5.0 GROUNDWATER RECOVERY

Groundwater in the eastern PRB is projected to recover to near pre-mining and pre-CBNG development levels once these industrial uses of groundwater have ceased. Because neither activity is expected to be completed by the year 2020, estimates of groundwater recovery are longer term and are based on assumed dates for the cessation of CBNG development and coal mining in the eastern PRB. For CBNG development, it was assumed that CBNG development and associated groundwater pumping and discharge in the eastern PRB would end in 2030. This assumption was based on the currently projected rate of CBNG development through 2020 and the expected decline in gas reserves in the coal seams of the eastern PRB. For coal mining, it was assumed that open-pit coal mining and associated dewatering of the Fort Union and Wasatch Formations in advance of mining, as well as mine reclamation, would end in 2050. The BLM selected this date based on the currently projected rate of coal mining through 2020 and because of the lack of geologic data needed to extend coal mining projections much beyond 2050. Therefore, for modeling purposes, groundwater recovery related to the cessation of CBNG development started in year 2030, with CBNG-related groundwater pumpage and discharge rates remaining constant at the projected 2020 rate from year 2020 to year 2030. Groundwater recovery related to the cessation of coal mining started in year 2050, with groundwater pumpage rates remaining constant at the projected 2020 rate from year 2020 to year 2050.

Groundwater recovery following cessation of CBNG pumping in 2030 was modeled by letting the CMGM resaturate with groundwater after all CBNG wells had been turned off, but with the coal mines continuing to remove groundwater at the 2020 rate up to the year 2050. For recovery after the cessation of coal mining in 2050, the CMGM was allowed to resaturate with no dewatering of the mines and no pumping by CBNG wells. Also, the municipal wells at Gillette were turned off in the CMGM at year 2050 in order to better evaluate CBNG and coal mining effects. The full resaturation of the CMGM thus began in year 2050.

For the resaturation modeling to estimate groundwater recovery in the eastern PRB, recharge from regional precipitation was continued in the model based on precipitation recharge for year 2020. All model boundary conditions were left unchanged. MODFLOW drain cells that represented coal mine pit dewatering were replaced with regular model cells to represent the mine pit backfill aquifers that would replace the mine pits as the pits are backfilled with spoils material following cessation of mining. The hydraulic conductivity of the backfill aquifer model cells was set at 0.5 feet per day. This value was selected based on review of published coal mine pit backfill aquifer hydraulic properties for reclaimed coal mines in the western U.S., with emphasis on values from the PRB of Wyoming and Montana (Martin et al. 1988). The recharge to these coal mine pit backfill aquifers was set at 5 percent of precipitation because of the higher porosity of the pit backfill material compared to the bedrock formations (Wasatch and Fort Union) that had been mined.

When the Fort Union and Wasatch formations of the eastern PRB recover to near steady-state conditions, approximately 300 to 500 years following the assumed completion of coal mining in 2050 based on the resaturation modeling, groundwater will flow through the coal mine backfill aquifers and westward into the PRB. This will result in the transport of groundwater with elevated TDS from the pit backfill aquifers into the Wasatch and Fort Union aquifers of the eastern PRB. The extent of the transport of elevated TDS groundwater from the coal mine pit backfill aquifers

westward into the basin was modeled by coupling the CMGM with the U.S. Geological Service fate and transport code MT3DMS (Zeng and Wang 1999).

Data on the TDS in coal mine pit backfill aquifers was obtained from GAGMO reports (GAGMO 2003, 2000). Each of the coal mine pods in the three coal mine subregions was assigned a starting TDS value for transport modeling purposes based on the average TDS in pit backill aquifers available from the GAGMO reports. For modeling purposes, it was assumed that the starting TDS would remain constant through time, thus resulting in a conservative estimate of the extent of transport of elevated TDS westward from the mines. In reality, the TDS in the pit backfill aquifers will decrease with time due to repeated flushing of the backfill aquifers by groundwater and infiltration of precipitation. According to Martin et al. (1988), the pit backfill aquifers may be flushed after two to three pore volumes of groundwater have passed through the aquifers. Assuming a maximum of 5 pore volumes is needed to reduce the elevated TDS to a value below 1,000 mg/L, and assuming it takes approximately 100 years for each pore volume flush, the coal mine backfill aquifers are anticipated to have a TDS well below 1,000 mg/L after 500 years.

5.1 Recovery in the Wasatch Formation

Groundwater recovery for the Wasatch Formation was modeled relative to year 1975. This date was selected as a time before coal mines began serious pumping of groundwater and before CBNG pumpage. Thus, 1975 represents near steady-state for the eastern PRB in the CMGM model for the Wasatch Formation.

5.1.1 Year 2050

Figure B-43 in Appendix B presents modeled groundwater levels in the eastern PRB for year 2050, which is 20 years after the cessation of CBNG pumpage and discharge (2030) and the last year of coal mine pumpage. The groundwater levels show an eastward flow of groundwater in the Wasatch south of Wright, with Antelope Creek acting as a gaining stream (i.e., receiving flow of groundwater). East of Wright, groundwater flow turns northward and flows west-northwest toward Montana and out of the model domain. Groundwater flows into the Subregion 3 coal mines. For the Subregion 2 coal mines, groundwater flows northward through the mine areas, and there is a groundwater mound west of the mines that is the result of past CBNG discharge. The area south of Gillette shows the effect of municipal pumpage, which stops in 2050 in the modeled resaturation scenario. Groundwater in the Subregion 1 coal mines flows northwestward through the mines.

Figure B-44 in Appendix B shows the modeled groundwater level changes relative to 1975 in the Wasatch Formation for year 2050. Groundwater drawdown exists around the Subregion 3 coal mines due to continued pumpage by the mines through 2050. Some of the drawdown isopleths are west of the base year (2002) extent of mine workings; however, they are within the projected extent of mine workings for 2050. The Subregion 2 and Subregion 1 coal mine areas show very little drawdown, suggesting that groundwater levels by 2050 are nearing those of 1975. Up to 20 feet of drawdown exists in the Wasatch south of Gillette, due to past municipal pumpage.

5.1.2 Year 2100

Figure B-45 in Appendix B shows the modeled groundwater levels in the eastern PRB model domain for year 2100, which is 50 years after cessation of coal mining and 70 years after cessation of CBNG pumpage and discharge. The groundwater flow patterns are similar to those for year 2050. Groundwater flows into Antelope Creek, which is a gaining stream. Groundwater in the Wasatch flows into the reclaimed mine pits for the Subregion 3 coal mines, as it did in 2050. For the Subregion 2 and Subregion 1 coal mines, groundwater flows north to northwest through the reclaimed pit areas. There is still a groundwater mound west of the Subregion 2 mines, and there is still residual drawdown in the Wasatch south of Gillette. Groundwater flow south of Wright is to the east-northeast, toward the Subregion 3 coal mines. North of Wright, groundwater flow is north to northwest.

Figure B-46 in Appendix B shows the modeled groundwater drawdown for year 2100 relative to the pre-mining steady-state year of 1975. Drawdown around the Subregion 3 coal mines is up to 40 feet in the western extension of the mine pit areas. There is little drawdown around the Subregion 2 and Subregion 1 coal mines. There is residual drawdown of up to 20 feet south of Gillette.

5.1.3 Year 2250

Figure B-47 in Appendix B shows the modeled groundwater levels and groundwater flow patterns in the Wasatch for year 2250, which is 200 years after cessation of coal mining (2050) and 220 years after cessation of CBNG pumpage (2030). Groundwater flow patterns are similar to those found in the model results for year 2100. Antelope Creek is a gaining stream, and groundwater south of Wright flows northeast into the Subregion 3 reclaimed coal mine areas. North of Wright, groundwater flows northwest toward Montana. In the Subregion 2 and Subregion 1 coal mine areas, groundwater flows northwest through the reclaimed mine areas. A groundwater depression still exists south of Gillette, and a slight groundwater mound is present west of the southern group of mines in Subregion 2.

Figure B-48 in Appendix B, which shows the modeled drawdown for year 2250, shows that the modeled drawdown in the western extension of the reclaimed mine pits in Subregion 3 has decreased to 10 to 20 feet. There is still a slight drawdown around the Subregion 1 and Subregion 2 coal mines and south of Gillette.

5.1.4 Steady-state for the Wasatch Formation

Figure B-49 in Appendix B presents the modeled steady-state for the Wasatch Formation following recovery. Groundwater levels are projected to rebound and reach approximately 80 percent of steady-state in 300 to 500 years after the cessation of coal mining, which places it around 2350 to 2550. Groundwater flow paths are similar to those modeled for year 2250 (**Figure B-47**). South of Wright, groundwater in the Wasatch flows to the northeast toward the Subregion 3 coal mines. Antelope Creek is a gaining stream, with groundwater flowing into the stream from the Wasatch aquifer. Groundwater flows into the reclaimed Subregion 3 coal mines in the Wasatch in part because the reclaimed mine pits have not fully recovered and reached steady-state. Recovery occurs somewhat faster west of the mine pits because of the merging of stratigraphic databases

and in part due to lower hydraulic conductitivity values for the Wasatch than are found in the reclaimed pit backfill aquifers. For the Subregion 2 and Subregion 1 coal mines, groundwater flows northwest through the reclaimed mines. North of Wright, groundwater flows to the northwest into Montana. A slight groundwater mound continues to exist west of the Subregion 2 coal mines, and a slight groundwater depression continues to exist south of Gillette. There is no remaining residual drawdown compared to 1975.

Overall, the Wasatch Formation is projected to recover from CBNG pumpage and discharge and coal mine dewatering in approximately 300 to 500 years (**Figure B-49**). This recovery is a modeled recovery, and the assumption in the CMGM is that the Wasatch is a continuous aquifer. In reality, the Wasatch is not a continuous aquifer, but a complex fluvial/deltaic depositional system with local areas of groundwater and sometimes fairly continuous zones of groundwater within sand lenses. These areas of groundwater may recover faster than has been estimated by the CMGM model, or in some cases, they may take longer than the model-estimated 300 to 500 years. Therefore, the estimated steady-state for the Wasatch of 300 to 500 years is approximate and based on assumptions that were required for construction of the CMGM that may not apply to all areas of the Wasatch. Also, the Wasatch would continue to be used for stock water and locally for domestic water supply following the end of coal mining and CBNG development. Recovery modeling assumed that no use of groundwater in the Wasatch would continue after year 2050. Thus, some areas of the Wasatch may recover very slowly to pre-mining or pre-CBNG groundwater levels.

5.2 Recovery In The Upper Fort Union Formation

Groundwater recovery for the Fort Union Formation was modeled relative to year 1975. This was a time before coal mines began serious pumping of groundwater and before CBNG pumpage. Thus, 1975 represents near steady-state for the eastern PRB in the CMGM model for the Fort Union Formation.

5.2.1 Year 2050

Figure B-50 in Appendix B shows the modeled groundwater levels in the Fort Union for year 2050. As with the Wasatch Formation, year 2050 represents the time of cessation of coal mining and 20 years after cessation of CBNG pumpage and discharge. Groundwater flow south of Wright is to the northeast toward the Subregion 3 coal mines. In the vicinity of the coal mines, the groundwater flow patterns are complex due to pumpage by the mines. Groundwater flows into the reclaimed mine areas. Between the coal mine group on the north and the one to the south in Subregion 3, there is a small groundwater high resulting from overlapping drawdown areas from the two mine groups. Northwest of the northern group of coal mines in Subregion 3, there is a groundwater high that may be the result of drawdown between the high and the coal mines (see **Figure B-51**). Groundwater flow in the vicinity of the Subregion 2 coal mines is toward the mines; however, west of the mines, groundwater flow is to the northwest. In the Subregion 1 coal mines, groundwater flow is to the northwest and through the mined areas. There is a groundwater depression northeast of Gillette. Along the southeastern boundary of the model domain, groundwater in the Upper Fort Union east of the Subregion 3 mines flows eastward out of the model domain due to the general head boundary along that part of the model boundary. East of the Subregion 2 coal mines, groundwater flow in the Upper Fort Union east of the mines is to the north. North of Wright, groundwater flow is to the northwest.

Figure B-51 in Appendix B shows the modeled residual drawdown in year 2050 compared to 1975 for the Upper Fort Union in year 2050. Drawdown west of the Subregion 3 coal mines is in the range of 10 to 50 feet, with local zones of tight drawdown up to 110 feet centered on the western extent of mine pits. For the Subregion 2 coal mines, there is very tight drawdown up to 120 feet centered on the southern group of mines, and a zone of tight drawdown centered on the western extent of coal mine pits in the southern portion of the northern group of mines. Drawdown west of the Subregion 2 mines is approximately 10 to 20 feet. For the Subregion 1 mines, drawdown is approximately 20 to 40 feet, and for Gillette, residual drawdown is approximately 10 feet in the Upper Fort Union.

5.2.2 Year 2100

Figure B-52 in Appendix B shows the modeled groundwater levels and groundwater flow patterns for the Upper Fort Union in year 2100, 50 years after the cessation of coal mining and 70 years after the cessation of CBNG pumpage and discharge. The groundwater level contours are similar to those for 2050. Flow south of Wright is to the northeast and toward the Subregion 3 coal mines. North of Wright, flow is to the northwest and toward Montana. Around the Subregion 3 reclaimed coal mines, the groundwater level contours indicate continued flow into the former mine pits from the west. East of the coal mines in the Subregion 3 area, groundwater in the Upper Fort Union is flowing eastward and leaving the model domain, suggesting that groundwater in the Upper Fort Union in the southeastern part of the model domain is flowing eastward through the reclaimed coal mines and out of the model domain. For the Subregion 2 coal mines, groundwater flow is northward through the coal mine areas. The same is true for the Subregion 1 coal mines. Around Gillette, a groundwater depression is present east of the town due to pumping of municipal wells. Areas of elevated groundwater levels are present in the Subregion 2 and Subregion 3 coal mine areas that probably are the result of differential drawdown in surrounding areas, leaving residual areas of elevated groundwater levels between the areas of drawdown.

Figure B-53 in Appendix B shows the modeled residual drawdown for year 2100 in the Upper Fort Union. Drawdown exists in most of the same areas as was observed in year 2050 (**Figure B-51**), but to a lesser degree. Drawdown west of the Subregion 3 coal mines ranges from 10 to 30 feet, with localized drawdown up to 45 feet in the western most extension of the former coal mine pits. Drawdown around the Subregion 2 coal mines is 10 to 20 feet, and around the Subregion 1 coal mines the residual drawdown is 20 feet or less. Approximately 10 feet of residual drawdown continues east of Gillette.

5.2.3 Year 2250

Figure B-54 in Appendix B shows the modeled groundwater levels for the Upper Fort Union in year 2250. The groundwater level contours are similar to those modeled for year 2100 (**Figure B-52**). South of Wright, groundwater flow in the Upper Fort Union is to the northeast, toward the Subregion 3 coal mines. This flow continues through the reclaimed mine areas and eastward out of the model domain through the general head boundary condition along the southeastern boundary of the model domain. Groundwater flow for the Subregion 2 mines continues to be northward through the reclaimed mines, and for the Subregion 1 mines, groundwater flow is northwestward through the mines. There is a small groundwater depression east of Gillette, and the areas of groundwater

elevation around and west of the Subregion 3 and Subregion 2 coal mines observed in 2050 (**Figure B-50**) continue to be present. The groundwater mounds found in Subregion 3 and Subregion 2 for year 2100 also are present in year 2250.

Figure B-55 in Appendix B shows the modeled residual drawdown compared to the steady-state year 1975 for the Upper Fort Union in year 2250. Drawdown is considerably less than in year 2100 (**Figure B-53**), and for the Subregion 3 coal mines, the residual drawdown is in the range of 10 to 20 feet. For the Subregion 2 coal mines, drawdown is 10 feet or less. There is no residual drawdown for the Subregion 1 coal mines.

5.2.4 Year 2350

Figure B-56 in Appendix B presents the modeled groundwater levels for year 2350. This would be 300 years after cessation of coal mining and 320 years after cessation of CBNG pumpage and discharge in the Upper Fort Union. The groundwater level contours are similar to those for year 2250 (**Figure B-54**), as would be expected this long after the cessation of coal mining. South of Wright, groundwater flow in the Upper Fort Union is to the northeast, toward the Subregion 3 coal mines. This flow continues into the reclaimed mine areas. East of the reclaimed mines, groundwater flow is eastward out of the model domain through the general head boundary along the southeastern boundary of the model. This eastward flow may be due to a groundwater divide east of the clilnker areas in the Subregion 3 coal mines, resulting in eastward flow for the Upper Fort Union east of the mines. Groundwater flow for the Subregion 2 mines continues to be northward through the reclaimed mines, and for the Subregion 1 mines, groundwater flow is northwestward through the mines. A small groundwater depression continues east of Gillette. Groundwater mounds observed in year 2050, that are the result of model design rather than actual conditions, continue in the Subregion 3 coal mines. Similar mounds are found around the Subregion 2 coal mines. Groundwater flow north of Wright is northwestward toward Montana and out of the model domain.

Figure B-57 in Appendix B presents the modeled residual drawdown compared to 1975 for the Upper Fort Union in modeled year 2350. Little drawdown remains around the coal mines, suggesting that the model is approaching steady-state. For the Subregion 3 coal mines, residual drawdown is in the range of 10 to 15 feet and localized in specific areas of the former mine pits. For the Subregion 2 coal mines, residual drawdown is approximately 10 feet. For the Subregion 1 coal mines, there is no apparent residual drawdown. East of Gillette, there is a residual drawdown of approximately 10 feet.

5.2.5 Steady-state for the Upper Fort Union

Figure B-58 in Appendix B presents the modeled groundwater levels for estimated steady-state for the Upper Fort Union, which is approximately 300 to 500 years after cessation of coal mining. The modeled groundwater level contours are very similar to those for year 2350, as would be expected since there was little residual drawdown for year 2350. The discussion presented for year 2350 (**Figure B-56**) also applies to this figure and to modeled steady-state in the Fort Union. Important features to note are the northeastward flow of groundwater south of Wright that continues into the reclaimed coal mines and the eastward flow out of the model domain for areas east of the mines, due possibly to a groundwater divide east of the clinker zones. East of Wright, groundwater flow

turns north, and north of Wright, groundwater flow in the eastern PRB for the Upper Fort Union is northwestward toward Montana and out of the model domain. For the Subregion 2 and Subregion 1 reclaimed coal mine areas, groundwater flow is north-northwest through the coal mine areas.

Overall, the Upper Fort Union recovers to near steady-state conditions in approximately 300 to 500 years (**Figure B-57**). The estimated final steady-state for the Upper Fort Union is approximately 500 years. Pumpage of groundwater from the Upper Fort Union has been from the coal-bearing zones, either for removal of CBNG or for removal of coal in the coal mines in the eastern PRB that follow the outcrop of the coal along the eastern structural boundary of the PRB. For recovery to occur in the Upper Fort Union, water has to flow back into the coal-bearing formations affected by groundwater removal. In the CMGM model, this recovery is controlled by the boundary conditions of the model, the distribution of recharge, and the overall distribution of hydraulic conductivity and storage in the Upper Fort Union (Layer 5 in the CMGM model). Also, recovery of the Upper Fort Union may take longer than the model-estimated 300 to 500 years. Recovery of a groundwater system that took millions of years to develop often can be a slow process and require more time than that estimated by a numerical model. It is assumed in the modeling of recovery by the CMGM, that all pumpage in the eastern PRB ceases in year 2050. Assuming Gillette continues its municipal pumpage, and other areas of the eastern PRB utilize groundwater in the Upper Fort Union after year 2050, recovery of the groundwater levels in the Upper Fort Union may take longer than the model-estimated 300 to 500 years.

5.3 Transport of Elevated TDS Water From Coal Mine Pit Backfill Aquifers

Based on data in the GAGMO (2003, 2000) reports, the average TDS in coal mine pit backfill aquifers in the PRB is approximately 3,700 milligrams per liter (mg/L), with the highest average value for any coal mine subregion being approximately 4,800 mg/L for Subregion 1. Coal mine pit backfill aquifer water has an average TDS below Wyoming stock water standards (5,000 mg/L). Thus, movement of pit backfill water westward into the Wasatch and Fort Union aquifers would not degrade the water quality of these aquifers relative to use for stock watering. The westward extent of the 1,000 mg/L TDS isopleth after 500 years was modeled to represent the location where the TDS of groundwater leaving the coal mine backfill aquifers would be reduced through groundwater flow and dispersion to a level approximately equal to the current TDS in the Wasatch and Fort Union aquifers. The distance from the reclaimed coal mine pit boundaries after 500 years for the 1,000 TDS isopleths is approximately 1,000 to 2,000 feet for both the Fort Union and the Wasatch aquifers. This distance is approximately the same for all three coal mine subregions in the eastern PRB, because the hydraulic conductivity of the Wasatch and Fort Union aquifers west of the three subregions is approximately the same. Thus, after 500 years (the estimated time for the backfill aquifers to be flushed by groundwater flow) potential impacts to the Wasatch and Fort Union aquifers are projected to be limited to a distance of up to 2,000 feet west of the reclaimed coal mine pits. West of the projected 1,000 TDS isopleth, groundwater in the Upper Fort Union and Wasatch aquifers is projected to be similar to pre-mining conditions.