-Management Realities.....	291
8.5.2. The “Groundwater Sustainability” Concept (Alley, Reilly, and Franke, 1999, U.S. Geological Survey Circular 1186, p. 3) .....	291
8.6. VIABLE PROSPECTS FOR LONG-TERM GW-RESOURCE DEVELOPMENT IN THE UNITED STATES PART OF THE MESILLA GW BASIN.....	294
8.6.1. Background .....	294
8.6.2. Potential Long-Term Pumping Effects on Aquifer-Framework Properties .....	296
8.6.3. Inner Mesilla Valley Area .....	299
8.6.3a. Options for Long-Term GW-Resource Development.....	300
8.6.3b. Hydrogeologic Factors Affecting Surface-Water and GW Connectivity in the MeV.....	300
8.6.3c. Managed Aquifer Recharge (MAR) Potential in Mesilla Valley Border Areas....	302
8.6.4. Options for GW-Resource Development in the Mesilla GW Basin-West Mesa Area....	303
8.6.5. Optimal Hydrogeologic Settings for Brackish GW (BGW) Development .....	304
8.6.6. Sources of Energy for Groundwater Desalination and Other Purposes .....	305
8.6.6a. Geothermal.....	305
8.6.6b. Hydrogen .....	306
8.6.6c. Solar .....	306
8.7. CONCLUDING REMARKS.....	307
8.7.1. Recommendations for Future Hydrogeologic Investigations in the MBR.....	307
8.7.2. A “Design with Nature Now” Approach to GW-Resource Development in the MBR...	307
CITED REFERENCES IN NM WRRI-TCR 363.....	309

## TABLES AND FIGURES IN BODY OF REPORT

### List of Tables

<b>Table 1-1.</b> (Modified from Hawley 2005, <b>TBL. 1</b> ) Index to (1) Physiographic and Tectonic Provinces, and (2) Major Terrain and Landform Features that are shown on <b>Figure 1-4</b> .....	7
<b>Table 1-2.</b> Definitions of Common Geologic, Geohydrologic, and Hydrogeologic Terms .....	21
<b>Table 1-3.</b> Divisions of Geologic Time Referred to in this Report ( <i>cf.</i> <b>Fig. 3-5, TBL. 2</b> ).....	22
<b>Table 1-4.</b> Names and Acronyms of Hydrogeologic Subdivisions shown on Maps, Cross-Sections, and the Well-Information Spreadsheet ( <b>PLS. 1 to 8, TBLS. 1 to 3, and Fig. 1-8 and Tbl. 1-5</b> ) .....	25-26
<b>Table 1-5.</b> Basin- and Subbasin-Boundary Fault Zone Acronyms and Names on <b>Fig. 1-8</b> .....	27
<b>Table 1-6.</b> Sources of Published Information on the Hydrogeologic Framework of the International Boundary Zone (IBZ), many of which were used in Report preparation .....	32
<b>Table 3-1.</b> Explanation of Basin-fill and Bedrock Mapping Units on <b>Figures 3-10 and 3-11 (PLS. 8A and 8B)</b> . Time-Rock Class, Lithostratigraphic and Hydrostratigraphic Unit, and Fault-Zone Category Definitions on <b>Figure 3-5, and Tables 1-2 and 1-3 (cf. TBL. 2)</b> .....	86
<b>Table 3-2.</b> Explanation of Lithostratigraphic Units on <b>Figures 3-12 and 3-13</b> .....	90
<b>Table 3-3.</b> Explanation of <b>Figure 3-15</b> Alpha-Numeric Symbols for Pliocene and Early Pleistocene Distributive Fluvial Systems (DFSS) of Ancestral Rivers with Fluvial-Deltaic Termini in the Paleo-Lake Cabeza de Vaca (LCdV) Complex.....	99
<b>Table 3-4.</b> Explanation for <b>Figure 3-18</b> Content and Key to Cited References .....	104
<b>Table 4-1.</b> Summary of Depositional Setting and Dominant Textures of Major Lithofacies Assemblages (LFAs) in Santa Fe Group Basin Fill (1-10) and Rio Grande Valley fill (a-c) in Intermontane Basins of the Rio Grande Rift Tectonic Province. Modified from Hawley and Kernodle (2000).....	120
<b>Table 4-2.</b> Summary of Major Sedimentary Properties that Influence Groundwater-Flow and Aquifer-Production Potential of Lithofacies Assemblages (LFAs) 1 to 10 in Santa Fe Group Basin Fill. Modified from Haase and Lozinsky (1992). <i>See Figure 4-3, and Table 4-1</i> .....	121
<b>Table 4-3.</b> Summary of Major Sedimentary Properties that Influence Groundwater-Flow and Aquifer-Production Potential of Lithofacies Assemblages (LFAs) a to c in Post-SFG Deposits. Modified from Hawley and Kernodle (2000) .....	121

<b>Table 6-1.</b> Names and Acronyms of Hydrogeologic Subdivisions shown on Maps, Cross-Sections, and the Well-Information Spreadsheet ( <b>PLS. 1 to 8, TBLs. 1 and 2, and Fig. 6-1</b> ).....	148-149
<b>Table 6-2.</b> Names and Acronyms for Boundary-Fault Zones of the Study Area’s Major GW Basins ( <b>TBL. 3; PLS. 1, 2, 5 and 9, and Tbl. 6-1</b> ).....	150
<b>Table 6-3.</b> Explanation of Lithostratigraphic Units on <b>Figures 6-2 and 6-3</b> .....	153
<b>Table 6-4.</b> Names and Acronyms for Major MeB Hydrogeologic Subdivisions on Maps, Cross-Sections, and the Well-Information Spreadsheet ( <b>PLS. 1 to 8, and TBLs. 1 and 1B</b> ). <i>See Tbls. 1-3 and 6-2</i> for Boundary-Fault Zone (fz) Names and Acronyms .....	160
<b>Table 6-5.</b> (Nickerson 2006, Tbl. 4) Measured <sup>14</sup> C Composition, Partial Pressure of Carbon Dioxide, Saturation Index for Calcite, and Apparent Age of Groundwater Sampled in 2003 at Piezometer Sites LMV-1A [ <b>Part 6.3.5b</b> ], LMV-2A and 2B [ <b>6.3.4a</b> ], and LMV-3 [ <b>6.3.4b</b> ].....	190
<b>Table 7-1.</b> Summary of Major Sedimentary Properties that Influence Groundwater-Flow and Aquifer-Production Potential of Lithofacies Assemblages (LFAs) 1 to 10 in Santa Fe Group Basin Fill. Modified from Haase and Lozinsky (1992). <i>cf. Fig. 7-3 and Tbl. 7-1</i> .....	225
<b>Table 7-2.</b> Summary of Major Sedimentary Properties that Influence Groundwater-Flow and Aquifer-Production Potential of Lithofacies Assemblages (LFAs) <i>a</i> to <i>c</i> in Post-SFG Deposits. Modified from Hawley and Kernodle (2000). <i>cf. Fig. 7-3 and Tbl. 7-1</i> .....	225
<b>Table 8-1.</b> Names and Acronyms of Hydrogeologic Subdivisions shown on Maps, Cross-Sections, and the Well-Information Spreadsheet ( <b>Fig. 8-2; PLS. 1 to 8, TBLs. 1 and 2</b> ).....	279-280
<b>Table 8-2.</b> Names and Acronyms for Boundary-Fault Zones of the Study Area’s Major GW Basins ( <b>TBL. 3; PLS. 1, 2, 5 and 9; and Tbl. 8-1</b> ).....	281
<b>Table 8-3.</b> Explanation of Lithostratigraphic Units on <b>Figures 8-5 and 8-6</b> .....	285
<b>Table 8-4.</b> Explanation of <b>Figure 3-14</b> Alpha-Numeric Symbols for Pliocene and Early Pleistocene Distributive Fluvial Systems (DFSs) of Ancestral Rivers with Fluvial-Deltaic Termini in the Paleo-Lake Cabeza de Vaca (LCdV) Complex.....	288
<b>Table 8-5.</b> Major Stages of Hydrogeologic-Framework Development during the Past 30 Ma.....	290
<b>Table 8-6.</b> Number of Deep-Borehole Control Points in Selected Hydrogeologic Subdivisions of the MeB-West Mesa area ( <i>cf. PL. 3, Fig. 8-2, Tbl. 8-1 and TBL. 1</i> ) .....	303

**List of Figures**

**Figure 1-1.** Index map for the United States-Mexico borderlands region that covers parts of southern New Mexico, western Texas, northern Chihuahua, and northeastern Sonora..... 2

**Figure 1-2. Frontispiece.** Index map of the Mesilla Basin region (MBR) showing locations of the Study Area (**Fig. 1-3**, red outline), major landscape features in the northern Mexican Highland section of the B&R province, and basins of the southern RG-rift province (**Fig. 1-1**). 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 Zona Hidrogeológica de Conejos Médanos/El Barreal basin complex, and the Tularosa Basin. Swanson Geoscience, LLC compilation on a 2017 Google Earth® image-base. EPdN=El Paso del Norte..... 3

**Figure 1-3.** Study Area index map showing locations of the Mesilla, Southern Jornada, and El Parabién groundwater (GW) basins. Also shown are the locations of hydrogeologic cross-section **A-A'** to **S-S'** major terrain features (incl. the Mesilla Valley, Selden Canyon and El Paso del Norte of the Rio Grande), and the Las Cruces and El Paso/Ciudad Juárez metropolitan centers ..... 4

**Figure 1-4.** (Hawley 2005, FIG. 1) Index map showing locations of physiographic provinces and their section subdivisions, and major landscape features in the binational New Mexico region..... 6

**Figure 1-5.** (Frenzel and Kaehler 1992, Fig. 4) 1990 USGS index map showing locations of the Mesilla “groundwater” Basin (MeB-dashed outline), the Mesilla Valley (MeV-shaded area), the “West Mesa,” major bedrock uplifts (Mountains, Sierras), and “El Paso (del Norte) Narrows.” ..... 9

**Figure 1-6.** U.S. Bureau of Reclamation Map showing locations of major surface-water management structures of the Rio Grande Project between the San Marcial (removed 1964) and Fort Quitman Gaging Stations. EBID indicates Elephant Butte Irrigation District operations (courtesy of Rhea Graham; *cf.* USBOR 2011)..... 12

**Figure 1-7.** Provisional hydrogeologic index map of the 2001-2006 NM WRRI Study Area (Hawley and Kennedy 2004, Hawley et al. 2005) ..... 19

**Figure 1-8.** (page-size **PL. 1B**) Index map for major hydrogeologic subdivisions of the Study Area (**Fig. 1-3** and **Tbls. 1-4** and **1-5**; **Fig. 1-4**)..... 24

**Figures 1-9a.** (page-size **PL. 4A**) Index map to major geohydrologic features of the NM WRRI Study Area (~1976 potentiometric-surface altitude in feet)..... 29

<b>Figures 1-9b.</b> (page-size <b>PL. 4B</b> ) Index map to major geohydrologic features of the NM WRRRI Study Area (~1976 potentiometric-surface altitude in meters) .....	30
<b>Figure 1-10.</b> (page-size <b>PL. 11</b> ) Index map for major GW-management and geohydrologic units in Mexico and the United States south of 32° N latitude .....	33
<b>Figure 1-11.</b> IBWC (2011) Acuífero Conejos-Médanos: Binational Waters map.....	34
<b>Figure 1-12.</b> ( <b>PL. 12</b> ) Index map of the “International-Boundary Zone (IBZ)” as provisionally defined in this investigation.....	35
<b>Figure 1-13.</b> Detailed index map for the new JMASCJ well field and the 42-inch (~1.1 m) water-transmission line (red-solid and dashed) that connects it with central Ciudad Juárez. ( <b>Figs. 1-10</b> and <b>1-11</b> ) .....	36
<b>Figure 1-14.</b> (courtesy of PBS-New Mexico in Focus—Our Land) Fall 2019 aerial photograph of a newly completed section of the US-Mexico Border Wall in the southern Mesilla basin at the 31° 47' N Parallel ( <i>cf.</i> <b>Fig. 1-15</b> ).....	37
<b>Figure 1-15.</b> Oblique 2017 Google Earth® image that is centered on the International Boundary between Paso del Norte and the East Potrillo Uplift ( <b>Fig. 12</b> ) .....	38
<b>Figure 2-1a.</b> New Mexico well-numbering system.....	42
<b>Figure 2-1b.</b> Texas well-numbering system.....	43
<b>Figure 2-2.</b> ( <b>PL. 3</b> ) Index map showing locations of the 395 key wells (blue) that were the primary sources of the subsurface hydrogeologic information used in this study .....	46
<b>Figure 2-3.</b> Page-size reproduction of <b>PLATE 5o</b> series of down RG Valley/Canyon (NNW to SSE) hydrogeologic cross-sections O-O'-O''-O''' , with locations on shown on inset index maps ( <b>Fig. 1-3</b> ). Base elevation-msl and VE-5x.....	50
<b>Figure 2-4.</b> (page-size reproduction of <b>PLATE 5i</b> to <b>5l</b> and <b>5s</b> panel) Transverse (W to E) hydrogeologic cross-sections I-I' to L-L' and S-S' that span the northern and central parts of the International Boundary Zone (IBZ— <b>Fig. 1-11</b> ).....	51
<b>Figure 2-5.</b> ( <b>PL. 6C-2</b> page-size reproduction) Schematic representation of the Study Area’s basal basin-fill topography and primary structural components, with the MeB outlined in green. Variable structure-contour interval at 25, 50, and 100 m amsl ( <i>cf.</i> <b>Figs. 1-9, 2-5</b> and <b>3-12</b> ) .....	53

<b>Figure 2-6.</b> (page-size <b>PL. 7A</b> ) Study Area isopleth map of the saturated part of HSU-USF that schematically depicts its LFA composition and thickness .....	54
<b>Figure 3-1.</b> (Gile et al. 1981, FIG.1; modified <i>from</i> Hawley 1975, Fig. 1) Index map to physiographic subdivisions and major landforms in southeastern Basin and Range province region of New Mexico, Trans-Pecos Texas, and Chihuahua ( <i>cf.</i> Hawley 1969, Underwood 1980, Gile et al. 1981).....	57
<b>Figure 3-2.</b> (adapted by H.C. Monger [1999] <i>from</i> Gile et al. 1981, FIG. 1) Schematic block diagram of the Desert Soil-Geomorphology Project and USDA-ARS Jornada Experimental Range areas of the northeastern Mesilla and Southern Jornada RG-rift basins ( <b>Figs. 1-1 to 1-3, and 3-2</b> ) .....	58
<b>Figure 3-3.</b> (Hawley et al. 2009, Fig. 10; <i>cf.</i> <b>Fig. 3-6</b> ) Schematic depiction of major Quaternary-landscape features of the Mesilla Basin region on USGS-DEM base.....	59
<b>Figure 3-4.</b> (Gile et al. 1981, Fig. 4) Schematic profiles of major landform types and outline of dominant geomorphic processes in the Mexican Highland section of the Basin and Range province and the southern Rio Grande rift tectonic province: <b>3-4a</b> —Intermontane basin, and <b>3-4b</b> —River valley ( <b>Fig. 3-3</b> ).....	63
<b>Figure 3-5a.</b> (INEGI 1999, Fig. 5.3.A) Index map to hydrographic units/fluvial systems in the western part of Región Hidrológica (Hydrologic Region) RH34—Cuencas Cerradas del Norte (endorheic basins of the north) in northwestern Chihuahua .....	69
<b>Figure 3-5b.</b> (INEGI 1999, Fig. 5.3.B) Index map to hydrographic units/fluvial systems in the northeastern part of Región Hidrológica (Hydrologic Region) RH34—Cuencas Cerradas del Norte (endorheic basins of the north) in northern Chihuahua.....	70
<b>Figure 3-6.</b> (modified from Hawley et al. 2009, Fig. 6; <i>cf.</i> <b>Tbl. 1-3, TBL. 2</b> ) Correlation diagram of major time-rock (chronostratigraphic) classes, lithostratigraphic, allostratigraphic, and hydrostratigraphic units (HSU) of Cenozoic age in the southern RG-rift region ( <i>cf.</i> NACOSN 2005, <b>APNDX. G</b> ).....	76
<b>Figure 3-7.</b> (Hawley et al. 2009, Fig. 9) Schematic depiction of the approximate area where fluvial and fluvial-deltaic deposits of the Ancestral Rio Grande (ARG) form the dominant Upper SFG basin-fill component.....	78
<b>Figure 3-8.</b> (page-size <b>PL. 2A</b> ) Digital overlay of Bouguer isostatic-residual gravity map (4 milligal contour interval) on the Study Area’s hydrogeologic-basemap ( <b>Fig. 1-8 [PL. 1B]</b> ) .....	81

**Figure 3-9a.** (modified from Jiménez and Keller (2000, Fig. 7, p. 82); reproduced with permission from the New Mexico Geological Society, Inc.; *cf.* **Fig. 3-8**). Gravity map (4 milligal contour interval) with an interpreted extent of the major RG-rift basins in the border region that is “based on the integrated analysis of gravity, drilling, geologic, and remote-sensing data.” ..... 82

**Figure 3-9b.** (modified from Jiménez and Keller (2000, Fig. 6); reproduced with permission from the New Mexico Geological Society, Inc.) Western part of computer model of gravity profile A-A' (right; and red line, right and left), and schematic geologic section (left), with Cenozoic Laramide and RG-rift basin fill shown with open polygons (SFG/TIs – **Tbl. 3-2**). ..... 83

**Figure 3-10.** (page-size **PL. 8A**, with stratigraphic-unit definitions on **Table 3-1**) Block diagram of the central Mesilla Basin that schematically portrays major RG-rift stratigraphic and structural features at 1x vertical exaggeration (VE) and a base elevation of 25,000 ft (7.6 km) below mean sea level ..... 84

**Figure 3-11.** (page-size **PL. 8B**) Northeast-facing block diagram of the southern Mesilla Basin, with its southern panel at the International-Boundary and stratigraphic-unit definitions on **Table 3-1** ..... 85

**Figure 3-12.** (page-size **PL. 2B**) Schematic depiction of basin-fill subcrop topography, and primary lithostratigraphic and structural components in the Study Area (25, 50, and 100 m contour intervals), with explanation on **Tables 1-4** and **3-2** ..... 88

**Figure 3-13.** (page-size **PL. IIC**) Schematic geologic cross-sections I-I' to III-III' that show major subsurface stratigraphic and structural relationships in the central and southern parts of the Study Area. Explanation on **Table 3-2**, with geologic-section locations on **Figure 3-12**..... 89

**Figure 3-14.** (Gile et al. 1981, Fig. 5 [modified from Hawley 1975, Fig. 2]) Schematic depiction of the general area occupied by the distributive drainage network of the upper ARG during much of Pliocene and Early Pleistocene time (*cf.* Connell et al. 2005, Fig. 11b and 11c) ..... 95

**Figure 3-15.** (adapted from Hawley 1975, Fig. 2) Pliocene and Early Pleistocene depositional setting of the ARG distributive fluvial system (DFS-red lines) that terminated in the paleo-Lake Cabeza de Vaca (LCdV) complex of W.S. Strain (1966, 1971)..... 98

<b>Figure 3-16.</b> (Seager 1981, Fig. 84) Fillmore Pass and the DFS apex of the ARG “Camp Rice Fan Delta” of Seager (1981, p. 78-84) is shown with an <b>a5</b> in <b>Figure 3-15</b> .....	100
<b>Figure 3-17.</b> (Gates and Stanley 1976, FIG. 5a, p. 33) Approximate flight line location and response curves for airborne-electromagnetic survey lines in the western Hueco Bolson.....	101
<b>Figure 3-18.</b> (Gile et al. 1981, Fig. 8) Correlation diagram for representative stratigraphic units and geomorphic-process categories of Late Pliocene and Quaternary age in the southern Rio Grande rift region of south-central New Mexico and Trans-Pecos Texas .....	103
<b>Figure 3-19.</b> (Gile et al. 1981, FIG. 6) Hydrogeologic cross-section of the northern Mesilla and Southern Jornada groundwater Basins, which are separated by the shallowly buried Tortugas Uplift (US-70—Hydrogeologic Section DD' alignment, <b>PL. 5d</b> ) .....	107
<b>Figure 4-1.</b> (Kennedy et al. 2000, Fig. 1; reproduced with NM Geological Society, Inc. permission.) Generic block diagram that illustrates basic hydrogeologic framework and groundwater-flow system interrelationships in a group of topographically <i>closed</i> and <i>open</i> ( <i>endorheic</i> and <i>exorheic</i> ) B&R province basins, most of which have a regional GW-flow component .....	111
<b>Figure 4-2.</b> (Anning and Konieczki 2005, Fig. 2) Block diagrams that schematically illustrate a “conceptual model of hydrogeologic components of a hydrogeologic area and types of hydrogeologic areas in a hydrogeologic flow system” in the B&R province .....	114
<b>Figure 4-3.</b> (modified from Hawley and Kernodle 2000, Fig. 5) Schematic distribution patterns of major lithofacies assemblages (LFAs) in intermontane-basin and river-valley fills of the RG-rift province ( <i>see Fig. 4-4</i> and <b>Tbls. 4-1 to 4-3</b> ) .....	118
<b>Figure 4-4.</b> Triangular diagram of dominant textural classes in lithofacies assemblages (LFAs) 1 to 10, and primary LFA composition of SFG Hydrostratigraphic Units (HSU)—USF/MSF/LSF ( <i>see Fig. 4-3</i> and <b>Tbls. 4-1 to 4-3</b> ) .....	119
<b>Figure 6-1.</b> (page-size <b>PL. 1B</b> ) Index map for major hydrogeologic subdivisions of the Study Area ( <b>Tbls. 6-1 and 6-2</b> ; <i>cf. Parts 2.3.2</i> and <i>3.4</i> ). <b>PLATE 1</b> (USGS DEM) base .....	147
<b>Figure 6-2.</b> (page-size <b>PL. 2B</b> ) Schematic depiction of basin-fill subcrop topography, and primary lithostratigraphic and structural components in the Study Area, with explanation on <b>Tables 6-1 and 6-3</b> .....	151
<b>Figure 6-3.</b> (page-size <b>PL. 2C</b> ). Schematic geologic cross-sections I-I' to III-III' that show major subsurface stratigraphic and structural relationships in the central and southern parts of the Study Area. Explanation on <b>Table 6-3</b> , with geologic-section locations on <b>Figure 6-2</b> .....	152

**Figure 6-4.** (Nickerson and Myers 1993, Fig. 36) Electrical-resistivity log of USGS-EPWU Lanark test-hole (**TBL. 1**, no. 236), with current interpretations of HSU contact depths (bgs): USF—/MSF2 - 530 ft (162 m), MS—2/LSF - 1,120 ft (340 m), and LS—/TmLC - 1,490-ft (454 m). Depth to water was 383 ft (117 m) in July 1986 ..... 166

**Figure 6-5.** (Nickerson and Myers 1993, p. 62, Fig. 40) Chemical analyses of water from selected depth intervals in the Lanark test hole (USGS-EPWU, **TBL. 1**, no. 236)..... 167

**Figure 6-6.** (Nickerson and Myers 1993, p. 62, Fig. 38) Electrical-resistivity log of USGS-EPWU Noria test hole (USGS-EPWU, MT-4, **TBL. 1**, no. 253), with current interpretations of HSU contact depths (bgs): USF—/MSF2 - 540 ft (165 m), MS—2/LSF - 1,170 ft (357 m), and estimated L—F/Tls - 1,530-ft (466 m). Depth to water was 327 ft (100 m) in September 1986..... 170

**Figure 6-7.** (Nickerson and Myers 1993, Fig. 42, p. 64) Chemical analyses of water from selected depth intervals in the Noria test hole (USGS-EPWU, **TBL. 1**, no. 253)..... 171

**Figure 6-8.** (Nickerson and Myers 1993, Fig. 35) Electrical-resistivity log of USGS-EPWU Afton test-hole MT-1 (**TBL. 1**, no. 175), with current interpretations of HSU contact depths (bgs): USF—/MSF2 - 690 ft (210 m), MS—2/LSF - 1,530 ft (466 m), and LS—/Tlvs - 1,900-ft (579 m). Depth to water was 366 ft (117 m) in June 1986 ..... 175

**Figure 6-9.** (Nickerson and Myers 1993, Fig. 39, p. 61) Chemical analyses of water from selected depth intervals in the USGS-EPWU Afton test hole (MT-1, **TBL. 1**, no. 175)..... 176

**Figure 6-10.** Index hydrogeologic section showing six key-well sites in the Kilbourne-Noria Subbasin (KNSB) and adjacent parts of the southern East Potrillo Uplift (EPU-PRS, **5.4.1a**) and the South Mid-Basin High (SMbH, **6.3.2b**). **PLATE 5k (K-K')** alignment west of **PLATE 5q**..... 183

**Figure 6-11.** (Nickerson 2006, Fig. 4) Selected borehole-geophysical logs and piezometer-completion depths at the LMV-2 site (**TBL. 1**, no. 229)..... 188

**Figure 6-12.** (Nickerson 2006, Fig. 5) Distribution of major constituents in groundwater-quality samples from selected depth intervals at the LMV-2 site (**TBL. 1**, no. 229)..... 189

**Figure 6-13.** (Nickerson and Myers 1993, Fig. 37) Electrical-resistivity log of USGS-EPWU La Union test hole (USGS-EPWU MT-3, **TBL. 1**, no. 242), with current interpretations of HSU contact depths (bgs): USF—/MSF2 - 530 ft (162 m), MS—2/LSF - 1,735 ft (529 m), and estimated L—F/Tls - 2,500-ft (762 m)..... 194

<b>Figure 6-14.</b> (Nickerson and Myers 1993, p. 63) Chemical analyses of water from selected depth intervals in La Union test hole (USGS-EPWU MT-3, <b>TBL. 1</b> , no. 242) .....	195
<b>Figure 6-15.</b> (Nickerson 2006, Fig. 6) Selected borehole-geophysical logs and piezometer-completion depths at the LMV-3 site ( <b>TBL. 1</b> , no. 248) .....	196
<b>Figure 6-16.</b> (Nickerson 2006, Fig. 4) Distribution of major constituents in groundwater-quality samples from selected depth intervals at the LMV-3 site ( <b>TBL. 1</b> , no. 248) .....	197
<b>Figure 6-17.</b> “GENERALIZED GEOLOGIC CROSS-SECTION A-A', CROWDER WELL FIELD, SANTA TEREI[ST]...” (Brown and Caldwell-unpublished, <i>ca.</i> 1975, Fig. 4) .....	199
<b>Figure 6-18.</b> (Hawley and Kennedy 2005, Pl. A5) Index hydrogeologic section showing positions of 11 key-well sites on the MeB West Mesa between I-10 and the Santa Teresa Industrial Park ( <i>cf.</i> <b>Part 6.3.3b</b> ).....	201
<b>Figure 6-19.</b> (Nickerson 2006, Fig. 2) Selected borehole-geophysical logs and piezometer-completion depths at the LMV-1 site ( <b>TBL. 1</b> , no. 344), with the base of the “Freshwater zone” at about 660 ft (200 m) bgs .....	206
<b>Figure 6-20.</b> (Nickerson 2006, Fig. 3) Distribution of major constituents in groundwater-quality samples from selected depth intervals at the LMV-1 site ( <b>TBL. 1</b> , no. 344) .....	207
<b>Figure 6-21.</b> Index map of the “International-Boundary Zone (IBZ)” as provisionally defined in this investigation. It is located between the 31° and 32° N latitude and the 106°30' and 108° W longitude ( <i>cf.</i> <b>Part 1.8.2</b> ).....	211
<b>Figure 6-22a.</b> (adapted from Jiménez and Keller 2000, Fig. 7; reproduced with New Mexico Geological Society, Inc. permission) Gravity map (4 milligal contour interval) with interpretations of major RG-rift basin extent that is “based on the integrated analysis of gravity, drilling, geologic, and remote-sensing data.” .....	212
<b>Figure 6-22b.</b> (adapted from Jiménez and Keller 2000, Fig. 6, p. 82; reproduction of original illustration with New Mexico Geological Society, Inc. permission) Western part of computer model of gravity profile A-A' (right, and red line, right and left), and schematic geologic section (left), with Cenozoic Laramide and RG-rift basin fill shown by open polygons.....	212

<b>Figure 6-23.</b> (CONAGUA 2020, p. 20) Geologic Cross-Section (BB') of the IBZ ( <b>Fig. 6-21</b> ) that is located near 31°40-45' N, and extends from the Palomas volcanic field west of Puerto Palomas to the Hueco Bolson east of Ciudad Juárez.....	213
<b>Figure 7-1.</b> Index map of the binational/tristate Mesilla Basin region (MBR) that shows locations of the Study Area (magenta outline), major landscape features in the eastern B&R physiographic province, and basins of the southern RG-rift tectonic province ( <i>cf. Figs. 7-2 and 7-5</i> ).....	218
<b>Figure 7-2a.</b> (page-size <b>PL. 4A</b> ) Index map for major geohydrologic features of the NM WRRRI Study Area (~1976 potentiometric-surface altitude in 10 and 100 ft amsl intervals).....	219
<b>Figure 7-2b.</b> (page-size <b>PL. 4B</b> ) Index map to major geohydrologic features of the NM WRRRI Study Area (~1976 potentiometric-surface altitude in 5, 10, and 30 m amsl intervals).....	220
<b>Figure 7-3.</b> (page-size <b>PL. 11</b> ) Index map for major GW-management and geohydrologic units in Mexico and the United States that is compiled on a 2018 Google Earth® image-base.....	222
<b>Figure 7-4a.</b> (modified from Hawley and Kernodle 2000, Fig. 5) Schematic distribution patterns of major lithofacies assemblages (LFAs) in intermontane-basin and river-valley fills of the RG-rift province ( <i>see Fig. 7-4b and Tbls. 7-1 and 7-2</i> ).....	223
<b>Figure 7-4b.</b> Idealized triangular diagram of dominant textural classes in lithofacies assemblages (LFAs) 1 to 10, and primary LFA composition of SFG Hydrostratigraphic Units (HSUs)–USF/MSF/LSF ( <i>cf. Fig. 4-3, and Tbls. 7-1 and 7-2</i> ).....	224
<b>Figure 7-5.</b> (modified from Hawley et al. 2009, Fig. 6) Correlation diagram of major time-rock classes, and lithostratigraphic and hydrostratigraphic units of Cenozoic age in the southern RG-rift region of New Mexico, Texas, and Chihuahua.....	226
<b>Figure 7-6.</b> (Hawley et al. 2009, Fig. 9) Schematic illustration (USGS DEM base) of the approximate area where fluvial and fluvial-deltaic deposits of the Ancestral Rio Grande (ARG) form the dominant Upper SFG basin-fill component.....	230
<b>Figure 7-7.</b> (Hawley et al. 2009, Fig. 10; <i>cf. Fig. 7-5</i> ) Schematic illustration of major Quaternary-landscape features of the Mesilla Basin region.....	232
<b>Figure 7-8.</b> (FIG. 10 <i>in</i> Nickerson and Myers 1993) Diagram showing the generalized circulation of water in the Rio Grande channel and floodplain area of the inner Mesilla Valley.....	235

**Figure 7-9.** Page-size reproduction of **PLATE 5o** series of down RG Valley/Canyon (NNW to SSE) hydrogeologic cross-sections O-O'-O''-O''' , with locations shown on inset index maps (**Fig. 1-3**). Base elevation-msl and VE-5x..... 237

**Figure 7-10.** Page-size reproduction of **PLATE 5i to 5l** and **5s** panel. Transverse (W to E) hydrogeologic cross-sections I-I' to L-L' and S-S' that span the northern and central parts of the International Boundary Zone (IBZ—**Fig. 7-5**), with section locations shown on **Fig. 1-3**, and panel inset index maps ..... 238

**Figure 7-11.** (facsimile copy of central and southern parts of Plate 1 *in* Conover 1954 [partial **PL. 9A**]) Map showing the approximate 1947 water-table altitude in central and southern Doña Ana County, with estimated depths to water in the 300 to 400 ft and > 400 ft ranges shown, respectively, with light greenish yellow and green dotted patterns ..... 243

**Figure 7-12a.** (middle part of **PL. 9B**) Map showing approximate water-level (blue) and land-surface (black-dashed) altitude for the middle MeB and the southern end of the Southern Jornada Basin (King et al. 1971, PL. 1) 1965-1968 water-level compilation, with N to left map orientation..... 244

**Figure 7-12b.** (lower part of **PL. 9B**) Map showing approximate water-level (blue) and land-surface (black-dashed) altitude in the southern Mesilla Basin area (King et al. 1971, PL. 1) 1965-1968 water-level compilation, with N to left map orientation ..... 245

**Figure 7-13.** (southern part of **PL. 9C**) Map showing approximate water-level contours, Mesilla Basin, New Mexico and Texas (modification of Wilson et al. 1981 [PL. 9] by Frenzel and Kaehler 1992 [PL. 1]) ..... 247

**Figure 7-14.** (Teeple 2017a, Fig. 47) Potentiometric-surface map, with inferred GW-flow paths, developed from mean winter 2010-11 water-level altitudes measured in wells completed in the SFG aquifer system of Doña Ana County, NM and El Paso County, TX.....248

**Figure 7-15.** Facsimile copy of Figure 7 in Frenzel and Kaehler (1992) showing annual Rio Grande discharge at Leasburg Dam and El Paso Narrows (Courchesne Bridge Gaging Station).... 251

**Figure 7-16.** (Frenzel and Kaehler 1992, fig. 11, modified from Hawley 1984 [pl. 5]) Schematic hydrogeologic section, in the approximate position of **PLATE 5e**, which extends ENE across the northern MeB and the Southern Jornada Basin (SJB) W of the Organ Mountains Uplift..... 253

<b>Figure 7-17.</b> (upper-left part of <b>PL. 9C</b> ) Map showing approximate water-level contours [alt. in ft amsl] in the NW part of the MeB W of Las Cruces, NM (modification of Wilson et al. 1981 [PL. 9] by Frenzel and Kaehler 1992 [PL. 1]).....	257
<b>Figure 7-18.</b> Facsimile copy of the Texas Water Development Board (TWDB) compilation of “Water Quality” data for the region west of El Paso/Ciudad Juárez in the west-central part of <b>PLATE 10</b> (Hibbs et al. 1997) .....	261
<b>Figure 7-19.</b> (Hawley et al. 2000, Fig. 4-8) Chloride concentrations (mg/L) of water from selected wells in the Mimbres Basin and contiguous parts of the Lower [Rio] Casas Grandes Subbasin and the Bolsón de los Muertos [El Aguaje Uplift, and Malpais and El Parabién Basins]....	263
<b>Figure 8-1.</b> Index map for the US-Mexico borderlands region that covers parts of southern New Mexico, western Texas, northern Chihuahua, and northeastern Sonora.....	268
<b>Figure 8-2.</b> Study Area index map showing locations of the Mesilla, Southern Jornada, and El Parabién groundwater (GW) basins. Also shown are the locations of hydrogeologic cross-section <b>A-A'</b> to <b>S-S'</b> major terrain features (incl. the Mesilla Valley, Selden Canyon and El Paso del Norte of the Rio Grande), and the Las Cruces and El Paso/Ciudad Juárez metropolitan centers. ....	269
<b>Figure 8-3.</b> (page-size <b>PL. 4A</b> ) Index map for the Study Area’s primary geohydrologic features on a <b>PLATE 1</b> hydrogeologic-map base .....	276
<b>Figure 8-4.</b> (page-size <b>PL. 1B</b> ) Index map for the Study Area’s major hydrogeologic subdivisions on USGS DEM base (PL. 1). Explanations of subdivision names and acronyms are on <b>Tables 8-1</b> and <b>8-2</b> .....	278
<b>Figure 8-5.</b> (page-size <b>PL. 2B</b> ) Schematic depiction of basin-fill subcrop topography, and primary lithostratigraphic and structural components in the NM WRRRI Study Area. <b>PLATE 1</b> Hydrogeologic-Map base, with explanation on <b>Table 8-3</b> .....	283
<b>Figure 8-6.</b> (page-size <b>PL. 2C</b> ) Schematic geologic cross-sections I-I' to III-III', which show major subsurface stratigraphic and structural relationships in the central and southern parts of the NM WRRRI Study Area. Explanation on <b>Table 8-3</b> , with geologic-section locations on <b>Figure 8-5</b> .....	284
<b>Figure 8-7.</b> (adapted from Hawley 1975, Fig. 2) Pliocene and Early Pleistocene depositional setting of the ARG distributive fluvial system (DFS-red lines) that terminated in the paleo-Lake Cabeza de Vaca (LCdV) complex of W.S. Strain (1966, 1971) .....	287

**Figure 8-8.** (Hawley et al. 2009, Fig. 10; USGS DEM base) Schematic depiction of major Quaternary-  
landscape features of the Mesilla Basin region ..... 289

## TABLES STORED IN DIGITAL FORMAT ON NM WRRI WEBSITE

Accessible at <https://nmwrri.nmsu.edu/publications/technical-reports/tr-reports/tr-363.html>

**TABLE 1.** Excel® Spreadsheet Compilation of Records of 395 Selected Wells in the Binational Study Area, with Location, Construction, and Hydrostratigraphic-Interpretive Information, and Reference Sources.

**TABLE 1A.** References cited in **TABLE 1**.

**TABLE 1B.** Names and Acronyms for Hydrogeologic Subdivisions Shown on Maps, Cross-Sections, and **TABLE 1**.

**TABLE 2.** Rio Grande-rift basin-fill and river valley-fill Hydrostratigraphic Units (HSUs), and bedrock-mapping units in hydrogeologic maps, cross-sections, and block diagrams of the Mesilla Basin regional Study Area (*cf.* **PLS. 1 to 9** and **TBL. 1**).

**TABLE 3.** Names of and acronyms for basin/inter-basin subdivisions shown on Study Area hydrogeologic maps and cross-sections (**TBL. 3A**). Names of and acronyms for primary basin- and subbasin-boundary fault zones in the Study Area (**TBL. 3B**).

## PLATES STORED IN DIGITAL FORMAT ON NM WRRI WEBSITE

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**PLATE 1.** Hydrogeologic index map of the Mesilla Basin regional Study Area. Hydrogeologic-subdivision categories of groundwater-basin and inter-basin map units are defined on **Tables 1-4** and **1-5**. The solid and dashed black map-unit boundary lines (mostly fault zones) are primarily defined for use in groundwater-flow and hydrochemical model development. Blue lines show locations of hydrogeologic cross-sections A-A' to S-S' (**PL. 5**). *See TABLES 2 to 4*, and **Tables 3-1 to 3-4** for additional information on hydrostratigraphic, lithostratigraphic, and structural components of cross-sections, subsurface maps, and block diagrams (**PLS. 5 to 9**). 1:100,000 scale compilation on Google Earth® DTM image base.

**PLATE 1A.** Bouguer [isostatic-residual] gravity-map overlay (4-milligal contour interval) on **PLATE 1** base. It covers most of the Study Area and was compiled by Jiménez and Keller (2000, Fig. 4). The Southern Jornada Basin (SJB), Mesilla Basin (MeB), and El Parabién Basin (EPB) are outlined in orange, green, and dark red, respectively.

**PLATE 1B.** Schematic depiction of the topography, and primary stratigraphic and structural components of the bedrock terrane that is buried by basin-fill deposits in the Study Area. The Mesilla GW Basin boundary is in green, with map-unit subdivisions are defined in **Tables 1-3** and **3-3**. The primary structure-contour interval on the bedrock surface is 100 ft (~30 m); and the red lines show

locations of three schematic geologic cross-sections (I-I' to III-III') on **PLATE 1C**. The general position of the deeply buried “Lanark igneous-intrusive complex (TmLC),” which forms the central part of the Mid-Basin High, is also shown (*cf.* **PLS. 5i** and **5q; Part 6.3.2a**; Clemons 1993). The map represents the first effort to create an approximation of the hydrogeologic “bottom” of the SFG basin-fill aquifer system. It is based on a synthesis of available geological and/geophysical information that has been acquired by the PI since 1962.

**PLATE 1C.** Schematic geologic cross-sections I-I' to III-III' that show major subsurface stratigraphic and structural relationships in the central and southern parts of the Study Area, with section locations shown on **PLATE 1B**. Section I-I' shows basic bedrock geologic relationships in the northern MeB/MeV and southern part of the Southern Jornada Basin (SJU). Section II-II' illustrates these relationships in a central MeB area that includes the deeply buried Lanark intrusive complex (TmLC) that forms much of the central Mid-Basin High (MeB-MBH; **Part 6.3.2a**). Section III-III' shows basic geologic relationships in an area located about 5 mi (8 km) south of the International Boundary.

**PLATE 2.** Study Area location-index maps (**PL. 1**-derivative base) that shows the names and locations of (1) major geographic and cultural features; and (2) hydrogeologic mapping-unit subdivisions. 1:100,000 scale compilations on Google Earth® DTM image base.

**PLATE 2A.** Primary Study Area index map on a **PLATE 1** Hydrogeologic Map base, with 10,000 m UTM-Zone 13 NAD83 and latitude/longitude coordinates. The UTM Zone 13N (NAD 1983) boundary coordinates for the 3,350 mi<sup>2</sup> (8,675 km<sup>2</sup>) Study Area are respectively 3,504,000 m and 3,611,000 m northing, and 302,000 m and 367,000 m easting. The Mesilla, Southern Jornada, and El Parabién groundwater (GW) basins are outlined in green, orange, and red, respectively; and blue lines show locations of Hydrogeologic Cross-Sections A-A' to S-S' (**PLS. 5a** to **5s**). The valleys of the Rio Grande-Rio Bravo fluvial system have a dashed-line pattern. Also shown are locations of major terrain features (including the major highland areas, Selden Canyon, and El Paso del Norte of the Rio Grande/Bravo), and the El Paso/Ciudad Juárez and Las Cruces metropolitan centers.

**PLATE 2B.** Index map showing names locations of major Hydrogeologic Subdivisions in the Study Area. The Mesilla GW Basin (MeB) is in blue shades, and the Mesilla Valley of the Rio Grande is in dark blue. El Parabién and Southern Jornada GW Basins (EPB and SJB) are in pink and light green, respectively. The acronyms for Selden Canyon and El Paso del Norte are SCyn and EPdN, respectively. Solid and dashed black lines are boundaries of interbasin-uplift and intrabasin subdivisions. Acronyms for Subdivision categories, including fault zones (lines with bar and ball symbols), are identified in **TABLES 2** and **3**.

**PLATE 3.** Index map showing locations of the 395 key wells (red dots) that were the primary sources of the subsurface hydrogeologic information used in this study. Well Numbers (1-395) correspond with entries in **TABLE 1** (Excel®-format): “Records of Selected Wells in the Binational Study Area, with Location, Construction, and Hydrostratigraphic-Interpretive Information, and Source References.” The Mesilla, Southern Jornada, and El Parabién GW Basins are outlined in green, orange, and violet, respectively; and explanations of names and acronyms of hydrogeologic mapping units, including fault zones (fzs) are also included in **Tables 1-3** and **1-4**. Well selection was based mainly on (1) depth and quality of the hydrostratigraphic and hydrochemical database, and (2) accuracy of predevelopment static water-level (swl) information. Compiled at 1:100,000 scale on 2018 Google Earth® image

**PLATE 4.** Index maps to major geohydrologic features of the Study Area on **PLATE 1** Hydrogeologic-Map base (**PL. 4A** ft and **PL. 4B** m). The Mesilla, Southern Jornada, and El Parabién GW Basin boundaries are in green, orange, and violet, respectively. Thin blue contour lines show the approximate pre-development (~1976) potentiometric-surface altitude (20 and 100 ft on **PL. 4A**, and 5, 10, and 50 m on **PL. B**). Major surface-watershed divides are shown by solid and dashed thick blue lines. The dashed blue line with arrows in the maps’ SW corner marks the approximate position of the regional GW-flow divide between Transboundary (El Paso del Norte)-directed, and Los Muertos Basin (EL Barreal)-directed underflow.

**PLATE 5.** Electronic-folder compilation of nineteen hydrogeologic cross-sections (1:100,000 plan-scale, 5X-vertical exaggeration [VE]) that schematically illustrates subsurface hydrostratigraphic and structural relationships to a mean sea level (msl) depth. Thirteen sections have a transverse basin/river-valley orientation (**PLS. 5a-5l** and **5s**) and six sections follow general basin and mountain-range trends (**PLS. 5m-5r**), and form a roughly orthogonal fence-diagram grid for the entire Study Area (*cf.* **Part 2.3.2**). The blue line in the upper part of each section marks the approximate water-table and/or potentiometric-surface position, and the most-productive upper and middle parts of the SFG basin-fill aquifer system are shown with lighter shades of yellow. Page-size reproduction of **PLATES 5i** to **5l** and **5s** (Figs. 2-3 and 7-7) provides a basin-scale perspective on basic hydrogeologic relationships in the International Boundary Zone (IBZ) part of the Study Area.

**PLATE 6.** Structure-contour maps of the three hydrostratigraphic-unit (HSU) surfaces that form the primary framework components of the hydrogeologic model (*cf.* **CHPT. 3-Part 3.4.3**). They schematically illustrate best-available interpretations of subsurface topography and major geologic boundary features of basal surfaces of the HSU layers that are designed specifically for the use of future groundwater-flow models: (1) contact of SFG-basin and/or RG-Valley fill aquifer systems on a buried

bedrock substrate\*, (2) Middle/Lower Santa Fe **HSU** boundary, and (3) Upper/Middle Santa Fe **HSU** boundary. Initial compilation scale of 1:100,000 on **PLATE 1**-derivative planimetric base.

*\*Structure-contour intervals in 100 and 200 ft, and 25, 50, and 100 m.*

**PLATE 7.** Three isopleth\* maps of the Study Area that show the primary lithofacies-assemblage composition of the saturated parts of hydrostratigraphic units USF, MSF, and LSF (**LFAs 1-10: Figs. 4-3 and 4-4, Tbls. 4-1 and 4-2**). The southern sections of the maps also provide a provisional, but conceptually consistent hydrogeologic interpretations of subsurface conditions in the 12.5 mile (20 km)-wide strip south of the International Boundary that includes the new JMASCJ well field south of the Santa Teresa-San Jerónimo Port of Entry. Initial compilation scale of 1:100,000 on **PLATE 1**-derivative planimetric base.

*\*Isopleth map units are the general equivalent of the “voxel” units of Sweetkind (2017, 2018)*

**PLATE 8.** Northeast-facing block diagrams of the central (**8A**) and southern (**8B**) Mesilla Basin that schematically portray major RG-rift stratigraphic and structural features at 1x VE to a base elevation of 25,000 ft (7.6 km) below msl. 1:100,000 compilation scale, with stratigraphic-unit definitions on **TABLE 2** and **Table 3-2 (cf. Tbl. 1-3)**.

**PLATE 8A.** Block diagram with 32° N-latitude base panel. Inset cross-section I-I' (**PL. 5i**) is one of 19 hydrogeologic sections that show lithofacies, hydrostratigraphic and structural relationships at scales appropriate for *compilation-scale* groundwater-flow and hydrochemical modeling. It also depicts major components of the deeply buried Mid-Basin High in the area of the large Lanark igneous-intrusive complex of Oligocene age (TmLC).

**PLATE 8B.** Block diagram of the southern Mesilla Basin, with south-facing panel on International-Boundary. It schematically portrays major RG-rift stratigraphic and structural features, including the Eocene\* Cristo Rey igneous-intrusive complex. Pale-blue shading at the southern edge of the 2017 Google Earth® background image show the approximate NE extent of pluvial-Lake Palomas at its Late Pleistocene high stands.

**PLATE 9-series maps** comprise facsimile copies of large-format maps of hydrogeologic and geohydrologic features, which are in the public domain but relatively difficult to access (*cf. Part 3.3*).

**PLATES 9A to 9 C** are copies of historic water-table/depth-to-water maps from the following Federal and State publications:

**PLATE 9A (Fig. 7-12)** is a facsimile copy of Plate 1 *in* Conover (1954) that shows approximate 1947 groundwater-level contours in central and southern Doña Ana County, New Mexico. Estimated

depths to water in the 300 to 400 ft and > 400 ft ranges, are shown, respectively, with light greenish yellow and green dotted patterns

**PLATE 9B (Fig. 7-13)** is a facsimile copy of map of approximate groundwater-level contours based on data collected and compiled in 1965 to 1968 by W.E. King and others (1971, PL. 1)

**PLATE 9C (Fig. 7-14)** is a facsimile copy of a map showing approximate water-level contours in the New Mexico and Texas parts of the Mesilla GW Basin (Frenzel and Kaehler 1992, Pl. 1). The map was modified from the compilation of water-level data collected through January 1976 by Wilson and others (1981, PL. 9).

**PLATE 10.** Overlay of groundwater-quality map in Stiff-diagram format on a 2017 Google Earth® image-base map of the Mesilla Basin region (*cf.* **Fig. 1-2, Report Frontispiece**). Information was compiled by the Texas Water Development Board (TWDB) for a report on “Transboundary Aquifers of the El Paso/Ciudad Juárez/Las Cruces Region” by Hibbs and others (1997; CD-ROM and map insert in Report back cover). The Mesilla, Southern Jornada, and El Parabién GW Basins have green, orange, and violet shading respectively; and maximum Late Pleistocene extent of pluvial-Lake Palomas has light-blue shading. The database includes water sampled from more than 200 wells in the El Paso and Hudspeth Counties (TX), Doña Ana and Otero Counties (NM), and adjacent parts of Chihuahua (*cf.* **Part 7.6**).

**PLATE 10-1** is a facsimile copy of the southwestern part of the TWDW map, and **PLATE 10-2** is an explanation of water-quality symbols

**PLATE 11 (Fig. 1-10)** is an index map for aquifer-management units in Mexico and major hydrographic boundaries in the United States south of 32° N latitude on a 2018 Google Earth® image base. The Acuífero Conejos-Médanos “delineación oficial” and the Zona Hidrogeológica de Conejos Médanos boundary are bounded, respectively, by dash-dot gray and solid yellow lines (INEGI 2012). The approximate area inundated of pluvial-Lake Palomas at its latest Pleistocene (~29 to 11 ka—3,970-ft/1,210 m amsl) highest stands is shown in light blue. The dashed-blue line shows the general position of the historic GW-flow divide between NE-directed underflow toward the lower Mesilla Valley, and SW-directed underflow toward the present ephemeral-lake plain (El Barreal) in the eastern Bolsón de los Muertos (*cf.* **Fig. 1-3**).

**APPENDICES STORED IN DIGITAL FORMAT ON NM WRRI WEBSITE**

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*\*Contents are briefly described in the EXECUTIVE SUMMARY (p. x-xvii)*

- A. BACKGROUND ON DEVELOPMENT OF DIGITAL HYDROGEOLOGIC-FRAMEWORK MODELS OF BASIN-FILL AQUIFER SYSTEMS IN THE MESILLA BASIN REGION
- B. BIBLIOGRAPHY ON TOPICS RELATED TO TRANBOUNDARY AQUIFER SYSTEMS IN THE NEW MEXICO, TRANS-PECOS TEXAS, AND NORTHERN MEXICO REGION
- C. REVIEW OF HYDROGEOLOGY-RELATED INVESTIGATIONS IN THE UNITED STATES PART OF THE MESILLA BASIN REGION—1890 to 2010
- D. FACSIMILE REPRODUCTIONS OF SELECTIONS FROM PUBLISHED WORK ON THE CENOZOIC GEOLOGY, HYDROGEOLOGY, AND GEOMORPHOLOGY OF THE NEW MEXICO-CHIHUAHUA BORDER REGION
- E. CHAPTER 8 SUPPLEMENT: CONSERVATION OF GROUNDWATER RESOURCES IN THE UNITED STATES PART OF THE BINATIONAL MESILLA BASIN REGION
- F. SELECTED PHOTOGRAPHS AND SATELLITE IMAGES OF REPRESENTATIVE LANDSCAPES AND HYDROGEOLOGIC FEATURES IN THE SOUTH-CENTRAL NEW MEXICO BORDER REGION
- G. GLOSSARY OF MORE THAN 250 COMMONLY USED SCIENTIFIC AND TECHNICAL TERMS IN PUBLICATIONS ON BASIN & RANGE PROVINCE HYDROGEOLOGY
- H. HISTORICAL BACKGROUND ON DEVELOPMENT OF SHARED GROUNDWATER RESOURCES IN THE BINATIONAL SOUTHERN MESILLA BASIN REGION—A HYDROGEOLOGICAL PERSPECTIVE

## ABBREVIATIONS AND ACRONYMS–GENERAL USAGE\*

*\*See TABLES 1 and 2, and APPENDIX G Glossary for More Specific References*

ACM	Acuífero de Conejos Médanos
amsl	above Mean Sea Level (altitude)
Ar	Argon
<sup>39</sup> Ar	Argon-39 is a radioactive isotope of Argon
<sup>40</sup> Ar	Argon-40 is a radioactive isotope of Argon
ARG	Ancestral Rio Grande
BCE	Before Common Era (also AD/BC)
BdlM	Bolsón de los Muertos
bgs/bls	below ground surface (elevation)
BGW	brackish groundwater (1,000-10,000 mg/L TDS)
bmsl	above Mean Sea Level (elevation)
BNSFRR	Burlington Northern & Santa Fe Railroad
BP	Before Present (1950 CE)
BR	bedrock
C	Carbon
<sup>14</sup> C	Carbon-14 is a radioactive isotope of Carbon
Ca <sup>2+</sup>	Calcium
CaCO <sub>3</sub>	Calcite
CaSO <sub>4</sub> ·H <sub>2</sub> O	Gypsum
CE	Common era (also AD)
CH <sub>4</sub>	Methane
CILA	Comisión Internacional de Límites y Aguas (IBWC-Mexico Section).
Cl <sup>-</sup>	Chloride
CONAGUA	Comisión National de Aguas
DCMI	domestic-commercial-municipal-industrial
δ <sup>13</sup> C	Ratio of stable isotopes <sup>13</sup> C: <sup>12</sup> C, reported in parts per thousand (per mil, ‰)
δD	Ratio of deuterium (or hydrogen-2, <sup>2</sup> H, D) and <sup>1</sup> H
δ <sup>18</sup> O	Ratio of stable isotopes oxygen-18 ( <sup>18</sup> O) and oxygen-16 ( <sup>16</sup> O)
DFS	Distributive Fluvial System
DM&I	domestic, municipal and industrial
DTW	Depth to groundwater (in ft bgs or m bgs/bls; <i>cf.</i> swl)

E	East
EBID	Elephant Butte Irrigation District EPB- El Parabién GW Basin
EPdN	El Paso del Norte
EPB	El Parabién GW Basin
EPW	El Paso Water (former EPWU)
EPWU	El Paso Water Utilities (now EPW)
ft	feet
Fm	Formation (as in Camp Rice Fm)
fz	fault zone
GISc	geographical information science
GIS	geographical information systems
Gp	Group (as in Santa Fe GP)
GW	Groundwater [i.e., subsurface water in the zone of saturation]
HB	Hueco Bolson
<i>Historic</i>	Post 1535-1598 CE from a New Mexico/American SW time perspective
HSU	Hydrostratigraphic Unit ( <b>TBL. 2, Fig. 3-5</b> )
IBWC	International Boundary and Water Commission-U.S. Section
IBZ	International Boundary Zone (informal, e.g., <b>Fig. 1-10</b> )
INEGI	Instituto Nacional de Estadística, Geografía e Informática
JMASCJ	Ciudad Juárez Junta Municipal de Agua y Saneamiento
K <sup>+</sup>	Potassium
Ka	kiloannum (1,000 years)
K <sub>hsat</sub>	saturated-horizontal hydraulic conductivities
L	liter
LFA	Lithofacies Assemblage ( <b>Fig. 4-3 and Tbl. 4-1</b> )
LRGWUO	Lower Rio Grande Water Users Organization
LSF	Lower Santa Fe HSU
LSFG	Lower Santa Fe Gp
m	meter
Ma	Mega-annum; million years (age, ago)
MAR	managed aquifer recharge
M&I	municipal and industrial
MbB	Mimbres GW Basin
MBR	Mesilla Basin Region

MeV	Mesilla Valley
MpB	Malpais GW Basin
mg	milligram
Mg <sub>2</sub> <sup>+</sup>	Magnesium
MLS	Undivided Middle/Lower Santa Fe HSU
msl	mean Sea Level (elevation)
MSF	Middle Santa Fe HSU
N	North
Na <sup>+</sup>	Sodium
NMBGMR	New Mexico Bureau of Geology & Mineral Resources-A Division of NM Tech; Prior to 2001: NM Bureau of Mines & Mineral Resources (NMBMMR)
NMISC	NM Interstate Stream Commission
NMOSE	Office of the New Mexico State Engineer
NM WRRI	New Mexico Water Resources Research Institute
NMSU	New Mexico State University
ppm	parts per million TDS
PI	Principal Investigator
RASA	Regional Aquifer-Systems Analysis
RG	Rio Grande
RGP	Rio Grande Project
RG-rift (RGr)	Rio Grande rift
RVB	Rincon Valley GW Basin
S	South
SCyn	Selden Canyon
SJB	Southern Jornada GW Basin
SFG	Santa Fe Group
SGM	Servicio Geológico de México
SJB	Southern Jornada GW Basin
SO <sub>4</sub> <sup>2-</sup>	Sulfate
SPRR	Southern Pacific Railroad
SRH	Secretaria de Recursos Hidráulicos
SWAB	Southwest Alluvial Basins
swl	static [ground] water level (in ft bgs/bls - <i>cf.</i> DTW)
TAAP	Transboundary Aquifer Assessment Program

TAMU	Texas A&M University
TBA	Transboundary aquifer
TDS	total dissolved solids, commonly expressed in mg/L
TWDB	Texas Water Development Board
UACJ	Universidad Autónoma de Ciudad Juárez
UPRR	Union Pacific Railroad
USACE	U.S. Army Corps of Engineers
USBOR	U.S. Bureau of Reclamation
USF	Upper Santa Fe HSU
USGS	U.S. Geological Survey
USEPA	U.S. Environmental Protection Agency
UT BEG	University of Texas Bureau of Economic Geology
UTEP	University of Texas El Paso
W	West
ZHGCM	Zona Hidrogeológica de Conejos Médanos