CBM CO-PRODUCED WATER MANAGEMENT, DISPOSAL, TREATMENT AND USE

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Introduction

CBM production, as well as conventional oil and gas, can be accompanied by the production of large volumes of water. In 2003, Wyoming produced over 565 million barrels (over 24 billion gallons) of water from CBM (Wyoming Oil and Gas Conservation Commission, 2004). This volume could satisfy the City of Laramie's municipal water demand for over 10 years at 2.2 billion gallons per year (High, 2004). Identifying and implementing appropriate beneficial uses for this produced water could provide enormous benefits for local communities or ecosystems while providing operators with flexible, cost-saving water management options (ALL Consulting, 2003).

It is important to note that the quality of water that is produced in association with CBM development will vary from basin to basin, within a particular basin, from coal seam to coal seam, and over the lifetime of a CBM well**.** A variety of potential beneficial uses for CBM produced water can be implemented to manage this resource but the produced water quality can be a deciding criterion for choosing an option. The potential also exists for this water to be treated by a variety of technologies to improve quality and allow increased beneficial use (ALL Consulting, 2003).

In addition to water quality, applicable regulations and cost dictate potential beneficial uses of produced water. In some cases poor quality water will require treatment before use. In most regions of the West, poor quality water has traditionally been disposed of via deep well injection to prevent environmental impacts to the surface. New treatment technologies are becoming more attractive for operators dealing with poor quality water (ALL Consulting, 2003). Advances in well completion technology are also making it possible to maintain desired gas production while reducing the volume of produced water.

In general, CBM produced water is characterized by elevated levels of sodium, barium, bicarbonates, iron, and dissolved solids. Concentrations of each will vary for any given water source depending on factors such as coal seam depth, peat metabolism processes, and aquifer recharge, and may require treatment depending on the intended beneficial use (ALL Consulting, 2003).

Water disposal and treatment costs are an important aspect of the CBM industry since the volume of water produced is significant, especially during initial production operations. To help alleviate growing concern for rising water management costs, various treatment technologies are

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being researched or developed that may provide cost-effective practical options for produced water use (ALL Consulting, 2003).

Surface Discharge

Surface discharge of CBM water has the potential of being a primary disposal method for producers. It can also be viewed as a beneficial use practice (Arthur, 2002).

Direct discharge to surface water

Description

CBM water can be delivered to a stream by pipeline or dry drainage where it mixes with existing stream flow, bolstering seasonal flows of local rivers and accommodating more beneficial uses. The use of pipelines avoids erosion and incorporation of suspended sediments, and aeration methods can precipitate iron from the water to reduce staining in the stream beds (U.S. Environmental Protection Agency [EPA], 2003). Discharge design requires site-specific characterization of the quality and quantity of CBM discharge water and existing stream water, stream channel vulnerability to erosion, channel soil chemistry, and changes to biota along the drainage (ALL Consulting, 2003).

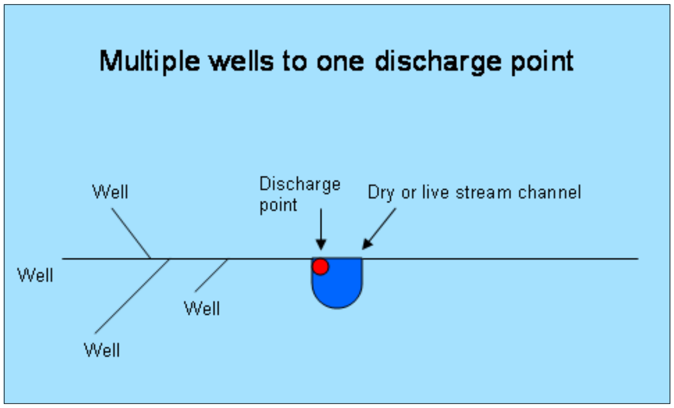


Fig. 1. Direct discharge from multiple wells to surface water

Environmental Consequences

Discharge of suitable CBM water can add to stream and riparian environments by supplying water during drought periods and by diluting poor quality water from subsurface aquifers during seasonal base-flow periods (ALL Consulting, Inc., 2003). Discharge to streams can lead to significant changes through increased flow volume either seasonally or throughout the year, and degraded or improved water quality (Argonne National Laboratory, 2003). Important factors to consider when planning discharges include stream bank erosion, water crossings (bridges and culverts) and riparian plants and wildlife (ALL Consulting, 2003).

Economics

Surface discharge to water can be one of the cheapest methods of CBM produced water management and is the most common and least costly practice for disposing of CBM-produced water in the Wyoming Powder River Basin (U.S. EPA, 2003). Equipment costs include pipelines or trucks to transport the water. Filtering and treatment may be required by the permitting agency, as well as characterization of the effluent stream rate and quality. Direct discharge economics will depend on the layout of the proposed project, the available utility routes, and the proximity to suitable receiving streams.

Data Needs

Discharge planning and permit applications require sufficient data to effectively evaluate how a watershed will react to discharge of CBM produced water (ALL Consulting, 2003). The Wyoming Department of Environmental Quality is in the process of establishing a watershed permitting program for surface discharge to better assess the cumulative impacts of CBM discharge water on surface water quality. In addition, a forecast of the volume of CBM water to be produced from the project will be needed.

Discharge to surface soil with possible runoff to surface water

Description

Under this alternative, water is discharged to fields and pastures by common irrigation methods to manage disposal of produced water through evaporation, plant uptake, and infiltration into the soil. Factors such as the quality of produced water; existing land uses; landowner's future plans for use, soil type, vegetative cover; and other factors all affect the land's ability to accept surface discharge produced water. These factors will effectively reduce the volume of discharged water but depending upon local conditions, some portion of the discharged water may eventually reach water-bodies down-gradient (ALL Consulting, 2003).

Fig. 2. Direct discharge to surface soil with possible run-off to surface water (ALL Consulting, 2003).

Environmental Consequences

Discharge to upland pastures may produce higher rates of plant growth and support grazing by livestock and wildlife. High slopes in upland areas will encourage and concentrate runoff into dry drainages, with some water loss to evaporation, and infiltration into the soil and sub-soil (conveyance loses) (ALL Consulting, 2003). Discharge can also be directed to bottom-land pastures and fields to grow hay, crops, or pasture land.

Discharge to ground surface should be managed to avoid significant amounts of runoff that may produce soil erosion and may reach live streams. Soil erosion from this type of discharge can be affected by soil type, surface vegetation, land slope, water volume, and other factors (ALL Consulting, 2003). When discharge water has a high sodium absorption ratio (SAR), clay soils can increase in sodicity (the amount of sodium in the soil), water infiltration decreases, and runoff increases. CBM water discharge can also have the cumulative effect of encouraging the establishment and proliferation of salt-tolerant, non-native and noxious weed species (ALL Consulting, 2003).

Economics

Dry pastures and drainages are often widely distributed in CBM project areas, and could be used as discharge sites with little or no extra cost. Erosion control measures may be needed. Costs associated with resulting soil erosion, such as filling in eroded channels and gullies, reclaiming salty soils, and replanting vegetation, may be incurred during production and postproduction periods (ALL Consulting, 2003).

Data Needs

The potential constraints described above can usually be mitigated by available management techniques. Appropriate mitigation designs require site-specific data including water quality, soil properties, discharge volumes, and conveyance losses. Conveyance losses can be estimated through several means:

- In several states, the State Engineer's Office (SEO) publishes average conveyance loss figures for watersheds. The Wyoming SEO has established the loss of 1.0% per mile of stream flow. This figure can be used to successively remove the CBM discharge volume after it has been added to the stream.
- The Natural Resource Conservation Service (NRCS) publishes detailed soil maps of many areas of the western United States, frequently including infiltration rates for soil types.
- Some stream reaches have detailed water budgets worked out by local researchers. The Wyoming office of the Bureau of Land Management (BLM) has assembled some of this data for the Powder River in Wyoming (ALL Consulting, 2003).

Atomization

Atomization is a process whereby water particles are separated into small droplets and dispersed under pressure through a specialized nozzle. In warm dry climates these droplets are more easily evaporated than water stored in impoundments. Evaporation reduces the volume of water that would have to be managed.

Environmental Consequences

Freezing conditions can transform the atomized mist into giant ice mounds, rendering the technology ineffective. The ice mounds turn into freeze/thaw/evaporation systems that concentrate salts and other constituents damaging the soils underneath. (Powder River Basin Resource Council, 2004)

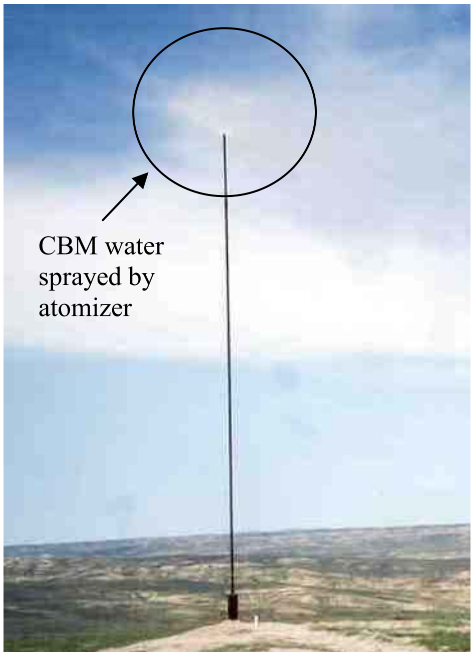


Fig. 3. Atomization.

Off- and On-Channel Impoundments

In some producing basins, such as the PRB, impoundments play a large role while in other basins impoundments may only be used during drilling operations. The regulatory authority in some states, including Wyoming, varies based on whether the impoundments are off- or on-channel (ALL Consulting, 2003).

Off-channel impoundments can be lined or un-lined and are constructed in areas that have the potential to collect and store minimal surface runoff, usually away from natural drainages of perennial and intermittent streams and coulees, and are constructed to prevent surface runoff from entering the ponds with either by-pass facilities or berms (ALL Consulting, 2003). With unlined impoundments there must be reasonable assurance that no direct subsurface hydrologic connection exists between produced water pits and surface waters. Discharge of CBM produced water to unlined containment structures may potentially affect the water quality in shallow aquifers. In the PRB the upper aquifers in the Wasatch sands tend to be of lesser water quality with a total dissolved solids (TDS) of 2500 to 3500 µg/L. In this case, the CBM produced water may improve the water quality of the receiving aquifer, depending on the contribution of leached constituents.

Most storage ponds in the PRB are off-channel and are designed to contain all CBM produced water without discharge to Class 2 waters. The only other input into off-channel ponds is precipitation. Off-channel ponds are generally used to prevent the water from contacting or influencing surface water flows.

On-channel impoundments are constructed by damming natural drainages where water runoff occurs at least part of the year. On-channel ponds have the potential to affect downstream water rights by capturing flow and have the potential for discharges from the impoundment to flow into downstream surface water bodies (U.S. EPA, 2003).

The following alternatives are available for using off- and on-channel impoundments (ALL Consulting, 2003). Environmental consequences and economics are discussed under each alternative, but in general, all alternatives are limited by the availability of a long-term supply of water. Data needs for all generally include quality and quantity of produced water, quality of surface or groundwater, soil type, water rights, and landowner needs.

Wildlife and livestock water (usually off-channel)

Impoundment water would increase the amount of grazing land available and lessen current impacts from overgrazing. In addition, there is some concern that CBM production may displace some wildlife and these impoundments could rectify that by providing habitat for some species (Arthur, 2002). The completion of CBM operations and subsequent loss of artificially constructed habitat would require wildlife to re-acclimate to pre-existing CBM conditions, unless other sources of water were used. Watering ponds are inherently self-sustaining, low cost operating systems that require minimum maintenance. Pond type, equipment, and travel distance

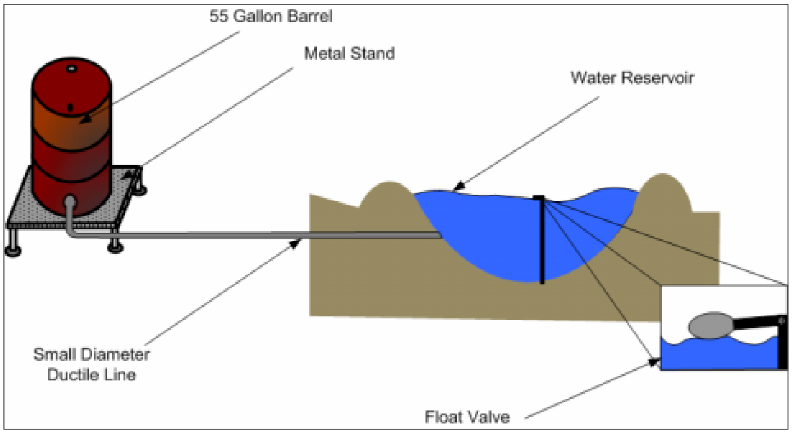


Fig. 4. Livestock/wildlife water hole (ALL Consulting, 2003)

will likely be the primary factors associated with construction and design costs (ALL Consulting, 2003).

Fisheries (off- or on-channel)

Constructed fisheries are water catchment systems. Fishponds are typically privately-owned reservoirs stocked by state agencies or individual landowners for recreational use (ALL Consulting, 2003). Non-treated CBM produced water is currently used to sustain privately-owned fishponds in some states, including Wyoming. The level of phosphates, heavy metals, salts, and pH in produced water affect the water's usability for fishponds. Produced waters containing elevated constituents of this type would have marginal fisheries use without prior treatment (ALL Consulting, 2003). The uncertain volume of supplied water could make it difficult to properly maintain nutrient levels, and also replace water lost to the system as a result of evaporation, infiltration, or biologic use. After conclusion of CBM operations, fish ponds supplied by produced water would require an alternate water supply or face potentially expensive closure fees (ALL Consulting, 2003). A small private fishing pond could be maintained relatively inexpensively if stocked with local native fish species. Larger commercial fisheries will be more expensive to maintain but cost could be offset by the commercial profits associated with sport fishing.

Recharge ponds (off- or on-channel)

Recharge or retention ponds are off- or on-channel reservoirs typically containing a permanent pool of water, especially during regional wet seasons (Stormwatercenter.net, 2002). Recharge ponds are traditionally used to restore depleted groundwater sources by water infiltration into subsurface aquifers, whereas retention ponds are permanent pools constructed to improve water quality, attenuate peak flows, and minimize flooding. Recharge ponds can also lower TDS by a settling removal mechanism or by water infiltration through a pre-fabricated pond liner. Construction costs for recharge ponds can be relatively inexpensive. Annual maintenance costs based on the costs of storm water ponds would be between 3-5% of the overall construction costs.

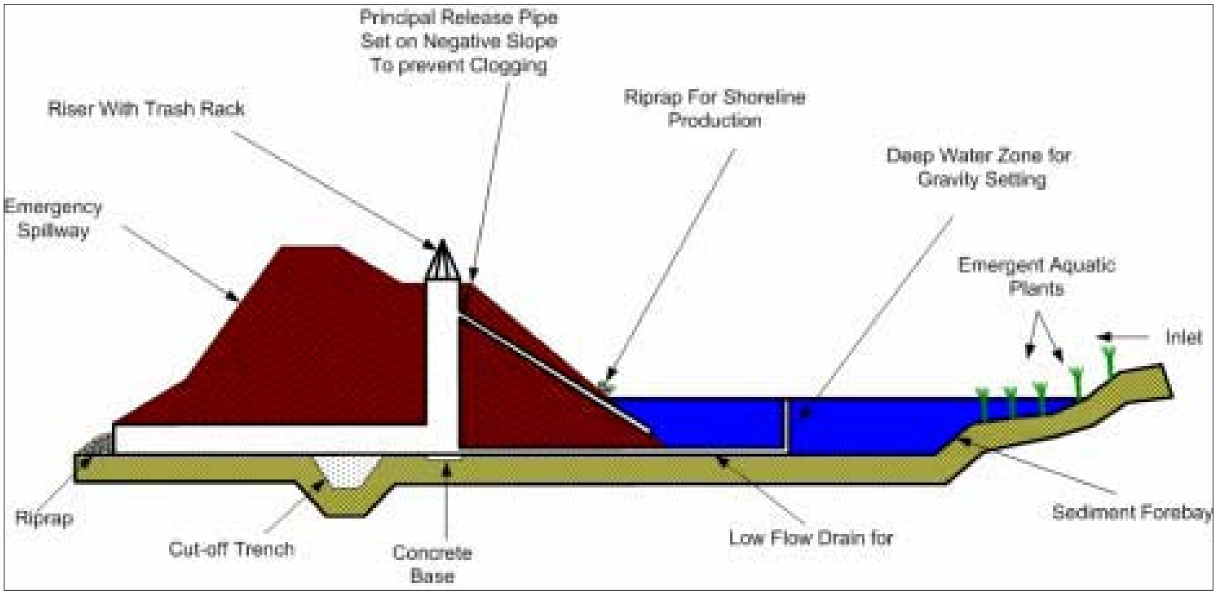


Fig. 5. Recharge pond (ALL Consulting, 2003)

Evaporation ponds (off-channel)

Evaporation ponds are usually off-channel impoundments designed to store water so that natural evaporation can move water from the land surface into the atmosphere. In areas where future CBM development is expected to occur, the potential exists for evaporation to result in a significant amount of managed water loss. Over time as more water is lost to the atmosphere, the water remaining in the pond can become more concentrated brine. Depending on the water quality and soil type, the bottom and toe areas may need to be lined to prevent concurrent infiltration of the water. Maintenance costs for evaporation ponds will vary depending on the quality of the produced water; waters with higher TDS will result in more concentrated brines which may increase disposal and reclamation costs associated with closing the pond (ALL Consulting, 2003).

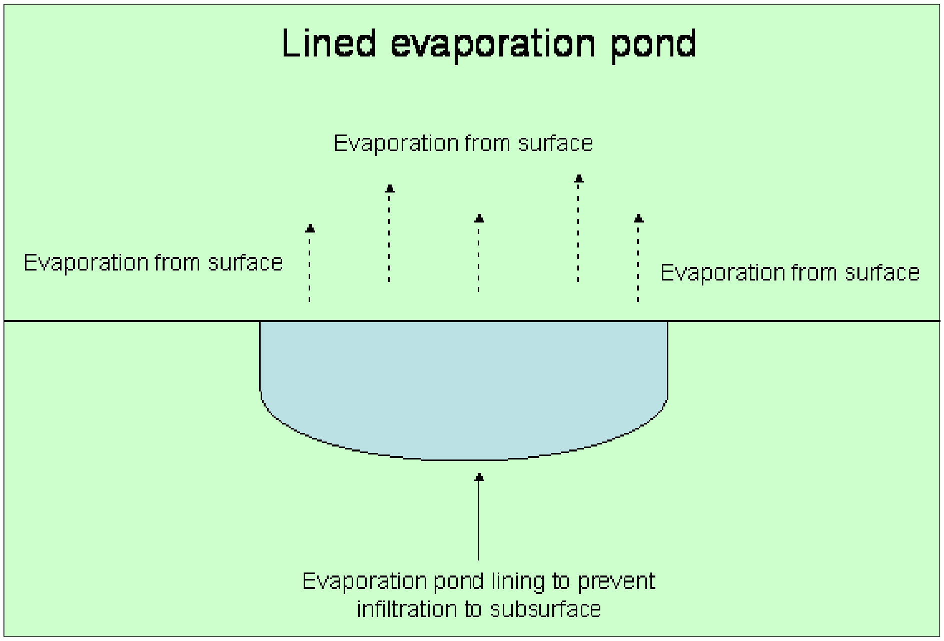


Fig. 6. Evaporation pond

Recreation (off-channel)

Depending on CBM water quality and volume, available lands could be converted into large artificial lakes used for boating, fisheries, and wildlife habitat. Fluctuations in available water could limit both the size of the impoundment and any associated beneficial uses. This particular impoundment type may best be suited for federal or state lands. Management and liability implications could be overwhelming for private landowners who, in general, may have more practical uses for the water. Costs of construction and maintenance of a recreation pond will vary depending on pond size and design, permit requirements, and water supply once produced water is no longer available.

Constructed wetlands (off- or on-channel)

Wetlands are typically constructed by damming a natural drainage area where water runoff occurs at least part of the year. They allow water to infiltrate into the alluvium or be discharged downstream at constant or periodic rates depending on the design and season. To maintain water quality, it is intended that some water will flow into a surface

Fig. 7. Constructed wetland (ALL Consulting, 2003)

receiving water after leaving the wetland (Kuipers et al., 2004). Construction of a wetland system to receive produced waters could increase wildlife distributions, reduce displacement, and enhance diversity by improving quality habitat. Wetlands provide natural nutrient recycling and sediment filtration which may help improve the water quality of neighboring water systems. Furthermore, wetland plant communities and soil store available carbon preventing release of carbon dioxide into the atmosphere. Research sponsored by Marathon Oil Company in 2000 involving an artificial sedge wetland system determined after one year that the wetland system could effectively treat iron and possibly barium, but not SAR (ALL Consulting, 2003). Construction and maintenance costs vary with water quality, soil, and hydrological conditions.

Injection

Description

The injection of water into subsurface aquifers is a proven technology both for disposal of waste water and for storage of potable water. As a beneficial use of CBM produced water, underground injection activities could be used to provide temporary storage of the water or to recharge depleted aquifers. Further, deep injection wells could be an integral part of enabling a beneficial use or water reuse system to properly function.

For regulatory control purposes, underground injection is grouped into five classes of injection wells (Argonne National Laboratory, 2003).

1. Class I wells – inject hazardous and nonhazardous fluids (industrial and municipal wastes) into isolated formations beneath the lowermost underground source of drinking water (USDW).
2. Class II wells - inject brines and other fluids associated with oil and gas production. The Wyoming Oil and Gas Conservation Commission issues permit for Class II injection wells for CBM water in Wyoming.
3. Class III wells - inject fluids associated with solution mining of minerals.
4. Class IV wells – inject hazardous or radioactive wastes into or above a USDW, banned unless authorized under other statutes for groundwater remediation.
5. Class V wells - include underground injection wells not included in Classes I through IV. Class V governs wells that inject nonhazardous fluids into or above a USDW — typically shallow, onsite disposal systems, such as floor and sink drains discharging directly or indirectly to ground water, dry wells, leach fields, and similar types of drainage wells (ALL Consulting, 2003).

Several alternatives exist for injection of CBM produced water, including (ALL Consulting, 2003):

- **Aquifer Recharge.** In arid climates such as that of the Western US, during dry seasons and droughts, shallow surficial aquifers can experience significant water level declines. In addition, the production of CBM would result in the lowering of water levels in coal seam aquifers. Depending on the situation, produced water could be used to recharge

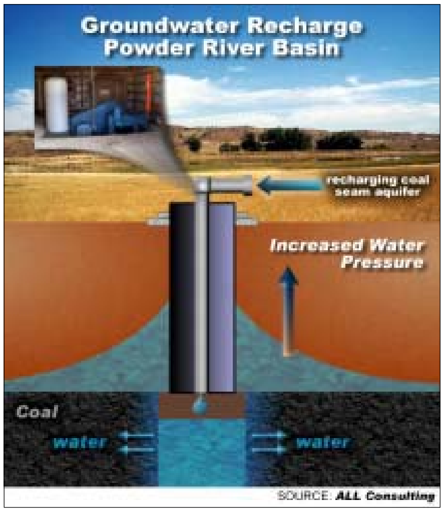
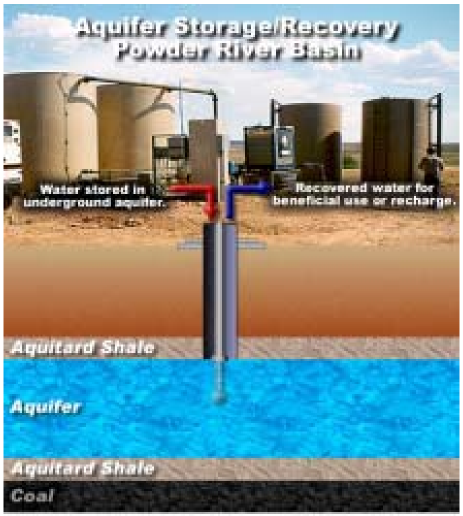


Fig. 8. Coal aquifer (ALL Consulting, 2003)

groundwater aquifers and provide recharge for depleted coal seam aquifers (Arthur, 2002).

- **Aquifer Storage and Recovery.** In areas with distinct wet and dry seasons, water supplies are often depleted during the dry season. In some areas, water is captured from surface streams and other sources then stored in permeable aquifers for use during the dry season. Aquifer Storage and Recovery (ASR) is a proven technology in which underground aquifers are used as reservoirs to store water which may be later withdrawn for use. In the case of CBM, large quantities of produced water could be stored in depleted aquifers or coal seam aquifers (Arthur, 2002).
- **Deep Injection:** The injection of water into deep reservoirs is a standard practice for disposal in the conventional oil and gas industry. Injection wells and injection technology are regulated by state agencies and the EPA. The injection of CBM produced water into deep subsurface formations provides an alternative for management that would not require the treatment of water, or result in the degradation of surface water, groundwater, or further erosion of the surface soils. It may also serve as an integral element of an overall water management system (Arthur, 2002).



SOURCE: ALL Consulting

Fig. 9. Non-coal aquifer (ALL Consulting, 2003)

The WOGCC has not issued any Class II re-injection permits in the PRB because the CBM water has to go into zones with poorer water quality. The WOGCC has approved 25 permits for injection of CBM water pilot projects. The Wyoming Department of Environmental Quality has written three general Class V injection well permits (5C5-1, 5C5-2, 5C5-3) for CBM operators in Campbell, Johnson, and Sheridan counties. (DEQ, 2004) Eighteen DEQ re-injection pilots with 44 wells have been attempted. Half the wells were successful and 12 worked for one year or more. The most successful pilot involved putting water into one of Gillette's slightly deeper sand aquifers (Likwartz , 2004).

Environmental Consequences

Environmental consequences associated with re-injection are not visible from the ground surface. However, through well design and regular monitoring, operators must show there is no significant movement of the injected fluid into a USDW. Depending on the quality of the injected fluid, migration or seepage into existing or future USDW's could result in health impacts to humans (Argonne National Laboratory, 2003).

Economics

Injection of CBM produced water is a viable and popular alternative for managing water; however, it is not feasible everywhere and is largely dictated by economic realities. Important factors influencing the economics of injection include depth of the injection zone, injection pressures, needs for transportation of water, and regulatory burden (ALL Consulting, 2003).

Data Needs

Data needs specific to injection are generally outlined in state and federal UIC program regulations. Data that should be given special attention relative to the beneficial use of produced water include:

- Characteristics of the receiving aquifer (depth, thickness, porosity, permeability)
- Characteristics of the fluid to be injected (chemistry and volume)
- Permit requirements
- Water rights requirements

Treatment and Re-Use Alternatives

The quality of water that is produced in association with CBM development will vary from basin to basin, within a particular basin, and over the lifetime of a CBM well. A variety of potential beneficial uses for CBM produced water can be implemented by CBM operators to manage this resource depending on the quality of the produced water. Treatment technologies exist to improve water quality and allow for increased beneficial use. Additionally, water that has been exposed at the surface is required to be sterilized before it can be injected into an aquifer (ALL Consulting, 2003).

The following section presents some of the water treatment options that are currently being evaluated or used for treatment of CBM produced water prior to discharge, injection or beneficial use (ALL Consulting, 2003). However, this list is not all-inclusive nor is it intended to show preferred treatment methods. These technologies may be used alone or in tandem with other listed treatment technologies, depending on the required purity of the water. See Appendix D-1 for additional information.

Reverse Osmosis

Reverse Osmosis (RO) is a proven technology for the treatment of water and the removal of TDS and other constituents. RO involves passing the water through a semi-permeable membrane. As pressure is applied, the semi-permeable membrane allows water to pass while the membrane retains the dissolved solids. The membranes are often cleaned by a cross flow which removes the molecules retained on the surface. These molecules are then collected and concentrated for disposal (Arthur, 2002). Prior to filtration by RO, the water must first pass through several pre-treatment processes to help improve the RO system performance and extend the life of the membrane (Kuipers et al., 2004). Pretreatment may include clarification, filtration, ultrafiltration, pH adjustment, and removal of free chlorine (ALL Consulting, 2003).

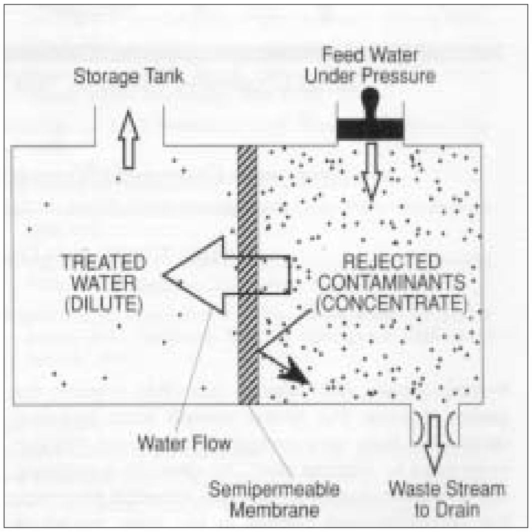


Fig. 10. Reverse osmosis (ALL Consulting, 2003)

Environmental Consequences

The disposal of brine in deep aquifers has potential drawbacks similar to the injection of untreated CBM-produced water (Kuipers et al., 2004). Environmental consequences associated with injection are not visible from the ground surface. However, through well design and regular monitoring, operators must show there is no significant movement of the injected fluid into an underground source of drinking water (USDW) through vertical channels adjacent to the well bore. Depending on the quality of the injected fluid, migration or seepage into existing or future USDW's could result in health impacts to humans (Argonne National Laboratory, 2003).

Economics

The initial costs of the RO membranes are high, they are subject to fouling, and are expensive to replace. Also, energy costs can be significant for pressurizing the RO tank. RO may not remove all compounds harmful to plants, soils, livestock, humans and aquatic life, such as ammonia and fluoride (Kuipers et al., 2004).

Data Needs

Depending on the chosen use of the treated water and disposal of the brine solution, data needs would be similar to those for surface discharge and/or injection (Kuipers et al., 2004).

Other technologies

These additional technologies are generally not cost-effective and are not often used.

- Ultraviolet Light Treatment
- Chemical Treatment
- Freeze/Thaw/Evaporation
- Ion exchange
- Deionization or Capacitive Desalination
- Electrodialysis Reversal
- Distillation

Agricultural Uses

CBM produced water supplied to landowners could create temporary opportunities for landowners to develop additional uses of their land such as additional acreage for farming, grazing or allow for residential development. Some examples of landowner uses include the following (Arthur, 2002):

Livestock watering

The layout of many CBM projects is particularly conducive to stock watering because CBM wells are spread out on 80 acre spacing, or greater. Stock watering may include discharge to reservoirs and stream drainages, or discharge to small containment vessels, such as tire tanks. Overflow from tanks or reservoirs at the head of a drainage could distribute water over a larger distance, potentially up to several miles.

Irrigation

Description

The limited water supplies and arid climate of the western US limit the use of land for crop production and land that is farmed is often irrigated. Most irrigation is limited to areas with access to surface waters or where seasonal irrigation can obtain water during high stream flows. The availability of CBM produced water could allow for additional acreage to be irrigated for farming (Arthur, 2002).

Environmental Consequences

The suitability of CBM produced water for use in agricultural irrigation is largely governed by the quality of the water and the physical and chemical properties of the irrigated soils (ALL Consulting, 2003). CBM water in the PRB of Wyoming tends to be high in salts. Increased salinity in the soil pore water reduces the availability of water for plant use. Therefore, plants must expend more energy to extract water from the soil when elevated concentrations of soluble salts are present in the root zone. The increase in energy required to extract water results in decreased plant productivity in soils with elevated concentrations of soluble salts. While all plants exhibit decreased productivity with increasing concentrations of soluble salts, the threshold and degree to which salinity affects crop yield varies between species (ALL Consulting, 2003).

The use of CBM water for irrigation can be facilitated by either treatment of the water to remove the salts or treatment of the soil so that the salts in the water won't affect plant growth (ALL Consulting, 2003).

Economics

If no water or soil pre-treatment is necessary, the use of CBM water for irrigation is relatively inexpensive, depending on the type of irrigation system used (flood, center pivot, side roll, automated big gun, or manual big gun system). If soil or water pre-treatment is necessary, costs can increase accordingly (ALL Consulting, 2003).

Data Needs

The data necessary to determine the irrigation suitability of CBM produced water include water quality, soil characteristics, and land management practices (ALL Consulting, 2003).

Aquaponics

Aquaponics is the combination of aquaculture and hydroponic systems. Aquaculture is the propagation of fish species in a controlled environment and hydroponics is the cultivation of plants without the use of organic soil (Jackson et al., 2002). Testing is underway in Wyoming at the Rocky Mountain Oilfield Testing Center (RMOTC) on using CBM produced water to raise the fish species tilapia and grow tomatoes (Jackson et al., 2002). However, the supply of CBM produced water will decrease over time and alternative future water sources are needed if the operation is to be sustainable. Aquaculture and hydroponics do not have to be combined operations and CBM produced water could be used for either aquaculture or hydroponics.

Commercial/Industrial Uses

A variety of existing industries could benefit from CBM water including: coal mines, animal feeding operations, cooling tower water for various industrial applications, car wash facilities, commercial fisheries, enhanced oil recovery, and fire protection. Industrial applications which may be less commonly considered but would still have the potential for the use of CBM produced water include: sod farming, bottled drinking water, brewery water, and solution mining of minerals. Each of the existing industries and emerging industrial applications would use produced water of varying quantities and quality (ALL Consulting, 2003).

Road dust suppression

The use of produced water for dust control offers multiple benefits from an environmental viewpoint, including the prevention of air quality concerns and the loss of surface soils. Possible applications of produced water for dust control include use on lease roads, other unpaved roads, construction sites where surface disturbances exist, and around surface coal mining activities (Arthur, 2002).

Animal feeding operations

CBM produced water could be supplied to Animal Feeding Operations (AFOs) and Concentrated Animal Feeding Operations (CAFOs) for livestock watering and the management of animal Wastes (ALL Consulting, 2003).

Cooling tower water for power plants, other industries

Numerous industrial activities and chemical plants use water as a cooling agent. High quality CBM produced water can be used as make-up water in a cooling tower system. The produced water would need to be low TDS water because mineralization generally leads to clogging of the cooling system (ALL Consulting, 2003). Industrial applications that use cooling tower systems include chemical plants, refineries and power plants. Numerous coal-fired power plants are located in areas near CBM producing fields and have the potential to use CBM produced water for cooling tower water (ALL Consulting, 2003).

Field and car wash facilities

Construction and other land-disturbing activities can lead to the spread of noxious plants, which can be reduced by washing vehicles and equipment before and after entering these areas. Many state and federal agencies (e.g., U.S. Forest Service, BLM) recommend vehicle-washing facilities as part of their Best Management Practices for controlling the spread of noxious weeds (ALL Consulting, 2003).

Fire protection

In areas where CBM development is near a municipality, produced water could be used to supply both fire hydrants and sprinkler systems. The supplies of CBM produced water stored in impoundments could provide an accessible option for fighting fires in remote areas in states such as Colorado, Wyoming, New Mexico, Montana, and Utah (ALL Consulting, 2003).

Enhanced oil recovery

Injecting water into a secondary or enhanced oil recovery well is referred to as water flooding, or steam flooding if the water is heated. Water or steam floods are relatively common practices that can be performed with varying quality water; possibly even with the poorest quality CBM produced water (ALL Consulting, 2003).

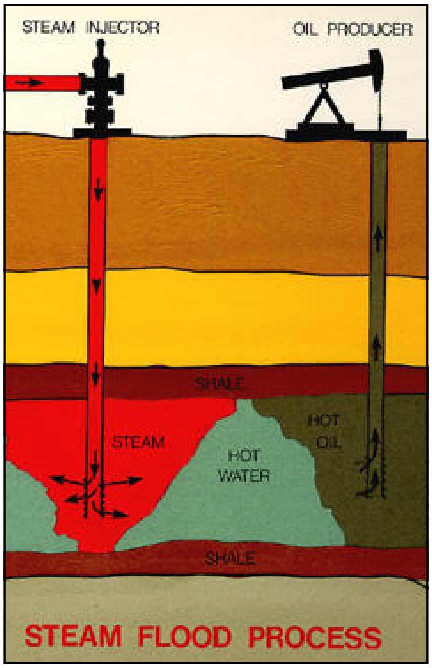


Fig. 11. Enhanced oil recovery using CBM water or steam from CBM water

Fisheries (see "Fisheries" in the "Off- and On- Channel Impoundments" section above)

Other industrial uses

Other options for use of CBM produced water which have been considered, but not analyzed in detail, have the potential to use large quantities of produced water. These potential industrial uses include (ALL Consulting, 2003):

- *Sod farming* – a pilot project is being conducted in the San Jan Basin
- *Solution mining for minerals* – Wyoming has several Class III injection wells for in-situ solution mining of uranium, some of which are in proximity of CBM development.
- *Bottled drinking water* – this has been done on a small scale in Wyoming by one CBM developer
- *Brewery water* - CBM produced water could be used not only in the manufacturing end of a brewery, but could also be used as irrigation water for the barley, hops, and other grains used in the manufacturing process.

Domestic and Municipal Water use

CBM produced water is of greater value when it meets or approaches drinking water standards. CBM produced water could serve to replace or augment rural wells and springs, augment municipal water supplies that are already strained from over-appropriation and drought conditions, replace residential wells of lesser quality water, or perhaps supplement other surface or groundwater sources.

Domestic Use

Because of its overall high quality in many areas, produced water from CBM wells has the potential to be used by residences for potable and non-potable uses (ALL Consulting, 2003).

- *Potable Water Use* - Produced water that meets drinking water standards can be used for human consumption, although treatment may be required (e.g., chlorination).
- *Non-Potable Water Use* - Non-potable produced water could be supplied to individual homes, perhaps using a dual water system, for uses such as lawn and garden irrigation, bathing, dishwasher and washing machine uses, vehicle washing, residential maintenance, and toilet flushing. An important aspect of a dual potable/non-potable water system is that the two water systems would require separate supply lines and a steady supply of both sources of water needs to be ensured.

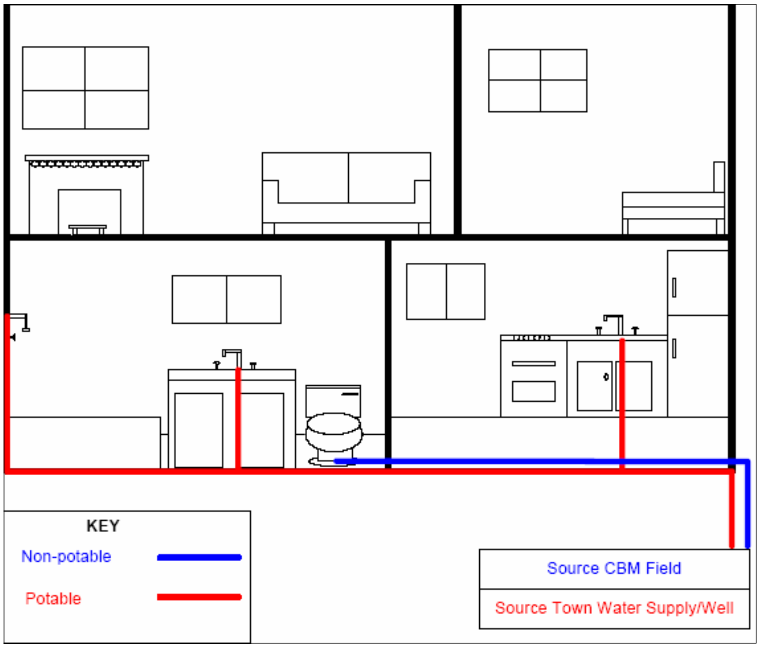


Fig. 12. Domestic use of CBM water (ALL Consulting, 2003)

Municipal Use

In addition to supplying water to rural landowners, CBM produced water could be used to augment municipal water supplies both for potable and for non-potable uses, including (ALL Consulting, 2003):

- *Potable Water Use* - High quality water could be supplied upstream of the existing water treatment facilities and distributed through the existing infrastructure with some modifications (such as gas separators).
- *Non-Potable Water Use* - Potential non-potable use for produced water in a municipality includes a dual water system for household uses as described in the previous section: showering, bathing, lawn and garden watering, and washing clothes and cars. In addition, municipalities could use produced water to supply water to fire hydrants, street cleaning equipment, and certain industries including commercial car washes.

New and Emerging Technologies

New or modified technologies applicable to CBM-produced water are currently being developed by industry, academia, and consulting/engineering firms who specialize in wastewater disposal and treatment (Kuipers et al., 2004). Advances in well completion technologies allow for consistent gas production while minimizing the production of water. Although none of the technologies discussed in this section currently are widely accepted or used by the CBM industry, many hold significant promise for improvements in process efficiency and cost (Kuipers, et al., 2004).

Downhole water/gas separation

Down hole separation utilizes specially designed pumps that separate produced water and gas by centrifugal or gravitational forces within the well bore or in the subsurface formation. These pumps can be used to lift fluids or reversed to inject fluids. Natural gravity separation occurs within the well as water settles to the bottom and the gas rises to the water surface. Gas is extracted while the remaining water is pumped into a deeper receiving formation through a separate injection line. Only a small amount of produced water, about 3%, actually reaches the ground surface. This could almost eliminate the need for impoundment structures or water treatment facilities, and could greatly reduce production costs for gas producers and surface soil and water impacts (Kuipers et al., 2004).

This system requires an adequate receiving formation with adequate separation between it and the producing formation (Kuipers et al., 2004). Very few areas in the Powder River Basin are likely to meet the criteria required to make down hole gas/water separation a practical option. In normally pressured hydrological regimes, like the Powder River Basin, the probability of finding a low-pressure, high injectivity disposal zone below the producing interval would be very low. In addition, it is unlikely that shallow, pressure-depleted zones will coincide with the areas of active CBM productivity (U.S. EPA 2003c).

Alternative wellbore completion methods

A common well completion technique used by many operators in the PRB is to drill to the coal seam and then under-ream the coal section to enlarge the hole and minimize the effects of any formation damage. In many cases, water is then pumped into the wellbore to “clean it out” and “enhance” production. This procedure is called water-enhancement and the pressure applied during this process can result in hydraulic fracturing of the coal. If the coal fractures vertically into the formation above the coal during the water-enhancement process, it could result in excess CBM water production (Colmenares and Zoback, 2004).

Research sponsored by several major CBM producers on well completion techniques in over 500 CBM wells in the PRB has provided the following preliminary findings.

- Water-enhancement activities during wellbore completion results in hydraulic fracturing of the coal.
- All of the wells with exceptionally high water production are associated with vertical fracture propagation.
- In these same wells, there are very significant delays in gas production, apparently due to inefficient depressurization of the coals.

- Approximately half of the wells characterized by vertical hydraulic fracturing are also characterized by excessive water production.

In light of these findings, the researchers recommend the following:

- In areas of known vertical fracture propagation it is necessary to limit the injection during the water enhancement tests.
- In areas where the type and amount of fracturing are unknown, water-enhancement procedures should be carried out in two steps.
  - A low pressure, short duration fracturing process (mini-frac) should be done to determine the nature of the coal and thus whether fracture propagation would be vertical or horizontal.
  - If the mini-frac test described above indicates a propensity for horizontal fracture under pressure, the water enhancement activities can proceed at whatever rate and duration the operator chooses. If the test indicates vertical fracturing could occur, the injection during water enhancement should be limited (Zoback and Colmenares, 2004).

This simple test prior to well completion could result in substantially reduced water volumes brought to the surface during gas production, which saves the developer the cost of water treatment and disposal.

Downhole raman spectroscopy tool

Raman spectroscopy directs a laser beam at a fluid sample and collects reflected light which is then plotted as a "spectrum" or color plot to provide the average chemical makeup or "fingerprint" of the fluid. One Wyoming-owned company has developed a proprietary downhole tool that uses raman spectroscopy to quantify chemicals in water. This can include the amount of methane found in water in a CBM well (WellDog, Inc., 2004).

This innovative tool quickly identifies wells with higher levels of methane saturation that will typically produce natural gas faster with less dewatering. An average test takes about four to five hours for a 2000 foot deep well. From the raman spectroscopy test results, an operator can prioritize development, maximize resources, more efficiently plan infrastructure, accelerate the booking of reserves and optimize the permitting process (WellDog, Inc., 2004).

Horizontal drilling

Horizontal drilling involves drilling vertically down to the gas producing formation and from there, extending a horizontal gas collection line through the producing formation, increasing the likelihood of intersecting more vertical fractures in the coal. With laterals in the coalbeds, the distance a gas molecule has to travel to the well is decreased and production time is minimized (Wight, 2004). Another advantage to horizontal drilling is that multiple drainage networks can be nested and drilled from a single well site to drain up to 1,200 square acres of coal. By comparison, traditional vertical drilling and fracturing recovery methods require one well for every 80 acres of coal. Reservoir benefits aside, the ability to drain gas from 1,200 acres of coal from one well site is a critical advantage since many CBM plays are located in areas where environmental sensitivities are high (Wight, 2004).

Accelerated recovery rates provide significant economic benefits, and economies of scale are achieved when a single 1,200-acre drainage network replaces 16 conventional vertical wells. Other benefits include minimal surface disruption, uniform drainage, increased safety in mining operations, and very low overall methane emission rates. Similar to underground drilling operations, surface-initiated horizontal wells also offer higher ultimate recoveries than vertically drilled and fractured wells. Yet, problems relating to dewatering and cost still remain.

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