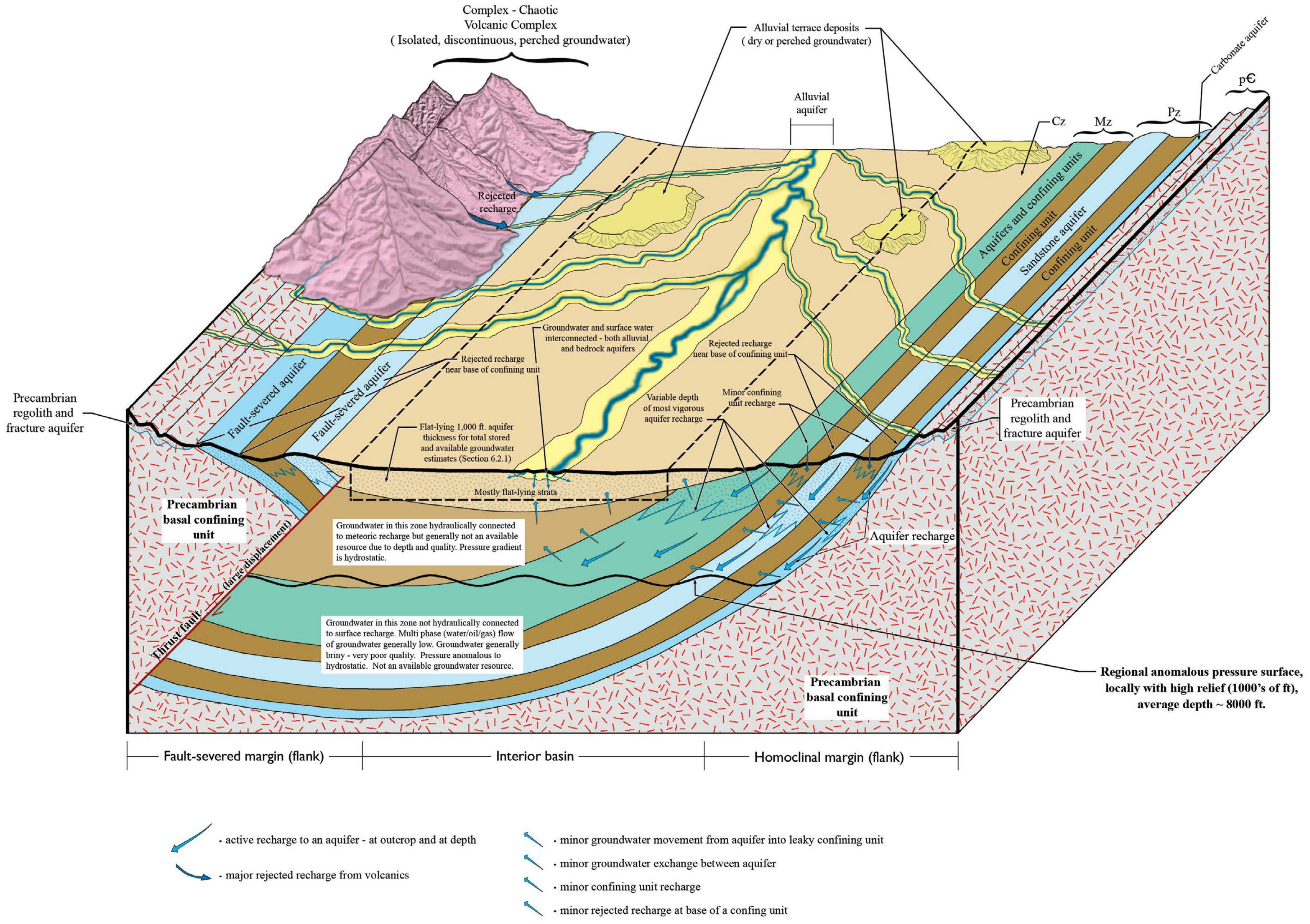

Chapter 1
Introduction

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Frontispiece. Conceptual block diagram of WBRB groundwater regime that illustrates various hydrogeologic concepts discussed in this memorandum, including:

- Paleozoic through Quaternary sedimentary geologic units progressively deposited on the Precambrian basement and subsequently folded, faulted, and eroded to form the current hydrogeologic framework of a structural groundwater basin
- Outcrop areas of various hydrogeologic units, where recharge infiltrates to the subsurface
- Typical settings for rejected recharge
- A thick pile of volcanic material deposited on an evolving landscape during the Tertiary
- A deep basin volume of rocks where development of multi-phase (hydrocarbons, water, gas) conditions substantially restricts groundwater flow
- The volume of the Q/T Aquifer that was the basis of stored and available groundwater estimates
- A depiction of the Quaternary Aquifer – deposited on rocks ranging in age from Precambrian to Tertiary – that was also the basis of stored and available groundwater estimates
- The exchange of groundwater between Quaternary and underlying hydrogeologic units

Part 1– scope, participating agencies, and legal framework

In 1973 the Wyoming State Engineer's Office (WSEO) compiled the first State Framework Water Plan. In 1979, the Wyoming State Legislature created the Wyoming Water Development Commission (WWDC) to coordinate water and related land resources planning for the state. Between 1979 and 1995, the WWDC completed several major river basin planning studies. In 1996 the Legislature directed WWDC to conduct a Water Planning Feasibility Study. On the basis of results of the feasibility study the Legislature funded the Statewide Water Planning Process in 1999 to update the original 1973 State Framework Water Plan, and specifically to:

- Inventory the state's water resources and related lands
- Summarize the state's present water uses and project future water needs.
- Identify alternatives to meet projected future water needs.
- Provide water resource planning direction to the State of Wyoming for a 30-year time-frame.

The resulting Wyoming Framework Water Plan (WWC Engineering, 2007) summarized the seven separate river basin plans for Wyoming's seven major drainage basins **(Figure 1-1)** compiled between 2001 and 2006 for the WWDC. The Wind/Bighorn River Basin plan (BRS Inc., 2003e) summarized several technical memoranda, including the initial Available Groundwater Determination for the Wind/Bighorn River Basin Technical Memorandum (Lidstone and Associates, Inc., 2003).

The present Available Groundwater Determination Technical Memorandum updates the 2003 Technical Memorandum; it will inform revisions of the 2003 Wind/Bighorn River Basin Plan and the 2007 Wyoming Framework Water Plan. It presents a new compilation of available information on the groundwater resources of the WBRB. While original maps and tables were developed for this memorandum, no original investigations were performed.

1.1 Scope

The WWDC and the Wyoming State Geological Survey (WSGS) entered into an Interagency Agreement in June 2008 to review and compile existing information to update the 2003 Available Groundwater Determination Technical Memorandum (Lidstone and Associates, Inc., 2003). A downloadable file containing the 2003 Memorandum is available online at the WWDC website,

http://wwdc.state.wy.us under River Basin Planning.

The scope of the project is as follows:

- Identify the major (most heavily used) aquifers in the WBRB.
- Describe the three-dimensional extent of the hydrogeologic units.
- Describe the physical properties of the lithostratigraphic units and the physical properties and chemical characteristics of the groundwater in the hydrogeologic units.
- Describe the aquifer recharge areas.
- Estimate aquifer recharge rates.
- Estimate total and available quantities of the water in the aquifers.
- Estimate "safe yield" potential for the aquifers.
- Describe areas where groundwater development may impact surface water use and areas of interference between aquifers.Discuss future groundwater development opportunities to satisfy projected agricultural, municipal, and industrial demands.

1.2 Agency participation, responsibilities, and oversight

This report is the result of a cooperative effort by the WWDC/WWDO, WSGS, the U.S. Geological Survey (USGS), and Wyoming Water Resources Data System (WRDS). The WSEO and the WDEQ contributed significant resources for developing some of the data presented in this report.

- The WWDO and WRDS provided the WSGS with overall program guidance and standards, software, and format requirements for deliverables (maps, databases, metadata, tables, graphs, etc.).
- The WSGS was the primary compiler of the deliverables associated with Chapter 6 and of the maps and databases for presenting available data on wells and springs.
- The USGS, under contract to the WSGS, was the compiler of the deliverables associated with Chapter 7, and with Section 5.6.1.
- The WSGS and USGS cooperated on sections of Chapters 5, 6, 8, and 9.
- The WRDS aided the WSGS with the hard copies of the final report for this project, and hosts the report and associated deliverables on the Internet on behalf of WWDC/WWDO.

The USGS provides maps, reports, and other information to help states meet their needs to manage, develop, and protect America's water, energy, mineral, and land resources. The USGS was a primary developer and contributor of the groundwater information provided in this Technical Memorandum.

The Wyoming Water Resources Data System (WRDS) is a clearinghouse for hydrological data. The WRDS is funded by the WWDO to provide a variety of services including the online provision of groundwater resources information, maps, and publications. The WRDS assisted in the development and presentation of the State Water Plan and this Technical Memorandum.

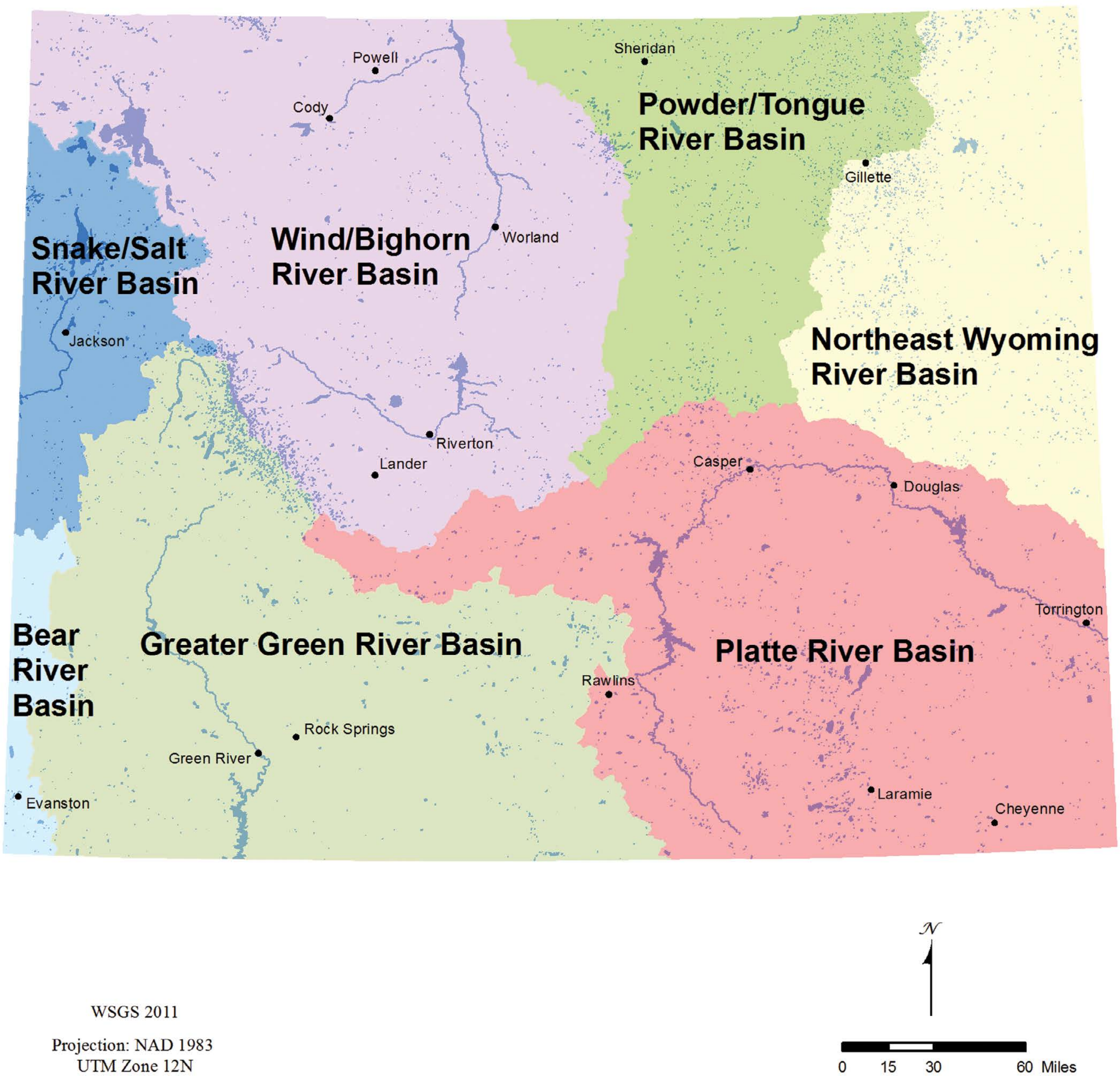

Figure 1-1. Major drainage basins, Wyoming.

The Wyoming Water Development Commission (WWDC) is the water development planning agency for Wyoming. They administer new public-funded development, construction, rehabilitation, and related groundwater studies. WWDC programs are administered primarily by the Wyoming Water Development Office (WWDO).

The Wyoming State Engineer's Office (WSEO) and WWDO cooperate on many projects. WSEO personnel coordinate river-basin planning and other WWDC projects. WWDC-funded groundwater development projects generally require permits from both the WSEO and WDEQ (Pers. Comm., Keith Clarey, WWDO).

The U.S. Bureau of Reclamation (BuRec), an agency under the U.S. Department of the Interior, oversees and manages water resources specifically related to the operation of numerous water diversion, delivery, storage, and hydroelectric power generation projects built by the federal government throughout the western United States. The U.S. BuRec cooperates with the WSEO and the WWDC (primarily with the WSEO), but as a federal agency may execute some programs unilaterally. The BuRec coordinates releases from Wyoming's reservoirs with the WSEO. (Pers. Comm., Keith Clarey, WWDO). Agencies with oversight over groundwater quality are described below in Sections 1.3.2. and 5.6.1.

1.3 Legal authority

Wyoming laws that govern the appropriation, development, and beneficial use of water resources are based on the doctrine of prior appropriation, commonly stated as *"first in time is first in right."* This means that the first party to put a source of water to beneficial use has a "priority" water-right that will be honored prior to those of other users with later water-rights during periods of limited supply. An exception is that municipalities can obtain water-rights from earlier priority uses through eminent domain under specific conditions. Because all waters within Wyoming are property of the State, a water-right does not grant ownership, but only the right to use water for beneficial purposes. Use of water resources for domestic and livestock purposes customarily take precedence over other uses. In Wyoming, water-rights are attached to the land and can be transferred. The laws and regulations pertaining to the appropriation, development, and beneficial use of groundwater are administered by the WSEO and a Board of Control made up of the superintendents of the four state water divisions and the State Engineer. The entire WBRB is included in Water Division III. Comprehensive discussion of the laws that govern all Wyoming water resources is provided in the main updated Wind/Bighorn River Basin Water Plan (MWH, 2010) and online at

http://seo.state.wy.us/PDF/b849r.pdf
http://seo.state.wy.us/PDF/b-969r.pdf

1.3.1 Wyoming water law – groundwater appropriation, development, and use

Groundwater within the state is owned and controlled by the State of Wyoming. Under Wyoming law, groundwater includes any water (including geothermal waters) under the land surface or under the bed of any body of surface water. The WSEO is responsible for the permitting and orderly development of groundwater in Wyoming. The updated WBRB Water Plan (MWH, 2010) provides the following discussion of Wyoming water law specific to groundwater:

> "Wyoming's groundwater laws were originally enacted in 1945 and amended in 1947. These laws were replaced by new groundwater laws on March 1, 1958, which were then amended in 1969. Groundwater is administered on a permit basis. The acquisition of groundwater rights generally follows the same permitting procedures as surface water rights, except that a map is not required at the time of permit application. Applications are submitted to and approved by the WSEO prior to drilling a well. With the completion of the well and application of the water to a beneficial use, the appropriation can then be adjudicated. The issuance of well permits carries no guarantee of a continued water level or artesian pressure."
>
> "As with surface water rights, groundwater rights are administered on a priority basis. For all wells drilled prior to April 1, 1947, a statement of claim process was followed to determine the priority date of the well. For wells drilled between April 1, 1947 and March 1, 1958, the priority date is the date the well was registered. For wells drilled after March 1, 1958, the priority date is the date the application was received at the WSEO."
>
> "Domestic and stock wells are those wells used for non-commercial household use, including lawn and garden watering that does not exceed one acre in aerial extent, and the watering of stock. The yield from these wells cannot exceed 25 gallons per minute (gpm). Prior to the 1969 amendment, domestic and stock wells were exempt from the requirement to obtain a permit and held a preferred right over other wells. The 1969 amendment established priorities for domestic and stock wells similar to those for other wells. The Groundwater Division also issues permits for spring developments where the total yield or flow of the spring is 25 gpm or less and where the proposed use is for stock and/or domestic purposes."

The potential for interconnection between groundwater and surface water is presently a prominent water-rights issue in the Platte River Basin and is of increasing concern throughout Wyoming. Surface flows are generally subject to strict water rights, and conflicts among users within the state or across state lines may arise where groundwater extraction can affect surface flows.

1.3.2 Wyoming water law – groundwater quality

The Denver office of the U.S. Environmental Protection Agency (USEPA) Region 8 has primary control (primacy) over Wyoming's public drinking water supplies. Wyoming is the only state in which USEPA has primacy over drinking water systems. The USEPA monitors water quality for the several hundred public water systems in Wyoming. Information on Wyoming's public drinking water systems is available on the USEPA Wyoming Drinking Water website,

http://www.epa.gov/safewater/dwinfo/wy.htm

and on the WWDC website.

Except on the Wind River Indian Reservation, The Wyoming Department of Environmental Quality (WDEQ) enforces groundwater quality regulations under the Wyoming Environmental Quality Act, with guidance from the Wyoming Environmental Quality Council. The WDEQ administers provisions of the Federal Clean Water Act Amendment of 1972 (Section 208) that provide for water quality management by state and local governments, as well as provisions of the Federal Water Pollution Act, by developing a State Water Quality Plan approved by the EPA. In general, operations under the jurisdiction of the Wyoming Oil & Gas Conservation Commission and the U.S. Bureau of Land Management (or the EPA or U.S. Forest Service) that cause groundwater contamination are referred to the WDEQ; the WOGCC and BLM have jurisdiction over Class II underground injection wells dedicated to disposal of produced water from state and federal oil-and-gas leases, respectively. Groundwater quality issues on the Reservation are generally referred to the EPA and BLM, with potential involvement of the Wind River Environmental Quality Council or the Bureau of Indian Affairs.

1.3.3 Interstate agreements

As established by the Wyoming state constitution, all surface water and groundwater within Wyoming's borders is property of the state. However, surface water in the various river basins is subject to interstate river basin compacts that limit the depletion of stream flow within Wyoming. While most compacts do not include groundwater, the interstate nature of groundwater resources along state lines and where groundwater interconnects with surface water is recognized by Wyoming agencies involved with groundwater. Like surface water, groundwater is shared with Wyoming's neighbors; groundwater development near state borders must take water-resources agreements into account.

1.4 Authorship

The principal authors of this report were

Paul Taucher, Energy Compliance LLC, Laramie, Timothy T. Bartos, U.S. Geological Survey, Wyoming Water Science Center, Cheyenne, and the Wyoming State Geological Survey, Laramie.

1.5 Acknowledgements

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The Wyoming State Engineer's Office (WSEO) provided groundwater permit data for Wyoming. We would like to express gratitude specifically to Jeremy Manley and Nancy McCann at the WSEO for many data transfers, phone calls, and quality control checks. The Wyoming Oil and Gas Commission (WOGCC), Casper, specifically Rick Marvel and Robert Meyer, compiled and provided a produced-water-quality dataset for the study area. The Wyoming Department of Environmental Quality (WDEQ) contributed several datasets that are presented on the potential aquifer contaminant figures. Special thanks are expressed to Chad Kopplin, Ben Way, Adrienne Nunn, Bill DiRienzo, Marica Murdock, Bonnie Pierce, Kim Medina, and many other, unnamed folks at the WDEQ. Jeff Hammerlink from the Wyoming Geographic Information Science Center (WyGisc) provided the data used to describe aquifer sensitivity and recharge.

Past State Geologists Ronald Surdam and Wallace Ulrich provided guidance and support throughout the project. Map editing and direction was provided by Richard "Dick" Jones, P.G., WSGS map editor. We thank Keith Clarey, WWDO: he compiled Appendix A, made major contributions to chapters 5 and 8, and answered many questions. Immense gratitude is expressed to document and map editor David Copeland, who through many hours of dedication greatly improved the quality of the work presented in this document, and to Brett Worman for his perspicacious editorial assistance. We recognize Chamois Andersen for document preparation and layout. Tomas Gracias, Brett Worman, Robin Lyons, Phyllis Ranz, and J. Fred McLaughlin at the WSGS provided appreciable help. At the WSGS, Nik Gribb did the digital cartography for Plates I, IV, and V; Tomas Gracias did layout and digital work for Plates VII and VIII; Allory Deiss designed Figure 6-1 and solved problems on many other WSGS figures; Melissa Thompson designed and produced nearly all WSGS figures for this report;

and Richard Hays culled through several consulting reports to provide Appendix B. Suzanne Roberts, USGS illustrator, generated Plates XII, XIII, and XIV; figures in chapter 7; and Appendices E–H.

The authors wish to thank all these named and many unnamed who helped during the preparation of this report.

Coauthors who contributed to the various chapters were	
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Part 2– WBRB groundwater regime

1.6 Basis of this groundwater assessment

Because the assessment of groundwater resources on a basin-wide scale is data limited, the approach in this study was to develop a conceptual model of the overall hydrogeologic system based on available data and the findings of previous studies. The various methods commonly used by hydrogeologists and groundwater engineers to define specific groundwater development prospects were scaled-up, and very general assumptions were utilized, to characterize a hypothetical basin-wide resource **(Section 6.2)**. The lack of the data that would be required to provide a comprehensive basin-wide evaluation of any single aquifer or area limits the level of detail that can be applied to specific development prospects. In most cases hydrogeologic and hydrogeochemical data available for areas that have not already been developed are sparse. While this study provides a summary of available information and general guidance on the groundwater resource potential of the WBRB, new development of groundwater in sufficient and sustainable quantities and quality to meet supply requirements will require some degree of site-specific hydrogeologic investigation and analyses. We discuss in Chapter 9 the few site-specific, aquifer-specific, and project-specific development prospects that we are able to distinguish.

The feasibility of developing groundwater to meet large-volume supply requirements (e.g. municipal, industrial, agricultural) depends on a favorable coincidence of several factors:

- A demand for the groundwater resource – any aquifer (by definition) and some water-bearing units that are not classified as aquifers (confining units) could provide useful groundwater supplies should sufficient demand exist
- Water quantity and quality that meet the requirements of the project
- Recharge conditions and hydrogeologic characteristics of the prospect aquifer(s) that could sustain production
- Amenable legal, institutional, and cultural conditions (water rights, land ownership, point of use relative to location of the resource, pipeline right-of-way, accessibility of drilling location, etc.)
- Funding adequate to properly develop the resource

Optimum conditions for the development of large-volume groundwater supplies are realized when all of the above favorable hydrogeologic and non-technical factors exist. None of the aquifers identified in this study are accessible throughout the WBRB, nor can they be expected to produce water in sufficient quantity and quality to meet demand requirements in all locations where they are accessible. In some areas, useable groundwater resources are not available.

1.7 Hydrogeology

Plates II, III, and IV outline the hydrogeologic units present in the WBRB. **Plate IV** is a map of the surface hydrogeology of the WBRB, the outcrop areas of identified aquifers and confining units. It includes near-surface structures that affect the occurrence and flow of groundwater. The frontispiece and Figure 5-0 are conceptual diagrams of a typical Rocky Mountain Laramide basin (basin formed during the Late Cretaceous-early Tertiary Laramide Orogeny) that illustrate the groundwater resource concepts and information presented in this study.

Because recharge occurs primarily in *aquifer outcrop areas*, groundwater in these areas is shallowest and of the best quality. Paleozoic and Mesozoic aquifers that crop out in the mountain ranges and foothills around the margins of the Wind River and Bighorn basins dip beneath younger formations into the structural basins, and groundwater tends to flow from these recharge areas downdip into the basins to the extent permitted by favorable hydraulic characteristics and continuity. The entire thickness of the Paleozoic and Mesozoic geologic section is commonly exposed in upland areas surrounding the basins. Recharge is more efficient where infiltration and percolation occurs parallel to bedding, generally the direction of highest permeability. Where favorable conditions prevail, good-quality groundwater can be available from productive basin-margin aquifers for several miles basinward of their outcrop areas (at increasing depth). Unconfined conditions generally prevail in outcrop areas. Where an aquifer is overlain by less-permeable strata, confined conditions prevail. The Paleozoic and Mesozoic aquifers are present beneath essentially the entire basin; however, in the absence of favorable structures, the prospects for development diminish as depth increases basinward, along with increasing costs of exploration and production, declining water quality, and in some cases declining permeability (e.g., carbonate aquifers and cementation).

As discussed in **Section 5.4**, except in the Quaternary alluvial and relatively flat-lying Tertiary bedrock aquifers, geologic structure (folds and faults) can be an important or controlling factor in developing groundwater resources, especially in the more structurally complex mountain and foothill areas that surround the basins. Shallow large-scale structures are rare and, therefore, much less important in the basin interiors. In the soluble carbonate (limestone and dolomite) aquifers, groundwater circulation within faults and fractures increases pore size and permeability, sometimes as expressed dramatically in the formation of cave systems, but mostly at smaller scales. Where the Paleozoic carbonate aquifers are characterized by highly productive karstic transmissivity, their recharge areas in the uplands around the perimeter of the basins are well-connected with the deeper basins, and groundwater circulation is relatively vigorous; useable groundwater resources, in terms of both quantity and quality, can be available some distance from the outcrop areas, although at greater depth than normally expected.

Aquifers exposed in the interior lowlands of both structural basins are primarily Quaternary alluvial and lower Tertiary hydrogeologic units. Recharge to unconsolidated alluvial aquifers from precipitation and irrigation is effective, even across bedding, except where erosion has exposed the strata of Tertiary bedrock units; recharge to these units occurs mostly across bedding, generally the direction of lowest permeability. Most recharge to, and the highest yields from, both Quaternary and Tertiary aquifers occurs in areas adjacent to active streams and areas under irrigation. The alluvial aquifers are not evenly distributed, and the bedrock aquifers were deposited in fluvial environments; the result is a lenticular distribution of the sand and gravel lithologies that are most favorable for groundwater development. Unconfined conditions generally prevail in alluvial and shallow bedrock aquifers, and progressively confined conditions are encountered with depth in the bedrock aquifers. Because the interior areas of the basins are generally accessible, the technical potential for developing mid- to high-yield groundwater resources in this setting depends primarily on a spatially variable combination of recharge and favorable aquifer characteristics. The level of recharge in the interior basins is generally lower than in the surrounding foothills and mountains; nevertheless, useful groundwater resources can be found at most locations but may be adequate only for low-yield uses (e.g., rural domestic and stock). The widespread occurrence of shallow groundwater confirms the conservative estimates for recharge in the interior basin areas proposed in the analysis presented in **Section 6.2.2**. Fractures, especially in areas where they are associated with the course of a surface drainage, may also play a role in the recharge of the lower Tertiary aquifers, but not to the extent that fractures are associated with groundwater resources in the Paleozoic carbonate aquifers.

As discussed in **Section 5.1**, because unconfined aquifers yield substantially more water per unit decline in hydraulic head over a much smaller area than will confined aquifers, unconfined aquifers are generally more attractive prospects for development. In interior basin areas, unconfined aquifers are widely exposed and can be recharged over a much larger area than confined aquifers. Unconfined aquifers are at shallower depth, and therefore are easier and substantially less costly to investigate and develop. The generally shallow depth of unconfined aquifers and their lack of a protective overlying confining layer also present the disadvantage of being vulnerable to contamination from a variety of sources (**Section 5.7**).

1.8 Current and historic groundwater development and use patterns

Current and historic groundwater development and use patterns are important considerations in evaluating an area's potential for groundwater development, and may be adequate for shallow, low- to mid-range (mostly stock and domestic use) yields; however, evaluation and development of an area's potential for deeper, high-range sustainable flows for municipal, industrial, and irrigation uses may vary significantly from historic patterns. Factors that change historic development patterns are technical (e.g., better understanding of local hydrogeology, improved drilling and treatment technologies) or cultural (e.g., changes in surface development, land ownership, demand).

Historic development patterns reflect both favorable hydrogeologic conditions and demand. There are areas where groundwater is available but population is inadequate to justify development. There are areas where low yield and marginal groundwater quality is the only option to meet demand. And there are areas where the conditions that have concentrated population are coincident with optimal conditions for groundwater development; for example, where communities develop on the alluvial plain surrounding a major river.

The best general settings for groundwater development in the WBRB have been identified for many years and are reflected in where drilling has occurred over the last and during the current century **(Plate IV)**. WWC Engineering et al. (2007b) reported that groundwater yields of less than 5 gpm are widely available throughout Wyoming. Yields ranging from 5 to 50 gpm are generally available from most of the "major aquifers" identified in this study. Yields greater than 50 gpm generally require favorable local hydrogeologic conditions. In general, groundwater availability is greatest within specific areas of the alluvial aquifers in both basins, and to a lesser extent within the lower Tertiary bedrock aquifer in the Wind River Basin. **Plates IV and X** show that most groundwater permits in the WBRB have been issued within the interior basin areas, where Quaternary alluvial and Tertiary bedrock aquifers provide groundwater supplies for a variety of uses over a wide range of permitted yield. Current yields of 1,000 gpm or more are only available from specific areas of highly productive alluvial, lower Tertiary bedrock, and Paleozoic carbonate aquifers (primarily the Madison–Bighorn aquifer). The Paleozoic aquifers have potential for developing high-yield wells adjacent to and downgradient from their recharge areas exposed in the mountain ranges surrounding the structural basins that is highly dependent on local hydrogeologic conditions.

Figure 5 in the Executive Summary of the WWDC 2003 WBRB Water Plan (BRS, Inc et al., 2003b) mapped several areas potentially favorable for new and additional groundwater development in the WBRB, based on hydrogeology and historic development patterns, including:

- the Quaternary alluvial aquifers of both groundwater basins
- areas where structure (fractures) and dissolution have potentially enhanced the permeability of the Paleozoic carbonate aquifers in both groundwater basins
- the Lower Tertiary aquifer in the Wind River Basin

These prospective areas are shown on **Plate X** in relation to surface hydrogeology mapped as outcrop areas of hydrogeologic units, major faults, and other lineaments. Information on groundwater permits issued since 2000 including locations, depths, and yields (by well symbol); tabulation of depth vs. yield; and charts depicting summary statistics for well use and average depth by use are also included in **Plate X** to illustrate how development in the WBRB has proceeded since the "Potential Areas of Future Ground Water Development" prediction was presented in the 2003 WBRB water plan. Comparison of **Plate IV** (all groundwater permits in the WBRB) with **Plate X** shows that groundwater development since 2000 has continued historic trends, and that permits have been located in the outcrop areas of most hydrogeologic units identified in the WBRB, including confining units, ranging from Quaternary through Precambrian, both within and outside the "Potential Areas" identified in 2003.

1.8.1 Alluvial aquifer potential groundwater areas

Most groundwater permits issued for the WBRB, both through 2009 and from 2000 through 2009 have been in areas underlain by the alluvial aquifers near major drainages where the alluvial aquifer has been historically developed, both within and outside of the "Potential Areas …" identified in 2003. **Plate IV** shows, and the **Chapter 8** discussion on historical development indicates, that of all groundwater permits to date, most by far have been issued for areas underlain by alluvial aquifers. **Figures 8-2, 8-7, and 8-9** for Domestic, Stock, and Miscellaneous permits, show that most of these permits are for relatively low production (25 gpm or less) and for depths of 500 feet or less. That a substantial fraction of the wells permitted within areas underlain by alluvial aquifers were for depths (50 to 500 feet) that generally exceed alluvial thickness indicates that many of these wells were completed within lower Tertiary aquifers, and that cultural factors related to surface development along major drainages may have played a significant role in where development occurred. It is not apparent that the 2003 designation of the alluvial aquifers prospective areas had an effect on historical development patterns for low-yield groundwater resources.

The 2003 "Potential Areas of Future Ground Water Development" did not identify an area for future potential development within the interior Bighorn Basin in either the Tertiary or Quaternary alluvial aquifers. Nevertheless, there was a substantial amount of groundwater permitting, both before and after 2000, in interior basin areas underlain by alluvial aquifers. Both **Plates IV and X** show that there has been very little development where the Tertiary bedrock aquifers are exposed in the interior Bighorn Basin; this low level of development reflects both less favorable hydrogeologic conditions in the Willwood and Fort Union aquifers and lack of demand outside of the areas surrounding the major drainages of the basin.

1.8.2 Tertiary aquifer potential groundwater areas

A large area for future groundwater development within the lower Tertiary aquifers in the Wind River Basin is outlined in "Potential Areas of Future Ground Water Development" (BRS, Inc., 2003b). In several cases, wells are clearly permitted in areas where the Tertiary aquifers are exposed; however, as discussed above, a substantial number of wells permitted for lower yields and at depths ranging from 50 to 500 feet in areas where the alluvial aquifer is exposed are probably completed within lower Tertiary aquifers. Most permits within the interior Wind River Basin are within the "Potential Areas" identified in 2003; however, the prospective area covers a very large portion of the basin, so that it is unclear to what extent the designation had an effect on recent groundwater development patterns.

1.8.3 Paleozoic aquifer potential groundwater areas

The 2003 "Potential Areas of Future Ground Water Development" (BRS, Inc., 2003b) outlined areas with potential enhanced permeability in the Paleozoic aquifer around the perimeters of both the Wind River and Bighorn basins where folds and faults are expressed in outcrops of pre-Tertiary geologic units. Relative to the interior basins, a larger proportion of groundwater permits issued since 2000 in these areas (and adjacent areas outside the 2003 "Potential Areas") have been for greater depths ranging to more than 1000 feet across a wide range of yields. Many of the permits in the 2003 "Potential Areas" and adjacent areas have been located proximal to or generally along trend with mapped faults and anticlines. Many of these permits have surface locations within overlying Mesozoic aquifers and confining units. While many of the deeper wells probably targeted the Paleozoic aquifers, several are likely completed within Mesozoic units. It is apparent that a deeper understanding of the role of solution-enhanced permeability in Paleozoic carbonate aquifers **(Section 5.4)** has had a positive effect on groundwater development in the Paleozoic aquifers along the eastern flank of the Bighorn Basin.