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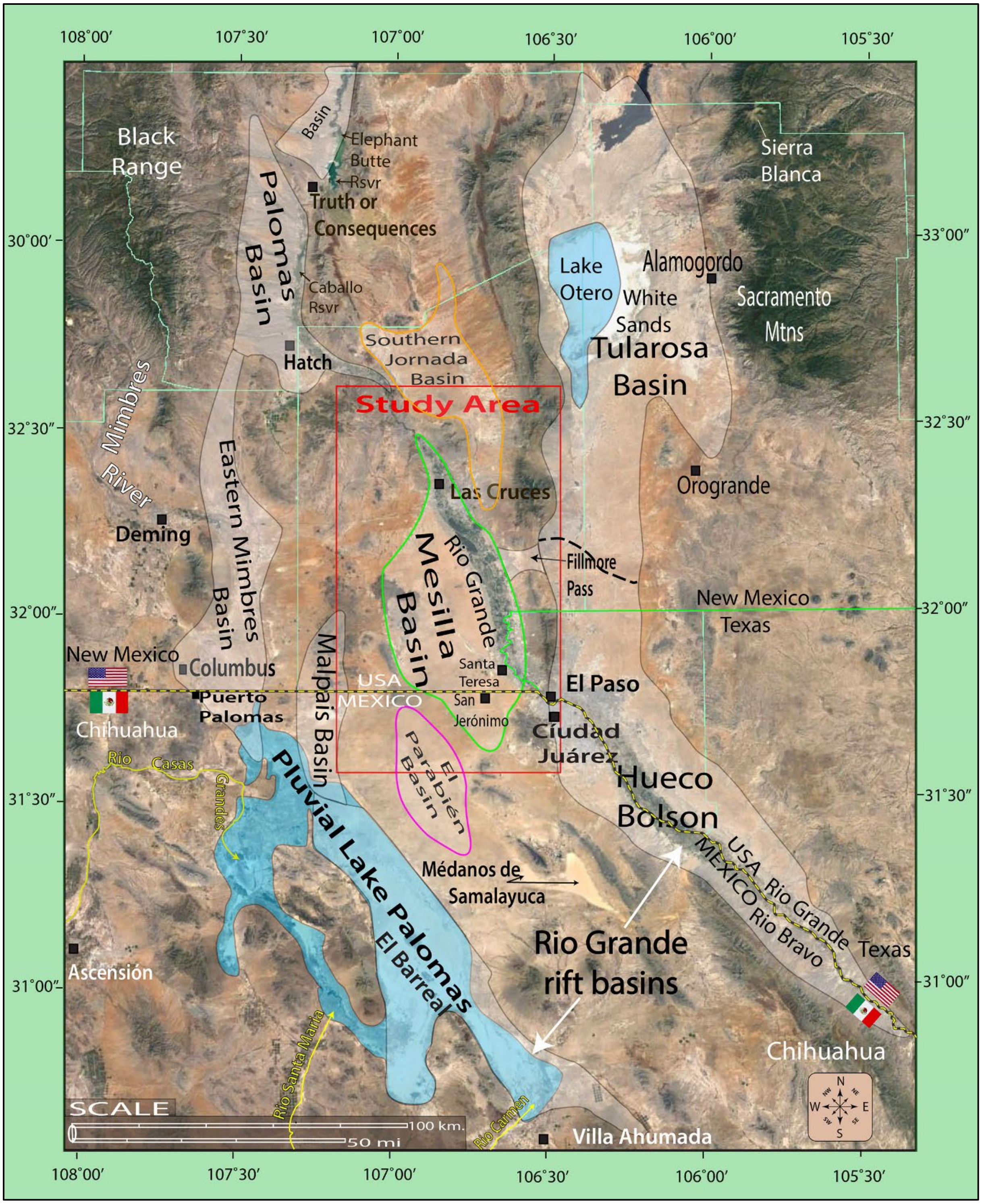

Frontispiece. Index map of the Mesilla Basin region (MBR) showing locations of the Study Area (**Fig. 1-3**, red outline), major landscape features in the northern Mexican Highland section of the B&R province, and basins of the southern RG-rift province (**Fig. 1-1**). Blue shading shows the approximate 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.

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

By

John W. Hawley[1], Principal Investigator—Hydrogeology and Environmental Geology

Baird H. Swanson[2], Geoscience Specialist in Cartography and Electronic-File Management

J. Steven Walker[3], Former GIS Coordinator, New Mexico Water Resources Research Institute

S. Heather Glaze[4], Former GIS Coordinator, New Mexico Water Resources Research Institute

Catherine T. Ortega Klett[5], Former Sr Program Manager, New Mexico Water Resources Research Institute

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[1]Visiting Senior Hydrogeologist, NM Water Resources Research Institute; and Emeritus Senior Environmental Geologist, NM Bureau of Geology & Mineral Resources, NMIMT 1000 Vassar Dr. NE Albuquerque, NM, 87106-2631 hgeomatters@gmail.com

[2]Swanson Geoscience, LLC, 6508 Natalie NE, Albuquerque, NM 87110 clearwater1012@gmail.com

[3] Hydrogeologist and Program Manager, City of Santa Fe, NM 87504 jswalker@santafenm.gov

[4]GIS Specialist, Public Works Department, City of Las Cruces, NM 88001 shglaze@gmail.com

[5]OK Editorial Services, 4507 Mockingbird St., Las Cruces, NM 88011 coklett@gmail.com

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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^2 (8,675 km^2) 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

Standard—The purpose of New Mexico Water Resources Research Institute (NM WRRI) technical reports is to provide a timely outlet for research results obtained on projects supported in whole or in part by the institute. Through these reports, the NM WRRI promotes the free exchange of information and ideas, and hopes to stimulate thoughtful discussions and actions that may lead to resolution of water problems. Through peer review of draft reports, considerable attempts are made to substantiate the accuracy of the contained information, but the views expressed by their authors do not necessarily reflect those of the cooperating entities, public and private, nor does the mention of trade names or commercial products constitute their endorsement. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Geological Survey.

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 National de Aguas (CONAGUA), Servicio Geológico de México (SGM), International Boundary and Water Commission-U.S. Section (IBWC), and Comisión Internationial de Limites y Aguas (CILA).

SPECIAL NOTE ON REPORT AUTHORSHIP

The PI has had sole responsibly 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.

ACKNOWLEDGEMENTS

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Labor-intensive and high-quality GIS support of the following graduate and undergraduate students was an essential part of early stages of hydrogeologic-map and cross-section compilation: Michael Cleary (NMSU-Geological Sciences and NM WRRI Staff), Sean Carrasco and Marquita Ortiz (NMSU-Geography and NM WRRI Staff), B.V.N.P. Kambhammettu and S. Yeliz Çevik (NMSU-Civil Engineering), and Lauren Breitner (UNM-Civil Engineering and USGS-NMWSC Staff). Special thanks is also due to Dr. Alfredo Granados Olivas, and students and staff associates at the UACJ-Centro de Información Geográfica, for essential baseline information on the hydrogeologic framework of northern Chihuahua.

Others acknowledged for their substantial scientific and technical support include: Dr. Richard P. Lozinsky (now with Fullerton College, Fullerton CA), for invaluable contributions (1987-1992) on borehole-sample thin-section petrology and well-log interpretation; and long-time colleague Dr. William R. Seager (NMSU Emeritus Professor of Geology), who has done the seminal work on the geology of the south-central New Mexico border region since 1966. Special appreciation is also due to: Gene C. Doty (USGS-retired), Dr. Barry J. Hibbs (California State University, LA), Mike Hightower (Sandia Natl. Labs.-retired), Dr. Greg Mack (NMSU Geological Sciences Dept. Emeritus Professor, Dr. J. Phillip King (NMSU Civil Engineering Dept. Emeritus Professor), Drs. K.C. Carroll and H. Curtis Monger (NMSU Plant & Environmental Sciences Dept.), Dr. Erek Fuchs and Gary Esslinger (EBID), James Witcher (consultant, formerly with NMSU Energy Institute), Deborah Hathaway (S.S. Papadopulos & Assoc.), Dr. William R. Hutchison (consultant, formerly with EPWU), Eddie Collins (UT BEG), Robert Myers and Kenneth Stevens (formerly with USGS), Drs. Diane Doser and Randy Keller (UTEP), Drs. David W. Love and Sean D. Connell (NMBGMR), Dr. Frederick M. Phillips (NM Tech Dept. of Earth & Environmental Science, Emeritus Professor), Dr. Christopher J. Eastoe (UAZ Dept. of Geology), Dr. James F. Hogan (UAZ SAHRA), Dr. Thomas Maddock III (UAZ Dept. of Hydrology and Water Resources), Dr. Rolf Schmidt-Peterson and Dale Doremus (NM Interstate Stream Commission), Dr. Zhuping Sheng (TAMU Texas AgriLife Research Center), Gilbert Anaya (US IBWC), Chester J. Callahan (Marathon Oil Co.-retired), and Grace Klement Gunaji (consulting geologist).

Many individuals, living and deceased, working outside the geoscience and geotechnical community have also contributed substantially to hydrogeologic investigations in the Study Area during the past six decades. These include water-well drillers, mineral-resource explorationists, farmers, ranchers, and real-estate developers, with special acknowledgement due to those in the well-drilling profession, notably: Eddie Boone; Raeford, Michael and Padrick Guffey; Floyd and Larry Johnson; W.H. (Hard Rock) Schieffer; and John (Toby) Tipton. Visionary Charles L. (Charlie) Crowder's long-term support for hydrogeologic studies in the binational Santa Teresa area has played an essential role in their success (*cf.* Wilson et al. 1981, Kocherga 2018b, Pacheco 2018c; **Fig. 6-7**).

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 WRRI 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. Kottlowski (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^2 (8,675 km^2), 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^2) 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 **e**xplanations 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://nmwrri.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 WRRI 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^3).
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.

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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.

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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)

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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 Parabien 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

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ABBREVIATIONS AND ACRONYMS–GENERAL USAGE*

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

ACM	Acuifero de Conejos Médanos
amsl	above Mean Sea Level (altitude)
Ar	Argon
^{39}Ar	Argon-39 is a radioactive isotope of Argon
^{40}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
^{14}C	Carbon-14 is a radioactive isotope of Carbon
Ca^{2+}	Calcium
$CaCO_3$	Calcite
$CaSO_4 \cdot H_2O$	Gypsum
CE	Common era (also AD)
CH_4	Methane
CILA	Comisión Internationial de Limites y Aguas (IBWC-Mexico Section).
Cl^-	Chloride
CONAGUA	Comisión National de Aguas
DCMI	domestic-commercial-municipal-industrial
$\delta^{13}C$	Ratio of stable isotopes ^{13}C: ^{12}C, reported in parts per thousand (per mil, ‰)
δD	Ratio of deuterium (or hydrogen-2, ^2H, D) and ^1H
$\delta^{18}O$	Ratio of stable isotopes oxygen-18 (^{18}O) and oxygen-16 (^{16}O)
DFS	Distributive Fluvial System
DM&I	domestic, municipal and industrial
DTW	Depth to groundwater (in ft bgs or m bgs/bls; *cf.* 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
Historic	Post 1535-1598 CE from a New Mexico/American SW time perspective
HSU	Hydrostratigraphic Unit (**TBL. 2**, **Fig. 3-5**)
IBWC	International Boundary and Water Commission-U.S. Section
IBZ	International Boundary Zone (informal, e.g., **Fig. 1-10**)
INEGI	Instituto Nacional de Estadística, Geografía e Informática
JMASCJ	Ciudad Juárez Junta Municipal de Agua y Saneamiento
K^+	Potassium
Ka	kiloannum (1,000 years)
K_{hsat}	saturated-horizontal hydraulic conductivities
L	liter
LFA	Lithofacies Assemblage (**Fig. 4-3** and **Tbl. 4-1**)
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_2+	Magnesium
MLS	Undivided Middle/Lower Santa Fe HSU
msl	mean Sea Level (elevation)
MSF	Middle Santa Fe HSU
N	North
Na^+	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
$SO4^{2-}$	Sulfate
SPRR	Southern Pacific Railroad
SRH	Secretaria de Recursos Hidráulicos
SWAB	Southwest Alluvial Basins
swl	static [ground] water level (in ft bgs/bls - *cf.* 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