HYDROGEOLOGIC RESPONSES TO 50 YEARS OF SURFACE COAL MINING AND 20 YEARS OF COALBED-METHANE PRODUCTION IN SOUTHEASTERN MONTANA

with an emphasis on reclamation at Big Sky Mine

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ABSTRACT

Coalbeds have played a significant role in eastern Montana's history because of their multiple functions. They are important aquifers, used throughout eastern Montana as a reliable source of domestic and stock water. As an energy source, coal and the naturally occurring methane in some coalbeds is used locally, regionally, and internationally. Because there are multiple stakeholders and multiple resource owners, conflicts can and do occur. The potential for conflicts of interest between energy and agricultural users and the need for published information for resource development and permitting decisions, in addition to the scientific value, are the reasons that the MBMG coal hydrogeology program has been an important source of third-party information for so many years.

Coal mining and coalbed-methane (CBM) production interrupt the storage and flow of water in the coalbeds. Both processes require removing large volumes of water from the coal; in the case of coal mining, the aquifer material itself is removed and replaced with spoils. In addition to groundwater-level decline, there are water-quality considerations associated with the salinity of the newly created spoils aquifers, and sodicity (sodium concentrations) in CBM produced water. The importance of the coalbeds as aquifers was recognized in the rules for mine reclamation adopted by the Montana Department of Environmental Quality. Bond release for coal mines stipulates that the essential hydrologic functions and agricultural productivity on alluvial valley floors be reestablished. Also, the Montana Statewide Oil and Gas Environmental Impact Statement requires that groundwater monitoring will continue until at least 95% recovery of static water levels has been achieved at the end of coalbed-methane development.

Spoils aquifers that replace coal and overburden aquifers have highly variable hydraulic and chemical properties. The spoils aquifers in southeastern Montana comprise broken sandstone, siltstone, and shale, in proportions dependent upon the original makeup of the overburden. The composition and hydrologic behavior of coal mine spoils are therefore heterogeneous within and between reclaimed areas. However, understanding the parameters of the spoils aquifer is important to predict hydrologic targets such as time required for saturation and for flushing of mobilized salts.

Periodic sampling of the Big Sky mine spoils aquifer shows salinity "hot spots" that freshened with time from the 1970s through the 1990s and 2010s. The freshening effect of flushing from groundwater influx appears to be strongest to the north and south where recharge from undisturbed coal aquifers would be occurring. In comparing the three sampling periods, the majority of the flushing occurred during the first 20 years after reclamation was completed. As the spoils aquifer stabilizes with time at salinity levels consistent with the surrounding aquifer, the spoils aquifer should be suitable for uses similar to those of surrounding groundwater and pre-mining uses. In this area, groundwater is typically used as a stock water source.

Hydrostatic heads in the Dietz and Canyon coal aquifers have been lowered as much as 150 and 300 ft, respectively, within areas of CBM production. The magnitude and distance of actual water-level drawdown, 1.5 to 2 mi in most locations, is less than the approximately 5 mi predicted in the Montana CBM environmental impact statement and initial groundwater modeling efforts. Faults tend to act as barriers to groundwater flow;

drawdown has not been observed to migrate across fault planes in most locations. Vertical migration of drawdown tends to be limited by shale layers. The strong controlling role faulting plays in water-level drawdown is evident in the potentiometric surface in the Decker area, where coalbed-methane production in Wyoming has reversed the water flow direction in some fault blocks.

Water-level recovery in some wells began in 2004 due to the discontinuation or reduction in nearby CBM production; some wells have recovered to within 80 percent of baseline levels. However, as of 2018—several years after the discontinuation of CBM in most locations in Montana and northern Wyoming—some water levels are still declining. The extent of drawdown was, and rates of recovery will be, determined by the rate, intensity, and continuity of CBM development; site-specific aquifer characteristics, including the extent of faulting and proximity to recharge areas; amount, timing, and location of precipitation; and other significant groundwater withdrawals such as from coal mining.

Since 1968, the MBMG has maintained a network of dedicated monitoring wells in the Powder River Basin. The well network, information, and methods developed for the coal mine groundwater-monitoring program were translated over to CBM hydrologic monitoring when CBM production began in Montana in 1999. Monitoring will continue until the hydrologic disturbance from energy production in the Powder River Basin has returned to baseline. The results of the MBMG's long-term monitoring and site-specific studies have proven to be an invaluable source of information for landowners, regulators, and industry representatives in addition to academic research.

INTRODUCTION

Coalbeds have played a significant role in eastern Montana's history because they perform multiple functions. They are the most laterally continuous aquifers, carrying recharge water to springs, wells, and ultimately baseflow in streams. As an energy source, Montana coal is used locally, nationally, and internationally. Since the late 1990s, the naturally occurring methane in some coalbeds is extracted and sold as a source of natural gas for domestic and industrial use. As a water source, coalbeds are used throughout eastern Montana as a reliable source of domestic and stock water. Coalbeds are also common sources of springs, which are used year-round by livestock and wildlife (Wheaton and others, 2008).

Because there are multiple uses and multiple resource owners, conflicts can occur. The activities of one stakeholder can impact the ability of another to develop their resources. For example, energy production that dewaters coalbeds can reduce stock water availability for ranchers. This potential conflict, based on multiple interests in a single geologic unit, is the reason that the MBMG coal hydrogeology program has been an important source of information for over 50 years.

Geologic Setting

The Powder River Basin (PRB) is both a structural and hydrologic basin bounded by the Black Hills to the east, the Bighorn Mountains to the west, the Miles City Arch near the Yellowstone River to the north, and the Laramie Mountains and Hartville Uplift to the south, near Casper, Wyoming (fig. 1). About one-third of the basin lies in Montana and two-thirds in Wyoming (Meredith and others, 2012). The basin formed in the Paleocene. It is an asymmetric syncline with

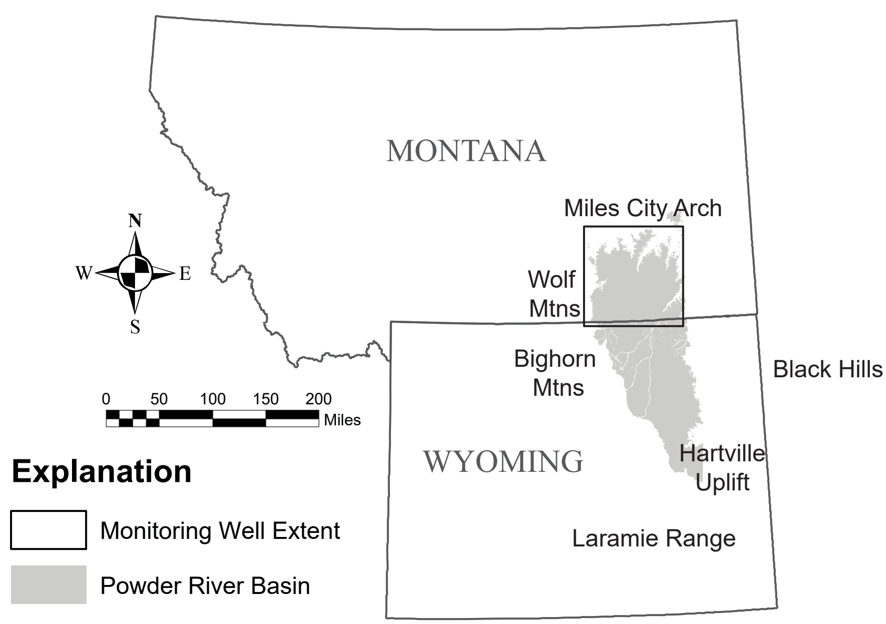


Figure 1. The Powder River Basin is both a structural basin and hydrologic basin (the watershed of the Powder River). For the purposes of this chapter, we refer to the structural basin. Approximately 1/3 of the basin lies in Montana, while the majority of the basin is in Wyoming.

gentle dips on the eastern limb and steeper dips on the western limb. The basin axis is near the western side, running northwest in Wyoming and turning to the northeast in Montana.

Coalbeds in the Powder River Basin are the geologic remnants of large, freshwater swamps within a fl uvial system (Seeland, 1993; and see Gunderson and Wheaton, 2020 for a more detailed description of depositional environments). During lithification, desiccation, faulting, and structural warping of the basin rocks, the coalbeds developed fractures, or cleats, that allow water storage and movement. Interbedded with intermittent channel sands and fine-grained overbank deposits, the coals are common targets for water well development because of their continuity and transmissivity. The Tongue River Member of the Fort Union Formation, in which the coalbeds occur (fig. 2), is one of the most predominant geologic units in eastern Montana (Vuke and others, 2007).

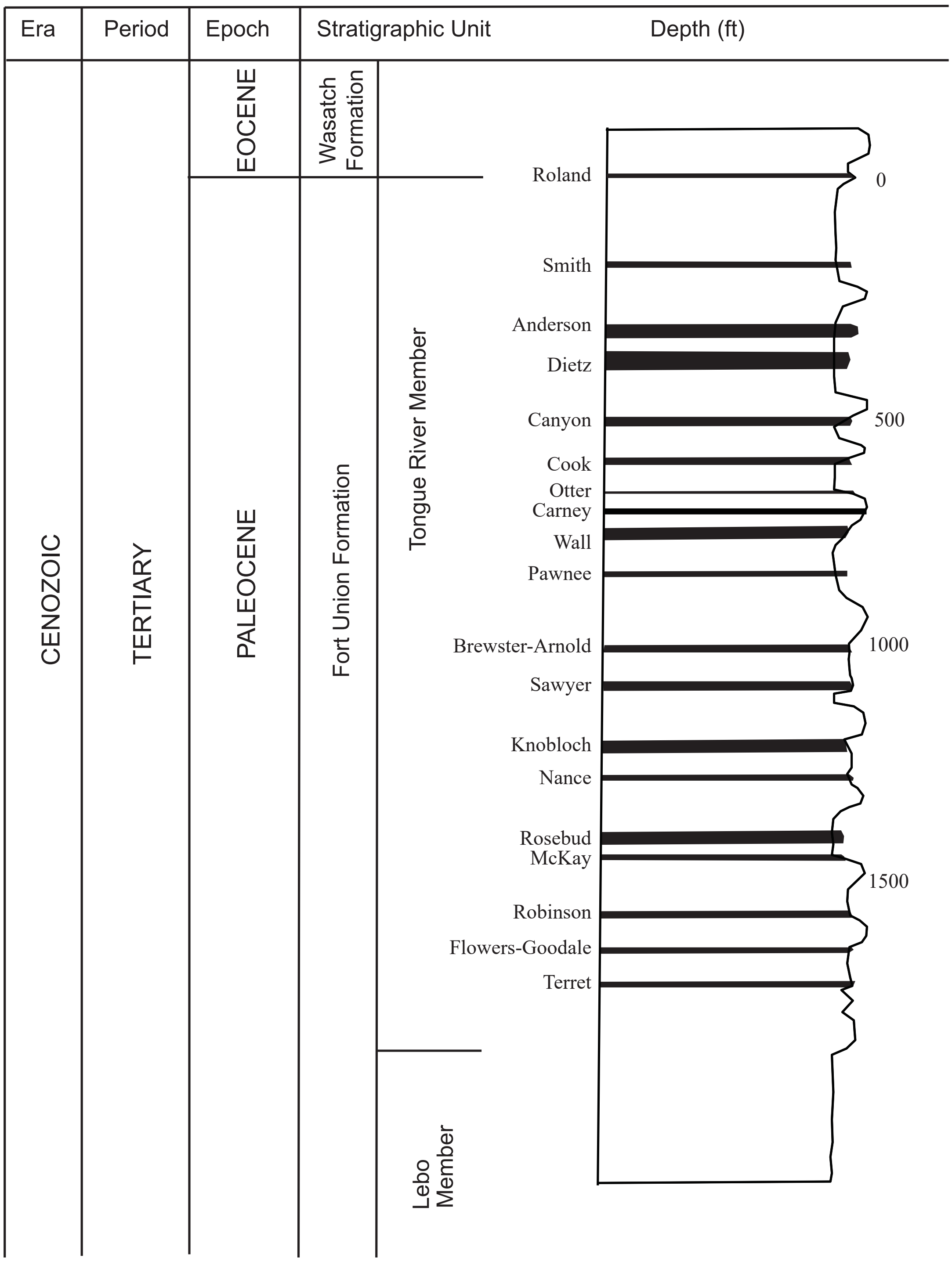


Figure 2. The Fort Union stratigraphy in the Powder River Basin includes significant coalbeds, such as the Anderson, Dietz, McKay, and Rosebud, which are the targets for surface coal mining. The Anderson, Dietz, Canyon, Wall, and other thinner coals, are the targets for CBM development. The general relative positions of the coals are shown here; the indicated depths are approximations.

Within the PRB, there are local groundwater flow systems, intermediate systems above the Lebo Shale, and deeper regional flow systems of the Tullock Member of the Fort Union Formation and the Fox Hills–Lower Hell Creek aquifer (Slagle and others, 1983). Generally described, groundwater flows from the edges of the basin toward the center and north toward the Yellowstone River (Slagle and others, 1985; Wheaton and others, 2008a). Recharge occurs in clinker-capped ridges and areas of coal and sandstone outcrop. Shallow, local systems reflect local topography, receiving recharge from local ridges and flowing toward nearby drainages to discharge as springs or baseflow to streams. Progressively deeper flow systems show progressively less topographic control (Wheaton and others, 2008b). Discharge from flow systems in the Tongue River Member are constrained by the Lebo Shale aquitard and discharge south of the Yellowstone River in tributary valleys. The regional groundwater flow systems are recharged primarily along the basin flanks. Near the Montana/Wyoming border, groundwater recharge occurs both along the Wolf Mountains on the western limb and the high hills near the Powder River. Flow from these areas augments northward flow coming from Wyoming.

Water Quality in Coal Aquifers

The physical and chemical processes that determine the ultimate chemical composition of groundwater in coal aquifers in the Fort Union Formation can be considered in five stages: dissolution of salts, pyrite oxidation, cation exchange, sulfate reduction, and methanogenesis (Brinck and others, 2008; Van Voast and Reiten, 1988). The groundwater chemistry is determined by the combination of soils and geology along the flow paths. In semi-arid climates, such as the Powder River Basin, salt accumulates through the evaporation of rain and through the chemical and physical decomposition of minerals. Infiltrating precipitation brings soluble salts into solution and increases the calcium, potassium, chloride, and sulfate concentration of the groundwater. Chloride concentration is relatively low compared to other constituents due to the non-marine nature of the depositional setting.

Chemically mature coal groundwater has a composition dominated by sodium and bicarbonate, and the presence of methane is common (see sidebar: Geochemical evolution of groundwater in coal aquifers). The TDS (or salinity) of mature coal groundwater is generally between 1,500 and 2,500 mg/L. Coal aquifer water can have any intermediate water quality from calcium–magnesium–sulfate near recharge to sodium–sulfate along the flow paths, to strongly sodium–bicarbonate-dominated chemistry.

Colstrip area coal aquifers tend to have groundwater quality dominated by salt dissolution and, to a lesser extent, cation exchange (Van Voast and Reiten, 1988). The McKay and the Rosebud coal mined in the Colstrip area have groundwater predominantly dominated by magnesium–calcium–sulfate with some water samples transitioning to sodium–sulfate-dominated.

The sodium–bicarbonate groundwater chemistry in coal aquifers near the Decker and Spring Creek coal mines is characteristic of mature coal aquifer water, including the presence of methane, which has made the area a target for coalbed-methane (CBM) production.

Hydrogeologic Impacts

Both coal mining and CBM production interrupt the storage and flow of water in the coalbeds. Both processes require removing large volumes of water from the coal; in the case of coal mining, the aquifer material itself is removed and backfilled with spoils. In addition to groundwater-level decline, there are water-quality considerations associated with soluble salts in the newly created spoils aquifers, and sodicity (sodium concentrations) in CBM produced water.

Hydrogeological impacts due to coal mining and CBM production include direct impacts during production and residual impacts after production and reclamation. Direct impacts include aquifer removal and water-level drawdown, which result in declining water levels in wells completed in the coal and, to a lesser degree, in adjacent aquifers. Additionally, discharge from springs originating from the coal can decrease or cease entirely. These effects are generally predictable and well understood.

The residual impacts after a coal mine has closed operations include a duration of limited groundwater availability, increased salinity in spoils groundwater, and off-site effects from the newly created hydrogeologic conditions (Van Voast and Reiten, 1988). Residual impacts include lowered water levels from CBM production and the possibility of increased salinity and sodicity in surface water, in groundwater, and in soils resulting from handling of CBM co-produced water at the surface. Residual effects are harder to predict and are poorly understood.

Geochemical evolution of groundwater in a coal aquifer

In general **rainwater**, made slightly acidic by the carbon dioxide in air and in the soil rooting zone (eq. 1), **dissolves calcite and dolomite** cement in sandstone to bring calcium and magnesium ions into solution (eq. 2):

$$\underset{rain}{H_2O} + \underset{carbon\ dioxide\ in\ air}{CO_2} \rightarrow \underset{carbonic\ acid}{\mathrm{H_2CO_3}} \qquad \text{EQ. (1)}$$

$$\underset{carbonic\ acid}{\mathrm{H_2CO_3}} + \underset{calcium\ carbonate}{\mathrm{CaCO_3}} \text{ or } \underset{dolomite}{CaMg(CO_3)_2} \rightarrow Ca^{2+}, Mg^{2+} + HCO_3^- \qquad \text{EQ. (2)}$$

Within the coal aquifer, **pyrite oxidation** increases the iron and sulfate concentrations of the groundwater (eq. 3). In the Fort Union Formation, the acidity generated is quickly buffered by calcite dissolution.

$$\underset{iron\ pyrite}{\mathrm{4FeS_2}} + 15O_2 + 14H_2O \rightarrow \underset{iron\ oxide}{\mathrm{4Fe(OH)_3}} + \underset{sulfate}{\mathrm{8SO_4^{2-}}} + \underset{acidity}{\mathrm{16H^+}} \qquad \text{EQ. (3)}$$

Dissolution of gypsum increases the calcium and sulfate concentrations (eq. 4).

$$\underset{gypsum}{CaSO_4 \cdot 2H_2O} \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \qquad \text{EQ. (4)}$$

Along the flow path, water exchanges cations with the prevalent clays and shales (eq. 5). The **ion exchange** process increases the sodium and decreases the calcium and magnesium concentrations.

$$Ca^{2+} + Mg^{2+} \xleftrightarrow{exchange} 4Na^- \qquad \text{EQ. (5)}$$

Bacterially mediated sulfate reduction decreases the sulfate concentration and generates bicarbonate (eq. 6).

$$\underset{coal\ substrate}{2CH_2O} + SO_4^{2-} + 2H_2O \xrightarrow[sulfate\ reducing\ bacteria]{} H_2S + 2HCO_3^- \qquad \text{EQ. (6)}$$

The increase in bicarbonate drives the **precipitation of calcite**, which lowers the bicarbonate, calcium, and concentration of total dissolved solids (TDS; eq. 7).

$$HCO_3^- + Ca^{2+} \rightarrow \underset{calcite}{CaCO_3} + H^+ \qquad \text{EQ. (7)}$$

Methanogenesis (generation of methane) occurs in sulfate-depleted groundwater through two pathways:

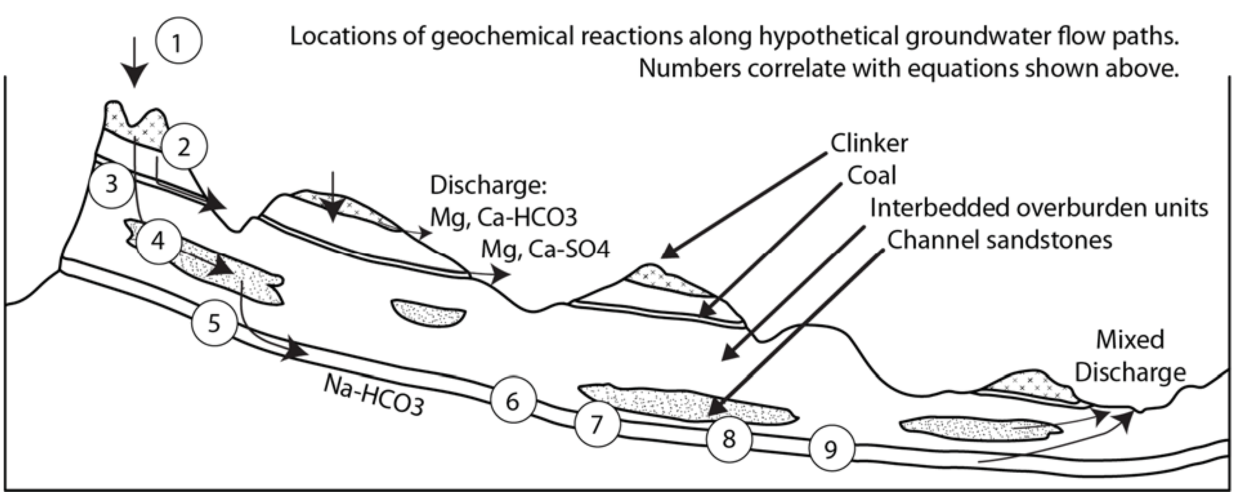
(1) bicarbonate reduction (eq. 8)

$$HCO_3^- + 4H_2 + H^+ \rightarrow CH_4 + 3H_2O \qquad \text{EQ. (8)}$$

and

(2) acetate cleavage (eq. 9)

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad \text{EQ. (9)}$$



In some older mine areas, poorly plugged exploration drill holes allowed groundwater to flow vertically from deeper aquifers into the mine and mine spoils (Wheaton and Reiten, 1996). Improved reclamation practices in large part based on high-solids bentonite hole plug research (Wheaton and others, 1994; Wheaton and Regele, 1997) have greatly reduced this concern.

Groundwater Monitoring and Research

The Montana Bureau of Mines and Geology began studying the hydrogeology of areas disturbed by coal mining when the large-scale surface mining operations began in the late 1960s. Monitoring and hydrologic studies focused on the mines near Colstrip and Decker (fig. 3) and several areas where future mining was anticipated. Since that time, monitoring efforts have focused on areas where energy development has been increasing and where it is anticipated to occur. Areas with no mining or CBM development have been monitored as control (background) sites to distinguish natural groundwater fluctuations from energy development impacts.

The MBMG monitoring well network, information, and methods developed for the coal mine groundwater monitoring program were adapted to CBM hydrologic monitoring when CBM production began in Montana in 1999. Groundwater samples are collected for major and minor constituent analysis periodically in both coal and CBM development areas. More frequent sampling occurred just after remediation on reclaimed spoils areas, with less frequent sampling in subsequent years. Monitoring will continue until the hydrologic disturbance from energy production in the Powder River Basin has returned to baseline.

The results of the MBMG's long-term monitoring and site-specific studies have proven to be an invaluable source of information for landowners, regulators, and industry representatives in addition to academic research. The results have been applied by State and Federal regulators for leasing, data standards, mine permits, methods, and reclamation decisions (Van Voast and Reiten, 1988). The unusually high frequency, density, and long history of the data make it useful for more abstract hydrological investigations by university researchers, including those looking at methanogenesis, sulfate-reducing bacteria, chemical evolution in coal aquifers, and other reclamation issues (Bates and others, 2011; Barnhart and others, 2016; Van Voast, 2003; Brinck and others, 2008).

COAL STRIP MINING HYDROGEOLOGIC RESPONSES

As of 2018, coal was mined in six locations in Montana: five surface mines and one underground mine (fi g. 3). Eastern Montana holds large reserves of lignite and subbituminous coal (Gunderson and Wheaton, 2020). At this time, subbituminous coal is the primary source of commercial development because the beds are valued for lateral continuity, thickness, low sulfur content, and shallow depths (Van Voast and Reiten, 1988). From 2007 through 2016, Montana produced between 32 (2016) and 45 million (2008) tons of coal per year (Gunderson and Wheaton, 2020), ranking it sixth in production among the 15 major coal-producing states (Montana Coal Council, 2018).

During coal strip mining, overburden rock is blasted and removed by means of draglines, direct push with bulldozers, or truck and shovel hauling. Topsoil is stockpiled separately for reclamation. Depending on the handling method, the backfi ll (mine spoils) can be compacted or fairly loose. As spoils material is dumped out of a dragline bucket, the spoils pile tends to sort by size, creating a relatively coarser rubble zone at the spoils base with fi ner material grading to the top.

From a hydrogeologic perspective, overburden or coal groundwater fl ow systems disturbed by mining are replaced during mine reclamation with a spoils aquifer. The spoils material, which was originally layers of shale, siltstone, and sandstone, is a comingled, non-layered backfi ll. The structure of the spoils is irrespective of the original hydrologic function of the overburden. The overburden siltstone, clay, and sandstone layers are broken and reconfi gured into a mix of boulder to silt-sized material that makes up the spoils. The spoils material saturates, forming a spoils aquifer that, to achieve bond release, must serve the same hydrologic function as the coal.

The importance of the coalbeds as aquifers was recognized in the rules for mine reclamation adopt-ed by the Montana Department of Environmental Quality. Administrative Rule of Montana 17.24.1116 (MT DEQ, 2007) outlines the requirements for coal mining companies to achieve bond release through four phases. Phase IV stipulates that fi sh and wildlife habitats and related environmental values have been restored; disturbance to the hydrologic balance has been minimized; alternative water sources have been developed to replace water supplies that have been ad-

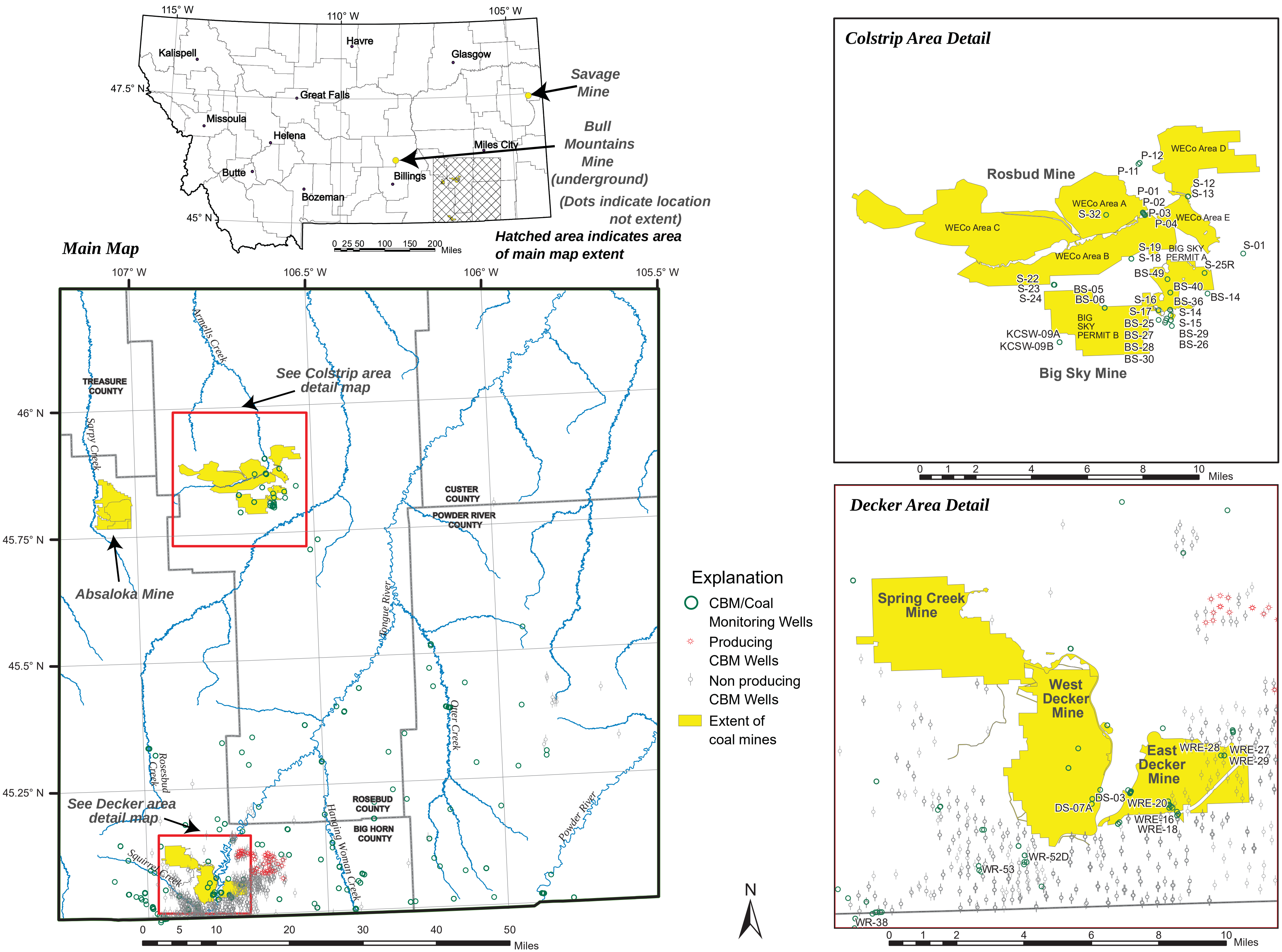


Figure 3. The MBMG has monitored the groundwater responses to energy development in southeastern Montana since the late 1960s. The network of long-term monitoring wells in the Powder River Basin extends from the Tongue River to the Powder River and from the state line to Colstrip.

versely affected by mining and reclamation operations; and the essential hydrologic functions and agricultural productivity on alluvial valley floors have been reestablished. Meeting these requirements can take years. Of the 41,314 acres disturbed by surface coal mining in Montana, 23,995 acres have been backfilled, and 2,516 acres have received full bond release (2017 data; MT DEQ, 2017). With time, soluble salts should flush from the spoils aquifer, and water quality should stabilize salinity levels consistent with the surrounding aquifers. The spoils aquifers are expected to be suitable for uses similar to those of surrounding groundwater and pre-mining uses. In this area, groundwater is typically used as a stock water source.

Direct Impacts

Water-level drawdown due to mining is closely related to the position of the mine within the groundwater flow regime. Surface coal mines in settings such as the Powder River Basin begin at the coal outcrop where overburden thickness is minimal. Each successive mine pit typically involves removing thicker overburden. Due to basin structure, Montana coal strip mines are generally in groundwater discharge areas (Van Voast and Reiten, 1988; Hedges and others, 1998). The region of drawdown is therefore asymmetrical, limited in one direction by proximity to the outcrop.

Faulting also influences the magnitude and extent of groundwater drawdown. The extensive faulting around Decker focuses water-level drawdown along fault blocks. Drawdown is magnified along these fault corridors such that the drawdown is in excess of what would normally have been predicted within the block, and less so outside the block. The water level across a fault from development can have little to no drawdown (Van Voast and Hedges, 1975). Unmapped faulting can make predicting drawdown magnitudes and timing of recovery difficult. The heterogeneity of drawdown responses can also either lessen or enhance the dewatering necessary for energy development.

Residual Impacts

Residual impacts are harder to predict than direct impacts for a number of reasons. The nature of the spoils aquifer is dependent upon several factors, including the geologic composition of the overburden, the particle size of the material emplaced after handling, the amount of compaction during reclamation, and the chemical reactability of the minerals composing the overburden rocks. In addition, the method of spoils emplacement can impact the spoils aquifer water quality. The unsaturated, undisturbed column of overburden material is naturally higher in soluble salts near ground surface in many areas (Van Voast and Reiten, 1988). Common mine practices invert the overburden column as it is stripped of the coal and placed as spoils into the adjacent pits. This puts the highest soluble salt potential in the saturated interval after reclamation and establishment of the spoils aquifer.

The source of spoils aquifer recharge is generally assumed to be lateral inflow from the coal aquifer that was left undisturbed during mining; however, the original aquitard layers that originally restricted vertical infiltration of precipitation, having been blasted and handled, are no longer intact. The lack of horizontal structure in spoils aquifers may allow precipitation recharge. Additionally, the rate of recharge is difficult to predict because, while the coal hydraulic properties may be well understood, the spoils aquifer is heterogeneous and physical properties at any specific location are difficult to predict.

The original discharge site of the coal aquifer, whether to an alluvial aquifer or to the surface as a spring, may also serve as the discharge site for the spoils aquifer. The higher salinities representative of spoils aquifers have been found outside of the mine disturbance area in limited instances.

Water quality in the spoils is impacted by the chemical reactions described above. As the recharge water rewetting front crosses the spoils, minerals dissolve and the water reaches saturation with respect to dissolved ions. The TDS at saturation is dependent upon local conditions, and it indicates the dissolved-solids concentration is at a maximum. Flushing of salts from the spoils material is necessary before water quality can return to pre-mining conditions. Flushing happens at the recharge boundary first, and no subsequent or downgradient flushing can happen since the saturated groundwater is then at chemical equilibrium with the surrounding spoils material. Salt flushing is expected to proceed from the recharge boundary of the spoils to the discharge boundary in a series of pore volumes. The number of pore volumes required has been estimated from as low as a minimum of 1 (Van Voast and Reiten, 1988) to as high as 110 (Davis, 1984). The estimated duration for flushing to occur ranges from years to centuries; in the reclaimed Big Sky spoils aquifer, the salinity in most areas returned to the range of the coal aquifer's salinity within 20 to 30 years.

It was reported by Van Voast and Reiten (1988) that the only environmental concern from mine effluent (groundwater discharged during the mining process) was the occasional high levels of nitrate from the ammonium–nitrate explosives used to blast coal and overburden. The groundwater withdrawn from the coal during mining is indistinguishable from the coal aquifer groundwater that naturally discharges to the surface at outcrop; however, the amount of water discharged and the location of discharge can be sources of concern and should be taken into account when considering the environmental impacts of mine effluent water.

Transmissivity Measurements in Coal and Spoils Aquifers

The hydrologic characteristics of coal aquifers have been extensively tested. Coal mining companies measure coal aquifer conductivity to improve predictive capabilities for permitting and planning purposes. Additionally, the MBMG tested aquifer properties as part of their monitoring efforts. The MBMG compiled available test aquifer results from research publications, mine permit applications, and other studies (MBMG file data). For all coals in the Powder River Basin, the range in hydraulic conductivity values was from 0.001 to nearly 1,100 ft/day, and the geometric mean was 1 ft/day based on 397 tests, as reported by Wheaton and Metesh (2002).

Spoils aquifers that replace coal and overburden aquifers have highly variable conductivity values. The spoils aquifers in southeastern Montana are composed of broken sandstone, siltstone, and shale, in proportions dependent upon the original overburden. The composition and hydrologic behavior of coal mine spoils is therefore heterogeneous within and between reclaimed areas. However, in order to predict important hydrologic targets such as time required for saturation and for flushing of mobilized salts, the physical aquifer parameters of the spoils need a level of definition.

Based on results from six available tests of spoils aquifers in the Decker area, Van Voast and Reiten (1988) reported a geometric mean hydraulic conductivity value of less than 0.2 ft/d. In Colstrip area spoils aquifers, they reported 1 ft/d. In Decker, these values are lower than the mean for coal , but for both areas the range of values for coal and spoils overlap (fig. 4; Van Voast and Reiten, 1988). Van Voast (1982) found, upon replicating bailer tests of spoils aquifers after 2 or more years, that for those conductivities that were at least 0.1 ft/d, no substantial changes occurred. Low conductivity measurements were subject to significant error, so differences in test results were not interpreted to indicate systematic changes in the aquifer properties. Van Voast (1982) recommended periodic repeat tests to identify whether gradual compaction or settling of the spoils changes the hydraulic conductivity.

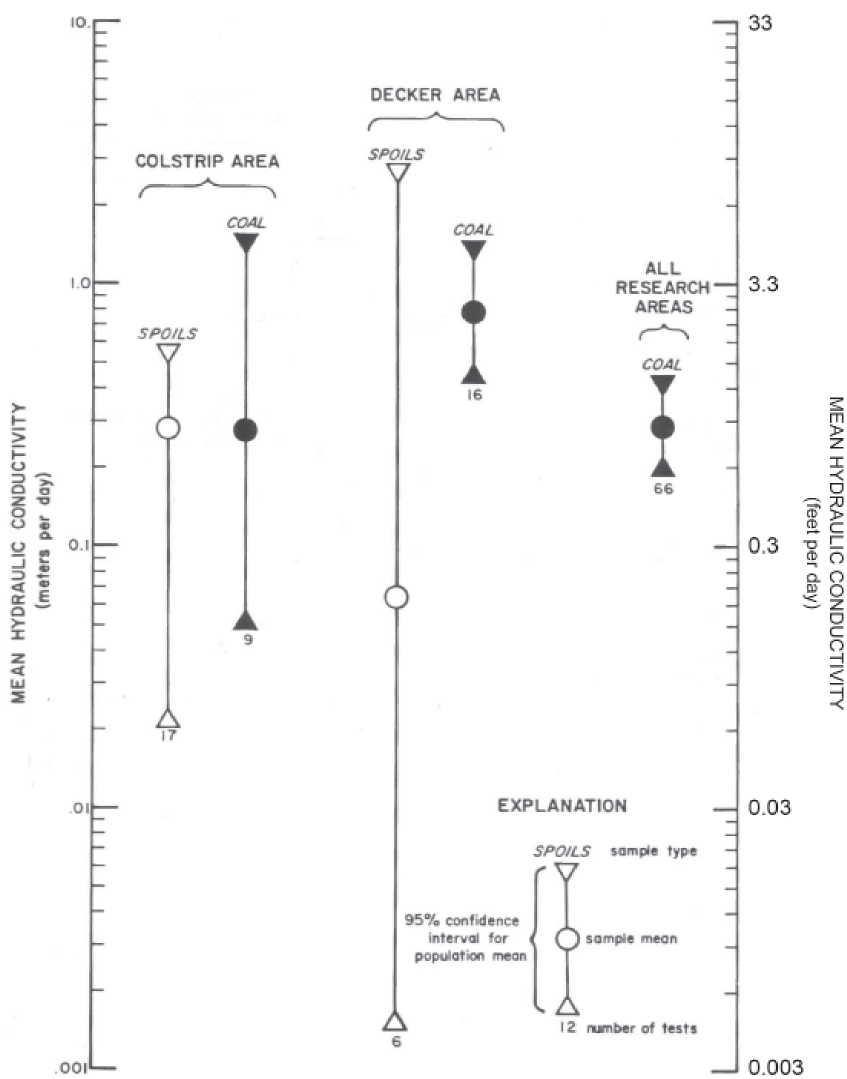


Figure 4. Spoils aquifer hydraulic conductivity varies by several orders of magnitude

The wide range in reported coal and spoils aquifer hydrologic properties reflects the intrinsic variability of the secondary permeability of coal (cleat development and interconnectedness), sorting and compaction in spoils, the method used for the test, and the condition of the well that was used for the test. Drilling in coal generates fine-grained dust that builds wall cake and penetrates into the coal fractures, blocking water movement around the well. Proper well development is difficult, and efficient wells may be rare for testing purposes. The same holds true for spoils wells, where clay and fine-grained fractions from drilling plug the well bore (Wheaton and Reiten, 1996; Wheaton and others, 1996; Wheaton and Regele, 1997).

Post-Mining Hydrologic Conditions at Big Sky Mine, Colstrip

Both the McKay and Rosebud coals were mined by Peabody Coal Company at areas A and B at Big Sky mine approximately 5 mi south of Colstrip (figs. 1, 3). Area A was opened in 1969 and mining was completed in 1989. Area B operated from 1989 to 2006. The two areas were separated by about 2.5 mi.

Water-Level Recovery

In response to the dewatering of open mine pits, water levels in the coal aquifer outside the mined area are lowered. After mining and the pit are reclaimed, water levels recover and respond to climatic conditions, as shown at well BS-30 (fig. 5A). In both the Rosebud and McKay coals, at Area B, water levels did not fully recover after mining (fig. 5B). The reason for this has not been determined.

The spoils aquifer began to resaturate as soon as the reclamation was completed. Full saturation of the spoils in Area A took approximately 5 yr in most locations (figs. 5C, 5D, 5E, 5F). The rapidity with which the saturation occurred indicates that the recharge mechanism is more than direct infiltration of precipitation, but also lateral flow from the adjacent, intact coal and sandstone aquifers. A few locations within the spoils aquifer continue to have climbing water levels (e.g., fig. 5E), which may be caused by their location within the reclaimed mine and proximity to ongoing mining at an adjacent mine. Spoils water levels near well BS-40 (fig. 5C) indicate completion of mining in Emile Coulee and saturation within several years, reaching a stable level around 1980. A second duration of rising water level starting in the mid-1990s and continuing until the most recent measurements deserves additional attention. Final surface reclamation occurred in the area in the 1990s, and no open pits were within the area of influence of the spoils here.

Water levels within the spoils aquifer are responsive to precipitation patterns (fig. 5D). This behavior is typical of shallow, unconfined aquifers. Long-term trends of higher than average precipitation, such as that experienced from 1992 to 2000, have a greater influence on the water level than do single, large annual totals such as in 2005 and 2011. This implies that the recharge source is primarily lateral flow from adjacent aquifers rather than direct infiltration of precipitation. Spoils aquifer water levels reflect increased water levels in the adjacent coal aquifers caused by long-term precipitation trends.

At two monitoring sites near Colstrip, a spoils well was installed to replace coal monitoring wells that had been removed by mining. At each site, both the Rosebud and McKay coalbed water levels responded to climate and to proximity of mining (figs. 5E, 5F). Water levels in the spoils aquifer were expected to recover to near pre-mining levels in the coals. Near S-36 (fig. 5E), the Rosebud coal was mined, and the underlying McKay coal was left undisturbed. Mining has moved away from this site, but pits are still open and active within a mile. Water levels in the spoils continue to rise toward the Rosebud coal pre-mining levels. At the S-25R site (fig. 5F), both coalbeds were removed during mining. The area was backfilled and reclamation completed in 1989. The spoils water level has never risen above that of the lowest level recorded during mining in the lower McKay coal. Whether this is due to higher transmissivity values in the spoils than the coal, conversion from confined to unconfined conditions, or some feature that causes groundwater flow to bypass this location has not been identified.

Spoils Aquifer Water-Quality Trends

The primary water-quality concern associated with the spoils aquifer is from the increased salinity as compared to the coal aquifer groundwater. Increased acidity, a major concern in some coal mining areas, has not been an issue in eastern Montana (Van Voast and Reiten, 1988). Carbonates in the spoils rocks quickly neutralize acidity generated from pyrite oxidation. The return of hydrologic function, as required for bond release, is defined, in part, by the return to a groundwater salinity that allows for similar pre-mining groundwater uses. The TDS of groundwater is controlled by a number of factors, one of which is the

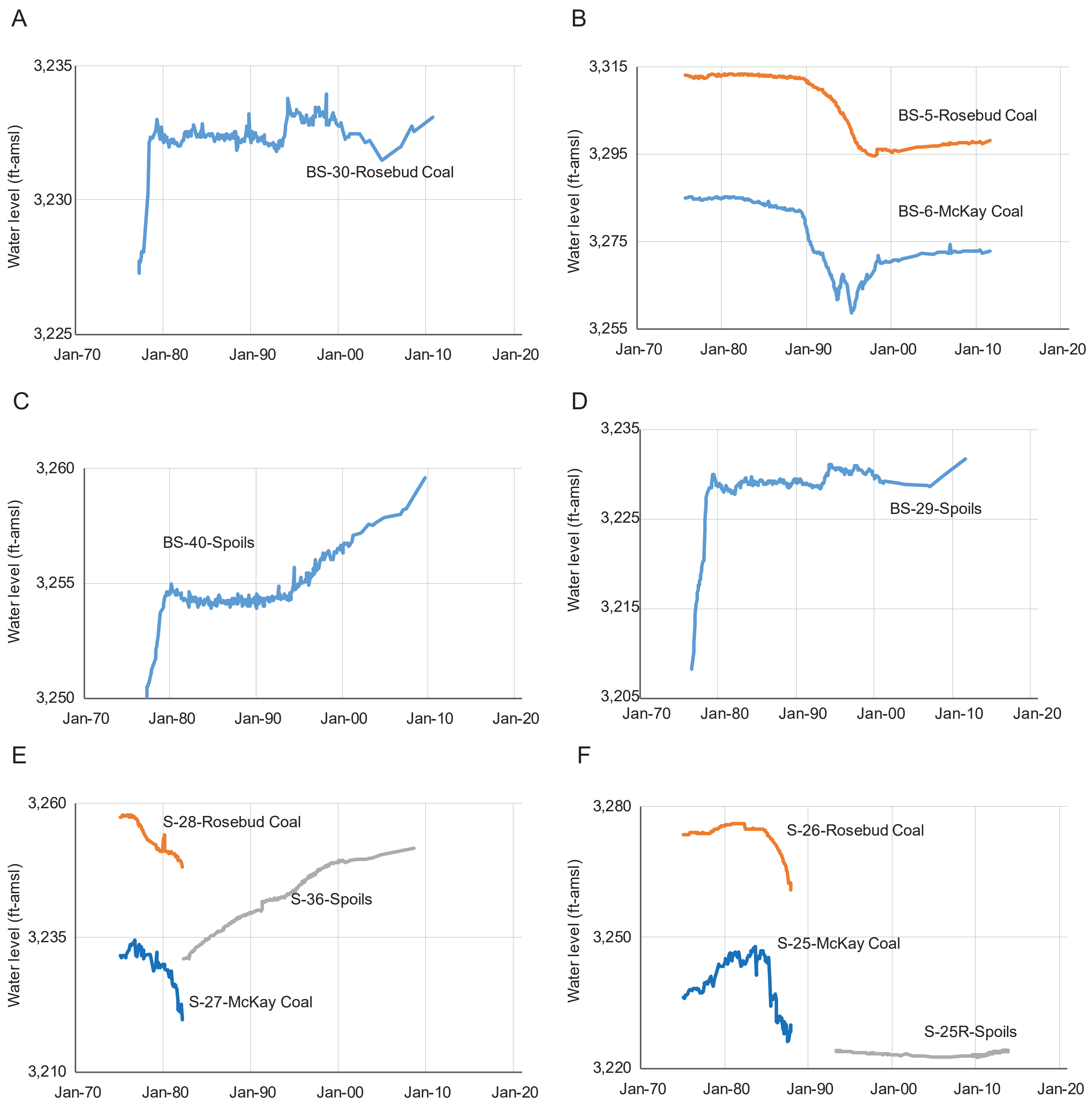


Figure 5. Coal aquifers adjacent to mine pits are drawndown but recover within several years once the mine pit is backfilled. Spoils saturate after pit closure; some quickly reach an equilibrium and some continue to rise for decades. At two locations, spoils wells were installed to replace coal-monitoring wells that had been removed by mining. The spoils water levels appear to reflect localized hydraulic conductivity conditions and recharge. Well locations are shown in figure 1.

water's interaction with the aquifer matrix. High TDS in groundwater can indicate an aquifer that has a large amount of soluble salts readily available.

As part of the monitoring effort by the MBMG and others on the reclaimed Big Sky Mine, water-quality samples have been collected from the spoils aquifer and the nearby coal and alluvial aquifers periodically since the 1970s. Van Voast and Reiten (1988) predicted that the salinity of the spoils aquifer groundwater would initially be elevated because of the exposure of the groundwater to previously unsaturated rock in the spoils. Flushing of the salts, they predicted, would require approximately two pore volumes of water to move through the aquifer before the salinity returned to pre-mining levels. However, in their 1988 report, Van Voast and Reiten also observed a lack of consistency in the salinity trends of the monitored wells, an observation that was replicated 20 years later (Kuzara and others, 2016). The heterogeneity of spoils aquifers, in combination with the ongoing mining activities in the area, results in both increasing and decreasing groundwater salinity levels (fig. 6).

The spatial variability of spoils aquifer salinity and its evolution with time show salinity "hot spots" that freshen from the 1970s through the 1990s and 2010s. The contour map of the 1970s aquifer (fig. 7A) shows a large range in salinity from a low of 2,738 mg/L near the pond, to a high of 6,140 mg/L in the

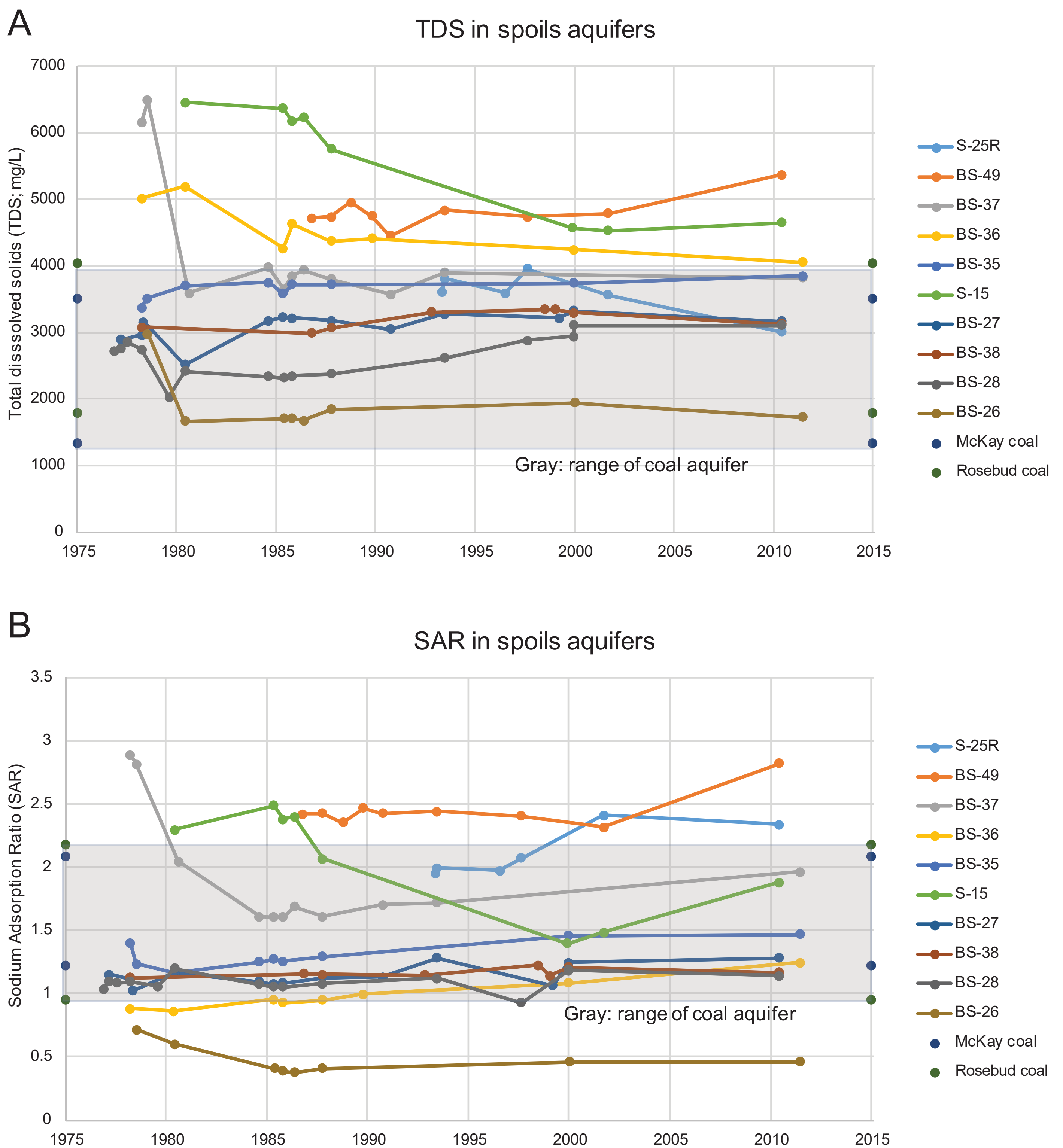


Figure 6. The salinity of spoils aquifer groundwater in the Big Sky mine (A) generally decreases with time, but there are some exceptions. The SAR of the spoils aquifer groundwater in Big Sky (B) also shows both increasing and decreasing trends. Overall the salinity and SAR of the spoils aquifer groundwater is within or near that of the nearby McKay and Rosebud coal aquifers. Well locations are shown in figure 1.

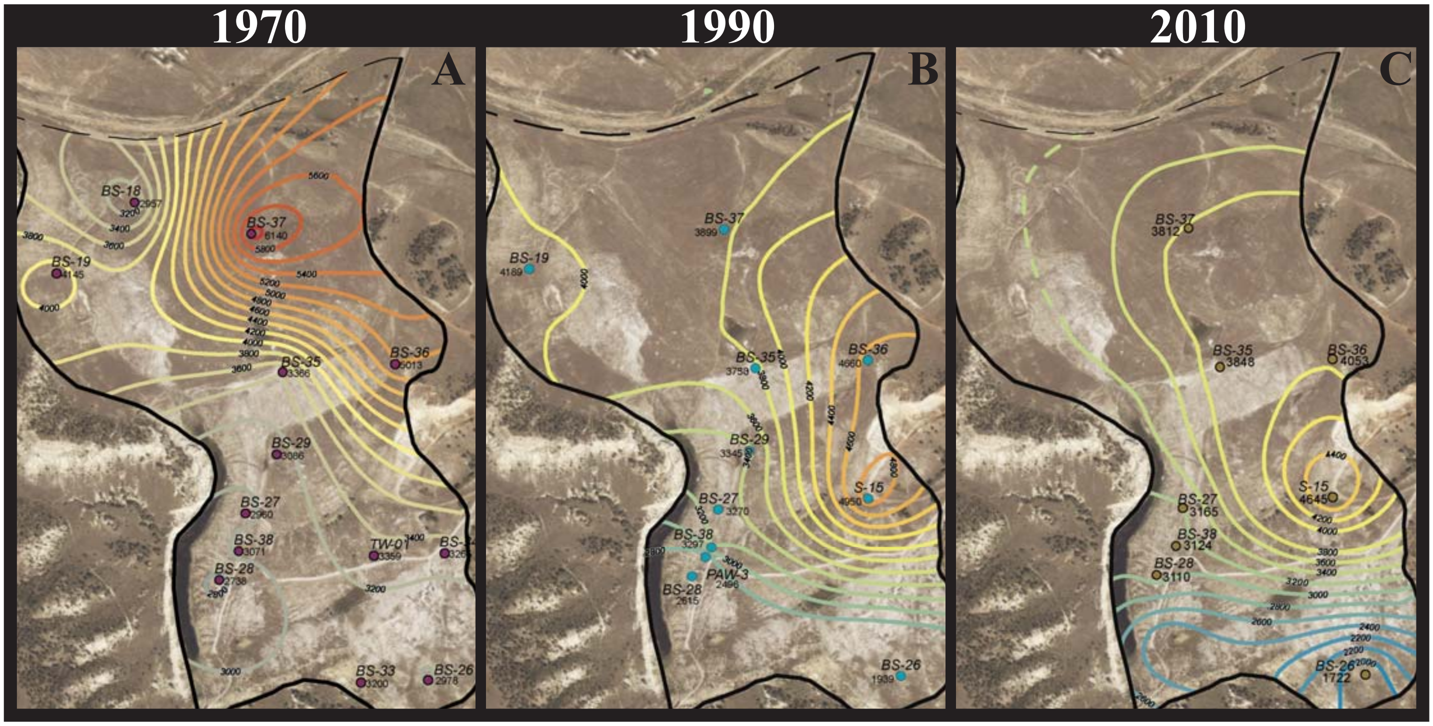


Figure 7. The TDS of the spoils aquifer at Big Sky mine has improved since the 1970s (A), through the 1990s (B) and 2010s (C); however, not to the extent predicted by Van Voast and Reiten (1988). The TDS contours were created using the Kriging method by Groundwater Modeling Software by Aquaveo. This method is a statistical interpretation that chooses the best linear, unbiased estimate for contour placement (Anderson and others, 2002). Modified from Kuzara and others (2016); used with permission.

northeast corner. The freshening effect of flushing from groundwater influx is seen in samples collected in the 1990s (fig. 7B). The salinity range within the aquifer is reduced to a minimum of 2,496 mg/L and a maximum of 4,950 mg/L. In contrast, the salinity map of the 2010s (fig. 7C) looks very similar to the 1990s in magnitude and spatial variability. The majority of the flushing occurred during the first 20 years after reclamation was completed (Kuzara and others, 2016). As predicted by Van Voast and Reiten (1988), flushing starts in the final highwall area (west in this area) and proceeds downgradient toward the discharge area (east in this area).

In June 2010, several water-quality samples were collected from the spoils, undisturbed coal, and the pond. All spoils samples (red symbols, fig. 8) cluster as magnesium–sulfate water-quality type. The pond sample (blue symbol, fig. 8) is also magnesium–sulfate type but is richer, proportionately, in magnesium. This may indicate a larger portion of the water in the pond is from recent precipitation as compared to the older coal aquifer water and spoils aquifer groundwater, or it may well indicate calcium uptake by diatoms in the pond water column. The coal aquifer water samples (black symbols, fig. 8) are balanced between magnesium–calcium and sulfate–bicarbonate. Two coal aquifer water samples plot as sodium–bicarbonate, KCSW-09A (McKay coal) and -09B (Rosebud coal), which is the geochemical signature of mature coal aquifer water.

Predicted vs Actual Water Chemistry Changes

Predictions of post-mining spoils water quality used in the permitting process are based upon column leach experiments, batch reaction vessels, or saturated paste extractions (Van Voast and Reiten, 1988). These tests give an indication of the ratio of available salts in the spoils, but in the field, the actual availability and concentrations can vary significantly. Additionally, these tests do not account for the source of recharge water. Predictions of water-quality trends along flow paths based on these laboratory scale tests included an empirical curve of increasing salinity with distance along a flow path. Based upon these trends, it was commonly included in pre-mining permits that the water quality would return to pre-mining salinity levels after one or two pore volumes of water had passed through the spoils. The return to pre-mining levels was documented in one location (fig. 7). The timeframe was on the order of several decades. Because nearly all spoils aquifer tests were single well tests and did not include storativity, no estimate of pore volumes can be made for this area.

Overview of Decker Area Mines

Multiple mines have operated near Decker (figs. 1, 3) within the areas of hydrogeologic studies conducted by the MBMG. A groundwater monitoring network, initiated in the 1970s and adjusted many times, is still active. The first major Decker area mine, the West Decker mine, opened in 1972. A small test pit, the Ash Creek mine, opened in 1976. The East Decker mine opened in 1977, and the North Decker pits began producing in 1991. The Spring Creek mine opened in 1979. As of 2018, the only active mining is from the East Decker pits and Spring Creek mine. The others are either being reclaimed or reclamation has been completed.

All mining in the Decker area has been within the Anderson–Dietz coalbeds. These coals split and merge into different configurations near the Montana–Wyoming state line (Van Voast and Reiten, 1988). This configuration has made it difficult to correlate coalbeds across the basin.

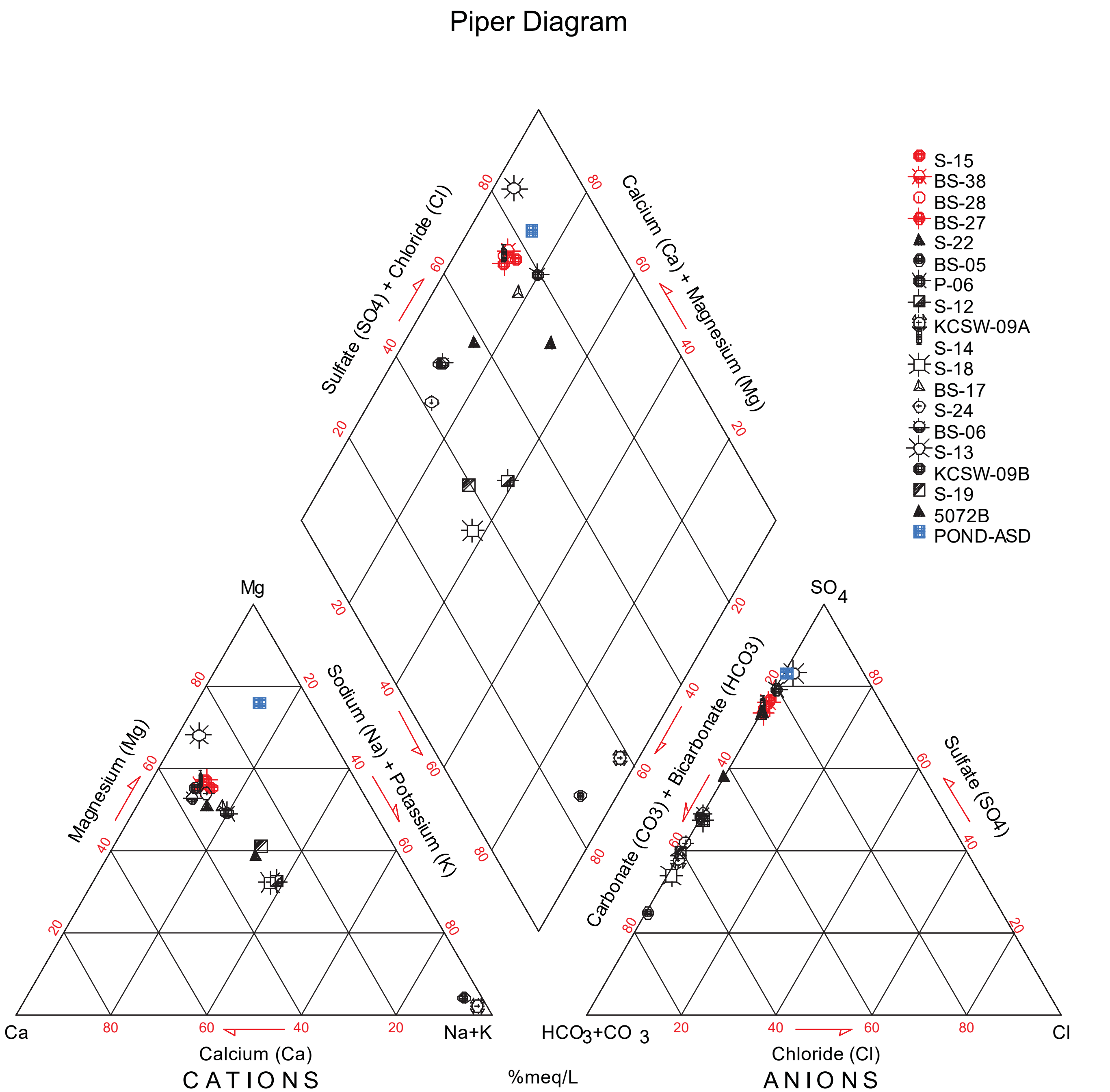


Figure 8. The geochemistry of the spoils aquifer water (red symbols) is similar to that of the surrounding coal aquifers (black symbols): magnesium/calcium–sulfate. The pond has proportionately more magnesium and may therefore represent more shallow runoff from precipitation. One coal aquifer monitoring site, KCSW, has a sodium-bicarbonate type water, dissimilar to the surrounding coal and indicative of mature coal aquifer groundwater.

Direct Impacts

Water level in mined coalbed aquifers lowers in response to mining, and rises as the mine pit is backfilled. The potentiometric depression is largest adjacent to the open mine pit and decreases with distance from the pit. Near Decker, areas of depressed water levels converged to form a combined area as much as 5 mi north/south and 15 mi east/west (Van Voast and Reiten, 1988). Drawdown of as much as 10 ft was recorded at a distance of 5 mi from the Decker mines after 30 years of mining (Wheaton and Metesh, 2002).

Underlying aquifer drawdown. Groundwater-level drawdown due to open mine pits is also documented in underlying aquifers (Van Voast and Reiten, 1988; Van Voast, 1974). This underburden drawdown in some cases exceeds that measured in the mined coals. The pathway for this migration of hydrostatic pressure may be, at least in part, due to water movement through exploration boreholes. In one study area, mine maps indicated as many as 5,000 exploration holes in a 10-mi^2 area. Calculations suggest leakage at a rate of 0.7 gpm through individual boreholes, depending on vertical gradient and type of hole-plugging material used (Wheaton and Reiten, 1996). Differences in aquifer storativity may also explain greater drawdown in the underburden.

Mined coalbed drawdown. In the vicinity of the East Decker mine, water levels in the Anderson, Dietz 1, and Dietz 2 coalbeds have been monitored since the 1970s at several sets of wells, including WRE-27, WRE-28, and WRE-29 (fig. 9A; Van Voast and Hedges, 1975). All three seams are mined at East Decker. Prior to mining, water levels above the bottom of the coal were 18 ft for the Anderson coal (WRE-27); 82 ft above the bottom of the Dietz 1 coal (WRE-28), and 130 ft above the bottom of the Dietz 2 (WRE-29). The coalbeds are exposed along the face of the mine pit and water levels at that point are at the base of each individual coalbed. The mine pit opened at nearly 2 mi from this well cluster, and advanced from 1977 until 1989 to within just over a half mile. The pit has not advanced since then. Because the starting head was higher than the other coals, the largest mining-related drawdown in this area occurred in the Dietz 2 coal. Drawdown was least in the Anderson coal. Once the pit advance stopped, the water-level drawdown also

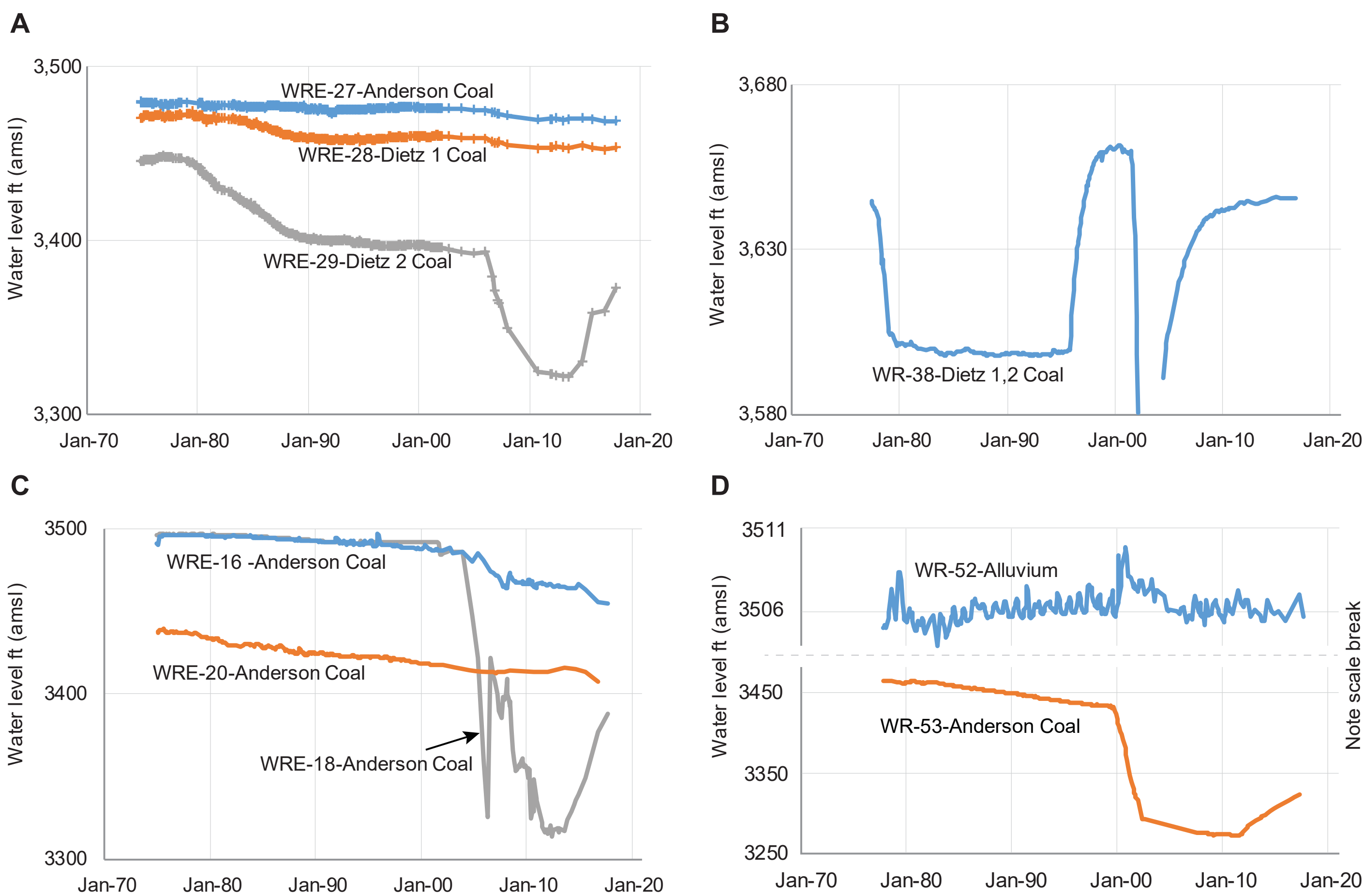


Figure 9. Groundwater levels in the Decker, Montana area respond to long-term climate, coal strip mining, and coalbed-methane production. Well locations are shown in figure 1.

stopped. Some drawdown is seen in the Dietz 2 (WRE-29) after 1993, which may relate to the expansion of an adjacent pit in the East Decker mine (fig. 9A).

Water-level declines occurred here in response to both the proximity of the open mine pit and the duration. As the mine pit moved closer, progressively steeper areas of the cone of depression reached the well site. Even if the location of the pit does not move, a cone of depression will continue to expand as the aquifer is drained until a source of groundwater recharge is encountered.

A small mine pit was opened in 1976, and water-level responses were shown in several studies, including Van Voast and Reiten (1988). The mine pit was left open and kept dewatered by pumping for 15 yr. Water levels in the Dietz coal, measured at WR-38, show the entire mine-related drawdown and recovery (fig. 9B). This well was installed shortly after the mine pit was opened, but the baseline water level is estimated to have been approximately 3,660 ft-amsl based on recovered water levels. Recovery of the 60 ft of drawdown occurred within about 4 yr. The mirror image of drawdown and recovery recorded at this well has been used as a model for understanding mine impacts because it is one of the few locations where the entire record is available from a single well. Precipitation during this recovery period, based on the Sheridan Field Station (Western Regional Climate Center, 2018), averaged 15.1 in per year, which is also the long-term average for the 82-yr period of record at this station.

Effects of faults. In the Decker area, faults offset flow paths and smear plastic clays across boundaries. They are described as blocking groundwater flow. A line of monitoring wells was installed just south of the East Decker mine by Van Voast and Hedges (1975) to investigate fault control. Ongoing water-level data show the effect clearly (fig. 9C). WRE-16 and WRE-18 are both completed in the Anderson coal, across a fault from mining. WRE-20, also completed in the Anderson coal (fig. 9C), is located on the mine side of the fault. From 1975 until 2001, water levels on the side farthest from the mine decreased slowly at an average slope of 0.3 ft/yr. Since the mine pit advanced toward the well site, the starting and the most recent distances are given. Across the fault, a total of 9 ft of drawdown was measured at a distance of from 5,200 to 2,300 ft from the mine at WRE-16, and 6 ft at a distance of 5,700 to 2,700 ft for WRE-18. On the side of the fault nearer the mine pit, the water level in the Anderson coal dropped at an average slope of 0.8 ft/yr. This was a total decrease of 21 ft as mining moved toward the well from 4,500 to 1,300 ft. As previously considered, the fault did not stop, but did reduce migration of mine drawdown. [The water-level drawdown after 2005 (fig. 9C) is discussed in the coalbed-methane section of this chapter.]

Drawdown in alluvium. Van Voast and Reiten (1988) noted that while drawdown extends horizontally for miles, vertical migration of drawdown to overlying alluvial aquifers has not been observed. Drawdown in the Anderson–Dietz coal has extended beneath Squirrel Creek (WR-53) but has not been reflected in the alluvial water levels (WR-52D; fig. 9D). Between 1977 and 1999, water levels in the coal dropped 32 ft (WR-53). During the same time, water levels in the alluvium showed no related response (WR-52D; fig. 9D).

Residual Impacts

Spoils water-level recovery. One of the early mining areas, opened in the early 1970s, was in the southeast portion of West Decker. Wells installed in this area as part of early MBMG studies and reported on by Van Voast (1974) continue to be monitored. Water levels in spoils aquifer monitoring well DS-03 rose 40 ft in 2 yr (1976–1978) in response to mine backfilling operations (fig. 10A). Initial saturation of the spoils aquifer monitored by well DS-07A occurred quickly: water levels rose more than 10 ft from 1978 to 1979 (fig. 10B). Following that initial saturation, seasonal fluctuations driven by water levels in the adjacent Tongue River Reservoir and periodic mine dewatering dominate this aquifer. As the rest of this mined area was backfilled, a long-term rise in the spoils aquifer water level occurred, overprinted by the seasonal fluctuations. The long-term rise has continued at both wells at an average rate of about 0.5 ft/yr. Original groundwater flow was from southwest to northeast, discharging to the Tongue River and the reservoir. Mining reversed that locally and the reservoir recharges spoils during high-water-level times of the year (Van Voast and Reiten, 1988). However, the reservoir water level fluctuates as much as 20 ft per year, compared to the spoils aquifer that fluctuates less than 5 ft. Due to the magnitude of annual fluctuations, when the reservoir water level is lowest, it is below the spoils water level, potentially allowing the groundwater flow to again discharge to the river and reservoir.

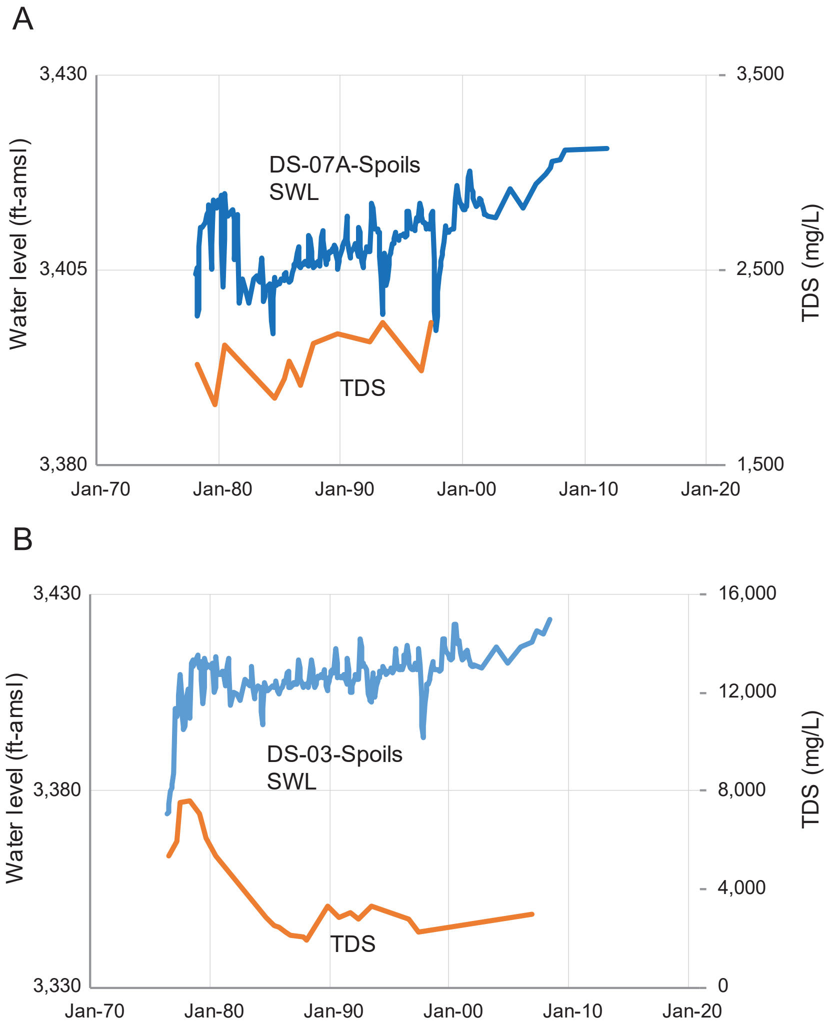


Figure 10. Saturation of mine spoils near Decker, Montana initially mobilizes available salts, and then flushes the salts, allowing the total dissolved solids concentration to return to approach pre-mining levels. Well locations are shown in figure 1.

Spoils water-quality recovery. Water quality in the spoils aquifer is generally more saline than the groundwater in surrounding, undisturbed aquifers due to dissolution of newly available salts in the spoils. But as the aquifer is flushed over time, the TDS concentration decreases (fig. 10B). Baseline water quality of Decker area spoils aquifers in 1975 and 1976 had TDS concentrations of between 1,000 mg/L and 5,800 mg/L (MBMG, 2018). The salinity of spoils aquifer samples collected in the 1990s ranged from 1,000 mg/L to 3,700 mg/L. The lowest salinity values likely reflect mixing of recharge from the Tongue River Reservoir due to the groundwater gradient reversal. The dominant ions in both the baseline data and the spoils water quality are Na and HCO_3. However, the decrease in TDS appears to be the result of decreasing concentrations of Na and SO_4.

The dominance of sodium ions in the spoils water quality in Decker mines, as compared to magnesium and calcium in Colstrip mine spoils, is due to differences in the mineralogy of the overburden units. Ion exchangeable sodium concentrations from solid-phase samples in Decker are about an order of magnitude higher than those from Colstrip, though the calcium and magnesium concentrations are similar (Clark, 1995).

COALBED METHANE HYDROGEOLOGIC RESPONSES

Commercial production of CBM began in Montana in April 1999 near the Decker coal mines (fig. 3). In 2008, there were over 670 producing coalbed-methane wells in the Powder River Basin of Montana, which produced over 1,000,000 MCF per month (thousand cubic ft per month) of methane gas; by 2017 that number had fallen to 37 wells and less than 60,000 MCF/month (fig. 11; Kuzara and others, 2017; MBOGC, 2018). From 2007 through 2015 coalbed-methane production in Montana withdrew 207 million barrels (26,700 acre-ft) of water from coal aquifers.

Coalbed-methane production is water intensive because it requires lowering hydrostatic head in the coal aquifer in order to release the trapped methane. Methane is held on the surfaces of the coal by weak van der Waals forces supplemented by water pressure. Groundwater is typically pumped at a rate and scale that reduces water pressure to a few feet above the top of each coal seam over large areas. Reducing the water pressure within the coalbeds allows the gas molecules to desorb from the coal. The gas then migrates toward lower pressured areas of the coalbeds. Water production from coalbed-methane wells lowers the hydrostatic pressure within the area of the cone of depression. In turn, the wells are also the centers of the low gas pressure and the destination of the migrating methane. Coalbed-methane wells perform two simultaneous functions: pump water to generate free gas and collect that gas.

Since CBM production brought very large quantities of water to the surface in a semi-arid environment, water management was a major concern. The stated goal of water management was to minimize waste of the water resource, minimize impacts to other resources, and minimize cost to the companies. This water

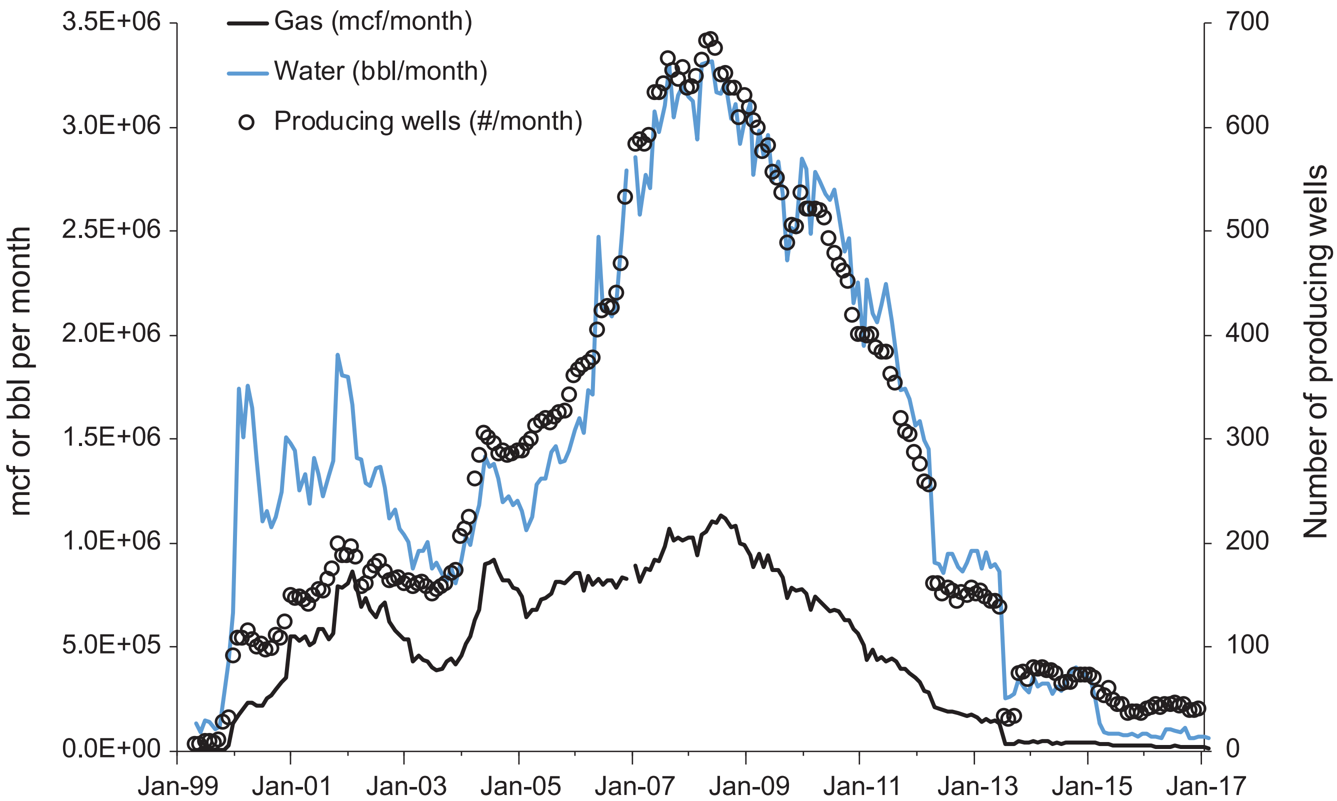


Figure 11. CBM production in Montana, including the number of wells (circles), the amount of water (blue line), and the amount of gas (black line), peaked in 2008 and has remained at a reduced rate since 2013. Modified from Kuzara and others (2017); used with permission.

was managed at the surface through a combination of methods, including: infiltration impoundments, evaporation (lined) impoundments, direct discharge to streams, reverse osmosis and ion exchange treatment followed by discharge to streams, irrigation application with soil amendments, and subsurface irrigation with water and soil amendments, among others. Additional information on specifics and differences in success of each of these is available in other publications, including Stine (2005), National Research Council (2010), and Zoback (2005).

Once the well no longer produces economical quantities of gas, water pumping is terminated. Water remaining in the coalbed will naturally redistribute and groundwater levels and pressures will partially recover within the coal. Water levels in monitored wells in areas of discontinued CBM development returned to 70 to 80 percent of baseline within 5 yr; the rate of recovery then slowed, making predictions of time to full recovery difficult (Kuzara and others, 2016; Meredith and others, 2012).

Coalbed-methane reclamation falls under Montana Board of Oil and Gas Conservation rules. These rules address concerns about the effects of development upon the groundwater in the area (MBOGC, 1999). Rules address spacing, well completion, assessment of water resources, water mitigation agreements, water monitoring plans, water-quality reporting, production reporting, and public notification. CBM operators are required to offer water mitigation agreements to water well and/or spring owners within at least 0.5 mi of a proposed CBM field. This boundary is automatically extended 0.5 mi beyond any adversely affected well or spring.

To address the water quantity and quality concerns surrounding CBM development, the MBMG maintains a network of over 200 monitoring wells and springs in the Powder River Basin. The network was initiated to document baseline hydrogeologic conditions in current and prospective CBM areas in southeastern Montana, to determine actual groundwater impacts and recovery, to help present factual data, and to provide data and interpretations to aid environmental analyses and permitting decisions. The current monitoring network consists of a combination of monitoring wells installed in response to coal mining and CBM production. The field measurements and water-quality analyses are stored on the GWIC database (MBMG, 2018) and presented and interpreted annually in a publicly available report (see appended: Coalbed Methane Bibliography).

Water-Level Drawdown

Hydrostatic heads in the Dietz coal were lowered as much as 150 ft or more within areas of production. The potentiometric surface in the Canyon coal was lowered more than 600 ft. During the peak CBM production years, the 20-ft drawdown contours for both the Dietz and Canyon coals extended approximately 1.0 to 1.5 mi beyond the boundary of the CX field (Kuzara and others, 2016). These distances are somewhat less than originally predicted in the Montana CBM environmental impact statement and initial groundwater modeling efforts (U.S. Department of the Interior, Bureau of Land Management, 2003, 2008; Wheaton and Metesh, 2002).

Early computer modeling of the groundwater response to CBM development (Wheaton and Metesh, 2002) indicated that water levels would initially rapidly recover as CBM production decreased, with recovery slowing as the water levels approached the original static level. Wheaton and Metesh (2002) included recharge from vertical leakage from streams and overlying rock units in model construction; however, vertical hydraulic conductivity has not been quantified in the Powder River Basin and is an important unknown quantity in models constructed for the Fort Union aquifers. Future modeling efforts likely should not include vertical recharge unless it has been documented.

Faults tend to act as barriers to groundwater flow and migration of drawdown across fault planes is rarely seen (fig. 9C); however, computer modeling of the Ash Creek mine area shows that the hydraulic conductivity of faults can vary significantly along their length from impermeable to permeable (Meredith and others, 2011). Vertical migration of drawdown tends to be limited by shale layers. The strong controlling role faulting plays in water-level drawdown is evident in the 2015 potentiometric surface in the Decker area. Coalbed-methane production in Wyoming has resulted in the water flow direction in some fault blocks reversing direction (fig. 12; Kuzara and others, 2016).

Water-level recovery in some wells began in 2004 due to the discontinuation or reduction in nearby CBM production (e.g., figs. 9A–9D; Kuzara and others, 2016). The extent of drawdown and rate of recovery are related to the rate, intensity, and continuity of

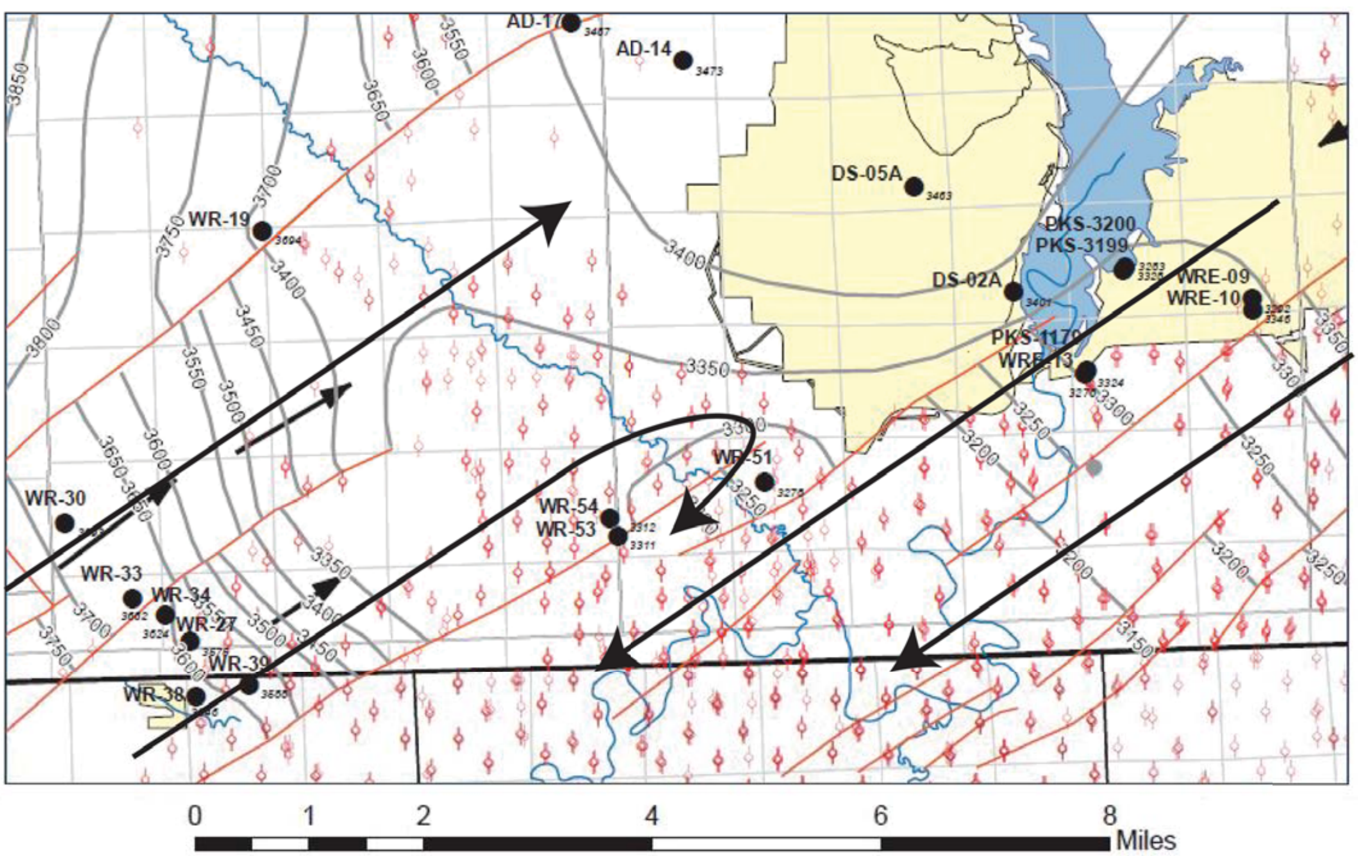


Figure 12. The direction of groundwater flow was reversed along some fault blocks due to CBM production drawing the water level down (arrows show approximate direction of groundwater flow; shut-in CBM wells are shown in red; producing CBM wells are gray circles). Faulting acts as a barrier to groundwater movement, making these sharp changes possible. The potentiometric surface for the Anderson coal aquifer was drawn using MBMG monitoring wells in the area (black circles; not all shown; this is a detail from plate 1 of Kuzara and others, 2016). Modified from Kuzara and others (2016); used with permission.

CBM development; site-specific aquifer characteristics, including the extent of faulting and proximity to recharge areas; amount, timing, and location of precipitation; and other significant groundwater withdrawals such as by coal mining. While recovery has been observed in many CBM fields, some coal aquifer groundwater levels continue to drop despite the discontinuation of nearby CBM production in 2015 (Kuzara and others, 2016).

Water Quality Considerations

CBM produced water quality concerns in Montana are linked to treated and untreated discharge to streams, the infiltration to groundwater from impoundments, and impact to soils. The primary concerns stem from the high sodium adsorption ratio (SAR), the ratio of sodium to calcium and magnesium, of CBM produced water. Produced water can have SAR values between 40 and 60 with total dissolved solids concentrations between 1,000 and 2,000 mg/L. The production water is typically of acceptable quality for livestock; however, its high SAR makes it undesirable for direct application to soils. Sodium, when not balanced by divalent cations, can disrupt soil structure important to fertility and permeability. Irrigators were particularly concerned that CBM produced water discharges to the Tongue River may reduce its suitability for irrigation. In response to these concerns, direct discharge of CBM produced water was limited through regulatory authorities. Stream water quality was monitored by the USGS, and a statistically significant increase of SAR was not found on the main stem of the Tongue River, but was found in the Powder River and some tributaries at low flow (Sando and others, 2014). A soils study along the Tongue River Valley found irrigation with Tongue River water that had a component of CBM water within the regulatory limits had a low likelihood of impacting soils. Further information is included in the final report (Osborne and others, 2010).

Impoundments, used extensively throughout the Powder River Basin, can be constructed either on or off existing channels, and can be lined or unlined. Depending upon the pond-site location, the infiltrating water from unlined ponds can mobilize significant levels of soluble salts from the soil and geologic material. Ponds constructed on existing drainages were found to have smaller salinity spikes in the groundwater below them than ponds constructed off existing channels. Typically, the salinity increases include high levels of calcium and magnesium, resulting in lower SAR values in the affected groundwater, and higher salinity.

The timeframe for the salinity spikes to dissipate depends upon the pond site, local soil types, initial coproduced water chemistry, infiltration rate, and groundwater flow rates. Groundwater below ponds in a Wyoming study typically returned to baseline salinity levels after 1 to 5 yr of use; however, some of the monitored ponds did not return to baseline in the 5-yr study period. Some ponds have been shown to have reduced infiltration with time due to the interaction of the sodium in the coproduced water with the clays in the pond floor. This limits the useful capacity of a pond considerably and illustrates the importance of proper site selection (Brinck and Frost, 2007; Brinck and others, 2008; Healy and others, 2011; Jackson and Reddy, 2007a,b; Meredith and others, 2012; McBeth and others, 2003; Milligan and Reddy, 2007; Patz and others, 2006; Wheaton and Brown, 2005; Wheaton and others, 2005; WDEQ, 2011).

The concern for the degradation of groundwater due to infiltration from ponds drove the development of the MBMG alluvial groundwater-quality monitoring along streams in the Powder River Basin. Semi-annual sampling illustrates the naturally high variability of total salinity in some of the alluvial systems (fig. 13). When upward trends in salinity were measured, additional upgradient, groundwater sampling sites were added. These additional samples have shown in each case that the increase in salinity has been local and not driven by infiltration of CBM produced water (Meredith and others, 2011).

DISCUSSION

Coal mining and CBM production are slowing in the Powder River Basin (fig. 11 and Gunderson and Wheaton, 2020). The hydrogeologic legacy of coal-related development includes lowered water levels and mobilized salinity in groundwater. Though permitted based in part on restoration of the hydrologic system, the duration of the development-related impacts is not yet known. Long-term monitoring has been key to identifying extent of drawdown, distinguishing the sources of drawdown, identifying sources of recharge, describing natural variability as compared to contamination, and accounting for climatic influences. The nearly 50-yr history of water-level and water-quality monitoring, in conjunction with ongoing monitoring and interpretation of the collected information by

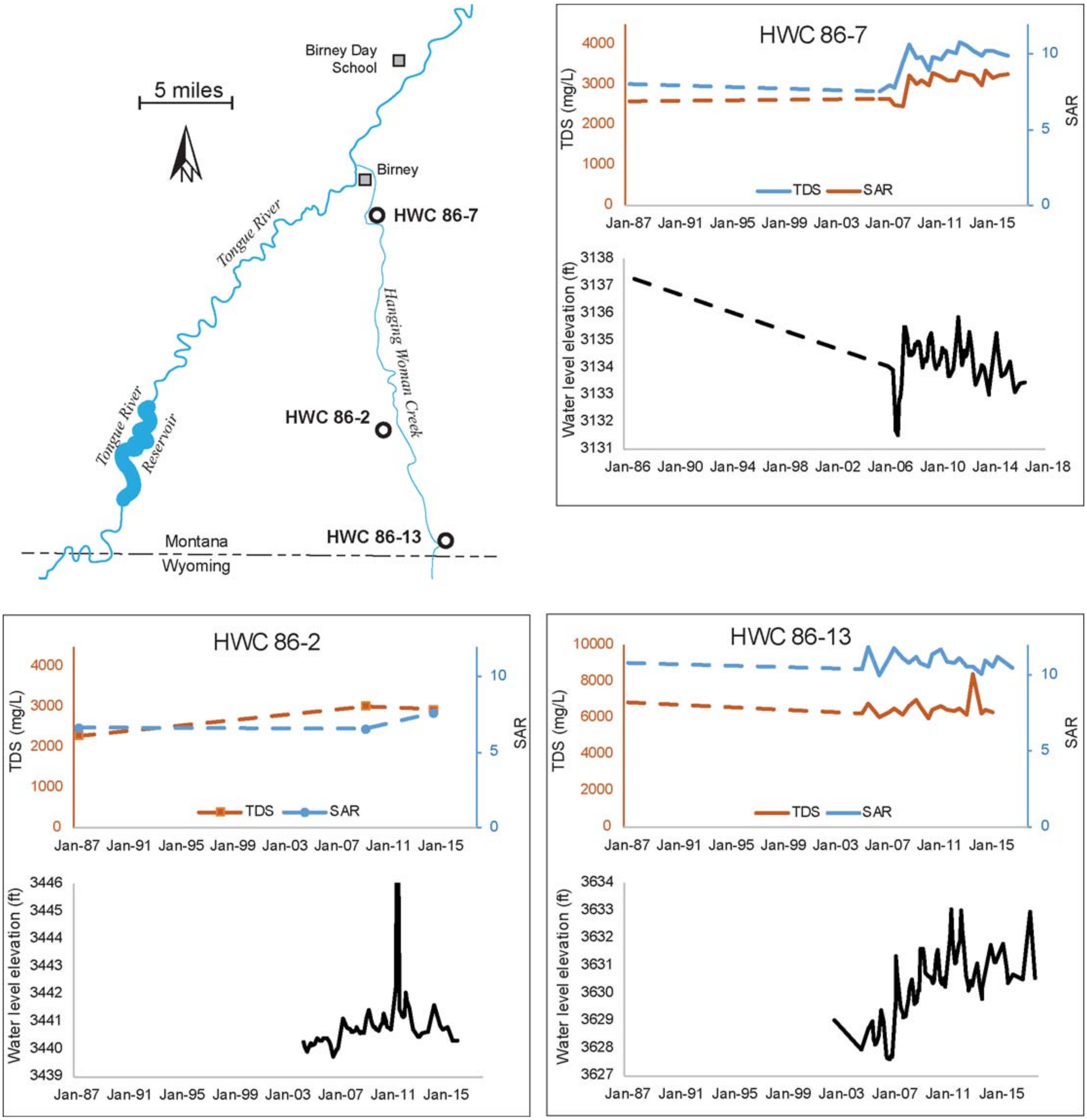


Figure 13. Upward trends in the salinity and SAR seen in well HWC 86-7 were not mirrored in upgradient wells HWC 86-2 or HWC 86-13, which indicates the CBM development in Wyoming is unlikely to be the cause. Modified from Meredith and others (2011); used with permission.

hydrogeologists, provides the basis for predicting and identifying the reestablishment of hydrologic function.

The groundwater monitoring network established around coal mining activities proved flexible enough to adapt to new groundwater monitoring needs when coalbed-methane production was introduced into Montana in 1999. The geologic and hydrogeologic data archived by the MBMG from the first 30 years of the program became the foundation for CBM exploration. The understanding of coal aquifer hydrogeology developed by the MBMG coal program was used in drafting the CBM environmental impact statements (U.S. Department of the Interior, Bureau of Land Management, 2003, 2008), and establishing a cross-state interagency working group to address technical issues surrounding groundwater impacts from CBM

(U.S. Department of the Interior, Bureau of Land Management, 2012). Few other examples of such long-term monitoring programs exist, and the value of these continuous records cannot be overemphasized (Van Voast and Reiten, 1988).

Over the years, the MBMG coal hydrogeology program has included coordination and cooperation from numerous State, Federal, and private agencies, researchers, and funding sources. The results of the MBMG coal program monitoring have been used at the Federal level at the U.S. Supreme Court (Supreme Court of the United States, 2011), at the State level to evaluate coal and CBM permits, and locally to identify drilling locations for stock wells as well as to distinguish natural variability from energy development impact in response to landowner inquiries.

ACKNOWLEDGMENTS

Data collection for the long-term monitoring around coal and coalbed-methane development has relied on a number of Montana Bureau of Mines and Geology staff starting in the late 1960s. We especially wish to recognize the role of Wayne Van Voast. Wayne realized the importance of long-term monitoring and the need for sound science from a neutral party for resource management decision making. By 1972 Wayne had established the MBMG coal hydrogeology monitoring program, which continues to this writing. Additional data used in hydrogeologic interpretations come from the coal mine and CBM operators. Exchange and comparison of collected data between the agencies, the companies, and the Montana Bureau of Mines and Geology add credibility and cohesiveness to the data and reporting. The authors thank everyone involved for ensuring the high level of quality data, and Tom Osborne and Peter Bierbach for improving this chapter through their reviews.

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