Powder River Basin Desalination Project Feasibility

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Powder River Basin Desalination Project Feasibility

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Introduction

Since 1997, coalbed natural gas (CBNG) development in Wyoming's Powder River Basin (PRB) has increased dramatically, resulting in both the generation of a huge energy resource and a set of serious environmental and regulatory impacts. The most serious impacts caused by CBNG development relate directly to production of the copious quantities of groundwater required to recover the natural gas. Not only are the thick coals in the PRB rich in natural gas, they are also an important regional aquifer system. In order to extract the absorbed natural gas from the coals, the formation pressure must be reduced by the production of groundwater from wells.

Importantly, the existing data[1] strongly suggest that during the next five years, CBNG activity in the PRB will expand west into deeper coals, the quality of water produced from the coal will deteriorate, and the volume of water produced per well will increase significantly (**Figure 1**). For example, the data show that the salinity of water produced from deeper wells in the west, when compared to that of water produced from the initial CBNG wells in the eastern part of the basin, will increase from approximately 500 to 3,500 milligrams per liter (mg/L), considered brackish, (**Figure 2**); the sodium adsorption ratio (SAR) will increase from 2-6 to 30-50 milliequivalents per liter (meq/L), (**Figure 3**); and the ratio of barrels of water to million cubic feet (MCF) of produced gas will increase from 2 to more than 2,000 (**Figure 4**). Therefore, all stakeholders in the PRB have focused on the collection and disposal of the water during CBNG activities. Consequently, a very contentious atmosphere has emerged concerning CBNG development, particularly with respect to the handling of the produced water. Most recently, the non-degradation ruling regarding waters entering the State of Montana will surely exacerbate the combative nature of the discussion of CBNG-produced water in both Montana and Wyoming.

Most of the disagreement among stakeholders in the PRB would disappear if the CBNG-produced water was treated and put to beneficial use. At present, much of the produced water is discharged into ephemeral streams or stored in fenced, lined or unlined, off-channel reservoirs for disposal by evaporation and/or infiltration into the alluvium. To many stakeholders in the arid Powder River Basin, this "preferred" water disposal procedure constitutes a waste of an important water resource. In order to alleviate the concerns of many stakeholders and prevent the waste of an important Wyoming resource, we must increase the beneficial use of CBNG-produced water in the PRB. In most cases, both the SAR and salinity of the produced water must be significantly decreased to accomplish this goal. Without SAR and salinity reduction, municipalities, agriculture, and industry will not be able to use the water in beneficial ways, and the discharge of waters produced from the deeper "Big George" coal seam into natural drainages will not be allowed in the future.

The SAR of the produced water is very important in evaluating potential problems related to discharging water onto soil because of how sodium affects clay minerals. Most soils found in Rocky Mountain Laramide structural basins are derived from Tertiary and Mesozoic shale beds that are rich in clay minerals, particularly smectites. These smectite-rich soils typically have exceptionally high water-absorbing and cation exchange capacities. If sodium-rich waters are applied to smectite-rich soils, sodium replaces calcium in the clay mineral and the water absorption and swelling capacity of the clay increases significantly, resulting in a low permeability, expanded greasy soil. As this soil dries, it becomes brick-like and mud-cracked.

[1] Data were obtained from various coalbed methane producers, from the National Pollution Discharge Elimination System (NPDES) and Wyoming Pollution Discharge ELimination System (WYPDES) permits issued and maintained by the Wyoming Department of Environmental Quality (DEQ), from the Water Resources Data System (WRDS), from the U. S. Bureau of Land Management (BLM) Casper Field Office, from the U. S. Geological Survey (USGS) Energy Program, from the USGS National Water Information System (NWIS), and from the Wyoming Oil and Gas Conservation Commission (WOGCC).

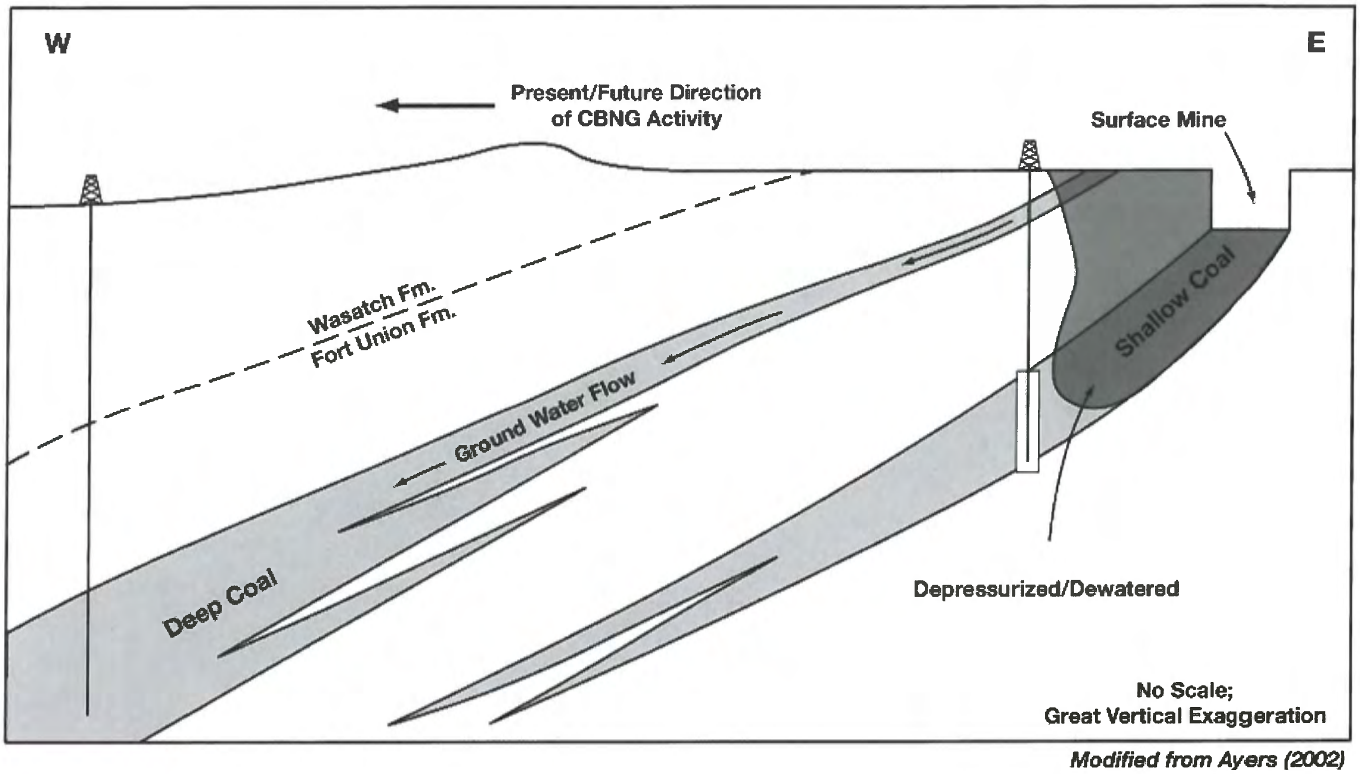


Figure 1. Early CBNG wells were located in depressurized strata adjacent to surface mines. Currently, CBNG activity is moving to the west and exploiting deeper and thicker coal beds in the Powder River Basin (i.e., the "Big George" coal bed).

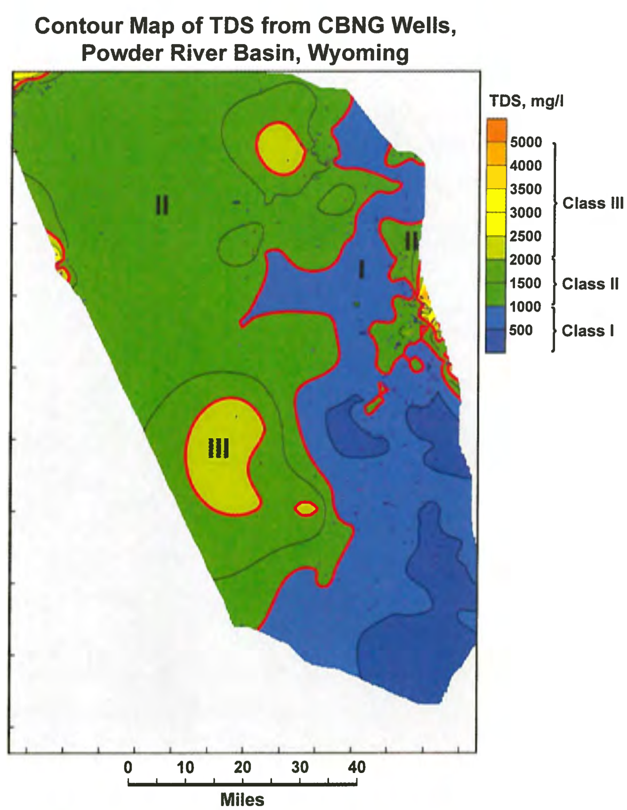


Figure 2. Contour map of water salinity from CBNG wells in the Powder River Basin, Wyoming. The total dissolved solids level (TDS) of the produced water is expressed in mg/L. Class I, II, and III are from the Wyoming Department of Environmental Quality water salinity classification.

Figure 3. Contour map of sodium adsorption ratio (SAR) from water produced during CBNG activities in the Powder River Basin. The sodium hazard classification shown in this figure is from the Wyoming Department of Environmental Quality.

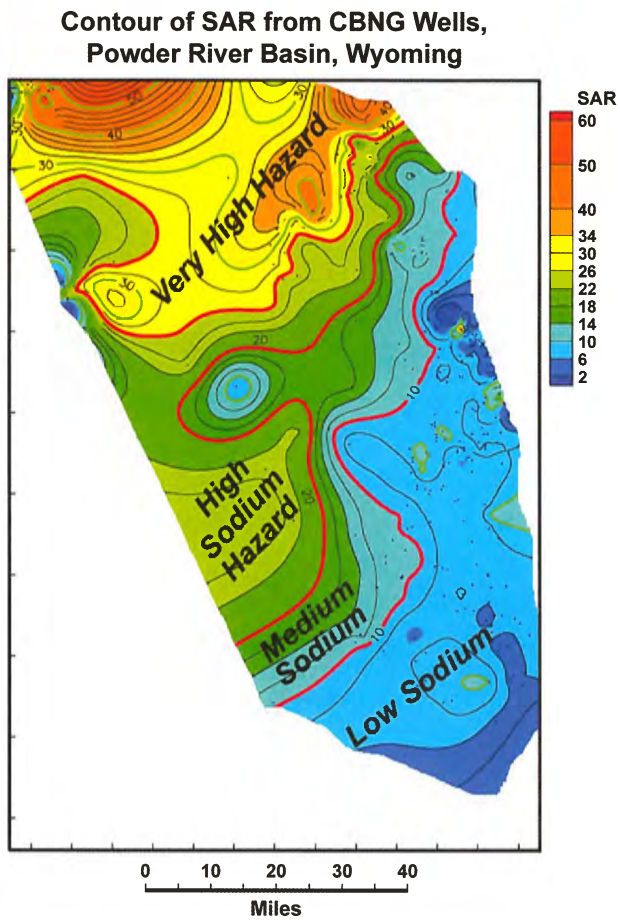
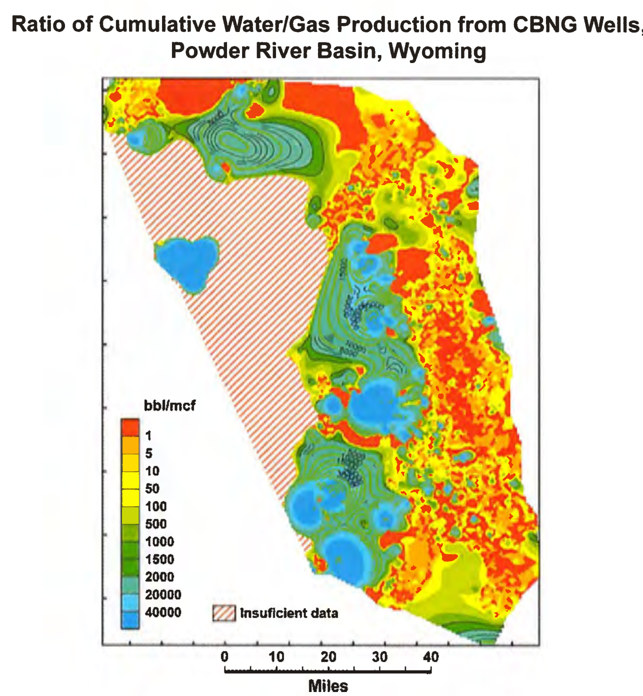


Figure 4. Map showing the ratio of cumulative water/gas production from CBNG wells in the Powder River Basin. The ratio is based on the number of barrels of water produced to recover one million cubic feet of gas. The Wyoming Oil and Gas Conservation Commission provided the data for this figure.



In addition, the shale-derived soils contain abundant sulfates derived from the oxidation of sulfides (i.e., pyrite) in the Tertiary and Mesozoic shale beds. In those portions of sodium-rich soils subjected to evaporative pumping in the vadose zone, the mineral mirabilite ($NaSO_4 \bullet 10 H_2O$) forms. With drying of the soil, the mirabilite dehydrates to form thenardite ($NaSO_4$) which forms the white evaporitic surface layer that is prevalent in topographic lows subjected to wet-dry cycles in Rocky Mountain Laramide structural basins. The end result of the application of relatively high SAR water on clay-rich soils is the deterioration of soil structures and a significant reduction of water penetration through the soils, which drastically decreases plant production and accelerates soil erosion. In addition, the uses of untreated brackish water in municipalities, agriculture, and industry are limited.

In summary, CBNG production in Wyoming benefits the state, but also generates relatively large quantities of moderate to low quality groundwater. The current water permitting system adds both time and monetary burdens to the growth and sustainability of the CBNG industry. Various methods of CBNG-production water discharge, treatment, and storage are currently being used. However, the prospective use and value of this available groundwater resource is largely lost to Wyoming's residents because the produced water is simply surface discharged or evaporated away. Collection and treatment of CBNG water for reuse has the potential to become an additional source of revenue for the state, help alleviate some of the permitting burden on the CBNG industry, and eliminate surface water and groundwater degradation. This document examines future CBNG water production, desalination plant data, uses for treated water, and piping costs, and outlines three specific desalination cost/location/use scenarios.

This report will address ways to economically, effectively, and efficiently optimize the beneficial use of water produced during PRB CBNG operations in the future.

Powder River Basin CBNG-Produced Water and Related Issues

The accompanying chart (**Table 1**) shows the previous five years of annual CBNG water production in the PRB. The number of producing wells has increased almost fourfold during this time period, while water production has only increased by approximately 30%. Not all of this produced groundwater is of a quality that requires treatment. As is typical of CBNG wells, initial water production exceeds natural gas production; subsequently, water production declines as the potentiometric surface elevation in the coalbed aquifer is lowered by pumping groundwater from CBNG production wells. As CBNG development progresses in the PRB, additional wells will go into production and total

Table 1. Summary of annual CBNG water production in the PRB of Wyoming.

Year of production	Produced water (barrels per day)	Average number of CBNG production wells	Average production per well (barrels per day)
2000	1,029,227	3,218	319
2001	1,421,000	6,546	217
2002	1,618,397	9,604	168
2003	1,562,071	11,633	134
2004	1,455,899	12,996	112

Wyoming State Geological Survey compilation based on Wyoming Oil and Gas Conservation Commission data, December 2005.

CBNG water production will remain relatively high, but is anticipated to decline over time.

A gradual decline in total CBNG water production is desirable, but the amount of water in need of disposal will remain relatively high for a considerable period of time. The projected economic production life of an individual CBNG well is currently unknown, but CBNG development in the PRB is expected to continue for another 25 years or more. In addition, current CBNG development is progressing westward into the "Big George" coal seam, which is located deeper in the PRB. The "Big George" coal bed has been shown to produce larger quantities of higher-salinity groundwater than current production wells do.

Presently, disposal of CBNG-produced groundwater is problematic at best. The highly variable quality of CBNG-produced groundwater complicates permitting by the Wyoming Department of Environmental Quality (WDEQ) and the Wyoming State Engineer's Office (WSEO). Costs of permitting are high and time-consuming for operators, the WDEQ, and the WSEO. The proposed desalination scenarios would streamline or omit permitting. Most of the CBNG-produced groundwater of moderate to low quality could be collected and transmitted by pipeline to a water treatment plant. The brackish saline groundwater would be treated and then made available for a variety of beneficial uses. Questions about the suitability of various CBNG-produced waters for use in variable circumstances (for example, SAR in relation to irrigation) would be greatly reduced or eliminated. Some of the treated water could also be made available for municipal use.

Projected Desalination Plant Costs and Capabilities

Initially, Streeter (1972) discussed desalination of the public groundwater supply for the City of Gillette. Since then, desalination technology has greatly improved, especially during the past decade. The cost of desalinating brackish water, such as saline groundwater, is half that of desalinating seawater. This lower treatment cost is due to the fact that brackish waters have less than half the salinity of seawater. Currently, there are approximately 1,500 brackish water desalination plants operating in the United States, generating approximately 1 billion gallons of treated water per day (Texas Water Development Board, December 2005). A list of Texas communities that operate brackish water reverse osmosis (RO) desalination plants can be found in the **Appendix**.

Reverse osmosis is the most common treatment process used for desalinating brackish groundwater. Reverse osmosis plants can be constructed in modules, have an approximate 90% recovery rate, use less energy, are simpler to construct, and screen out more biological components than other treatment options. These plants use high pressure pumps to force saline water through membrane tubes that screen out most non-water molecules. With proper maintenance, desalination plants can function for decades. The electrical power required to operate a desalination plant could easily be supplied by inexpensive and clean Wyoming coal. Close proximity to coal mines in the PRB and the use of trucks instead of trains to transport coal could further reduce operating costs. Operating large-scale desalination also reduces total capital facility costs and per barrel operating costs. **Table 2** illustrates the estimated capital cost of one to three plants divided by half the play's lifetime production and the total play lifetime production. **Table 3** shows the estimated per-barrel operating capital costs of different capacity RO plants.

Potential Beneficial Uses for Treated Water

The treated CBNG-produced groundwater resource has a near limitless number of valuable uses in an arid to semi-arid region such as Wyoming. A 600,000-barrel-per-day (BPD) capacity desalination plant produces a flow of water approximately equivalent to the average flow

Table 2. Typical desalination plant estimated capital costs.		
Total project plant capital	Capital cost per 1,000 barrels at 22 billion lifetime barrels produced	Capital cost per 1,000 barrels at 44 billion lifetime barrels produced
$50 million	$2.27	$1.14
$100 million	$4.55	$2.27
$150 million	$6.82	$3.41

Wyoming State Geological Survey compilation based on Wyoming Oil and Gas Conservation Commission data, December 2005.

Table 3. Treatment plant estimated cost by processing capacity.		
Processing capacity (barrels per day)	Plant capital cost	Processing cost per 1,000 barrels at 44 billion lifetime barrels produced
600,000	$50 million	$63.00
360,000	$35 million	$65.10
180,000	$20 million	$67.20

Texas Water Development Board, December 2005.

of Salt Creek or Crazy Woman Creek (approximately 69 acre-feet per day). Treated water can be used by nearby, growing, high-use municipalities such as Gillette, where water demand is currently between 4.4 and 13.6 million gallons per day (GPD) (105,000 BPD and 325,000 BPD) (City of Gillette, Wyoming, December 2005). Treated low-salinity groundwater could be discharged into river basins to supplement irrigation or discharged into surface waters of the Tongue, Powder, Belle Fourche, or North Platte river basins.

Treated water from a 600,000-BPD desalination plant could provide approximately 13% of the 217,000 acre-feet per year (4,600,000 BPD) of the North Platte River water allocated for irrigation use (Nebraska *v.* Wyoming, 2001). Low-salinity water is also desirable for use in dust suppression at surface coal mines, for electrical generation in future or existing power plants, and in proposed coal-to-liquids conversion plants. Coal mines in the PRB currently use between 200 and 800 acre-feet of water per year (4,250 to 17,000 BPD) (HKM Engineering, 2002) for dust suppression. A potential coal-to-liquids conversion plant is estimated to use 1,200 acre-feet of water per year (25,500 BPD), and a new electric generation plant will use approximately 23,000 to 34,000 acre-feet of water per year (495,000 to 725,000 BPD) (Purcell, 2001). An area of especially high demand is the Front Range urban development zone in Colorado, where water supply prices range from $3,000 to $10,000 or more per acre-foot, or $0.38 to $1.28 per barrel (Wyoming State Water Plan FAQ, January 2006). **Table 4** compares the demand for various water uses to the volume of treated water made available for use.

Out of every 10 barrels (420 gallons) of water processed, it is estimated that one barrel (42 gallons) of brine concentrate with a total salinity ranging from 10,000 to 15,000 mg/L, or parts per million (ppm), of total dissolved solids (TDS) is produced (Texas Water Development Board, December 2006). This level of brine concentrate salinity is approximately one-third to one-half that of seawater. Approximately 10% of the influent entering the treatment plant is produced as concentrated high-salinity effluent water.

Table 4. Water use comparison.		
Consumptive use	**Average water demand (BPD)**	**Percent of water demand generated by a 600,000-BPD plant**
Gillette municipal system	214,285	252%
North Platte River irrigation allocation	4,600,000	13%
Coal dust suppression	10,627	5081%
Coal-fired power plant	608,480	89%
Coal-liquid conversion	25,507	2117%

City of Gillette, December 2005; Nebraska v. Wyoming, 2001; and Wyoming State Water Plan, January 2006.

Effluent Disposal of High-Salinity Water Generated by Treatment Plant

During the desalination process, approximately 90% of the influent water received at the water treatment plant would be treated to very low salinity levels and then made available for beneficial use. The dissolved constituents removed by water treatment are concentrated into the remaining 10% of the influent water volume, which leaves the plant as brine concentrate. Brine concentrate resulting from the desalination process will require disposal, or could generate revenue if used in industrial processes.

This study has not investigated disposal options and associated costs for high-salinity effluent (brine concentrate) produced by the desalination plant. Each 600,000-BPD treatment plant would produce an estimated 60,000 BPD (2.5 million GPD) of brine concentrate. The estimated costs and methods of disposal would need to be addressed by an engineering feasibility study during the initial phase of any proposed desalination project to ensure project viability.

Disposal methods for the RO treatment effluent may include lined surface evaporation ponds, heated evaporation tanks, subsurface injection into deep formations with similar or higher salinities, and other methods. Either existing underground injection control (UIC) wells or future permitted UIC wells may be available for effluent disposal in deep formations located in the PRB. Alternatively, some of the effluent water may be suitable for use in water-flood enhanced oil recovery. In addition, the predominantly sodium bicarbonate-type groundwater produced from PRB coal beds and concentrated during RO treatment may constitute a desirable chemical plant feedstock.

The number of available subsurface geologic formations in the PRB that can be used for injection of fluids via UIC wells is limited. The paucity of such formations in the PRB has placed serious constraints on the potential for reinjecting the large volumes of water currently produced by CBNG activities. As such, the available formations suitable as fluid injection UIC wells in the PRB might be best used for effluent disposal of high-salinity water generated by desalination plants. Additional treatment methods for concentration of the high-salinity effluent may be required before injection and disposal.

Also, a preliminary review of existing oil fields in the PRB has identified several older oil field reservoirs that could be used for injection and disposal of the estimated quantity of produced effluent. One 600,000-BPD treatment plant is expected to produce approximately 22 million barrels of high-salinity effluent per year (at a rate of 60,000 BPD), or a total of approximately 660 million barrels over a 30-year operating period. Based on petroleum and water production data from the Wyoming Oil and Gas Conservation Commission, the estimated 660 million barrels of effluent could be injected into several PRB oil fields with a sufficient volume of availbale reservoir space. This alternative method of effluent disposal must be investigated further with an engineering feasibility and cost estimate study.

Plant Sites, Transmission Pipeline Location Scenarios, and Estimated Costs

Please refer to the accompanying map for plant and pipeline locations (**Plate 1**). Proposed sites for desalination plants were selected based on several parameters. Proximity to produced water sources would help reduce gathering costs. Proximity to existing pipeline corridors, power supplies, roadways, and railroad lines would help reduce permitting costs. Further, proximity to usage or storage points of desalinated water, including municipalities, would also help reduce overall costs. The potential water treatment plant sites are approximately located and the proposed sites may be adjusted for location onto state-owned land and/or closer to CBNG water production centers.

Potential desalination plant sites are: A) near Gillette; B) near Pine Tree Junction (southern end of CBNG play); and C) Dead Horse (near the "Big George" coal area).

Proposed underground transmission pipelines include: 1) Gillette to Keyhole Reservoir; 2) Gillette to Pine Tree Junction; 3) Pine Tree Junction to Douglas; 4) Pine Tree Junction to Casper; 5) Dead Horse to Lake De Smet; 6) Dead Horse to Gillette; and 7) Dead Horse to Pine Tree Junction.

Several combinations of multiple treatment plant sites and transmission pipeline routes are possible.

Transmission Pipeline Calculations

The following pipeline calculations are based on operating one desalination plant with a capacity for treating a total of 600,000 BPD of CBNG-produced water. The salinity of the CBNG-produced water before treatment is expected to range from 500 to 10,000 mg/L of TDS. The plant would produce 375 barrels of treated water per minute (15,750 gallons per minute (gpm)), which is 90% of the total influx of 600,000 BPD, or 17,500 gpm of CBNG-produced water at the plant. The maximum recommended flow velocity within a water pipeline is approximately 3 feet per second to avoid excessive head losses.

- An influent flow rate of 17,500 gpm is converted to 417 barrels per minute, 2,339 ft^3/minute, or 39.0 ft^3/second.

- An effluent flow rate of 15,750 gpm of treated good-quality water is converted to 375 barrels per minute, 2,106 ft^3/minute, or 35.1 ft^3/second. This quantity of treated water would be available for beneficial use, including drinking water.

- The water treatment plant would also produce an effluent waste stream of 1,750 gpm (41.7 barrels per minute or 234 ft^3/minute) of concentrated brine water (10% of the influent) for disposal. This brine concentrate flow rate would require a 16-inch-diameter pipeline and have a flow rate of 2.8 feet per second at 1,750 gpm from the plant. A disposal method for this brine concentrate effluent would need to be developed.

An underground 48-inch-diameter steel pipeline would be required with an internal pipeline volume calculated to be 12.57 ft^3 per linear foot of pipeline. A pipeline this size is capable of flowing 17,500 gpm at a flow velocity of 3.1 feet/second and 15,750 gpm at a flow velocity of 2.8 feet/second.

A water transmission pipeline construction project will likely need to include permitting, an environmental impact statement (EIS), pipeline alignment, land access agreements, engineering design and construction supervision, public bidding for a piping contractor, and construction of the pipeline. The pipeline project would probably require approximately one year to obtain the necessary permits/access/alignment, conduct the EIS, and prepare the engineering design. It would also require approximately one more year to construct the pipeline, depending on the amount of manpower provided by the construction contractor and the final design, alignment, and length of the pipeline.

For example, the engineering and construction of a 48-inch-diameter steel pipeline for a distance of 70 miles has an estimated total pipeline cost of $83.2 million. The estimated unit cost is $225 per linear foot in 2007 dollars, which includes an increase of $25 per linear foot from the estimated current piping cost of $200 per linear foot in 2006 dollars.

Estimated Water Treatment Plant and Pipeline Costs

Each 600,000-BPD desalination plant is estimated to cost $50 million. Calculated pipeline costs are estimated at $225 per linear foot (see discussion in the previous section). This cost estimate is based on engineering and constructing a 48-inch-diameter steel underground pipeline capable of carrying the estimated plant yield of 540,000 BPD of treated water. Two 600,000-BPD capacity plants would be needed to treat the amount of CBNG groundwater currently produced by CBNG operations in the PRB of Wyoming.

Estimated project engineering and construction costs are as follows:

- 600,000-BPD capacity desalination water treatment plants cost $50 million each.

- Optimal underground 48-inch-diameter steel water transmission pipelines cost:

  1) $39 million for the Gillette to Keyhole Reservoir pipeline;

  2) $72 million for the Gillette to Pine Tree Junction pipeline;

  3) $78 million for the Pine Tree Junction to Douglas pipeline;

  4) $78 million for the Pine Tree Junction to Casper pipeline;

  5) $44 million for the Dead Horse to Lake De Smet pipeline;

  6) $43 million for the Dead Horse to Gillette pipeline; and

  7) $69 million for the Dead Horse to Pine Tree Junction pipeline.

Obviously, the estimated costs for engineering and constructing pipelines are relatively high. Therefore, minimizing overall length of pipeline distances is critical to controlling total project cost.

Desalination Plant Sites and Transmission Pipeline Scenarios

Following are three scenarios that represent the most viable options for cost and/or desired uses based on the many possible combinations from the above pipeline locations. These scenarios focus on the most probable beneficial uses of treated water and site the desalination plants near the heaviest CBNG-produced water zones. All scenarios use the largest plant capacity due to the beneficial economics of lower per-barrel operating costs and the significantly lower pipeline costs associated with fewer locations. Scenarios 1 and 3 are relatively low-cost options that focus on localized use and reservoir storage. Scenario 2 is a higher-cost option developed to specifically supply additional water to the North Platte River to help satisfy requirements of the 2001 Modified Decree with Nebraska.

Cost-per-barrel estimates are the sum of per-barrel operating costs and per-barrel capital costs. The operating costs come from typical reported per-barrel estimates. The per-barrel capital costs are calculated from the total scenario capital cost divided by half of the total number of barrels the play will produce in its lifetime. The disposal of brine concentrate effluent from each desalination plant has not been addressed.

Scenario 1. Dead Horse-Gillette-Keyhole (Plate 1)

Plant Locations: Dead Horse (1 plant), Gil lette (1 plant).

Pipelines: Dead Horse to Gillette (1 pipeline at $43 million), Gillette to Keyhole Reservoir (1 pipeline at $39 million).

Treatment Capacity: 1,200,000 BPD

Total Cost: $182 million = $100 million (2 plants) + $82 million (2 pipelines).

Possible Add-ons: For enhanced capacity, another desalination plant at Dead Horse and another pipeline to Gillette could be added. This would add 600,000 BPD in treatment capacity and $93 million in additional piping and plant costs.

Cost per Barrel: $0.09 per barrel (includes operating, plant, and pipe capital).

Other Options: The treated water could be discharged into Donkey Creek, which flows into the Belle Fourche River and Keyhole Reservoir. This option would eliminate $39 million from the total cost and provide a much greater outflow capacity.

Treated Water Uses: Treated water produced in the Gillette area could generate revenue if sold to electric-power generation plants or coal companies for dust suppression. Non-revenue generating options include providing water to the Gillette water municipality for public consumption or putting water into the Belle Fourche River Basin for irrigation or recreation/storage in the reservoirs.

Obstacles: The 1943 water compact for the Belle Fourche River Basin between Wyoming and South Dakota ensures that almost all unappropriated river water belongs to South Dakota. Since this scenario includes storing water in Keyhole Reservoir, a negotiated deal would have to be reached concerning who owns the transferred groundwater to ensure that treated water is not claimed for use by another. Moving groundwater from the Tongue/Powder River Basin to the Belle Fourche River Basin could be considered a trans-basin diversion, and downstream states (Montana, North Dakota, and South Dakota) might contest this groundwater transfer if they consider themselves to be losing available surface water.

Summary: This is a lower cost option that assumes industrial water use near Gillette and storage of extra desalinated water in Keyhole Reservoir. Gillette is an ideal location for desalination plants because of accessibility, revenue possibility, and reservoir storage. Locating plants in the "Big George" coal area provides for nearby treatment of the largest quantities and lowest qualities of water in the basin.

Scenario 2. Dead Horse-Pine Tree Junction-North Platte River (Plate 1)

Plant Locations: Dead Horse (2 plants).

Pipelines: Dead Horse to Pine Tree Junction. (2 pipelines at $69 million each), Pine Tree Junction to Casper/Douglas (2 pipelines at $78 million each).

Treatment Capacity: 1,200,000 BPD.

Total Cost: $394 million = $100 million (2 plants) + $294 million (4 pipelines).

Possible Add-ons: Another desalination plant in the Dead Horse area and another 2 pipelines. This would add 600,000-BPD in treatment capacity and $197 million in additional piping and plant costs.

Cost per Barrel: $0.10 per barrel (includes operating, plant, and pipe capital).

Other Options: Relocating one or both plants from Dead Horse to Pine Tree Junction decreases the number of nearby CBNG well locations, however piping costs are reduced by $69 million per plant by placing the plants in Pine Tree

Junction instead of Dead Horse. A half scenario with one plant at Dead Horse and two pipes to Casper would cost less and has potential to help mitigate Wyoming's water debt to Nebraska for half the cost.

Treated Water Uses: Water treated in this scenario would serve to boost Wyoming's water supply to Nebraska via the North Platte River to meet compact requirements. The additional water could also be used for irrigation or recreation in the reservoirs. This would allow North Platte River irrigators to have a larger, more consistent supply of water.

Obstacles: Although transferring treated groundwater to the North Platte River Basin under the Modified Decree would benefit the state of Nebraska, the other states listed in Scenario 1 may take issue with the transfer of groundwater from a river basin that flows into their states.

Summary: This is a fairly costly option, and possible interstate concerns about trans-basin movement of treated groundwater may need to be overcome to render this scenario feasible. However, the higher cost of this project may well be worth it in the long run because it addresses the need to help supply additional water to the North Platte River Basin. Locating plants in the "Big George" coal area provides for nearby treatment of the largest anticipated quantities and lowest qualities of CBNG-produced water in the PRB.

Scenario 3. Dead Horse-De Smet (Plate 1)

Plant Locations: Dead Horse (1 plant), near Lake De Smet (1 plant).

Pipelines: Dead Horse to Lake De Smet (1 pipeline at $44 million).

Treatment Capacity: 1,200,000 BPD.

Total Cost: $144 million = $100 million (2 plants) + $44 million (1 pipeline).

Possible Add-ons: Constructing an additional plant in the Dead Horse area adds 600,000 BPD in capacity and $94 million in additional piping and plant costs.

Cost per Barrel: $0.08 per barrel (includes operating, plant, and pipe capital).

Other Options: One of the plants could be moved farther northwest, near Sheridan, to be closer to CBNG-produced groundwater from the Tongue River Basin. This would include adding a short pipeline segment estimated to cost approximately $35 to $45 million more.

Treated Water Uses: The treated water could be stored in Lake De Smet. From there it could be used for irrigation, piped to the Buffalo/Story/Sheridan area for public water supply use, or discharged into the Clear Creek drainage, which has a confluence with the Powder River near the Wyoming-Montana border.

Obstacles: Because the groundwater remains within the same river basin in this scenario, no interstate compact issues would exist. However, assurances would be needed to confirm adequate storage space in Lake De Smet for the quantity of treated water.

Summary: This option does not offer any immediate revenue-generating options, but it is relatively inexpensive, provides for transfer of treated water to a manageable reservoir, and keeps the groundwater within the same river drainage basin. Placing a desalination plant near Lake De Smet also reduces piping costs and favorably situates it to take advantage of the growing CBNG production near the lake. Locating plants in the "Big George" production area provides for nearby treatment of the largest quantity of lowest quality CBNG-produced water in the PRB.

Potential Legal/Regulatory Issues Concerning Interstate River Compacts

Parts of the greater Powder River geologic basin in Wyoming are located within the Little Bighorn, Tongue, Powder, Little Powder, Belle

Fourche, Cheyenne, and North Platte river basins. Water in the Yellowstone River Basin, which includes the Little Bighorn, Tongue, Powder, and Little Powder river basins in Wyoming, is part of the Yellowstone River Compact of 1950, signed with the states of Montana and North Dakota (W.S. Title 41, Chapter 12, Article 6). Water in the Belle Fourche River Basin is part of the Belle Fourche River Compact of 1943, signed with the state of South Dakota (W.S. Title 41, Chapter 12, Article 2).

The City of Gillette and Keyhole Reservoir are located within the Belle Fourche River Basin, and potential transfer of groundwater from the Tongue, Powder, and Little Powder River Basins may be considered a trans-basin water diversion under the terms of the 1950 compact. Article X of the Yellowstone River Compact states: "No water shall be diverted from the Yellowstone River basin without the unanimous consent of all the signatory states." However, Article II (g) of the 1950 compact states: "The terms 'divert' and 'diversion' mean the taking or removing of water from the Yellowstone River or any tributary thereof when the water so taken or removed is not returned directly into the channel of the Yellowstone River or of the tributary from which it is taken." The quoted definitions in Article II (g) appear to apply only to surface water located within the Yellowstone River Basin. In addition, the Yellowstone River Compact never specifically refers to groundwater. It is our understanding that the WSEO has investigated the 1950 compact and determined that the Yellowstone River Compact only applies to surface water within the Yellowstone River Basin. This WSEO determination may be challenged by Montana or North Dakota.

Although groundwater is not specifically mentioned in either the Yellowstone River or Belle Fourche River interstate compacts, any diversion of groundwater from the Tongue/Powder/Little Powder River Basins to the Belle Fourche River Basin may be considered a trans-basin diversion by the Wyoming Attorney General's Office (WAGO), WSEO, Montana, or North Dakota. The same may be true of diverting groundwater from the Lower Yellowstone River Basin to the North Platte River Basin. Legal and regulatory issues for potential trans-basin groundwater diversions would need to be clearly determined by the State of Wyoming prior to planning, design, or construction of any water system crossing the major surface water divides. The WAGO and WSEO will determine the legal, administrative, and water rights issues for the State of Wyoming.

Other Treatment Options

Another option, which would eliminate the expense of large treatment plants and long pipelines, is the use of mobile truck-mounted or skid-mounted RO units. These portable desalination units could be placed at water outfall locations when and where needed, and then moved to new locations as necessary. Treated water could be used near the portable treatment unit for irrigation, stock reservoirs, or dust suppression. These smaller desalination units are offered by various companies and produce anywhere from 500 GPD to more than 100,000 GPD (from 10 BPD to more than 2,500 BPD). The downside of this option is that the per-barrel operating cost is much higher than that of large-scale RO plants because portable units require a portable power source. Also, a method of disposal for the high-salinity effluent from the RO units would need to be established.

Future Water Supply Alternatives to CBNG-Produced Water

It is anticipated that the CBNG production of groundwater will decrease with time as economic CBNG production gradually declines in the PRB. As a result, any infrastructure projects completed in Wyoming that are specifically constructed to treat and beneficially use CBNG-produced water will likely require an alternative water supply at some time in the future. A reconnaissance-level investigation of potential alternative water resources in the Gillette area of the PRB was conducted to help identify possible water supplies for use as CBNG-produced water supply declines.

Surface Water Resources

Potential surface water resources present in the Powder River Basin area of Wyoming include the Tongue, Powder, Little Powder, Little Missouri, Belle Fourche, Cheyenne, and North Platte River Basins. The question has been asked: "How much unappropriated surface water is available in the Tongue River and Powder River drainage basins?" **Table 5**, based on information contained in the Wyoming Water Development (WWDC) River Basin Plans (HKM Engineering, 2002a and 2002b), summarizes the surface water resources available for use in Wyoming.

The preceding data are for dry years only. For normal and wet years, the quantity of available surface water for beneficial use in Wyoming increases in these river basins. The data for dry years was selected to identify the minimum amount of surface water that may be available in the future. Due to the highly seasonal nature of stream discharge in this area of Wyoming, water storage would be a requirement for year-round use of these surface water supplies.

Under the terms of the Yellowstone River Compact of 1950, the unappropriated or unused total divertible flow, after needs for supplemental supply for existing rights are met, is allocated to Wyoming and Montana as Tongue River (60% to Wyoming and 40% to Montana,) and Powder River and Little Powder River (42% to Wyoming and 58% to Montana). Currently, some of the tributary streams in both the Tongue River and Powder River drainage basins are fully appropriated during dry years (Sue Lowry, WSEO, personal communication, 2006).

The Belle Fourche River and Keyhole Reservoir have an agreement for unappropriated river flow of 10% to Wyoming and 90% to South Dakota. The entire quantity of the Keyhole storage water (10%) for current use in Wyoming is contracted by the Crook County Irrigation District (WSEO personal communication from Sue Lowry, 2006). Keyhole Reservoir and the Belle Fourche River Basin in Wyoming are regulated under the Belle Fourche River Compact of 1943. The Belle Fourche River Compact also states that no reservoir located in the Belle Fourche River drainage basin which is built solely to use water allocated to Wyoming shall have a capacity in excess of 1,000 acre-feet.

Groundwater Resources

With an anticipated decline in total CBNG water production in the PRB over time, contingency (replacement) well water may be needed for future use as feed water for the desalination plants. Each plant can treat approximately 600,000 BPD (17,500 gpm) and two plants could treat up to 1.2 million BPD (35,000 gpm). If we assume that there is no CBNG-produced water available for the desalination plants in the PRB, what kind of wells (depths and aquifers) and associated costs are projected for replacement groundwater supply?

For this study, potential aquifers in the Gillette area of Campbell County were investigated (Littleton, 1950; Wyoming Water Planning Program, 1977). Potential wells for construction in this area may include those listed in **Table 6**.

Table 5. Annual remaining allocation of surface water for the State of Wyoming.

Drainage basin	Total annual allocation of available surface water flow for dry years	
Tongue River	40,000 acre-feet	310 million barrels
Powder River	74,000 acre-feet	574 million barrels
Belle Fourche River	2,500 acre-feet	19 million barrels

WWDC River Basin Plans, HKM Engineering, 2002a and 2002b.

Table 6. Potential wells in the Gillette area for replacement groundwater supply.			
	Wasatch Formation	Fort Union Formation	Lance Formation
Well depths	182-355 ft.	900-1,200 ft.	2,000-4,000 ft.
Cost per well	$55,000-$107,000	$270,000-$360,000	$600,000-$1.35 million
Well yields	60-100 gpm	50-150 gpm	325-400+ gpm (950 gpm enlargement on 1 well)
Static water levels	60-80 feet below ground	400-450 feet below ground	450-824 feet below ground
Water quality	1,200-2,000 mg/L TDS	300-500 mg/L TDS	850-1,400 mg/L TDS

Littleton, 1950; Wyoming Water Planning Program, 1977.

Groundwater produced from the aforementioned aquifers will likely require some degree of water treatment for municipal or industrial use.

Potential deeper aquifers in the Gillette area include the Lower Cretaceous-age Cloverly/Inyan Kara Group (Fall River Sandstone and Lakota Sandstone members), the Jurassic-age Sundance Formation (sandstone beds), and the Mississippian-age Madison Limestone (limestone/dolomite) with potential well depths ranging from 8,100 to 10,700 feet in the Gillette area of Campbell County. Beneath the City of Gillette, the top of the Madison Limestone is present at a depth of approximately 10,000 feet below ground surface with relatively poor water quality. The Madison Limestone is approximately 700 feet thick in this area and the total well depth for constructing a Madison aquifer well near Gillette would be approximately 10,700 feet.

The estimated cost for drilling a relatively deep water well in Wyoming averaged approximately $250 per foot in 2005. Well drilling costs are estimated to increase at a rate of 10% to 20% per year for diesel fuel, steel, transportation, labor, and cement. Assuming a 20% increase from 2005 costs, it would likely cost up to $300 per foot for well construction in 2006. It is estimated that a 2,000-foot deep water well would cost approximately $600,000 in 2006 dollars to construct. The cost for each deep water well constructed into the Inyan Kara/Cloverly to Madison aquifers (8,100 to 10,700 feet deep) near Gillette is estimated to range from $2.4 million to $3.2 million in 2006 dollars.

Due to increased well depth, lower water quality, and associated higher costs for construction of water supply wells into the deeper aquifers in the Gillette area, the sandstone beds of the Wasatch, Fort Union, and Lance/Fox Hills are the most practical aquifers for future development of an alternative groundwater supply in the Powder River Basin. The Wasatch and Fort Union aquifers are currently being used by the City of Gillette, CBNG operators, surface coal mine operators, and other local well owners. The Fox Hills Sandstone also has good potential for construction of a future well field to supply replacement groundwater to desalination plants following a decline in CBNG water production.

Conclusion

With a combination of state funds (i.e., bonding and capital, and per-barrel water treatment fees charged to industry), the cost of a treatment/pipeline project could be promptly repaid. The amount of time and money spent on the water permitting process could be substantially reduced. High salinity groundwater would no longer be considered a pollutant to be disposed of or a roadblock to future CBNG production. Treated CBNG-produced water could become a valuable commodity and a useful water resource for the region.

In brief, the issues associated with CBNG-produced water in Wyoming will continue to grow and become more contentious as the development moves deeper and farther to the west in the PRB. In this report, the WSGS has explored an option for CBNG water treatment that overcomes the most significant challenges facing CBNG development. The basic premise is to treat all water produced during CBNG activities to drinking water standards. In this way, beneficial use of the water is optimized and the waste of the water resource is minimized. The proposed treatment (i.e., desalination) is based on available and well-tested technology. The adoption of such a plan depends on a cooperative partnership between the CBNG industry and the State of Wyoming. For the plan to work, the cost of such a project would have to be shared between industry and the state. The results of the project would greatly benefit both partners.

Acknowledgements

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Applicable Conversions

1 barrel = 42 gallons

1 acre-foot = 7,758.36 barrels = 325,851 gallons = 43,560 cubic feet

1 acre-foot per year = 21.26 barrels per day = 892.9 gallons per day

1 cubic foot = 7.48 gallons of water

$SAR=[sodium]/(([calcium]+[magnesium])/2)^{1/2}$

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Appendix. Texas cities and towns with desalination plants (> 1 MGD capacity).

Plant Name	County	Design Capacity (MGD)	Use	Source	Startup Year	Process	Blending	Disposal Method
City of Abilene	Taylor	8.000	DW	SW	2004	RO	No	EP
SWRA	Cameron	6.750	DW	GW	2004	RO	Yes	DSW
Lake Granbury SWATS	Hood	6.000	DW	SW	2003	RO	Yes	DSW
City of Fort Stockton	Pecos	6.000	DW	GW	1996	RO	Yes	Sewer
Horizon	El Paso	2.200	DW	GW	2001	RO	Yes	LA/IRR/EP
City of Primera	Cameron	2.000	DW	GW	2005	RO	Yes	DSW
City of Robinson	McLennan	1.800	DW	SW	1994	RO	Yes	DSW
City of Brady	McCulloch	1.500	DW	GW	2005	RO	Yes	DSW
City of Raymondville	Hidalgo	1.000	DW	GW	2004	RO	No	DSW
Windermere Water System	Travis	1.000	DW	GW	2003	RO	Yes	Sewer
City of Kenedy	Karnes	0.720	DW	GW	1995	RO	Yes	DSW
City of Seadrift	Calhoun	0.520	DW	GW	1998	RO	Yes	DSW
City of Seymour	Baylor	0.500	DW	GW	2000	RO	Yes	DSW
Valley MUD #2	Cameron	0.500	DW	GW	2000	RO	Yes	LA/DSW
City of Electra	Wichita	0.500	DW	GW	1999	RO	No	LA/IRR
City of Tatum	Rusk	0.290	DW	GW	1999	RO	Yes	Sewer
The Cliffs	Palo Pinto	0.200	DW	SW		RO	No	DSW
Holiday	Aransas	0.150	DW	GW	1998	RO	Yes	DSW
Study Butte Terlingua Water System	Brewster	0.140	DW	GW	2000	RO	No	DSW
River Oaks Ranch	Hays	0.140	DW	GW	1987	RO	No	EP
City of Beckville	Panola	0.140	DW	GW	2004	RO	Yes	Sewer
Midland Country Club	Midland	0.110	IRR/DW	GW	2004	RO	No	Yes
City of Laredo	Webb	0.100	DW	GW	1998	RO	No	Sewer

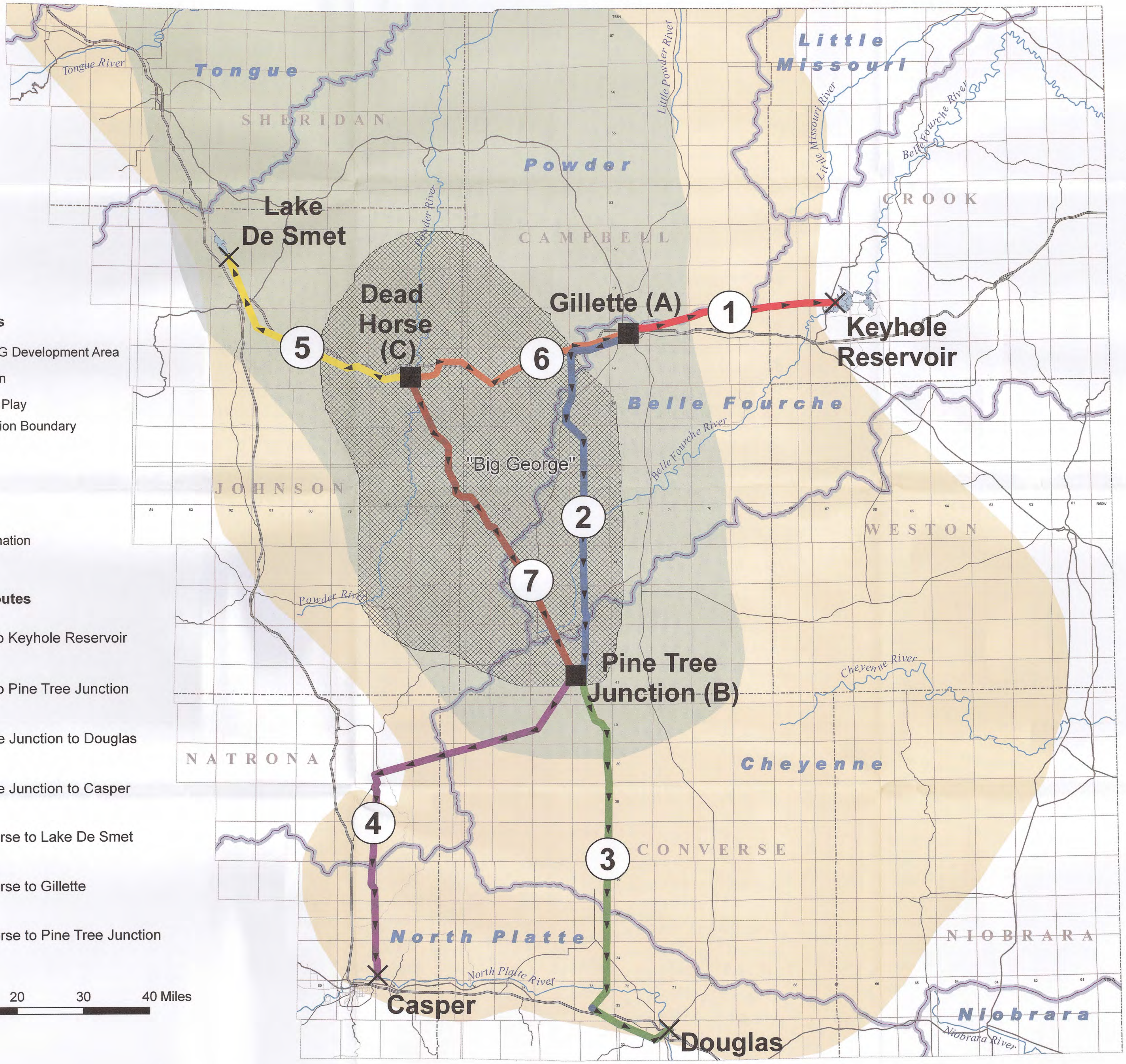
DW=Drinking Water; GW=Groundwater; IND=Industrial; SW=Surface Water; RO=Reverse Osmosis; EP=Evaporation Pond; IRR=Irrigation; LA=Land Application; DSW=Discharged to surface water.

Source: A Desalination Database for Texas. Texas Bureau of Economic Geology, prepared for Texas Water Development Board, Scott W. Tinker, John A. Jackson, Katherine G. Jackson, October 2005.

WYOMING STATE GEOLOGICAL SURVEY
Ronald C. Surdam, State Geologist
Laramie, Wyoming

Potential Powder River Basin Desalination Plants and Pipelines

Challenges in Geologic Resource Development NO. 1
Powder River Basin Desalination Project Feasibility
Plate 1



Regional Boundaries

- "Big George" CBNG Development Area
- Powder River Basin
- Powder River Gas Play
- Hydrologic Subregion Boundary

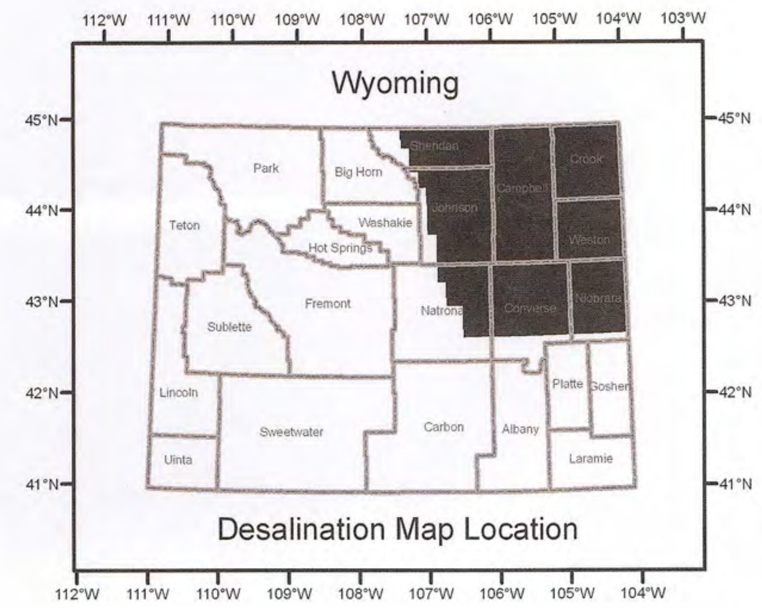
Pipeline Stations

- Plant Site
- Treated Water Destination

Optional Pipeline Routes

1. Gillette to Keyhole Reservoir
2. Gillette to Pine Tree Junction
3. Pine Tree Junction to Douglas
4. Pine Tree Junction to Casper
5. Dead Horse to Lake De Smet
6. Dead Horse to Gillette
7. Dead Horse to Pine Tree Junction

0 5 10 20 30 40 Miles



Desalination Map Location

Desalination concept by:
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Digital cartography by:
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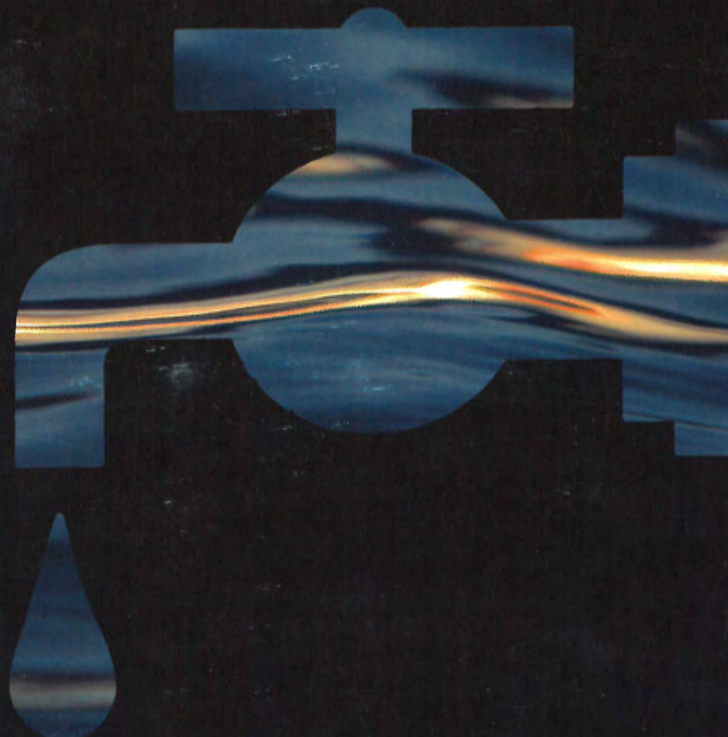
April 2006

Base map source: De Bruin, R.H., Oil and Gas Fields Map of the Powder River Basin, Wyoming: Wyoming State Geological Survey Map Series 51 (MS-51), scale 1:350,000, digital CD-ROM, version 8/1/05.



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