Subject: **Northeast Wyoming River Basins Plan**
Available Ground Water Determination
Task 3E

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Prepared By: HKM Engineering Inc.

INTRODUCTION

A qualitative summary of the ground water resources of the Little Missouri, Belle Fourche, Cheyenne and Niobrara basins of northeastern Wyoming is presented herein. Collectively, these basins are referred to as the Northeast Wyoming River Basins (planning area) in this memorandum. This memo summarizes the results of work associated with the performance of Task 3E – Available Ground Water Determination for the Northeast Wyoming River Basins Plan.

STUDY OBJECTIVES

The first objective of Task 3E was to inventory and catalog the Wyoming State Engineer's Office (WSEO) ground water permit database for various categories of ground water uses in the Basin Plan Area, and incorporate the extracted information into six GIS data layers. This was accomplished through a cooperative effort with personnel of the WSEO and Wyoming Water Development Commission (WWDC). GIS data layers prepared from information on file with the WSEO as of December 31, 2000 included:

- Permitted active agricultural wells with production rates greater than 49 gpm
- Permitted active municipal wells with production rates greater than 49 gpm
- Permitted active industrial and miscellaneous wells with production rates greater than 49 gpm
- Active permitted domestic wells
- Active permitted stock wells
- Permitted coalbed methane wells

The second objective of Task 3E was to inventory and document existing published data on ground water studies and ground water planning documents for the planning area. Some of the existing ground water studies and ground water planning documents overlap the geographic boundaries of the planning area and include the drainage basins of the Tongue and Powder Rivers.

Other objectives of Task 3E were as follows:

- Summarize existing information on aquifers with regards to location, storage, yield and development potential within the planning area.

- Summarize the potential effects that ground water development might have on the ground water and surface water systems in the basins within the planning area.

- Characterize coalbed methane development and its short and long-term effects on ground water and surface water supplies within the planning area.

It is the intention that this memorandum, the GIS data layers and the bibliography generated for this Basin Plan provides a starting point for site specific ground water investigations.

STUDY METHODS

There were no original investigations performed as part of Task 3E. The work consisted of performing an inventory, compilation and review of published literature on the geology and ground water resources of the planning area.

Records of wells maintained by the WSEO were inventoried and compiled by WSEO personnel as part of Task 3E. Format of the WSEO Data Query was established cooperatively by WWDC and HKM. The records provided by the WSEO were used in the preparation of GIS database layers for the uses of ground water as previously noted.

There is a wealth of published and unpublished reports of investigations on the geology and ground water resources of the Basin Plan area. The Powder River Structural Basin (PRSB), part of which is within the planning area, has been the subject of investigation and exploration as a result of interest in the development of energy and natural resources for at least the last 40 to 50 years. Resources of interest have included oil and gas, coal, uranium, coalbed methane and water.

A bibliography of published ground water studies and ground water planning documents for the Basin Plan Area is included with this memorandum as Appendix A. The references included in the bibliography provide an overview of ground water resources, and of some of the interests and concerns that have arisen as a result of the development of energy and natural resources in the planning area.

Additional information in specific geographic areas within the planning area is available through the U.S. Geological Survey (USGS) and other federal agencies. Two additional federal agencies active in ground water related issues in the PRSB include the U. S. Bureau of Land Management (BLM) and the U. S. Environmental Protection Agency (USEPA).

Several Wyoming state agencies have site specific information available in the planning area. These agencies include the Department of Environmental Quality (Land Quality and Water Quality Divisions), the State Engineer's Office, the Geological Survey, the Oil and Gas Conservation Commission and the Water Development Commission.

OVERVIEW

The Basin Plan Area lies in the northeastern and east-central part of the state and includes all or part of seven Wyoming counties. The planning area includes all of Weston, most of Crook and about forty percent of Campbell (central/east, south and southeast and northeast) Counties. The northeast and northwest parts of Converse and Niobrara Counties, respectively, as well as small parts of Natrona and Goshen Counties are also within the planning area.

Major communities in Campbell and Crook Counties include: Gillette, Wright, Hulett, Moorcroft, and Sundance. Newcastle and Upton are the primary towns in Weston County. Principal towns in Niobrara County include Lusk, Manville and Redbird.

Regionally, the planning area lies within the Missouri River drainage system and covers an area of approximately 11,943 square miles in northeastern Wyoming. The principal surface water systems within the planning area include the Little Missouri, Belle Fourche, Cheyenne and Niobrara Rivers and their respective tributaries. These drainage systems form the boundary of the planning area.

Altitudes are variable, generally ranging from 4200 feet (southwestern Crook County) to 5500 feet (northwest of Lusk in Niobrara County) in the western part of the planning area. Altitudes in the eastern part of the planning area generally vary from 4700 feet (Niobrara County at the Wyoming – Nebraska State line) to 6600 feet (northeastern Converse County) to 4750 feet at the crest of Bear Mountain in Crook County. The lowest altitude in the planning area is about 3100 feet where the Belle Fourche River crosses the state line in Crook County.

Climate is typical of the northern High Plains with low precipitation, high evaporation and wide ranges of temperatures. Annual precipitation varies from 12 to 16 inches in the lowlands to over 20 inches per year in the Black Hills. Generally, about fifty percent of the precipitation in the planning area occurs between April and July.

GEOLOGIC SETTING

Geologic formations in the planning area range in geologic time from Precambrian crystalline rocks to recent alluvial and eolian deposits generally consisting of clays, silts, sands and gravels. The PRSB, part of which is within the planning area, has over 17,000 feet of sedimentary strata. These sedimentary rocks have been divided into about 11,000 feet of Cambrian to Cretaceous pretectonic deposits and up to 7,000 feet of Tertiary deposits associated with the deformation of the PRSB. (Feathers, Libra, Stephenson and Eisen, 1981)

The older strata, which are exposed only in the northeastern part of the Basin Plan Area are economically important for oil production. The Tertiary deposits generally present in the west-central portion of the planning area contain significant coal reserves and are subject to mining and coalbed methane development. Both the Early Cretaceous Fall River Formation and the Early Tertiary Wasatch Formation have been important as uranium deposit sources in the Black Hills and the central to southcentral part of the planning area. (Feathers, Libra, Stephenson and Eisen, 1981)

The Basin Plan Area encompasses several tectonic elements that influence the geology and the occurrence and availability of ground water in the planning area. These structural features include the PRSB, mountain uplifts (Black Hills, Laramie Range and Bighorn Mountains) and broad uplifts of lesser magnitude (Hartville Hills and the Casper Arch). (Feathers, Libra, Stephenson and Eisen, 1981)

Figure 1.0 shows the general location of the planning area with respect to regional structural elements in northeastern Wyoming. Figure 2.0 presents a generalized geologic section of the PRSB including part of the planning area. Plates B.1 and B.2 of Appendix B present the generalized surficial and bedrock geology of the Basin Plan Area.

GEOLOGIC UNITS AND GROUND WATER

A geologic formation is a body or group of rock strata that consist dominantly of a certain lithologic type or combination of types. A general definition of an aquifer is a geologic formation or group of formations that are capable of yielding a significant quantity of water to wells or springs.

There are more than 30 geologic formations exposed on the margins of the PRSB. For this report, the formations were grouped into six principal aquifer systems that have historically been the major ground water sources of interest in the planning area. The grouping was based on those presented in the 1981 report "Occurrence and Characteristics of Ground Water in the Powder River Basin, Wyoming" by the Wyoming Water Resources Research Institute (WWRI) of Wyoming (Feathers, Libra, Stephenson and Eisen, 1981). Figure 3.0 graphically summarizes the geologic formations and their hydrogeologic role in the PRSB within the planning area.

The WWRI aquifer system division and the grouping used herein were based on aquifer hydrogeologic similarity and aquitard identification (Feathers, Libra, Stephenson and Eisen, 1981). The grouping allows for a simplified presentation of the principal sources of ground water in the planning area. The six major aquifer systems within the planning area are (oldest to youngest):

- Madison Aquifer System
- Dakota Aquifer System
- Fox Hills/Lance Aquifer System
- Fort Union/Lance Aquifer System

- Tertiary Aquifer
- Quaternary Aquifer System

The lithologic and hydrologic characteristics of bedrock units exposed on the east flank of the PRSB (Mesozoic to Precambrian (youngest to oldest)) within the planning area are summarized in Table 1.0. The lithologic and hydrologic character of shallower geologic units of the central PRSB (Cenozoic to Mesozoic (youngest to oldest)) within the planning area are summarized in Table 2.0. Table 2.0 also includes Quaternary, Tertiary and Latest Cretaceous Deposits. Both tables were taken directly from the previously identified 1981 WWRI report on ground water in the Powder River Basin (Feathers, Libra, Stephenson and Eisen, 1981).

Selected information on the hydrogeology and hydrologic characteristics for the major aquifer systems are presented in Appendix C. Information on specific capacities for wells completed in aquifers of the major aquifer systems within the planning area are also presented in Appendix C.

GROUND WATER QUALITY

Ground water quality data contained in USGS ground water reports for the planning area provided an overview of the general quality of water from the aquifer systems within the planning area. Table 3.0 presents a list of publications that contain water quality data or discussions on ground water quality reviewed for this memorandum.

The review included USGS selected analyses available from USGS data files as of March 26, 1982 (Larson and Daddow, 1984). The USGS 1984 report included information from the individual USGS reports listed in Table 3.0. The 2000 USGS publication on water co-produced with coalbed methane in the PRSB was also reviewed for this memorandum (Rice, Ellis and Miller, 2000).

1984 USGS Report

Data used in the 1984 report did not include all of the information available in USGS files at the time. Constituents were selected by USGS on the basis of their relative abundance and their inclusion in water quality criteria at the time. Water quality data available from the 1984 USGS report included: specific conductance, pH, temperature, dissolved-solids (TDS) concentration and concentrations of the major ions (calcium, magnesium, sodium, potassium, alkalinity (as bicarbonate), sulfate, chloride, fluoride, and nitrate, plus silica, boron, and iron). This data was from 748 ground water sites in the PRSB and adjacent areas. (Larson and Daddow, 1984)

Information on selected dissolved trace metals were reported for 220 ground water sites in the PRSB and adjacent areas in the 1984 USGS report. Data were reported for nine trace metals (arsenic, barium, cadmium chromium copper, lead, mercury, selenium, zinc) in the 1982 selection. (Larson and Daddow, 1984)

Radiochemical data was listed for 65 ground water sites in the PRSB and adjacent areas in the 1984 USGS report. The data included eight radiochemical analyses for each site (gross alpha-dissolved, gross alpha-suspended, gross beta-dissolved, gross beta-suspended, radium 226 dissolved radon method, radium 226 dissolved precipitation method, uranium-dissolved extraction method, uranium-dissolved direct fluorometric method). (Larson and Daddow, 1984)

2000 USGS Report

The 2000 USGS publication on water co-produced with coalbed methane in the PRSB contained data from 47 ground water sites in the PRSB. Approximately 32 of the sites were located within the planning area. The remaining 15 were located in the Powder/Tongue River Basin Plan Area. (Rice, Ellis and Miller, 2000)

Water quality data available from the 2000 USGS report included: pH, temperature, dissolved-solids (TDS) concentration and concentrations of the major ions and minor ions (fluoride, chloride, sulfate, bromine, alkalinity, ammonia, calcium, potassium, magnesium, sodium, barium, iron plus silica, strontium, and sodium-adsorption-ratio (SAR)). Data was also reported for seventeen trace elements (silver, aluminum, arsenic, boron, beryllium, bismuth, cadmium, cerium, cobalt, chromium, caesium, copper, mercury, lanthanum, lithium, manganese, nickel). (Rice, Ellis and Miller, 2000)

Water Quality Standards and Suitability for Use

The State of Wyoming has identified the following as standards for different classes of ground water (WDEQ, 1993):

- Class I ground water is defined as ground water suitable for domestic use.
- Class II ground water is defined as ground water suitable for agricultural use where soil conditions and other factors are adequate.
- Class III ground water is defined as ground water suitable for stock use.
- Class Special (A) ground water is defined as ground water suitable for fish and aquatic life.
- Class IV ground water is defined as ground water suitable for industry.
- Class V ground water is defined as ground water found closely associated with commercial deposits of hydrocarbons, or ground water which is considered a geothermal resource.
- Class VI ground water is defined as ground water that may be unusable or unsuitable for use.

Historically, major ground water uses in the planning area have been for domestic use, agriculture (stock and irrigation), and municipal/public water systems. A principal ground water use or withdrawal has been for industrial purposes including, coalbed methane production, petroleum production (secondary oil recovery) and refining, coal mining, coal fired steam generation, and uranium mining and processing. Ground water has also been used to support fish and aquatic life including fish hatcheries.

The fact that ground water is and has been successfully used for the above uses is a general, practical indicator of ground water quality in the planning area. A general, qualitative evaluation and comparison of ground water produced from the six aquifer systems was performed for this memorandum using the references identified in Table 3.0. The results of the evaluation, including a general characterization of water co-produced with coalbed methane are summarized in Table 4.0. The general availability and development potential for each aquifer system in the planning area are also summarized in Table 4.0.

Aquifer Sensitivity/Vulnerability

The University of Wyoming's Spatial Data and Visualization Center (SDVC) developed a system to assess the sensitivity and vulnerability of ground water to surface water contamination in Wyoming (Hamerlinck and Arneson, 1998). Development of the system was made possible through USEPA Section 319 Program funding. Additional financial support was provided by the Wyoming Non-Point Source Task Force, USEPA Region VIII, and the Wyoming Department of Environmental Quality, Water Quality Division. The Wyoming Department of Agriculture also provided support and guidance in the initial planning phase to develop the assessment system. (Hamerlinck and Arneson, 1998)

The SDVC developed aquifer vulnerability maps to define the potential for surface contamination to impact ground water in the uppermost aquifer throughout Wyoming. Plate D.1 of Appendix D is a map of aquifer sensitivity to contamination within the planning area. The highest rated lands generally are located on alluvial deposits adjacent to rivers, streams, and lakes, and are associated with slope wash, colluvium, residuum and eolian deposits or are on fractured bedrock areas.

Plate D.2 of Appendix D is a map of aquifer vulnerability to contamination for the uppermost or shallowest aquifers to contamination within the planning area. Ground water is vulnerable in areas with high water tables, sandy soils, and areas of presumed pesticide application. The areas with the highest vulnerability are also generally located in the floodplains of the major streams and/or associated with slope wash, colluvium, residium and eolian deposits within the planning area.

GROUND WATER DEVELOPMENT

Ground water is the major and in many cases, the only source of water within the Basin Plan Area. All six aquifer systems are important water sources in the planning area for all uses. As an example, ground water from each of the aquifer systems has historically been used at one time or another as a source for municipal/public water systems in the planning area. Ground water associated/co-produced with coalbed methane development is very important due to withdrawal impacts on water levels and existing wells completed in the Fort Union/Wasatch Aquifer System.

Existing Development

Selected existing and historical uses of ground water from the six aquifer systems within the planning area are summarized in Table 4.0. The significance of ground water in the planning area is demonstrated by the 15,793 active ground water permits (as of December 31, 2000) the WSEO inventoried for the preparation of the six GIS database layers for this Basin Plan.

Due to the significance of coalbed methane development in the planning area, the data base for coalbed methane ground water permits only, was updated to December 31, 2001. The total number of coalbed methane active ground water permits increased from 5,285 to 6,637 between December 31, 2000 and December 31, 2001. The number of permits for each use category used for the preparation of the GIS data layers are summarized below as of December 31,2000:

- 308 Permitted active agricultural wells with production rates greater than 49 gpm
- 76 Permitted active municipal wells with production rates greater than 49 gpm
- 608 Permitted active industrial and miscellaneous wells with production rates greater than 49 gpm
- 2,760 Active permitted domestic wells
- 6,756 Active permitted stock wells
- 5,285 Permitted coalbed methane wells

The geographic distribution of the permits for the above use categories with respect to surficial and bedrock geology are presented in Plates B.3 through B.10 in Appendix B. Inspection of the plates provides a preliminary, relative, indication of the significance of the geologic formations associated with each of the aquifer systems as ground water sources in the planning area.

Ground Water Monitoring Programs

Existing ground water monitoring programs will continue to be important in monitoring the status of ground water in the PRSB and the planning area for all activities. One program is the Wyoming statewide USGS cooperative program operated with the WSEO and other state, county, municipal and federal agencies.

The Gillette Area Groundwater Monitoring Organization (GAGMO) and the recently formed (April 1999) Powder River Basin Area Groundwater Monitoring Organization (PRAGMO) are for coal mining and coalbed methane development. GAGMO is operated by the coal mining industry and PRAGMO by the coalbed methane development operators. These programs provide a common database that satisfy federal and state agency requirements for the respective industries to track and evaluate impacts of their operations on ground water in the PRSB. (USDI, 1999)

Other state and federal agencies have their own monitoring programs associated with their management and regulatory responsibilities. State agencies include WSEO, Oil and Gas Conservation Commission and the Department of Environmental Quality. Federal agencies include the Bureau of Land Management and the Forest Service.

Agricultural, Municipal, Industrial and Miscellaneous, Domestic and Stock Uses and Ground Water

Out of total of 15,793 active ground water permits inventoried in December 31, 2000 for the preparation of the six GIS database layers for the Basin Plan, 10,508 of the permits were for WWDC categories other than coalbed methane development. Reported well depths for the permitted 111 active agricultural wells with production rates greater than 49 gpm ranged from 12 to 4,361 feet and averaged 511 feet. Reported depths to the top of the "main water bearing zones" in the permit data ranged from 5 to 3,346 feet and averaged 374 feet. The maximum and reported yields under "actual yields" of these wells in the permit data files ranged from 50 to 1600 gpm and averaged 523 gpm.

There were a total of 76 reported permitted active municipal wells with production rates greater than 49 gpm. Reported well depths ranged from 33 to 8,509 feet and averaged 2,056 feet. Reported depths to the top of the "main water bearing zones" in the permit data ranged from 21 to 3,220 feet and averaged 1,320 feet. Reported "actual yields" of these wells in the permit data files ranged from 55 to 1,400 gpm and averaged about 324 gpm.

Reported permitted active industrial and miscellaneous wells with production rates greater than 49 gpm totaled 608. Reported well depths ranged from 5 to 10,778 feet and averaged 1,748 feet. Reported depths to the top of the "main water bearing zones" in the permit data ranged from 5 to 8,430 feet and averaged 1,484 feet. Reported "actual yields" of these wells in the permit data files ranged from 50 to 3,500 gpm and averaged about 240 gpm.

A total of 2,760 permitted domestic wells were reported in the data for the planning area. Reported domestic well depths ranged from 1 to 10,480 feet and averaged 307 feet. Reported depths to the top of the "main water bearing zones" in the permit data ranged from 1 to 6,170 feet and averaged 302 feet. Reported "actual yields" of these wells in the permit data files ranged from 1 to 1,325 gpm and averaged about 18 gpm.

A total of 6,756 permitted stock wells were reported in the data for the planning area. Reported stock well depths ranged from 1 to 1,600 feet and averaged 31 feet. Reported depths to the top of the "main water bearing zones" in the permit data ranged from 1 to 4,194 feet and averaged 270 feet. Reported "actual yields" of these wells in the permit data files ranged from 1 to 1,600 gpm and averaged about 14 gpm.

As previously noted, the relative importance of each of the aquifer systems with respect to the category of uses is summarized in Table 4.0. Inspection of the previously mentioned plates in Appendix 4.0, combined with Table 4.0 can be used to make further inferences at an initial level, as to the relative importance of each of the aquifer systems with respect to the five non-coalbed methane use categories in the planning area.

Impacts on Ground Water and Surface Water Supplies

Impacts to ground water will depend on local geologic and hydrologic conditions in the areas of development. Possible impacts to ground water could include:

- The possible depletion of surface water that is interconnected with aquifer systems. The principal aquifer systems of concern with respect to this impact include the Madison and the Quaternary Alluvial Aquifer Systems. The geographic areas of concern with respect to the Madison Aquifer System, are along the northeastern part of the planning area where streams flow across Madison System outcrops. The areas of concern with respect to the Quaternary Alluvial Aquifer System, are throughout the entire planning area in the alluvium adjacent to surface water systems.

  Ground water development in any of these areas, irrespective of proposed use, will require detailed investigations that also address the possibility and degree of surface and ground water interconnection. Depending on proposed ground water use, the existing WSEO permitting process should be able to address the issue. The Wyoming Department of Environmental Quality, Water Quality Division (WDEQ/WQD) might also be involved in the permitting process with respect to surface ground water interconnection under provisions of the USEPA Safe Drinking Water Act (Ground Water Under the Direct Influence of Surface Water).

- Depending on location, geologic source, and water demand requirements, there is the possibility that domestic and stock well densities could create interference problems between wells and/or aquifer depletion problems. This is probably more of a probability in areas experiencing rural development of single family residences and/or multi-family subdivisions where individual or community public water supply wells provide water. The WSEO permitting process for ground water has historically addressed these issues.

  New legislation would be required to establish ground water control zones for any ground water use other than agricultural use experiencing declining water levels or aquifer depletion problems (such as use of aquifers of the Fort Union Formation in the Gillette area for public and domestic water sources). The potential problem in conjunction with coalbed methane development has also been recognized (depletion of aquifers and wells), and responsible state and federal agencies are attempting to address related ground water impacts.

- There is the possibility of aquifer systems being impacted due to oil and gas operations. The nature of these impacts would depend on the geographic as well as the geologic and stratigraphic location of the activity. A potential impact could involve aquifer depletion if water were used from one of the aquifer systems for secondary recovery operations (such as the Fox Hills Sandstone of the Fox Hills/Lance Aquifer System). Other impacts could be water quality related through drilling and recovery operations and leakage through inadequate and/or failed plugging and abandonment of production wells. The possibility of these impacts and other issues should be able to be addressed by existing regulatory activity and programs of the Wyoming Oil and Gas Conservation Commission, Wyoming Department of Environmental Quality and the WSEO.

- The Wyoming Department of Environmental Quality, Water Quality Division (WDEQ/WQD) is initiating a Source Water Assessment and Protection Program in 2002 for participating Public Water Systems throughout the state. This program should address issues regarding the safeguarding of aquifers for water quality considerations in areas where public water systems are located.

Coalbed Methane Development and Ground Water

For ease of reference, the main coal seam that is the target of coalbed methane development in the PRSB and within the planning area is referred to as the Wyodak-Anderson coal zone. Methane gas is trapped in micropores and cleat fracture systems within the coal, and is maintained in that state by the natural pressure of ground water. The gas is extracted using wells that are drilled and completed in the coal to remove water and lower the water pressure responsible for holding the gas. The gas moves out of the coal as the water pressure is lowered, and is recovered from the well along with the water.

As previously noted, a total of 5,285 coalbed methane wells were identified in the WSEO data query for the Basin Plan. Reported well depths ranged from138 to 5507 feet and averaged 772 feet. Reported depths to the top of the "main water bearing zones" in the permit data ranged from 124 to 1558 feet and averaged 703 feet. Reported "actual yields" of coalbed methane wells in the permit data files ranged from 1 to120 gpm and averaged 27 gpm.

The BLM has recently used 12 gpm (USDI, 1999) and 11.1 gpm (USDI, 2000) for average production rates of coalbed methane wells in the preparation of environmental impact statements for coalbed methane development within the planning area. The actual ground water production rate will probably be variable throughout the life of each well. As an example, the BLM projected the initial ground water production rates of the wells for the Lighthouse Coalbed Methane Project to be 11 gpm, with an interim average of 7 gpm, and a final rate of less than 3 gpm per well (USDI, 1995).

The USGS, in cooperation with the BLM and coalbed methane production companies, is conducting multidisciplinary studies in the PRSB in an effort to provide a better understanding of coalbed methane resources and associated water. A USGS report for one of the studies in progress provides preliminary compositional data on water from 47 coalbed methane wells sampled between June, 1999 and May, 2000 (Rice, Ellis and Bullock, 2000).

Water co-produced with coalbed methane is generally a sodium bicarbonate type. Of the 47 wells sampled by USGS, 32 were located within the planning area and 15 were within the Powder/Tongue River Basin Plan Area. Total dissolved solids content (TDS) of all 47 samples ranged from 270 to 2010 and averaged 850 mg/l. Values of the sodium adsorption ratio ((SAR), which is a relative measure of the suitability of water for irrigation due to sodium content) for the 47 samples ranged from 5.7 to 32 and averaged 12.

TDS and SAR of the 32 samples from coalbed methane wells in the planning area ranged from 270 to 1170 (mean 653 mg/l) and 5.7 to 12 (mean 7.85), respectively. TDS and SAR of the 15 samples from coalbed methane wells in the Powder/Tongue River Basin Plan Area ranged from 540 to 2010 (mean 1309 mg/l) and 7.7 to 32 (mean 19.82) respectively. The results of the USGS samples indicated that TDS and SAR of waters in the Wyodak-Anderson coal zone generally increase in the PRSB from south to north and from east to west. (Rice, Ellis and Bullock, 2000)

Concentrations of most of the 17 trace elements analyzed by USGS in samples of water from the 47 coalbed methane wells were below detection limits. All of the concentrations for the 17 trace elements were below the maximum contaminant levels of the Primary Drinking Water Standards of the USEPA. The USGS reported that there were no noticeable trends in trace element concentrations in the samples from the 47 wells. (Rice, Ellis and Bullock, 2000)

Coalbed Methane Impacts on Ground Water and Surface Water Supplies

Potential impacts to ground and surface water have been identified by BLM in the preparation of environmental assessments (EA) and environmental impact statements (EIS) for numerous coalbed methane projects in the PRSB within the planning area (USDI, 1995, 1999, 2000). Impacts to ground water will depend on local geologic and hydrologic conditions in the areas of coalbed methane development. Possible impacts to ground water that have been identified include:

- The dewatering of aquifers and the lowering of water levels and yields in production wells located in the vicinity of coalbed methane development. This includes wells that are completed in the Wyodak-Anderson coal zone and any aquifers that may be in hydraulic connection with the coal. Ground water modeling performed in association with the Wyodak Coalbed Methane Project EIS, predicted a fairly rapid recovery of water levels within a period of three to four years to within 20 or 30 feet of preoperational conditions at the cessation of coalbed methane operations. This estimate was based on the projected redistribution of the large amount of ground water in storage within the coal west, north, and south of the development. Total recovery was projected to take a very long time as recharge to the coal aquifer would be needed to replace that ground water removed from storage during coalbed methane operations. (USDI,1999)

- Possible methane seepage into wells and structures in the proximity of coalbed methane development that could pose a health and safety hazard to planning area residents.

- Possible increased infiltration of water from coalbed methane production into shallow alluvial ground water systems in the Gillette area that could aggravate subsurface structure problems.

- Possible increased infiltration of water from coalbed methane production into shallow ground water systems in the planning area that could impact the quality and use of ground water from shallow systems.

- Possible impacts to surface coal mining operations.

- Possible impacts to the in-situ leach extraction process of uranium mining in the southwest portion of the planning area.

Possible surface water related impacts that have been identified could include:

- Possible change in the drainage characteristics in draws and drainages from ephemeral to perennial. This could result in an increase in the erosion potential and sedimentation problems in receiving drainages. Coalbed methane generated water could result in increased flooding potential in receiving drainages. Higher flows could also impede landowner access to perform normal work associated with their operations.

- A possible alteration of the chemical characteristics of receiving surface waters due to coalbed methane generated water. This could include a change due to increased salinity and sodium content that could impact irrigation practices and the utilization of surface water for irrigation. Concern has also been expressed on the impacts of coalbed methane water on possible toxicity problems and aquatic habitats in receiving waters.

A more comprehensive discussion of impacts associated to coalbed methane development is available in the previously mentioned EAs and EISs prepared by BLM. The References section at the end of this report and the Bibliography (Appendix A) provide a selected list of publications for further consideration.

Future Development

The geology, drilling depths, hydrogeologic characteristics and ground water quality of aquifer systems differ throughout the planning area. All of the aquifer systems in the planning area previously discussed probably have some potential for development. Site specific investigations in conjunction with experience and common sense will be required to determine the opportunities available to develop ground water with wells of sufficient capacity for a specific use within the planning area.

Although there have been considerable investigations in the PRSB within the planning area, there have been few regional assessments of the annual recharge, storage and sustained yield capability of the major aquifer systems both in the PRSB and the planning area. General conclusions regarding ground water development potential of four of the six major aquifer systems in the planning area discussed in this memorandum are summarized below:

- The Madison Aquifer System may have the most development potential for high yield wells on a sustained basis within the planning area. Previous investigations have estimated that annual average recharge to this system is approximately 75,000 acre feet per year within the entire PRSB in northeast Wyoming (WSEO, 1973). Drilling depths and water quality may constrain development at specific locations within the planning area.

- The Fox Hills/Lance Aquifer System may have local potential for development of wells with low to moderate yields. The possible high fluoride content in water from this system might influence the desirability of use for a municipal/public supply without provision for treatment or special management, such as mixing with water from other sources. Wells completed in the Fox Hills/Lance Aquifer System may offer an alternative source to wells completed in the Fort Union/Wasatch Aquifer System impacted by coalbed methane development.

- The Fort Union/Wasatch Aquifer System is utilized for most uses in the PRSB within the planning area. The Wyodak-Anderson coal aquifer and hydraulically interconnected aquifers of the Aquifer System will be heavily impacted by ground water withdrawals near coalbed methane development. The water co-produced with coalbed methane may provide an opportunity for utilization, depending on location, quality and nature of potential use. Further consideration of injection of water co-produced with coalbed methane development into the Fox Hills/Lance and Fort Union/Wasatch Aquifer Systems is warranted in the planning area.

- Aquifers in the Alluvial Aquifer System within the planning area may have local development potential for wells with moderate yields if induced infiltration of surface water can be tolerated.

Table 4.0 summarizes the development potential of the above units and also the Dakota Aquifer System and the Middle Tertiary Aquifer (Arikaree Formation) in the planning area. Items of interest related to ground water availability/development potential are also summarized in Table 4.0. These items include the general lithologic and hydrologic character of the aquifer systems in addition to the general quality of ground water available from the systems.

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LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

Table C.4.1 Transmissivities of the Fort Union/Wasatch Aquifer System, Powder River Structural Basin, Northeast Wyoming River Basins Plan Area, Wyoming

Appendix C.5 Middle Tertiary Aquifer

Table C.5.1 Specific Capacities of Wells Completed in Middle Tertiary Aquifers of the Powder River Structural Basin, Northeast Wyoming River Basins Plan Area, Wyoming

Appendix D Aquifer Sensitivity to Contamination and Ground Water Vulnerability to Pesticides, Northeast Wyoming River Basins Plan Area

Plate D.1 Aquifer Sensitivity to Contamination

Plate D.2 Aquifer Vulnerability to Pesticides

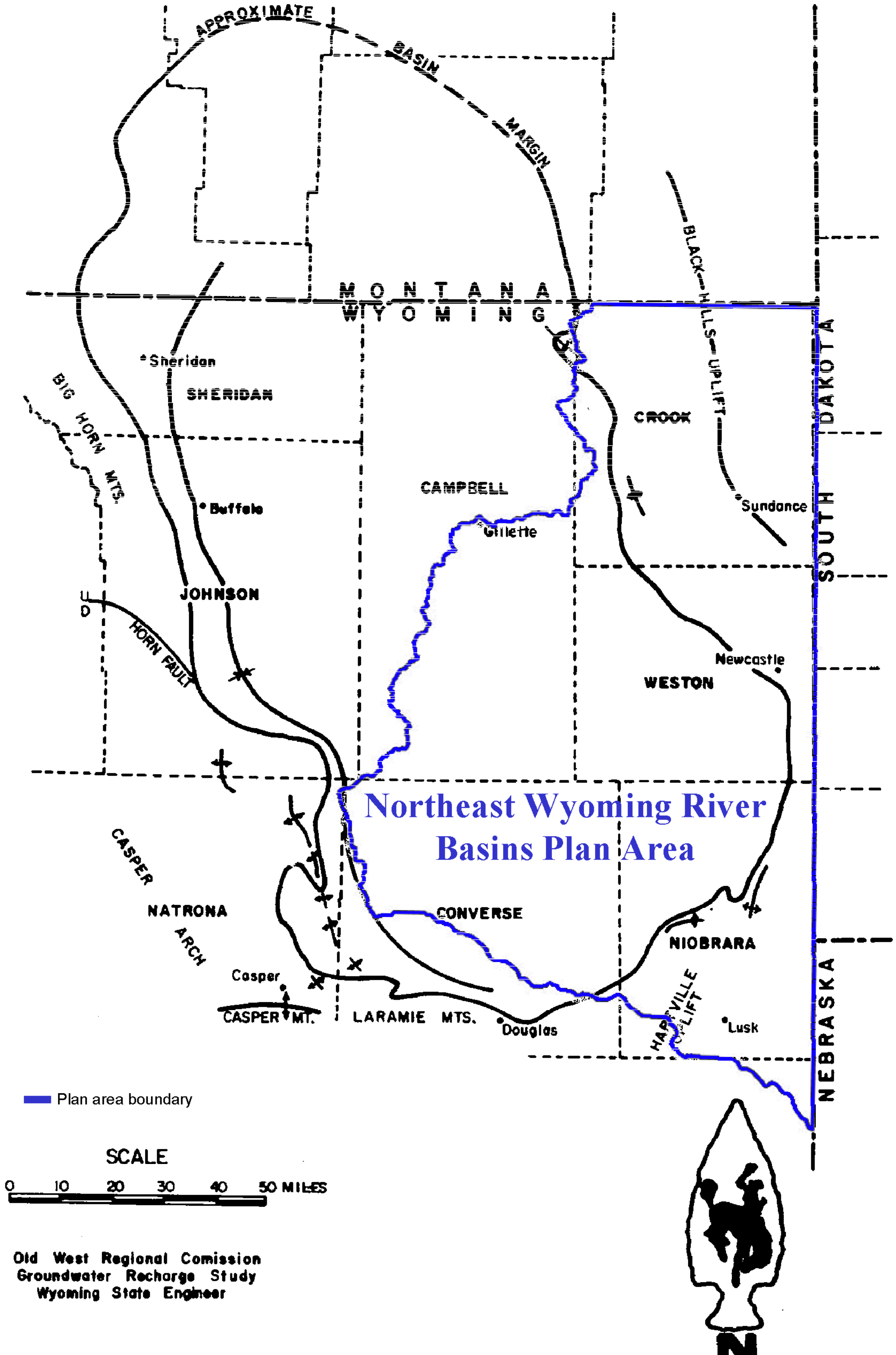

Figure Source: Wyoming State Engineer's Office, 1976

Figure 1.0. Location and Geologic Structure Map, Northeast Wyoming River Basins Plan Area, Wyoming.

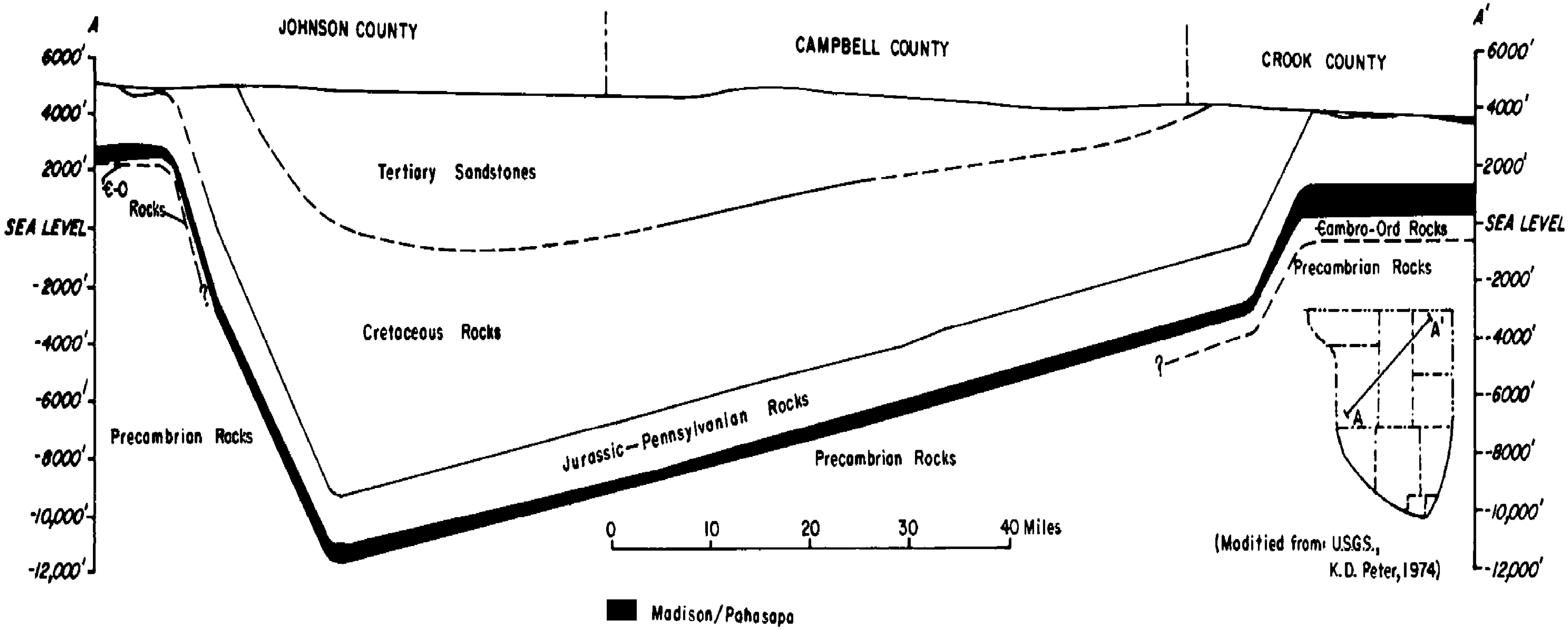

Figure Source: Wyoming State Engineer's Office, 1976

Figure 2.0. Generalized Geologic Section in Northeastern Wyoming.

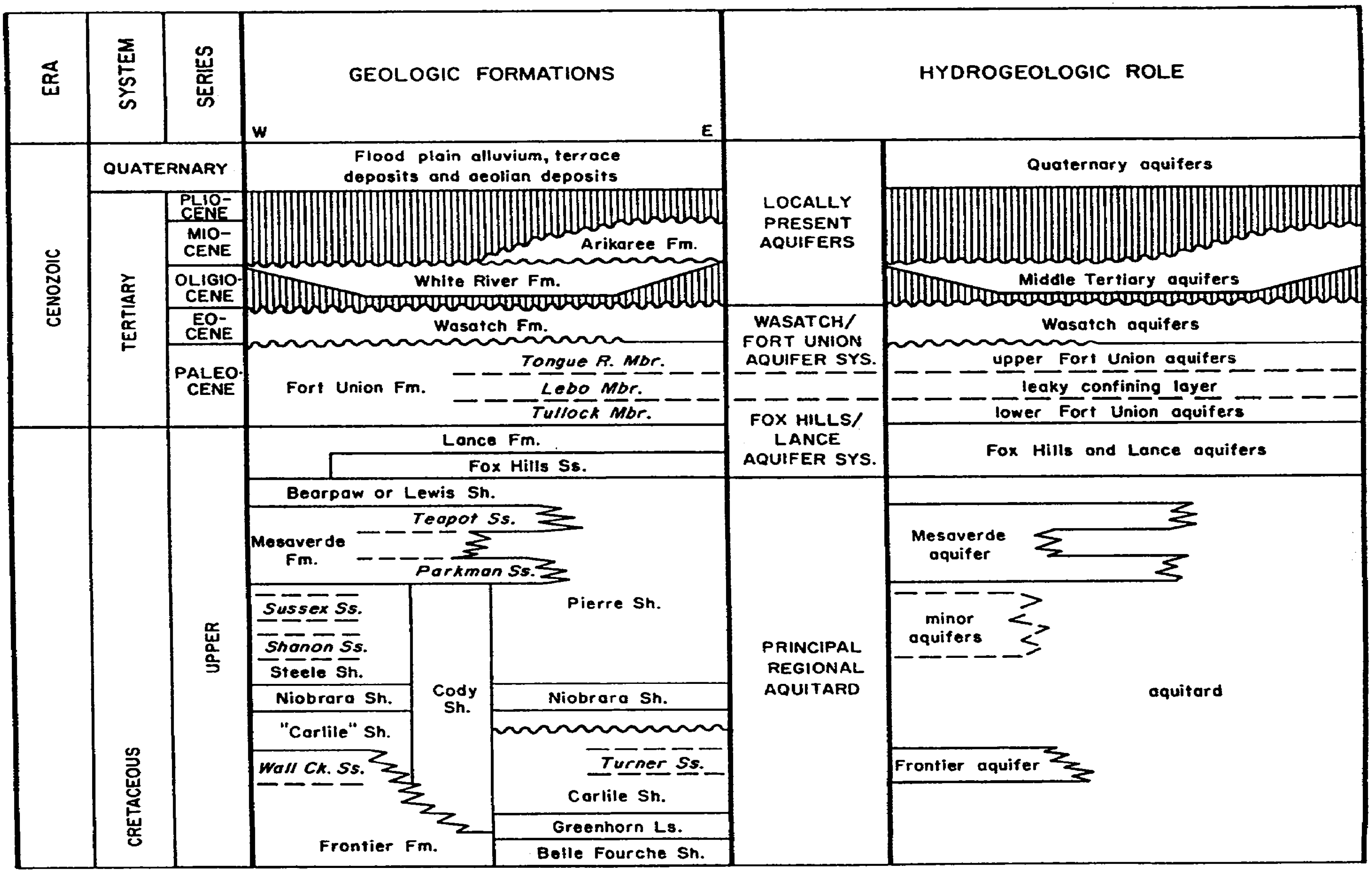

Figure 3.0. Diagrammatic Hydrostratigraphy of the Powder River Structural Basin within the Northeast Wyoming River Basins Plan Area.

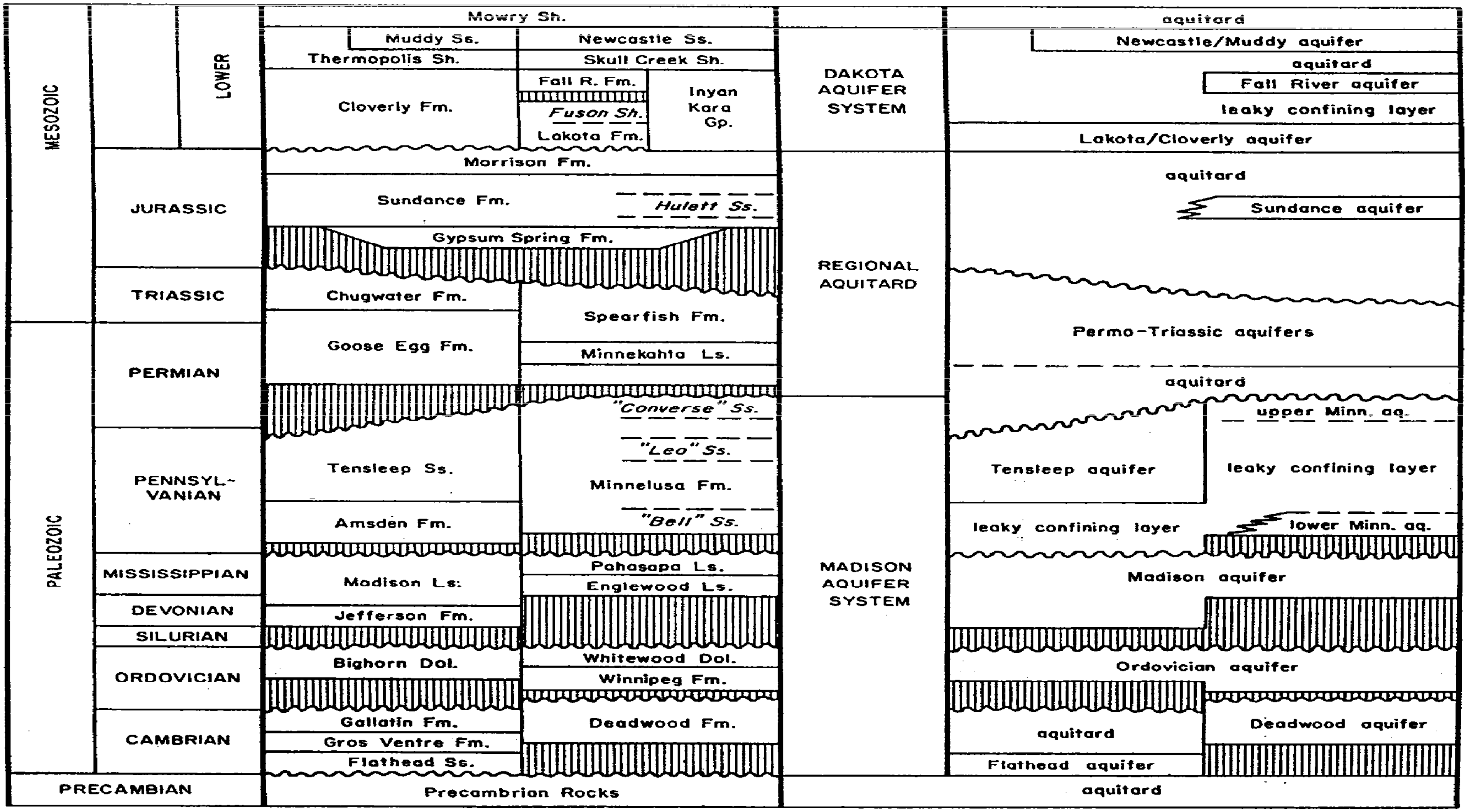

Figure Source: (Feathers, Libra, Stephenson & Eisen, 1981)

Figure 3.0. Diagrammatic Hydrostratigraphy of the Powder River Structural Basin within the Northeast Wyoming River Basins Plan Area (continued).

Table 1.0. Lithologic and Hydrologic Characteristics of Bedrock Units Exposed on the East Flank of the Powder River Structural Basin, Wyoming (compiled from numerous sources).

Erathem	System	Geological Unit	Thickness[a] (ft)	Lithologic Character	Hydrologic Character[b,c]
MESOZOIC	Cretaceous	Pierre Shale	2000± 2500-3100	Shale with some bentonite, thin siltstones, lenticular carbonates and sandstones. Contains Great Sandstone bed (0-125 ft) in north.	Regional aquitard but some low-yield wells in outcrop. Reported yield, none to 12 gpm; specific capacity, <0.1 gpm/ft.
		Niobrara Fm.	150-225 100-250	Shale, calcareous shale and marl with numerous thin bentonite beds.	Aquitard but some low-yield wells in outcrop.
		Carlile Shale	500-700 460-540	Shale, locally sandy. Contains middle Turner sandy member in north.	Aquitard but some low-yield wells in outcrop. Oil field data: porosity, 15%; permeability, 0.02 gpd/ft^2; transmissivity, 0.2-0.4 gpd/ft.
		Greenhorn Fm.	70-370 30-70	Shale, limey shale and marl with thin limestone beds.	Aquitard; no published records of wells. Oil field data: see Carlile Shale.
		Belle Fourche Sh.	450-850 400-850	Shale, dark gray to black, containing iron and limestone concretions and bentonite layers.	Aquitard but some wells near outcrop.
		Mowry Shale	180-230 220±	Siliceous shale with numerous bentonite layers.	Aquitard but some wells near outcrop; fractures enhance yield.
		Newcastle Ss.	0-60 0-100	Sandstone, fine- to medium-grained, locally conglomeratic, lenticular, with interbedded siltstone, shale and claystone.	Minor unit of Dakota aquifer system, exploited near outcrop only; often excessive pumping lift. Oil field data: porosity, 5-27%; permeability, <11 gpd/ft^2; transmissivity, 0-140 gpd/ft.
		Skull Creek Sh.	200-250 160-200	Shale, black, with iron concentrations.	Aquitard; no reports of wells.
		INYAN KARA GROUP:			
		Fall River Fm.	95-150 35-85	Sandstone, fine- to coarse-grained, with interbedded shale and siltstone.	Unit of Dakota aquifer system. Flowing yield 1-10 gpm; wells often also completed in Lakota Fm. Specific capacity, <0.5 gpm/ft. Oil field data: porosity, 11-23%; permeability, 0-36 gpd/ft^2; transmissivity, 1-900 gpd/ft.

Table 1.0. Lithologic and Hydrologic Characteristics of Bedrock Units Exposed on the East Flank of the Powder River Structural Basin, Wyoming (compiled from numerous sources).

Erathem	System	Geological Unit	Thickness[a] (ft)	Lithologic Character	Hydrologic Character[b,c]
		Lakota Fm.	45-300 115-200	Sandstone, fine- to coarse-grained, in places conglomeratic, very lenticular, irregularly interbedded with shale which becomes dominant at top (Fuson Sh.).	Unit of <u>Dakota aquifer system</u>. Flowing yield 1-10 gpm, up to 150 gpm. Water well data: specific capacity, 0.01-1.4 gpm/ft; permeability, 2-14 gpd/ft^2; transmissivity, 220-810 gpd/ft for 2 wells also in Fall River.
		- Unconformity -			
	Jurassic	Morrison Fm.	0-150 150-220	Varicolored claystone with thin beds of limestone or sandstone; locally fine-grained sandstone predominant.	Yields up to 10 gpm in outcrop area. Water well data: specific capacity, 0.2 gpm/ft; permeability, 5 gpm/ft^2; transmissivity, 160 gpm/ft. Oil field data: porosity, 11%; permeability, 0-74 gpd/ft^2; transmissivity, 0-260 gpd/ft.
		Sundance Fm.	300-400 330-365	Sandy and silty shale with thin limestones and thin to thick sandstones (e.g., Hulett Mem., 55-90 ft).	<u>Minor aquifer</u> (Crook County). Flowing yields up to 5 gpm, pumped yields up to 50 gpm in and near outcrop; specific capacity, <0.1 gpm/ft. Oil field data: porosity, 11-30%; permeability, 0-23 gpd/ft^2; transmissivity, <1250 gpd/ft.
		- Unconformity -			
		Gypsum Springs Fm.	0-125 absent	Massive white gypsum with interbedded red shale and cherty limestone.	Not considered an aquifer but may yield water to wells obtaining major supply from Sundance Fm.
		- Unconformity -			
MESOZOIC and PALEOZOIC	Triassic and Permian	Spearfish Fm.	450-825 550-600	Red shale, siltstone and fine-grained silty sandstone with lenses of gypsum, increasing in lower part.	<u>Minor aquifer</u> (Crook County). Yields average 13 gpm in outcrop area. Water well data: specific capacity, 0.6 gpm/ft; permeability, 6-8 gpd/ft^2; transmissivity, 150-370 gpd/ft.
PALEOZOIC	Permian	Minnekahta Ls.	40± 30-50	Fine-grained thinbedded limestone and dolomitic limestone.	<u>Minor aquifer</u> (Crook County). Yields average 7 gpm. USCS test: flowed 12 gpm; specific capacity, 0.1 gpm; permeability, 33 gpd/ft^2; transmissivity, 330 gpd/ft.
		Opech Fm.	60-90 50-100	Maroon sandstone, fine-grained, silty and shaley, alternating with siltstone, shale, claystone, and gypsum.	Aquitard; no published record of wells.

Table 1.0. Lithologic and Hydrologic Characteristics of Bedrock Units Exposed on the East Flank of the Powder River Structural Basin, Wyoming (compiled from numerous sources).

Erathem	System	Geological Unit	Thickness[a] (ft)	Lithologic Character	Hydrologic Character[b,c]
		- Unconformity -			
	Pennsylvanian and Permian	Minnelusa Fm. (Hartville Fm.)[d]	600-800 1000±	Sandstone, fine- to coarse-grained, interbedded with limestone, dolomite, and shale, locally gypsiferous, especially at top.	Upper part is unit of Madison aquifer system, middle is aquitard, lower is minor aquifer in hydraulic connection with Madison. Flowing yields over 200 gpm possible; specific capacity, 1-5 gpm/ft. Oil field data: porosity, 6-25%; permeability, <0.1-18 gpd/ft^2; transmissivity, 2-900 gpd/ft.
		- Unconformity -			
	Mississippian	Pahasapa Ls. (Madison Ls.) (Guernsey Fm., part)[d]	550-900 250±	Massive fine-grained limestone and dolomitic limestone, locally cherty or cavernous.	Principal unit of Madison aquifer system. Flowing or pumped yields up to 1000 gpm; specific capacity, 0.5-50+ gpm/ft, flow-dependent; transmissivity, 1000-60,000 gpd/ft, locally to 300,000+.
	Devonian	Englewood Ls. (Guernsey Fm., part)[d]	30-60 0-50±	Thin-bedded limestone, locally shaley.	Minor unit of Madison aquifer system; no published reports of water wells. USGS test: porosity, 15-18%; permeability, <0.1 gpd/ft^2.
		- Unconformity -			
	Ordovician	Whitewood Dol.	50-60 absent	Massive bedded dolomite, locally cherty.	Minor unit of Madison aquifer system; the few existing wells also produce from the Madison aquifer. USGS test: porosity, 10-25%; specific capacity, 15 gpm/ft; permeability, <0.1-11 gpd/ft^2; transmissivity, 6400 gpd/ft.
		Winnipeg Fm.	60-70 absent	Clayey siltstone (Roughlock), shale and silty shale (Icebox), fine- to medium-grained sandstone near base (Aladdin).	Aquitard
		- Unconformity -			

Table 1.0. Lithologic and Hydrologic Characteristics of Bedrock Units Exposed on the East Flank of the Powder River Structural Basin, Wyoming (compiled from numerous sources).

Erathem	System	Geological Unit	Thickness[a] (ft)	Lithologic Character	Hydrologic Character[b,c]
	Ordovician and Cambrian	Deadwood Fm.	300-500 0-50+(?)	Sandstone, locally dolomitic or conglomeratic, with interbedded shale, limestone, dolomite and siltstone.	Unit of Madison aquifer system but deep burial limits exploitation. USGS test: porosity, 13-20%; permeability, <20 gpd/ft^2.
		- Unconformity -			
PRECAMBRIAN	-	-	-	Complex of igneous and metamorphic rocks.	Locally yields water to shallow wells and springs in outcrops.

[a]First thickness range refers to northeastern basin while second refers to southeastern basin.

[b]Oilfield (and USGS test) data are variously derived resulting in internal inconsistencies in this compilation. Permeabilities are measured on cores or derived from other data and transmissivities are from drill stem tests or calculated from permeability. Test data are usually for limited horizons of high anticipated yields and are not therefore representative of the formation as a whole.

[c]Reported yields may reflect development needs rather than aquifer capability; higher yields can sometimes be expected, with corresponding drawdown increases. Reported water well transmissivities or permeabilities may be for wells completed in two aquifers or screened in only part of a single aquifer.

[d]Nomenclature for equivalent strata exposed in the Hartville uplift on the southeastern basin flank.

Table Source: Feathers, Libra, Stephenson and Eisen, 1981

Table 2.0. Lithologic and Hydrologic Characteristics of "Shallow" Geologic Units (Including Quaternary, Tertiary and Latest Cretaceous Deposits) of the Central Powder River Structural Basin, Wyoming (compiled from numerous sources).

Erathem	System	Series	Geologic Unit	Thickness (ft)	Lithologic Character	Hydrologic Character[a]
CENOZOIC	Quaternary	Holocene and Pleistocene	Alluvium and Terrace deposits	0-100+	Silt, sand and gravel; unconsolidated and interbedded; present along most streams.	Quaternary alluvial aquifers. Yield of 1000 gpm possible, often through induced recharge. Terraces topographically high and often drained. Specific capacity, 0.3-18 gpm/ft; porosity, 28-45%; permeability, 0.1-1100 gpd/ft^2; transmissivity, 15-64000 gpd/ft; specific yield, 2-39%. Coarser deposits have better aquifer properties.
			- Unconformity -			
	Tertiary	Miocene	Arikaree Fm.	0-500 (southeast only)	Tuffaceous sandstone, fine-grained, with silty zones, coarse sand lenses and concretionary zones.	Middle Tertiary aquifer. Yields up to 1000 gpm; specific capacity up to 232 gpm/ft; porosity, 5-24%; permeability, <1-300 gpd/ft^2; transmissivity, up to 77,000 gpd/ft.
			- Unconformity -			
		Oligocene	White River Gp.	0-1500 (isolated outliers except in SE)	Tuffaceous siltstone in upper part, underlain by claystone, both locally contain fine- to coarse-grained sandstone and conglomerate channel deposits.	Middle Tertiary aquifer. Not extensively developed because overlain by Arikaree Fm. in most places. Yields generally low and unpredictable. Specific capacity, <0.5 gpm/ft; permeability, 0.0002-0.03 gpd/ft^2, increases with fracturing.
			- Unconformity -			
		Eocene	Wasatch Fm.	Up to 1600	Fine- to coarse-grained lenticular sandstones interbedded with shale and coal, coarser in south and southwest, conglomeratic in west.	Part of Wasatch/Fort Union aquifer system. Yields generally <15 gpm, locally flowing wells exist. Specific capacity, 0.10-2 gpm/ft; porosity, 28-30%; permeability, 0.01-65 gpd/ft^2; transmissivity, average 500 gpd/ft, range 1-4000 gpd/ft.
			- Unconformity -			

Table 2.0. Lithologic and Hydrologic Characteristics of "Shallow" Geologic Units (Including Quaternary, Tertiary and Latest Cretaceous Deposits) of the Central Powder River Structural Basin, Wyoming (compiled from numerous sources).

Erathem	System	Series	Geologic Unit	Thickness (ft)	Lithologic Character	Hydrologic Character[a]
		Paleocene	Fort Union Fm.	1100-2500+	Sandstone, fine- to medium-grained, lenticular, interbedded with siltstone, coal and shale. Middle part may be shalier in north, upper part siltier in south. "Clinker" associated with coal outcrops.	Part of Wasatch/Fort Union aquifer system. Flowing yields of 1-60 gpm were confined. Pumped yields up to 250 gpm with several hundred feet of drawdown. Specific capacity, 0.1-2 gpm/ft; permeability, 0.01- 100 gpd/ft^2; transmissivity, 1- 5000 gpd/ft. Coal and clinker generally better aquifer properties than sandstones. Locally clinker transmissivity up to 3,000,000 gpd/ft; specific capacity over 2000 gpm/ft. Anisotropy and leaky confining layers are common.
MESOZOIC	Cretaceous	Upper Cretaceous	Lance Fm.	500-1000 (N) 1600-3000 (S)	Sandstone, fine- to medium-grained, lenticular, interbedded with sandy siltstone and claystone.	Unit of Fox Hills/Lance aquifer system. Yields up to 350 gpm but with large drawdowns and long perforated intervals. Locally flowing wells exist. Specific capacity, 0.05-2 gpm/ft; permeability, 6-35 gpd/ft^2; transmissivity, 170-2100 gpd/ft.
			Fox Hills Ss.	150-200 (N) 400-700 (S)	Sandstone, fine- to medium-grained, interbedded with shale and siltstone.	Unit of Fox Hills/Lance aquifer system. Yields up to 350 gpm but with large drawdowns and long perforated intervals. Locally flowing wells exist. Specific capactiy, 0.05-2 gpm/ft; permeability, 34 gpd/ft^2; transmissivity, 76-1600 gpd/ft for wells also completed in Lance.

[a]Reported yields may reflect development needs rather than aquifer capability; higher yields can sometimes be expected, with corresponding drawdown increases. Reported water well transmissivities or permeabilities may be for wells completed in two aquifers or screened in only part of a single aquifer. Reported ranges include varying amounts of data.

Table Source: Feathers, Libra, Stephenson and Eisen, 1981

Table 3.0
Publications Containing Ground Water Quality Data, Reviewed for the Northeast Wyoming River Basins Plan

Title	Authors	Publishing Agency/ Date of Publication
Occurrence and Characteristics of Ground Water in the Powder River Basin, Wyoming	K. R. Feathers, R. Libra, T. R. Stephenson and C. Eisen	Wyoming Water Resources Research Institute (1981)
Ground-Water Resources and Geology of Northern and Western Crook County, Wyoming (USGS Water-Supply Paper 1698)	H. A. Whitcomb and D. M. Morris	U.S. Geological Survey (1964)
Water Resources of Weston County, Wyoming (USGS Water-Resources Investigations Report 84-4079)	M. E. Lowry, W. J. Head, J. G. Runkel and J. F. Busby	U.S. Geological Survey (1986)
Ground-Water Resources and Geology of Niobrara County, Wyoming (USGS Water-Supply Paper 1788)	H. A. Whitcomb	U.S. Geological Survey (1965)
Geology and Ground-Water Resources of the Upper Niobrara River Basin, Nebraska and Wyoming (USGS Water-Supply Paper 1368)	E. Bradley	U.S. Geological Survey (1956)
Ground-Water-Quality Data from the Powder River Structural Basin and Adjacent Areas, Northeastern Wyoming (USGS Open-File Report 83-939)	L. R. Larson and R. L. Daddow	U.S. Geological Survey (1984)
Ground Water Quality in Wyoming (USGS Water-Resources Investigations Report 84-4034)	L. R. Larson	U.S. Geological Survey (1984)
Water Co-produced with Coalbed Methane in the Powder River Basin, Wyoming: Preliminary Compositional Data (USGS Open-File Report 00-372)	C. A. Rice, M. S. Ellis and J. H. Bulloch, Jr.	U.S. Geological Survey (2000)

Table 4.0 Summary of Ground Water Availability/Development Potential of Major Aquifer Systems, Central and Eastern Flanks of the Powder River Structural Basin, Northeast River Basin Plan Area, Wyoming (Feathers, Libra, Stephenson and Eisen, 1981)

Major Aquifer System	Geologic Unit	Thickness (Feet)	Lithologic Character	Hydrological Character[A,B]	General Water Quality	Availability/Development Potential [C]	Remarks
Quaternary Alluvial Aquifer System	Alluvium and Terrace Deposits	0-100+	Clay rich sandy silt, silt, sand and gravel; unconsolidated and interbedded; present along most streams. Thickness generally less than 50 feet but may be thicker. Coarser deposits in valleys of the Belle Fourche and the Cheyenne Rivers. Alluvium overlying formations of Tertiary age is generally fine to medium grained in central part of basin. (Hodson, Pearl and Druse, 1971)	Yield of 1000 gpm possible, often through induced recharge. Terraces topographically high and often drained. Specific capacity, 0.3-18 gpm/ft; porosity, 28-45%; permeability, 0.1-1100 gpd/ft^2; transmissivity, 15-64000 gpd/ft; specific yield, 2-39%. Coarser deposits have better aquifer properties.	TDS content generally range from about 100 to >4000 mg/l, and chemical characteristics of water differ geographically. Chemical type and mineralization of the water can be expected to vary depending on underlying rock types and the nature and degree of interconnection with underlying bedrock aquifers as well as surface water. Moderate to high mineralization tolerable for stock and domestic use. Suitability for irrigation generally limited to salt tolerant crops. Water in the alluvium in Black Hills generally is better quality than central part of basin (Hodson, Pearl and Druse, 1971).	Historical source for domestic and stock use. Production has ranged from 1 to 900 gpm. Ground water development potential generally better in coarse-grained deposits and poorer in fine-grained materials. Yields in the high end of the above range might be possible to optimally located and properly designed wells if induced infiltration from surface water can be tolerated (Belle Fourche, Cheyenne and Niobrara River Basins). Potential source for irrigation, municipal / public and industrial sources where more than 40 feet of saturated well sorted sand and gravel are present.	Quaternary alluvial aquifers generally in hydraulic connection with all bedrock aquifers in outcrop areas and also with surface waters. Alluvial aquifers in larger valleys provide hydraulic interconnection between otherwise hydraulically isolated bedrock aquifers (Whitcomb, 1965). Alluvial aquifers also serve as interchange point and storage for ground water in the hydrologic cycle (Davis and Rechard, 1977), (Davis, 1976). Induced recharge from surface waters is probable in areas of extensive development.
Middle Tertiary Aquifer	Arikaree Formation	0-500 (southeast only)	Tuffaceous sandstone, fine-grained with silty zones, coarse sand lenses and concretionary zones.	Yields up to 1000 gpm; specific capacity up to 232 gpm/ft; porosity, 5 24%; permeability <1-300 gpd/ft^2; transmissivity up to 77,000 gpd/ft.	TDS content of water ranges from 261 to 535 mg/l. Composition mainly Calcium Bicarbonate (Whitcomb, 1965). Median TDS content in samples from 12 wells in Niobrara County 321 mg/l (Larson, 1984).	Historical source for municipal / public, industrial, domestic, stock and irrigation supply with tested production ranging as high as 195 to 730 gpm (Whitcomb, 1965). Yields of 1000 gpm might be possible to optimally located and properly designed wells.	Water level data available from two observation wells located east and south east of Lusk in Niobrara County (32-62-05-baa01), (32-62-32-bbb01). Water levels have shown approximately 6 to 13 feet decline in water levels in the aquifer since the 1970s with possibly some stabilization and slight recovery since early to mid 1990s (USGS, 2001).
Fort Union / Wasatch Aquifer System	Wasatch Formation	up to 1600	Fine- to coarse-grained lenticular sandstones interbedded with shale and coal, coarser in south.	Yields generally <15 gpm, locally flowing wells exist. Yields historically could be expected to range from 10 to 50 gpm in the north part of the basin with the possibility of higher yields up to 500 gpm in the south part of the basin (Hodson, Pearl and Druse, 1973). Specific capacity, 0.10-14 gpm/ft (Hodson, Pearl and Druse, 1973); porosity, 28-30%; permeability, 0.01-65 gpd/ft^2; transmissivity, average 500 gpd/ft range 1-4000 gpd/ft.	TDS content of waters is variable and ranges from <200 to > 8000 mg/l (Hodson, Pearl and Druse, 1973). Sodium Sulfate and Sodium Bicarbonate are general dominate water types. Major ion composition varies with depth and shows more Sodium and Bicarbonate content with depth. Radium 226 + 228 may be of concern near uranium deposits.	Historical source for municipal / public, domestic and stock supply. Yields ranging from 10 to 50 gpm in the north part of the basin can be expected with the possibility of higher yields up to 500 gpm in the south part of the basin (Hodson, Pearl and Druse, 1973).	Water level data available from two observation wells located in Campbell County (50-72-21-aba01), (42-71-35-aaa01) and one observation well in Converse County (37-70-10-cbb01). Water levels in the aquifer have shown about a 40 feet rise between 1983 and 2000 in Gillette and about a 40 to 50 feet decline south east of Wright in Campbell County. Water levels in the aquifer in northwest Converse County have shown a rise of about 7 feet between 1988 and 1999 after a decline of about 6 feet between 1986 and 1988. (USGS, 2001).

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Fort Union / Wasatch Aquifer System (continued)	Fort Union Formation	1100-2270	Sandstone, fine- to medium-grained, lenticular, interbedded with siltstone, coal and shale. Middle part may be shalier in north, upper part siltier in south. "Clinker" associated with coal outcrops.	Flowing yields of 1-60 gpm where confined. Pumped yields up to 250 gpm with several hundred feet of drawdown. Specific capacity, 0.1-2 gpm/ft; permeability, 0.01-100 gpd/ft$^{2;}$ transmissivity, 1-5000 gpd/ft. Coal and clinker generally have better aquifer properties than sandstones. Locally clinker transmissivity up to 3,000,000 gpd/ft; Anisotropy and leaky confining layers are common.	TDS content and major ion composition of Fort Union Formation Waters as above. Water co-produced with coal bed methane is predominantly Sodium Bicarbonate type with TDS content and SAR (32 samples), 270 - 1170 mg/l (mean of 653 mg/l) and 5.7 - 12 (mean of 7.85) respectively (Rice, Ellis & Bullock, 2000). BLM Wyodak EIS assumed average TDS concentration of 764 mg/l (USDI,BLM, 1999). High radionuclide content of concern in areas near uranium ore zones.	Historical source for municipal / public, domestic and stock supply. Maximum expected yields of about 130 to 150 gpm (Hodson, Pearl and Druse, 1973), (Wester - Wetstein and Associates, Inc., 1994). Exploration and development of new Fort Union well field including conjunctive use / recharge of Coal Bed Methane production water under consideration for the City of Gillette.	Source for approximately 14 municipal and public water supply systems including the City of Gillette and adjacent Districts, Joint Powers Boards and Privately Owned Water Systems and Water Users Associations in Campbell County. City of Gillette mixes Fort Union Formation water with that from the Madison and Fox Hills/Lance system for municipal / public water supply. Total of 5285 Coal Bed Methane wells permitted with WSEO in planning area as of 12/31/00. Maximum, minimum and mean depths and range of actual yields listed on permits were 138 -5507 (mean 772) feet below ground surface (bgs), and 1 - 120 (mean 27) gpm respectively. Range of depths to main water bearing zone listed on WSEO Permits were 124 - 1558 (mean 124) feet bgs. BLM Wyodak EIS assumed average expected water production to be 12 gpm over the estimated 12 year life of each CBM well (USDI,BLM, 1999). BLM Wyodak Drainage EA assumed average water production for each CBM well to be 11.1 gpm (USDI,BLM, 2000).
Fox Hills/Lance Aquifer System	Lance Formation	500-1000 (North) 1600-3000 (South)	Sandstone, fine- to medium-grained, lenticular, interbedded with sandy siltstone and claystone.	Yields up to 350 gpm but with large drawdowns and long well completion intervals. Locally flowing wells exist. Specific capacity, 0.05-2 gpm/ft; permeability, 6-35 gpd/ft$^{2;}$ transmissivity, 170-2100 gpd/ft	TDS content in waters at Foxhills/Lance System outcrops north of Niobrara County range from 600 - 1,500 mg/l, and in Niobrara County range from 1,000 - 3,300 mg/l. Composition mainly Sodium - Bicarbonate - Sulfate. Fluoride enrichment is characteristic of Fox Hills/Lance Formation waters. Possible high Sodium, and radionuclide content could be of concern in some areas.	Lance Formation historical source for municipal / public, domestic and stock supply. Generally yields less than 20 gpm, but yields of several hundred gallons per minute may be possible from complete section of the formation. (Hodson, Pearl and Druse, 1973)	High Fluoride content is of concern for development as source for municipal / public water systems.
	Fox Hills Sandstone	150-200 (North) 400-700 (South)	Sandstone, fine-to medium-grained, interbedded with shale and siltstone.	Yields up to 705 gpm but with large drawdowns and long well completion intervals. Locally flowing wells exist. Specific capacity, 0.05-2 gpm/ft; permeability, 34 gpd/ft^2; transmissivity, 76-1600 gpd/ft for wells also completed in Lance.	Similar to Lance Formation	Historical source for municipal / public, industrial, domestic and stock supply. Tested yields of Gillette municipal / public supply wells have ranged from 85 to 705 gpm (Wester-Wetstein and Associates, Inc., 1994).	High Fluoride content is of concern for development as source for municipal / public water systems. Has been used for oil well water flooding operations. Water level data available from one observation well completed in the aquifer south east of Gillette in Campbell County (49-70-31bbb01) has shown approximately 50 feet decline since 1983 (USGS, 2001).

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Dakota Aquifer System	Newcastle Sandstone	0-60 (Northeastern Basin) 0-100 (Southeastern Basin)	Sandstone, fine-to medium-grained, locally conglomeratic, lenticular, with interbedded siltstone, shale and claystone.	Minor unit of Dakota Aquifer System exploited near outcrop only; often excessive pumping lift. Oil field data: porosity, 5-27%; permeability, <11 gpd/ft^2; transmissivity, 0-140 gpd/ft.	Waters at Dakota System outcrop generally contain over 1,000 mg/l TDS. TDS content 180 - 3200 mg/l in 17 samples in Weston County (Larson, 1984). Composition changes basinward from Calcium - Magnesium - Sulfate at outcrop to Sodium - Sulfate, to Sodium - Bicarbonate. Deep Basin waters > 10,00 mg/l TDS & are enriched to Sodium - Chloride. Possible high Fluoride, Selenium and radionuclide content could be of concern in some areas.	Dakota Aquifer System historical source for domestic and stock use.	Few reported wells in northern Black Hills (1958) due to excessive drilling depths except in outcrop areas. Yields typically adequate for stock and domestic purposes. Historically, wells typically have been completed in both the Lakota and Fall River Formations to obtain maximum production. (Whitcomb, Morris, Gordon & Robinove, 1958) Water level data available from one observation well completed in the aquifer (Lakota Formation) northeast of Lusk in Niobrara County (36-62-28ab02) has shown approximately 23 feet decline between 1974 and 2000 (USGS, 2001).
	Fall River Formation	95-150 (Northeastern Basin) 35-85 (Southeastern Basin)	Sandstone, fine-to coarse-grained with interbedded shale and siltstone.	Flowing yield 1-10 gpm; wells often also completed in Lakota Formation. Specific capacity, <0.5 gpm/ft. Oil field data: porosity, 11-23%; permeability, 0-36 gpd/ft^2 ; transmissivity, 1-900 gpd/ft.			
	Lakota Formation	45-300 (Northeastern Basin) 115-200 (Southeastern Basin)	Sandstone, fine-to coarse-grained, in places conglomeratic, very lenticular, irregularly interbedded with shale which becomes dominant at top (Fuson Shale).	Flowing yield 1-10 gpm, up to 150 gpm. Water well data: specific capacity, 0.01-1.4 gpm/ft; permeability, 2-14 gpd/ft^2 transmissivity, 220-810 gpd/ft for 2 wells also in Fall River.			
Madison Aquifer System	Minnelusa Formation (Hartville Formation)[D]	600-800 (Northeastern Basin) 1000± (Southeastern Basin)	Sandstone, fine-to coarse-grained, interbedded with limestone, dolomite, and shale, locally gypsiferous, especially at top.	Upper part has historically been considered part of Madison Aquifer System, middle is aquitard, lower is minor aquifer in hydraulic connection with Madison. Flowing yields of over 200 gpm possible; specific capacity, 1-5 gpm/ft. Oil field data: porosity, 6-25%; permeability, <0.1-18 gpd/ft^2; transmissivity, 2-900 gpd/ft.	Similar to Madison Formation Waters at Outcrop (TDS < 600mg/l, predominantly Calcium - Magnesium - Bicarbonate type water). TDS content 230 - 2450 mg/l from 26 samples in Crook County with median and mean of 520 and 773 mg/l respectively (Larson, 1984). Some east basin waters near outcrops show TDS up to 3,000 mg/l (Calcium & Sulfate enrichment). Deep basin waters TDS > 10,000 mg/l (mainly Sodium - Chloride type water). Fluoride enrichment characteristic of Madison System waters throughout the basin. Concentrations of radionuclides could be of concern in some areas.	Historical source for municipal / public water supply, domestic and stock use.	Large quantities of water produced from flowing wells at Huelett (1958). Generally deeply buried (> 600 - 700 feet minimum) in area (northern Black Hills - 1958), (Whitcomb, Morris, Gordon & Robinove, 1958). Subject of USGS investigation with Pahasapa / Madison Limestone (Ogle, 2001). Water level data available from one observation well located in Crook (44-62-36-cbb02) and one in Niobrara (36-62-28-bbd01) Counties. Water levels have risen about 2 feet (since 1998) and 15 feet (since 1995) respectively in the two observation wells (USGS, 2001).

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Madison Aquifer System (Continued)	Pahasapa Limestone (Madison Limestone)[D]	550-990 (Northeastern Basin) 250± (Southeastern Basin)	Massive fine-grained limestone and dolomitic limestone, locally cherty or cavernous.	Principal unit of Madison Aquifer System. Flowing or pumped yields up to 1000 gpm; specific capacity, 0.5-50+ gpm/ft, flow-dependent; transmissivity, 1000-60,000 gpd/ft locally to 300,000 gpd/ft+.	Waters at Outcrop (TDS < 600mg/l, predominantly Calcium - Magnesium - Bicarbonate type water). TDS increase basinward to > 3,000 mg/l, Sodium - Sulfate - Chloride predominating. Fluoride enrichment characteristic of Madison System waters throughout the basin. Concentrations of radionuclides could be of concern in some areas.	Probably most important high yield aquifer in Wyoming. Historical source for municipal / public water supply, industrial, irrigation and stock use. Several fish hatcheries use Pahasapa / Madison aquifer as water source. Base flow and spring discharge from the Pahasapa / Madison aquifer form part of the surface run-off in the Black Hills area. (Ogle, 2001) Tested pumping rate of seven City of Gillette Pahasapa / Madison aquifer wells ranged from 535 to 900 gpm (Wester-Wetstein and Associates, Inc., 1994).	Subject of USGS investigation with the Minnelusa Formation (Ogle, 2001). Water level data available from nine observation wells located in Crook (56-67-28-aab01), (56-67-28-aab02), (53-65-18bbd02), (52-63-25-dcd01), (49-62-36-cbb01), Weston (48-65-35ccb01), (46-66-25dbb01), (44-63-26cac01), and Niobrara (36-62-28-ab01) Counties. Water levels have generally risen from 13 to 40 feet in some of the observation wells since 1995 (USGS, 2001). Total estimated recharge to the Madison Limestone in the Powder River Basin in 1973 was about 75,000 acre feet/year (WSEO, 1976).
	Englewood Limestone (Gurnsey Formation, part)[D]	30-60 (Northeastern Basin) 0-50± (Southeastern Basin)	Thin-bedded limestone, locally shaley.	Minor unit of Madison Aquifer System; USGS test: porosity, 15-18%; permeability, <0.1 gpd/ft^2.			Generally no ground water development in area (Northern Black Hills - 1958). Formations may contain some water in permeable zones, but are generally considered to be too deeply bured to be considered important aquifers. (Whitcomb, Morris, Gordon & Robinove, 1958)
	Whitewood Dolomite	50-60 (Northeastern Basin) absent (Southeastern Basin)	Massive bedded dolomite, locally cherty.	Minor unit of Madison Aquifer System; the few existing wells also produce from the Madison aquifer. USGS test: porosity, 10-25%; specific capacity, 15 gpm/ft; permeability, <0.1-11 gpd/ft^2; transmissivity, 6400 gpd/ft.			

[A]Reported yields may reflect development needs rather than aquifer capability; higher yields can sometimes be expected, with corresponding drawdown increases. Reported water well transmissivities or permeabilities may be for wells completed in two aquifers or screened in only part of a single aquifer. Reported ranges include varying amounts of data. (Feathers, Libra, Stephenson and Eisen, 1981)

[B]Oilfield (and USGS test) data are variously derived resulting in internal inconsistencies in this compilation. Permeabilities are measured on cores or derived from other data and transmissivities are from drill stem tests or calculated from permeability.
Test data are usually for limited horizons of high anticipated yields and are not therefore representative of the formation as a whole. (Feathers, Libra, Stephenson and Eisen, 1981)

[C]Actual development potential will require site specific office and field investigations to define aquifer capability and constraints unique to each project and site.

[D]Nomenclature for equivalent strata exposed in the Hartville uplift on the southeastern basin flank (Feathers, Libra, Stephenson and Eisen, 1981).