Ground Water Conditions at the Sypes Canyon Temporary Controlled Ground Water Area

Montana Department of Natural Resources and Conservation

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Introduction

A petition requesting formation of the Sypes Canyon Controlled Ground Water Area (CGWA) was filed with the Montana Department of Natural Resources and Conservation (DNRC) on March 15, 2001 by the Sypes Canyon Homeowner's Coalition. The coalition petitioned for the control area because of concerns over increased residential development and uncertainties about aquifer conditions and recharge. They requested the department to control and prioritize water use, and conduct studies to determine the level of development that can be sustained without impacting existing water users. DNRC agreed that there had been a substantial increase in water withdrawals within the proposed control area, but did not agree that there was evidence that withdrawals had become excessive. Consequently, DNRC designated a temporary controlled ground water area (Figure 1) on April 26, 2002 for the purpose of *"gathering information on aquifer characteristics, aquifer recharge, and aquifer withdrawals to determine if withdrawals exceed recharge and if new wells will impair or substantially interfere with other ground water wells"*. The purpose of this report is to present the results of studies conducted pursuant to this order.

The specific objectives of this report are to:

- describe the hydrogeology of the aquifer system in the control area
- describe and evaluate the causes of ground-water level changes
- estimate a budget of aquifer recharge and withdrawals
- evaluate the effects of increased withdrawals for future developments

Methodology

The information presented in this report provides a basis for understanding how ground-water levels in the CGWA are affected by fluctuating recharge and increasing withdrawals. Information on streamflows, ground-water levels, precipitation and snowpack, geology and water consumption form the basis of this investigation. These data come from studies published by the U.S. Geological Survey and the Montana Bureau of Mines and Geology, masters theses, investigations conducted for water-right applications, the National Weather Service, and GLWQD.

Recharge components of the water budget calculated for the control area include direct infiltration of precipitation, seepage losses from streams, and inflow from bedrock in the Bridger Mountains. Discharge components include consumption of water withdrawn from wells, transpiration by phreatophytes, and ground-water outflow to alluvium of Bridger Creek and the East Gallatin River. Estimates of average monthly precipitation are based on data from the weather station at Montana State University (MSU) in Bozeman and GIS spatial coverage of annual and monthly precipitation obtained from the Natural Resource Information Service (NRIS). Streamflow measurements by Hay (1997) and Hackett (1960) and supplemented by DNRC are used to estimate seepage losses from streams and a ground-water flux calculation is used to estimate ground-water inflow from bedrock. Consumption by withdrawals from wells is estimated from standard guidelines and metered withdrawal records for a subdivision nearby the control area, reference information on plant irrigation requirements and return flows through septic waste disposal systems.

GLWQD measured water levels on roughly a quarterly basis in approximately 130 wells within and nearby the control area during the period of the temporary CGWA. DNRC and GLWQD surveyed locations and elevations of these wells using a survey-grade GPS system. Erickson (1995) and Hay (1997) monitored water levels in 30 wells within and nearby the control area monthly during 1995 and 1996 respectively, and the Montana Bureau of Mines and Geology currently monitor four wells nearby the control area quarterly and post the data on the Ground-Water Information Center Internet site. The Standard Precipitation Index (SPI) (McKee et al, 1993) calculated from a 40-year precipitation record at the MSU weather station in Bozeman and snowpack measured at the SNOTEL station at Brackett Creek are compared with hydrographs of ground-water levels measured in wells to help discern possible effects caused by withdrawals from wells from fluctuations in recharge. SPI is a measure of the variation of precipitation from the long-term mean for different time scales. For this discussion, SPI are calculated for 3 month to 96 month time scales of wet and dry periods to evaluate how precipitation and relative changes in recharge correlate to changes in ground water levels.

Steady-state and transient numerical models of an expanded area are used to investigate the properties of the aquifer system in the vicinity of the control area and to predict effects of future ground-water withdrawals. The steady-state model is constructed using estimates of recharge from precipitation, stream losses and seepage from bedrock, existing withdrawals from wells, and estimates of aquifer properties from aquifer testing and analysis of water-level fluctuations. Water levels in wells measured by the GLWQD and estimates for other wells are calibration targets for the steady-state model. The transient model is used to predict effects of increased withdrawals from wells in undeveloped areas of the CGWA.

Geography and Climate

The CGWA encompasses 4.7 square miles approximately two miles north of Bozeman on the west facing foothills of the Bridger Mountains (Figure 1). There are approximately 300 residences in established subdivisions within the control area on lots that are 2.5 acres on average. The remainder of the control area is undeveloped with a few scattered individual residences. Elevations in the vicinity of the CGWA range from approximately 4,500 feet along the East Gallatin River to nearly 9,000 feet along the crest of the Bridger Range. The CGWA is on an alluvial fan surface that slopes gently from the steeper slopes of the Bridgers to the alluvial plain of the East Gallatin River; a distance of approximately three miles. Vegetation on undeveloped land on the alluvial fan consists of grass, shrubs, and dry land grains. The mountains west of the CGWA are evergreen forests and the East Gallatin alluvial plain has irrigated hay and riparian vegetation mixed with residential development.

Annual precipitation at the weather station at MSU in Bozeman averaged 19.5 inches between 1967 and 2006 and is estimated to range from 15 to 28 inches within the study area (Daly and Taylor, 1998). Precipitation is greatest in the spring and early fall (Figure 2) and varies considerably from year to year and over longer period drought cycles (Figure 3). The period from 1997 through 2004 during which precipitation was below the 40-year average is of particular interest for the purpose of understanding patterns of water-level fluctuations in wells. The amount of water that is stored as snow and the timing of spring snowmelt also may be important for explaining water level fluctuations. Average annual snow water equivalent at the Brackett Creek SNOTEL station on the east side of the Bridger Mountains ranged from 4.8 to

13.2 inches between 1992 and 2006 (Figure 4). The variation in timing of snowmelt is apparent from flow records for the East Gallatin River. For example, peak flow occurred in June during 2004 and 2005, but occurred in April during 2006. Snowmelt when the ground is still frozen may limit recharge.

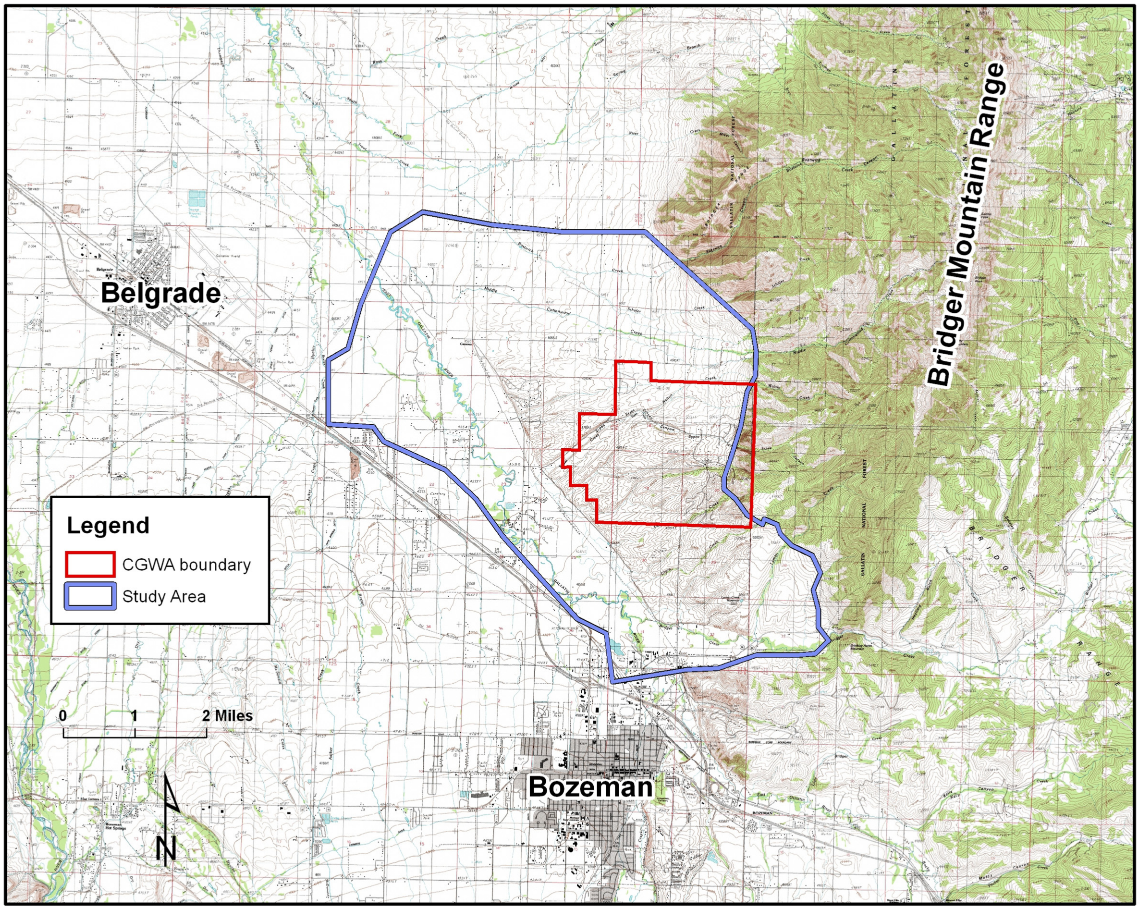


Figure 1. Location of Sypes Canyon Controlled Ground Water Area.

Potential evapotranspiration exceeds precipitation during much of the growing season, generally precluding recharge during those months except during periods of intense rain. In addition, frozen ground limits the amount of water that infiltrates to the water table during the winter. Therefore, most recharge from direct infiltration occurs in the months of April and May after the ground has thawed and snowmelt and spring rains occur, and to a lesser extent during September and October after evapotranspiration stops and autumn rains occur. Evapotranspiration from phreatophytes along the East Gallatin River where ground-water levels are mostly less than 10 feet below ground surface (Hackett et al, 1960) and the hydraulic connection between ground water and the East Gallatin may be important factors in determining the effects of new withdrawals.

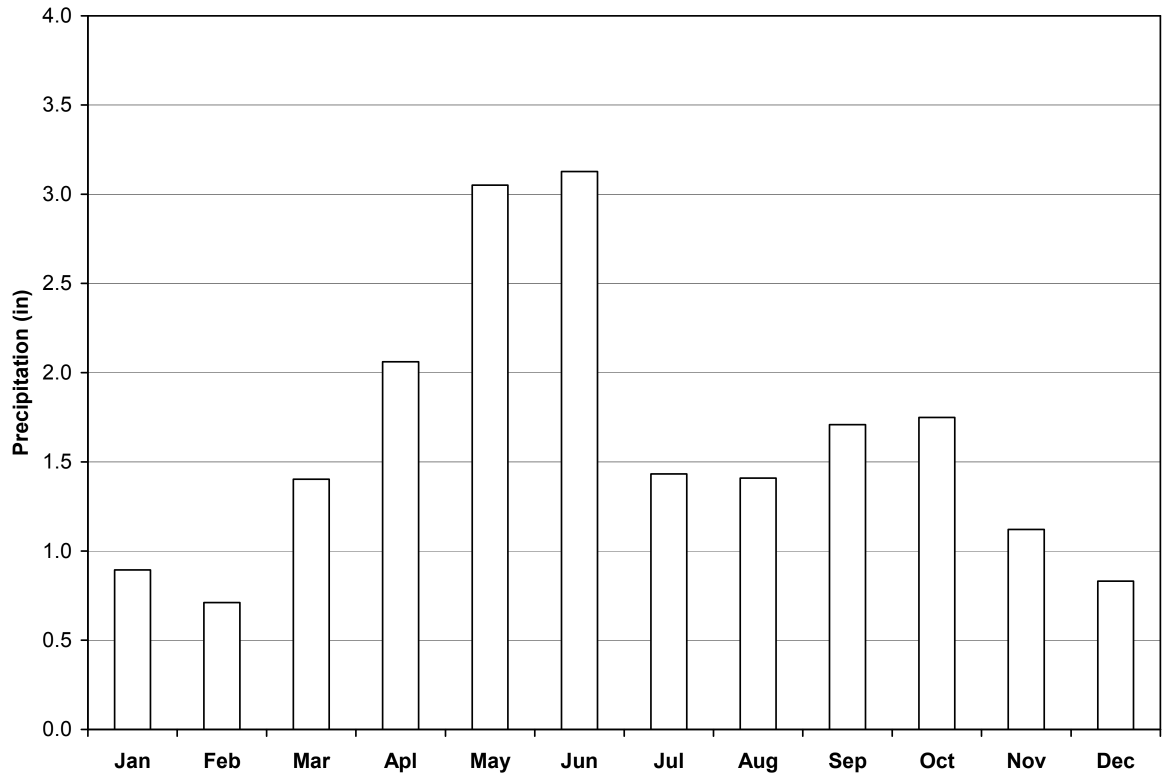


Figure 2. Average monthly precipitation at MSU from 1967 to 2006.

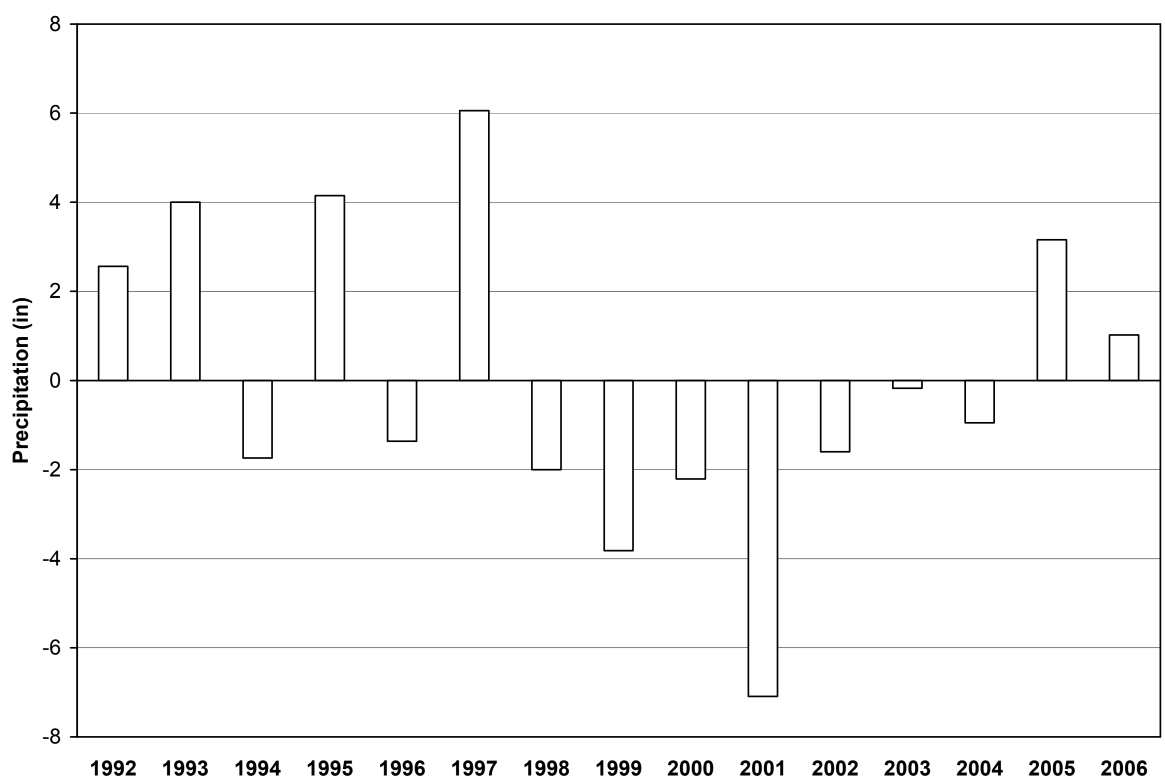


Figure 3. Deviations from average annual precipitation from 1992 to 2006 period of record.

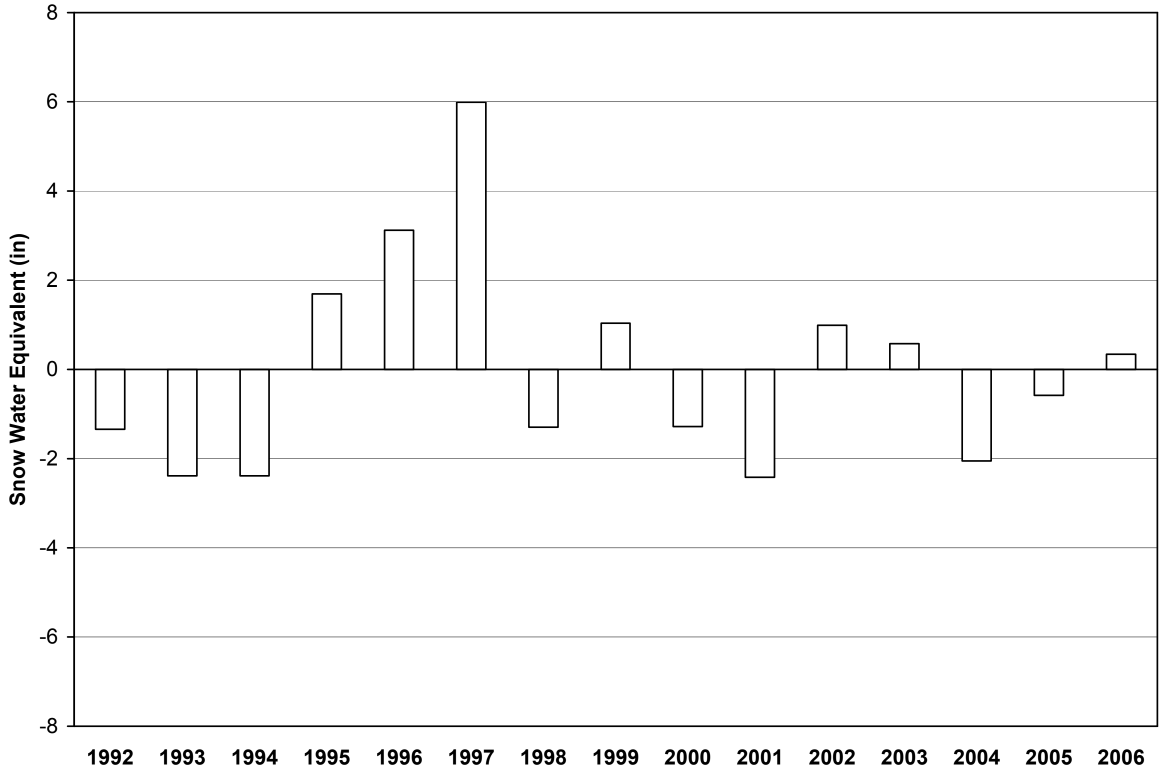


Figure 4. Deviations from average snow water equivalent at the Brackett Creek SNOTEL station from 1992 to 2006 period of record.

Hydrogeology

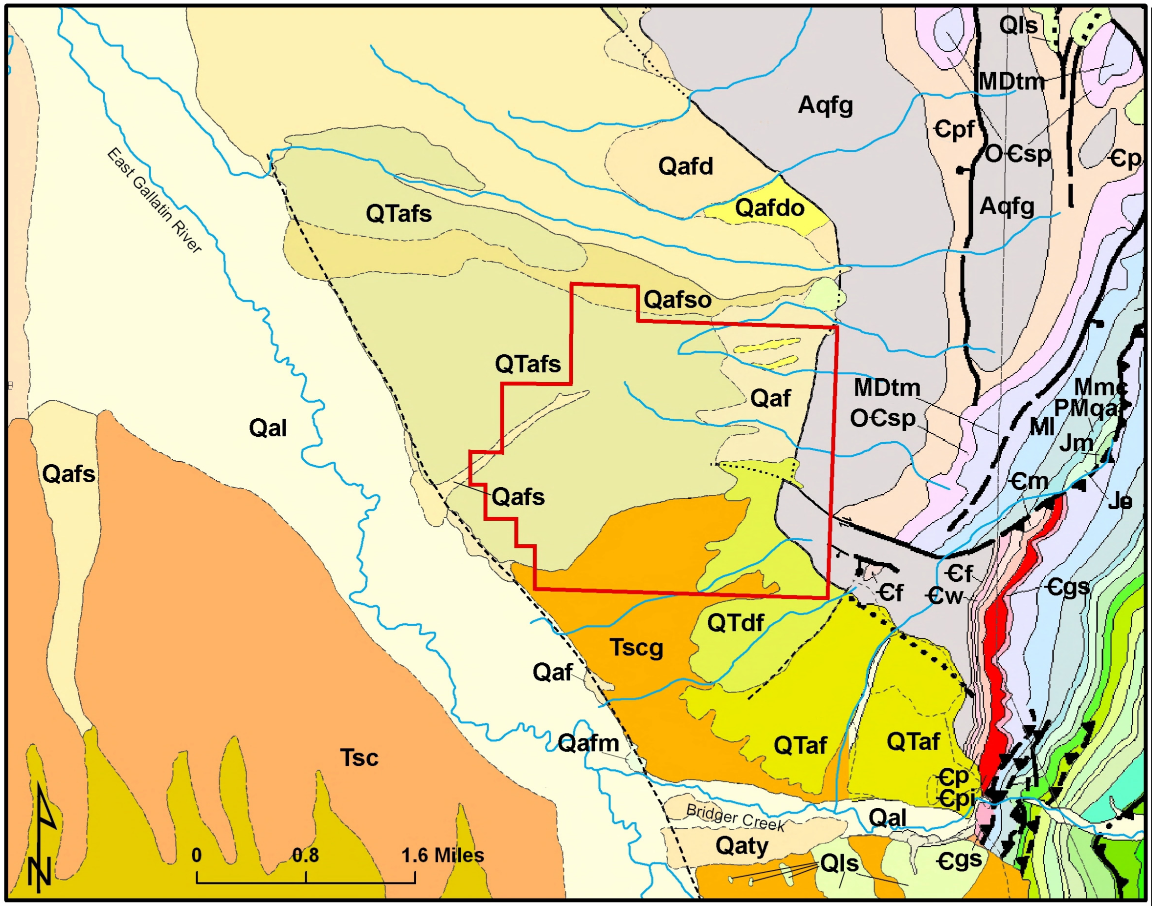
The Bridger Mountains immediately east of the CGWA consist of folded and faulted steeply dipping Paleozoic- to Mesozoic-age sedimentary rocks and Archean-age metamorphic rocks. Bedrock is down-dropped and buried by an undetermined thickness of alluvial deposits to the west of steep normal faults along the mountain front. The Mississippian age Madison Group is a carbonate rock aquifer that forms the spine of the Bridgers. Solution openings in the Madison are important conduits for water to infiltrate in higher-elevation portions of drainages along the western front of the range. Abundant water discharges from the Madison aquifer where it outcrops in the lower elevations of Lyman Creek, however Archean age rocks consisting primarily of metamorphic rock with low porosity and limited ability to transmit water separate the Madison Group rocks from the alluvial fan aquifer system along the CGWA. Fractures and faults in the gneiss provide the only conduits for transmission of water from the Madison aquifer in this area. Alan English of the GLWQD (personal communication, 2007) observed considerable clay and weathering of the gneiss within the fault zone. English also opined that water is dammed behind the fault zone based on observed water levels and spring flows.

The hydrogeology of the alluvial fan and fluvial sediments in the vicinity of the CGWA has been investigated by various environmental consultants to satisfy regulatory requirements for subdivisions and as part of two masters theses. Investigators have attempted to decipher the geometry of water-producing sand and gravel layers, and estimate aquifer properties by evaluating drillers' logs and conducting aquifer tests. Breuninger (1992) hypothesized that there are three separate confined aquifers in order to argue that proposed pumping for the Summer Ridge Subdivision would not affect other wells. Gaston (1996) identified a fourth aquifer beneath the adjacent Spirit Hills Subdivision. Erickson (1995) described the Sypes Canyon area as an eroded surface of overlapping alluvial fans derived from the Bridger Range and the sediments as interbedded sand, gravel, clay, and silt. Hay (1997) describes the aquifer system as Quaternary alluvium overlying Tertiary/Quaternary age alluvium consisting of discontinuous stringers of coarse and fine alluvial materials and very fine eolian deposits. According to Hay, the eastern part of his study area consists of alluvial fans containing metamorphic and sedimentary fragments with individual coarse units a few meters thick, tens of meters wide, and hundreds of meters long. Hay states that fine-grained sediments consisting of loess deposits that may be hundreds of square meters in extent and debris-flow deposits that may reach 10 meters wide by one hundred meters long form discontinuous aquitards in the eastern part of his study area. Hay states that alluvial materials are reworked by streams westward from the mountain front and are better sorted and could be interfingered with alluvium along the East Gallatin River. Hay calculated both a physical water balance and chloride mass-balance to obtain estimates of recharge to the aquifer system of 5,100 acre-feet per year and 3,000 acre-feet per year in the vicinity of the CGWA. Hay's estimates include contributions to the CGWA as well as the area to the north that receives recharge from Middle Cottonwood Creek.

Lonn and English (2002) mapped alluvial fan and fluvial sediment facies in the vicinity of the Sypes Canyon CGWA that are similar to the facies model described by McCloskey and Finnemore (1996) (Table 1) (Figure 5).They identify mostly poorly-sorted debris flow deposits (QTdf, Qafd, and Qafdo) near the mountain front and better-sorted fluvial dominated deposits at greater distances (Qafs, QTafs). In addition, Lonn and English (2002) classify a significant portion of the CGWA as Tertiary-age Sixmile Creek Formation.

Table 1. Descriptions of lithologic units in the vicinity of the Sypes Canyon CGWA, (Lonn and English, 2002).

Lithologic Units	Description
Qal	Well-rounded, well sorted, bouldery gravel and sand with some thin beds of clayey silt.
Tscg	Light brown to light gray, poorly stratified, poorly sorted, tuffaceous siltstone containing 10-50% fluvial channel conglomerate.
QTdf	Mostly poorly stratified, poorly sorted, pebbly sand, but includes some sub-angular bouldery gravel containing huge boulders up to 6 feet in diameter.
Qafs	Poorly to well-sorted, rounded to sub-angular gravel, sand, silt, and clay.
QTafs	Sub-rounded to rounded, moderately well-sorted, well stratified, bouldery gravel with interbeds of silt as much as 5 feet thick.
QTaf	Sub-angular to rounded, poorly to well-sorted, bouldery gravel with varying amounts of silt and clay and some interbeds of silt.
Qafd	Sub-rounded to sub-angular, poorly to moderately sorted, bouldery gravel, sand, silt and clay.
Qafdo	Sub-rounded to sub-angular, poorly to moderately sorted, bouldery gravel, sand, silt, and clay.



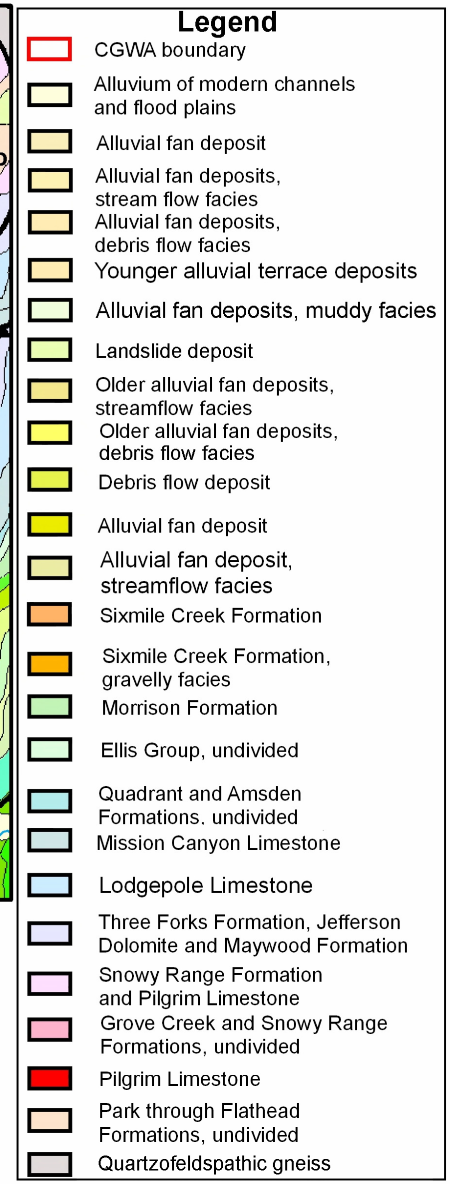


Figure 5. Geologic map of vicinity of the Sypes Canyon CGWA (modified from Lonn and English, 2002 and Berg and Lopez, 2000)

According to McCloskey and Finnemore (1996), alluvial fans "show an increase in the degree of sorting and large decreases in particle size and bedding thickness with distance from the fan apex". The same authors state that basin subsidence results in an upward increase in grain size and bedding thickness. Using this facies model, hydraulic conductivity of poorly sorted coarse sediments near their source and fine grained well sorted sediments at distance from their source are expected to be low. Facies with intermediate particle size and better sorting are expected to have the highest hydraulic conductivity.

Kaczmarek (2001) demonstrated through aquifer testing that water could be produced from depths greater than 500 feet and that pumping from deeper wells causes water levels in shallower wells to decline. Erickson (1995) and Hay (1997) also conclude that water-producing layers are discontinuous and interconnected, although they believe deeper parts of the aquifer have little development potential. Aquifer properties at different depths were estimated from constant-rate aquifer test data by several investigators in conjunction with subdivision or water right applications (Table 2). Breuninger and Mendes (1993) and Gaston (1996) based their evaluations on a conceptual model of multiple separate confined aquifers. However, Hay and Kaczmarek argue persuasively that the alluvial fan system is better described as a package of discontinuous and interconnected water-bearing intervals. Hay stated the water-bearing intervals alternatively could be considered as part of a single unconfined aquifer and applied the Neuman (1975) delayed-yield analysis method. Kaczmarek argued that the depositional environment and the nature of the hydraulic responses in the aquifer tests he conducted indicates individual water-bearing intervals are best described as leaky-confined strip aquifers consisting of stream channel deposits. Again, tests by Kaczmarek show that pumping from individual water-bearing intervals cause drawdown in shallower intervals, indicating leakage and that the alluvial fan aquifer system probably responds generally as an interconnected unconfined aquifer over seasonal or multi-year pumping periods.

The relatively short-duration aquifer tests conducted nearby the CGWA yield estimates of aquifer properties of discrete water-bearing intervals and not the entire interconnected aquifer system. Properties of a greater thickness of the aquifer system immediately north of the CGWA can be estimated from a seasonal ground-water level oscillation due to recharge from Middle Cottonwood Creek that is dampened as it propagates through the aquifer system. The ratio of water level oscillations in wells 01S06E18AAAA, 01S06E07DCBD, 01S06E07CDDC, 01S06E18BABB, and 01S06E07CCDD to the oscillation in well 01S06E8CBAA (Figure 6) located immediately adjacent to Middle Cottonwood Creek are plotted versus distance from well 01S06E9CBAA in Figure 7. These data, an estimate of specific yield (0.10) and a modification of the method using cyclic water-level fluctuations by Ferris (1963) yield a transmissivity estimate equal to 3,800 ft^2/day. Oscillations are not evident in wells in other parts of the alluvial fan system or more distant from the mountain front, probably because transmissivity in the vicinity of Middle Cottonwood Creek and north of Sypes Canyon is higher than more poorly sorted sediments south of Sypes Canyon.

Table 2. Representative aquifer properties for wells near the Sypes Canyon CGWA.

Source	Location	Method	Transmissivity (ft^2/day)	Storativity / Specific Yield
Breuninger and Mendes (1993)	01S05E13ACAB	Cooper-Jacob	760	0.00017
Breuninger and Mendes (1993)	01S05E13AAAA	Cooper-Jacob	1,700	.00003
Breuninger and Mendes (1993)	01S05E13AAAA	Cooper-Jacob	880	-----
Gaston (1996)	01S05E13BCAC	Cooper-Jacob	255	.00023
Hay (1997)	01S05E13AAAA	Neuman	608	0.00066 / 0.16
Kaczmarek (2001)	01S06E18DDDD	Papadopulos-Cooper	205	0.00025
Kaczmarek (2001)	01S06E18CBCC	Papadopulos-Cooper	182	0.00005

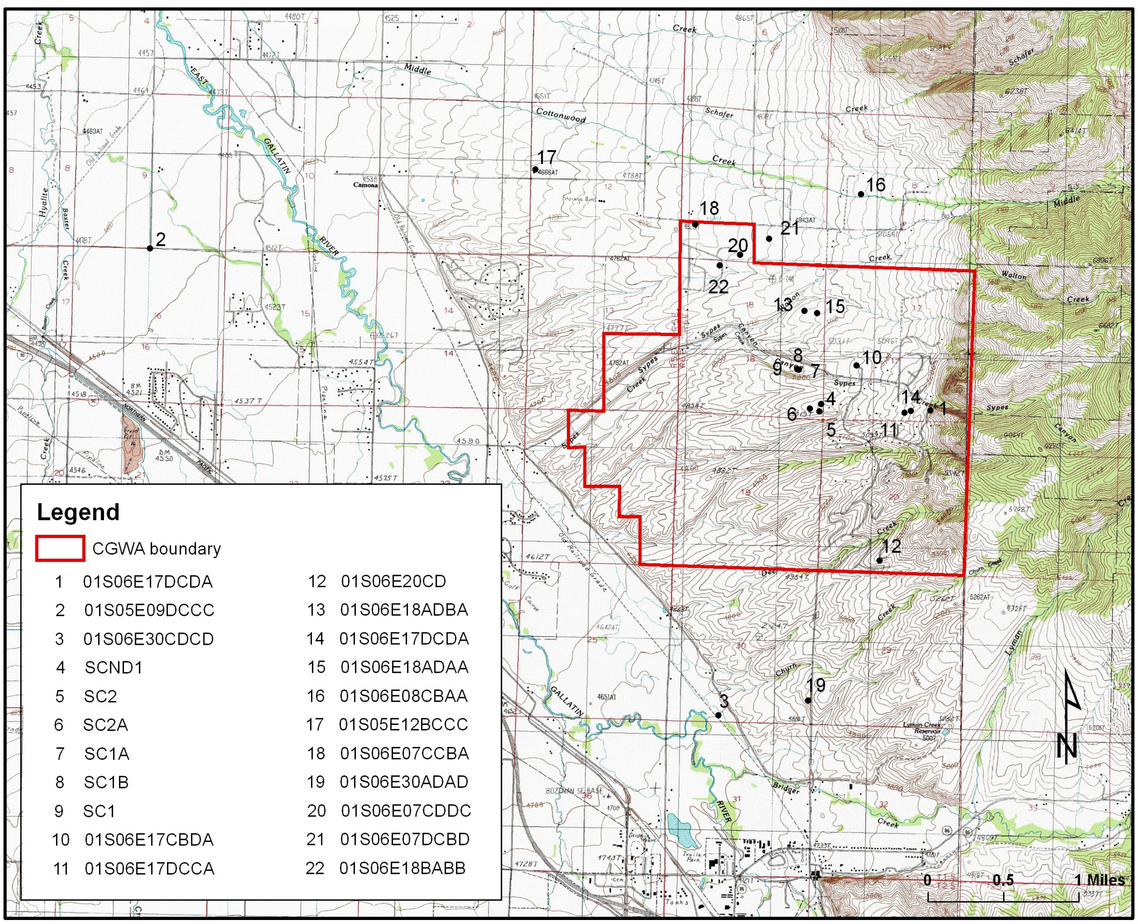


Figure 6. Locations of wells with hydrographs used in this report.

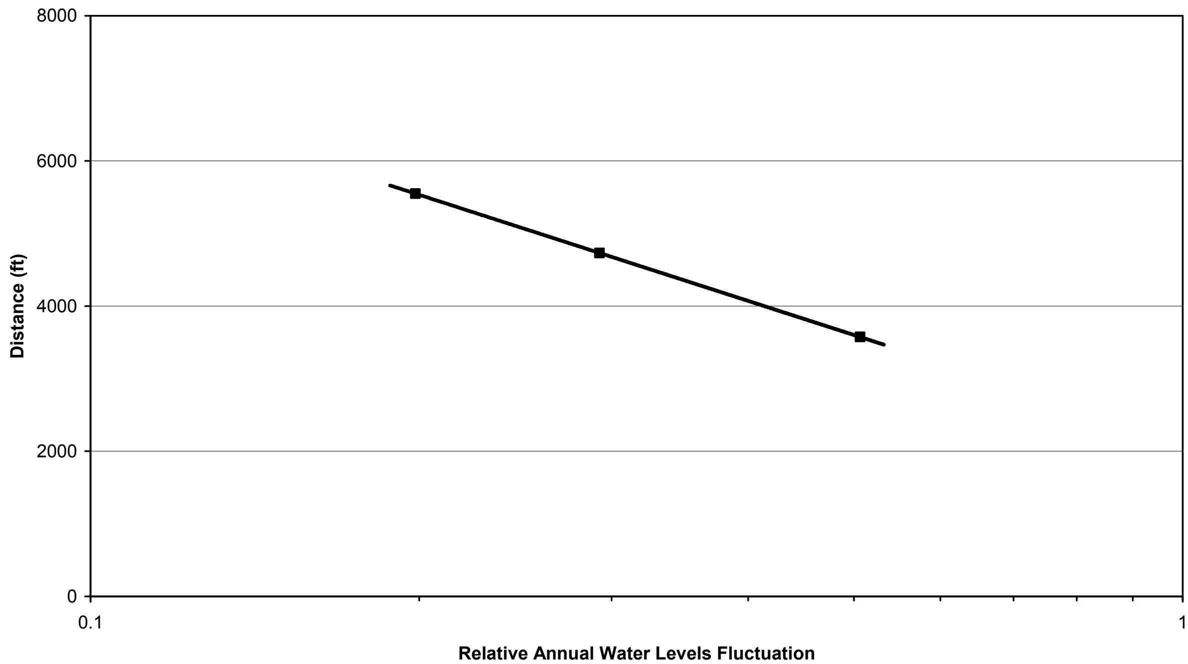


Figure 7. Ratio of water-level oscillations to maximum water-level oscillation versus distance from well 01S06E9CBAA.

Ground-Water Level Hydrographs

A record of ground-water levels measured generally on a quarterly schedule is available for eight wells in the vicinity of the CGWA for over 10 years spanning periods of above- and below-average precipitation (Figure 8). Current water levels generally are 5 to 20 feet lower in all wells over this period; however, they have fluctuated in response to changes in recharge and/or discharge over different time scales within the period of record. Water levels in wells 01S06E8CBAA (Figure 9) and 01S06E07CCBA (Figure 10) located near the mountain front exhibit annual oscillations in response to significant seasonal losses from nearby Middle Cottonwood Creek and probably discharge from the bedrock aquifer. Water levels in many other wells near the mountain front have similar seasonal patterns of fluctuations with varying magnitudes. As discussed in the previous section, water levels in wells west of well 01S06E9CBAA including wells 01S06E18AAAA, 01S06E07DCBD, 01S06E07CDDC, 01S06E18BABB, and 01S06E07CCDD exhibit annual oscillations with decreasing magnitude and time delay with distance from the source of recharge. Water levels in well 01S05E12BCCC (Figure 11) responded to seasonal recharge during wet years in the 1990s, but not after that. A possible explanation of the different seasonal pattern of water-level fluctuations in well 01S05E12BCCC in the last ten years is that Middle Cottonwood Creek may no longer be diverted to the ditch that runs near this well.

In addition to seasonal fluctuations, water levels in wells near and within the CGWA exhibit longer-period fluctuations that appear to correlate to precipitation patterns. For example, Figures 12 and 13 are plots of the 48-month SPI and iterated moving averages of water-level data calculated over a five quarter window (three iterations) for wells 01S06E8CBAA and 01S06E07CCBA respectively. A plot of water levels from wells 01S06E17DCDA and 01S06E17DCCA also correlate to the long-term precipitation pattern (Figures 14 and 15). Water levels in well 01S05E12BCCC have not recovered from dry years between 1998 and 2002 as fully as wells near the mountain front (Figure 16), possibly because of changing surface-water diversions and recharge evident in the changing seasonal pattern noted above. Well 01S06E17CBDA also has not recovered from low recharge during dry years and does not exhibit seasonal fluctuations observed in 1995 (Figure 17); although this well is located much closer to the mountain front than 01S05E12BCCC. The exact influences on water levels in well 01S06E17CBDA are uncertain, but there appears to be a mechanism that dampens recharge to the producing interval of this well.

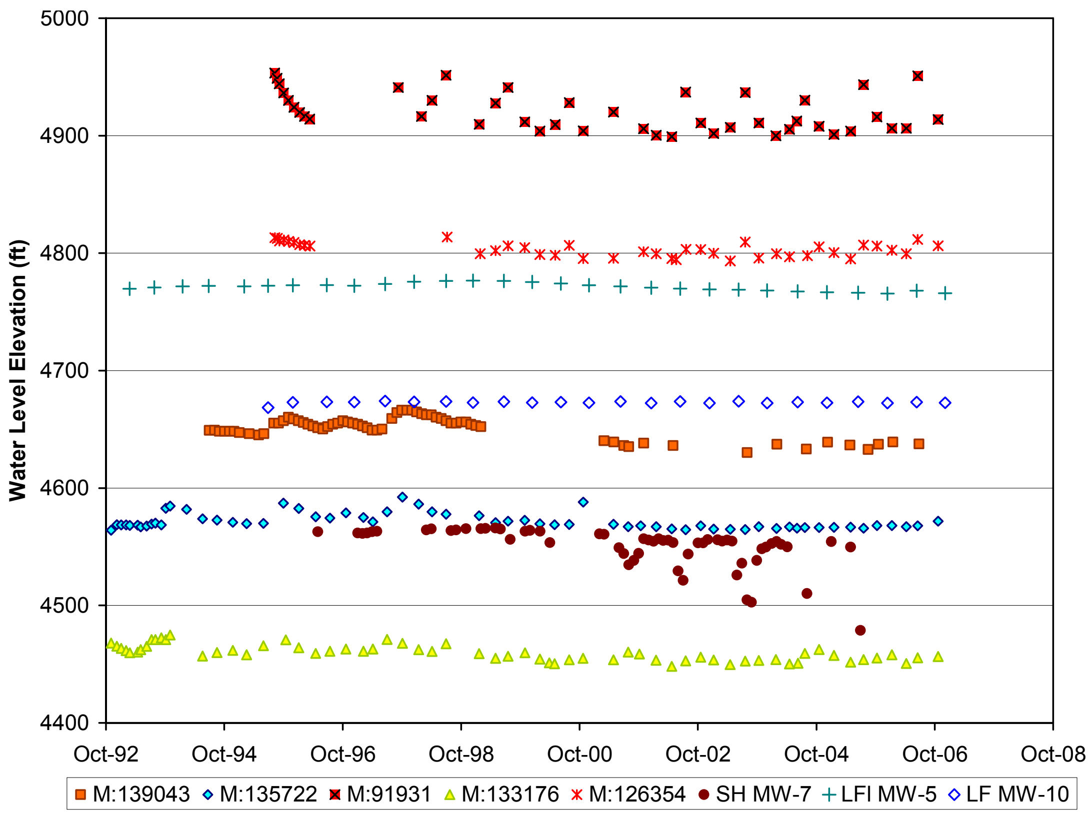


Figure 8. Water-level elevations in wells located within and near the Sypes Canyon CGWA.

Well 01S06E30DDAA located at the landfill southwest of the CGWA only exhibits a long-period water-level fluctuation that correlates to the 96-month SPI (Figure 18); probably because of distance and low hydraulic conductivity of the aquifer in this part of the fan system. Water levels measured in well 01S06E20CD located immediately up-gradient from well 01S06E30-1 also correlate to the 96-month SPI (Figure 19). Water levels in well 01S06E30-2, another landfill monitoring well, have remained essentially constant with small seasonal fluctuations because this well is shallow and completed in alluvium of the East Gallatin River (Figure 20). Water levels in a deeper well completed in the East Gallatin alluvium (01S05E09DCCC) exhibit seasonal fluctuations and dropped approximately 10 feet beginning in 1998 (Figures 21 and 22). Water levels in this well have not recovered, possibly as a result of reduced recharge from flood irrigation and residential development along the East Gallatin. Last, the graph in Figure 23 shows how fluctuations in bedrock water levels affect water levels in a nearby well completed in alluvial fan sediments. Water-level fluctuations in the bedrock are relatively large and precede water-level fluctuations in the alluvial fan indicating recharge to the alluvial fan from bedrock. Water-level fluctuations in the alluvial fan are smaller because of the larger specific storage relative to bedrock. Alan English (personal communication, 2007) identified relatively shallow wells completed in bedrock in the northeast ¼ of Section 20, Township 1 South, Range 6 East that have relatively stable water levels. English also points out that springs and small streams in this area start at about the same elevation as these wells and argues that clay within the fault zone could be damming water in this area. Under this conceptual model, recharge to alluvial fan sediments from bedrock discharge is expected to be concentrated at shallow depths. However, Figure 23 shows significant fluctuations in ground water levels in bedrock and, also that water is discharging from bedrock to alluvial fan sediments at greater depths either because of the absence of clay in some areas or because of slow seepage through clay. The relatively immediate response in water levels in the alluvial fan apparent from Figure 23 indicates the fault zone in this area is not damming water. Recharge from bedrock to the alluvial fan is expected to be concentrated at shallower depths regardless of whether water is dammed behind the fault zone, because water transmission from fractures and faults in the gneiss decreases with depth and increased weight of overlying rock.

Water levels in wells drilled for the Autumn Ridge development and completed at different depths (Figures 24 and 25) indicate that the vertical hydraulic gradient at that location is similar to the horizontal hydraulic gradient; these water-level data are evidence that low hydraulic conductivity layers inhibit vertical ground-water flow. The difference between water levels in wells 01S06E18ADBA and 01S06E18ADAA located 450 feet apart is additional evidence of the variability of properties of the alluvial-fan aquifer over short distances. These wells are 280 ft and 120 ft deep, respectively, with 135-foot difference in water levels and a vertical hydraulic gradient of 0.84. Well 01S06E18ADAA is either in a perched aquifer or the hydraulic conductivity of the intervening materials is very low.

In summary, water levels in wells within or near the CGWA and completed in the alluvial fan near the range-front fault generally fluctuate seasonally in response to recharge from streams and discharge from bedrock aquifers. Seasonal fluctuations of water levels in wells more distant from the primary sources of recharge are dampened and delayed or absent completely. Water levels in wells generally correlate with longer-period wet-dry cycles as indicated by the 48-month SPI; however, wells near the range-front fault appear to recover more quickly from periods of low precipitation and recharge. Wells completed in poorly connected water-producing intervals or more distant from sources of recharge follow even longer-period precipitation trends as indicated by the 96-month SPI. Aquifer testing demonstrates that water-producing intervals at different depths within the alluvial fan aquifer system are hydraulically connected; however water levels indicate low hydraulic conductivity layers inhibit vertical communication. Approximately fifty additional wells have been permitted within the CGWA since its inception in 2002; however, effects of withdrawals from these wells on water levels in pre-existing wells, if any, cannot be distinguished from water-level trends that correlate to precipitation trends.

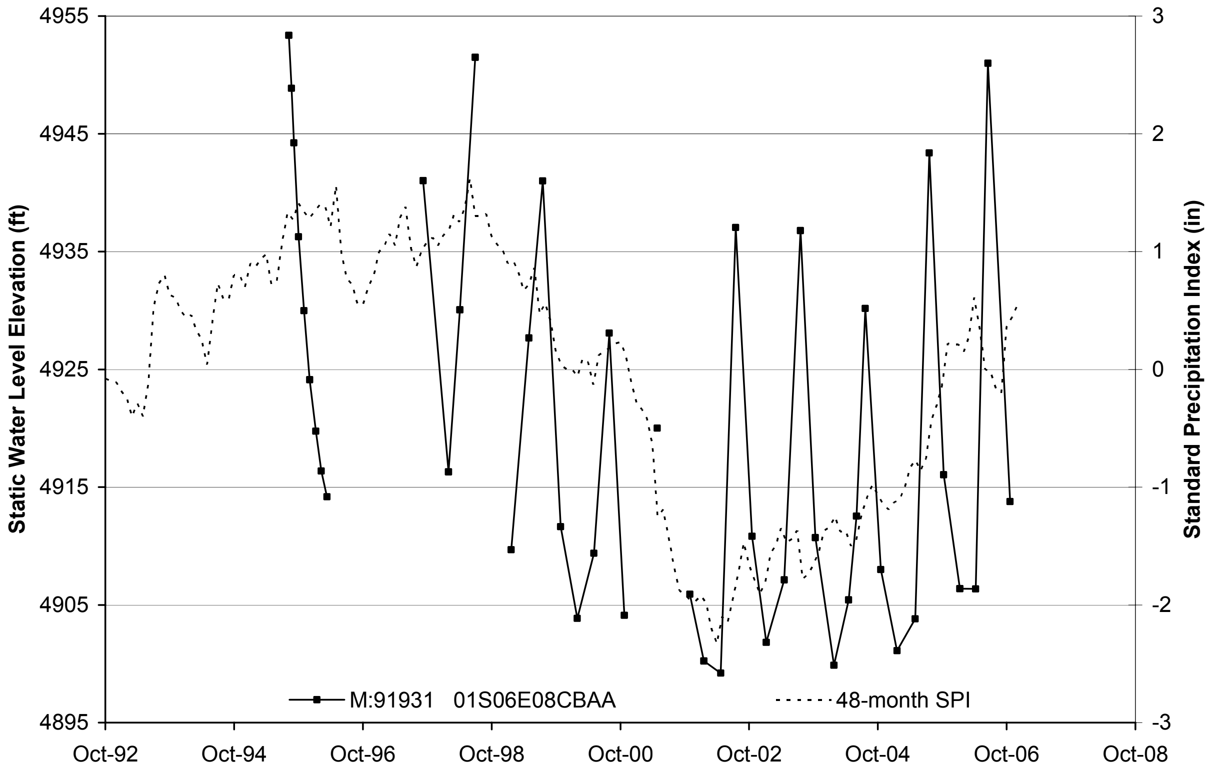


Figure 9. Water levels in well 01S06E08CBAA and 48-month SPI.

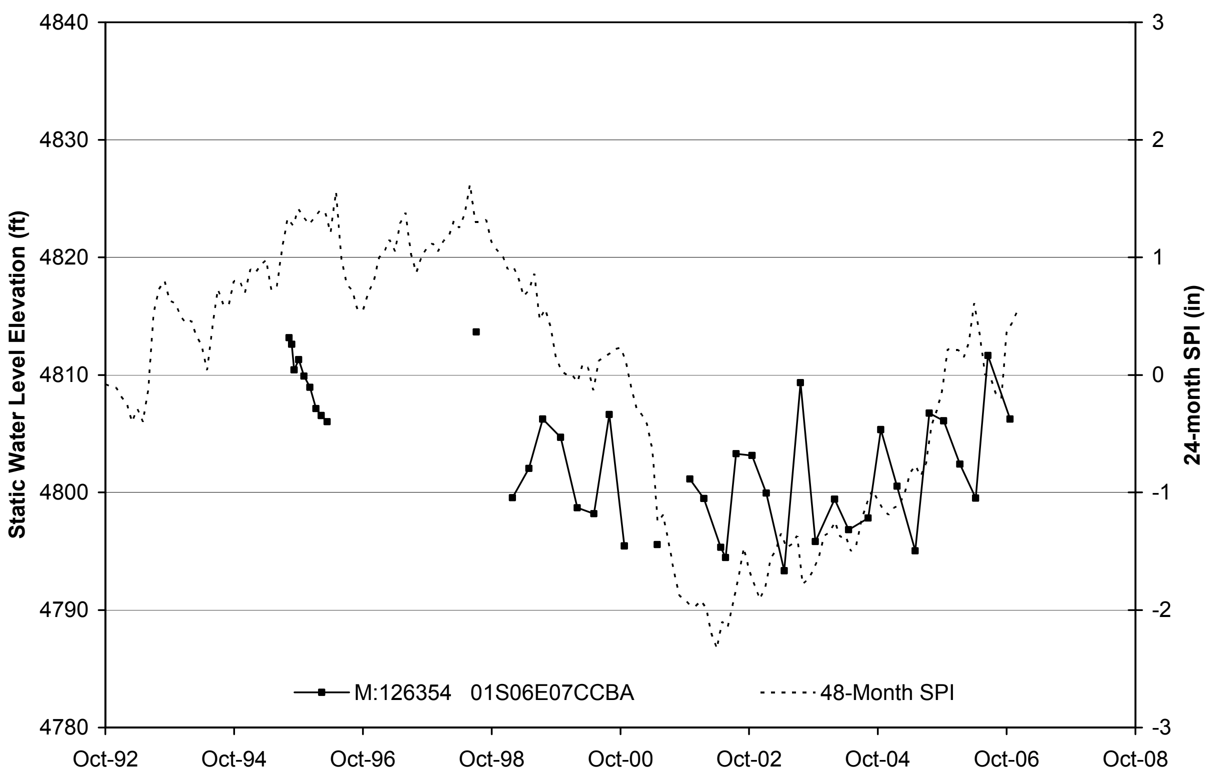


Figure 10. Water levels in well 01S06E07CCBA and 48-month SPI.

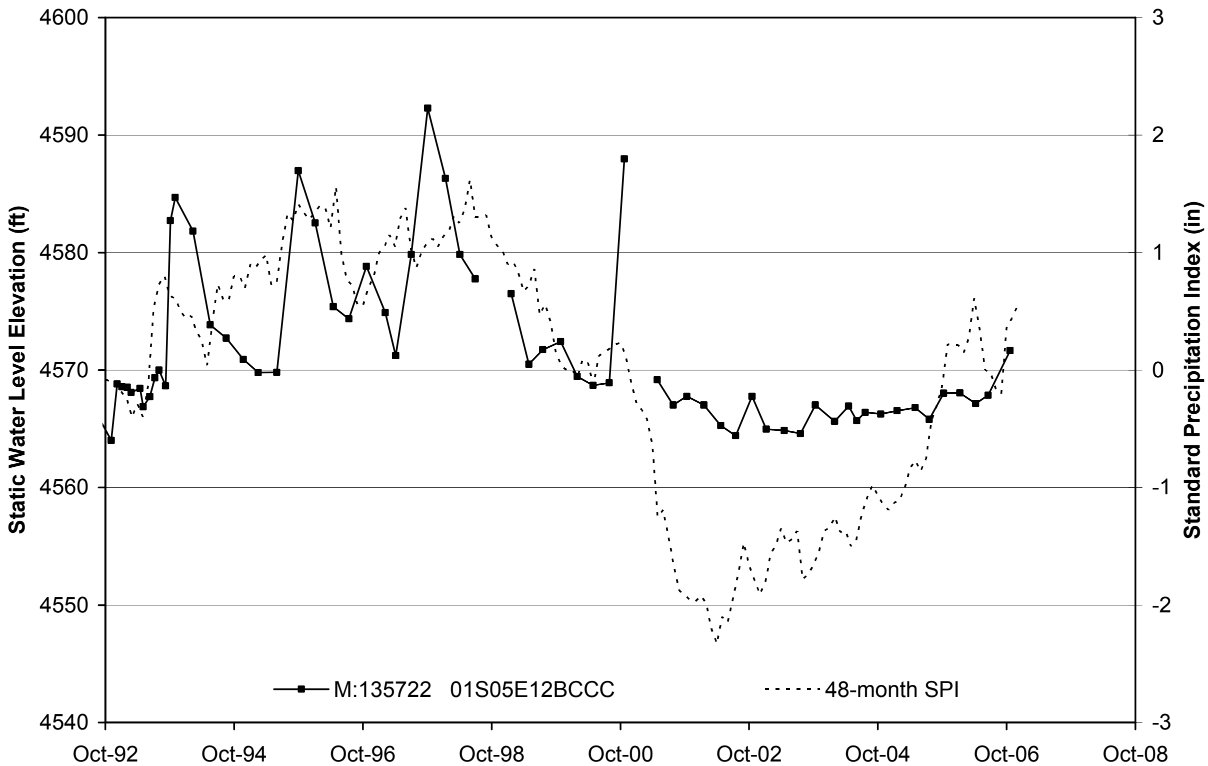


Figure 11. Water levels in well 01S05E12BCCC and 48-month SPI.

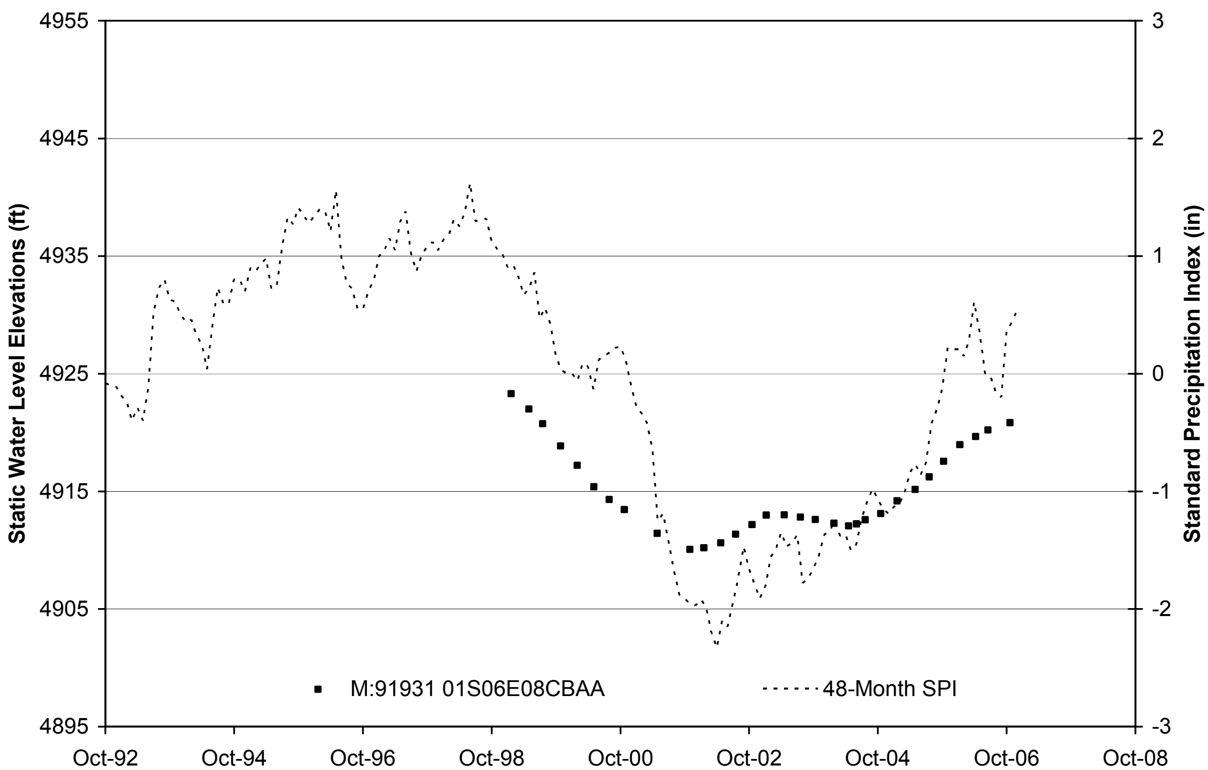


Figure 12. Moving average of water levels in well 01S06E08CBAA and 48-month SPI.

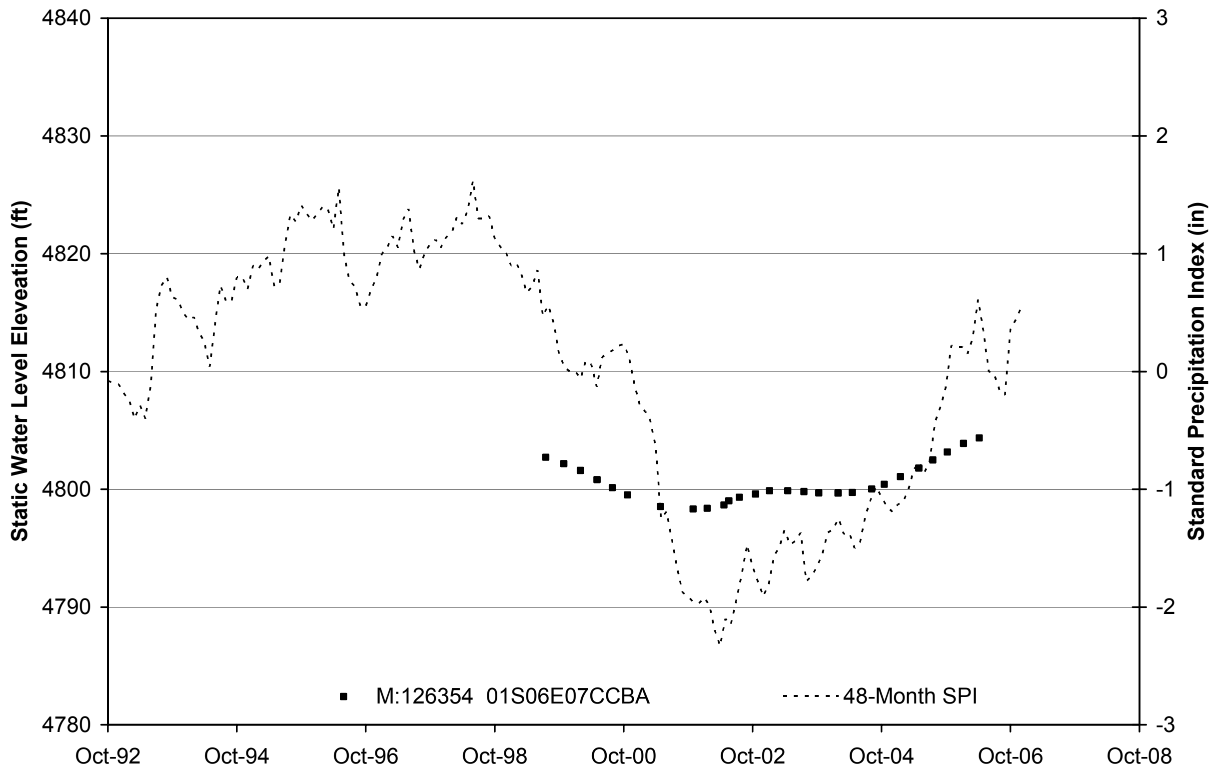


Figure 13. Moving average of water levels in well 01S06E07CCBA and 48-month SPI.

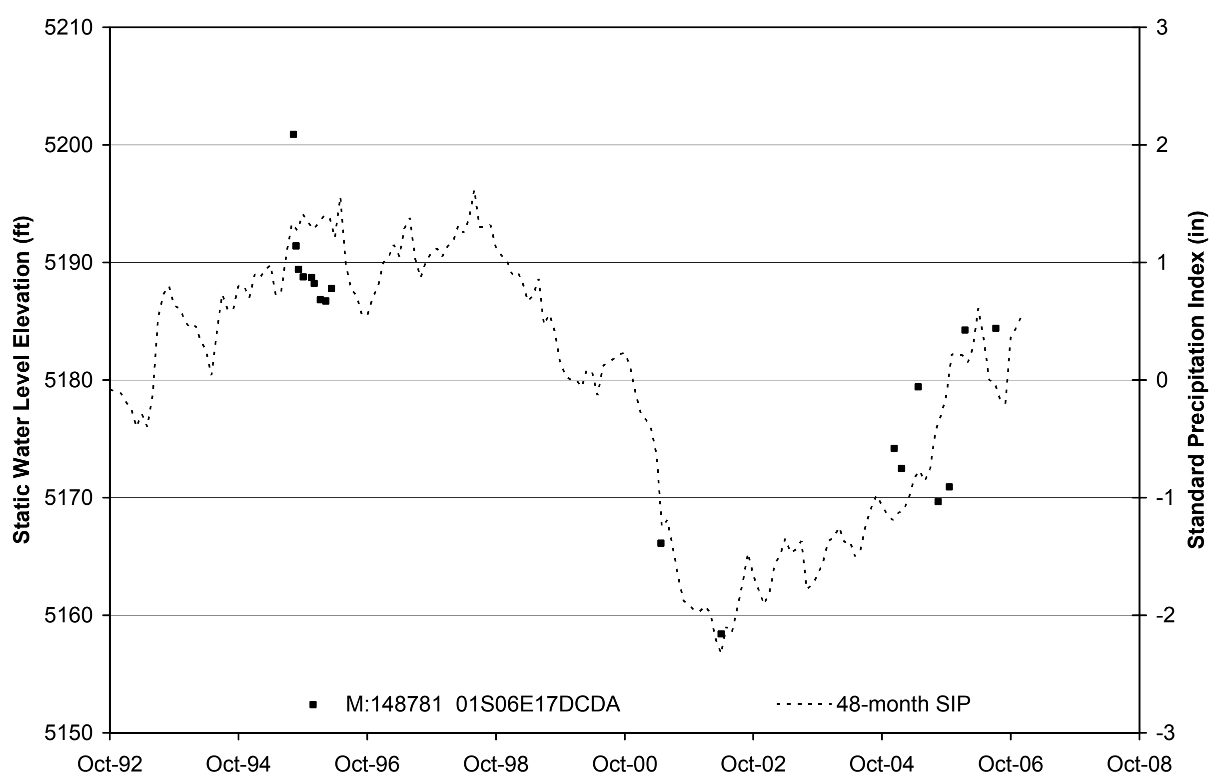


Figure 14. Water levels in well 01S06E17DCDA and 48-month SPI.

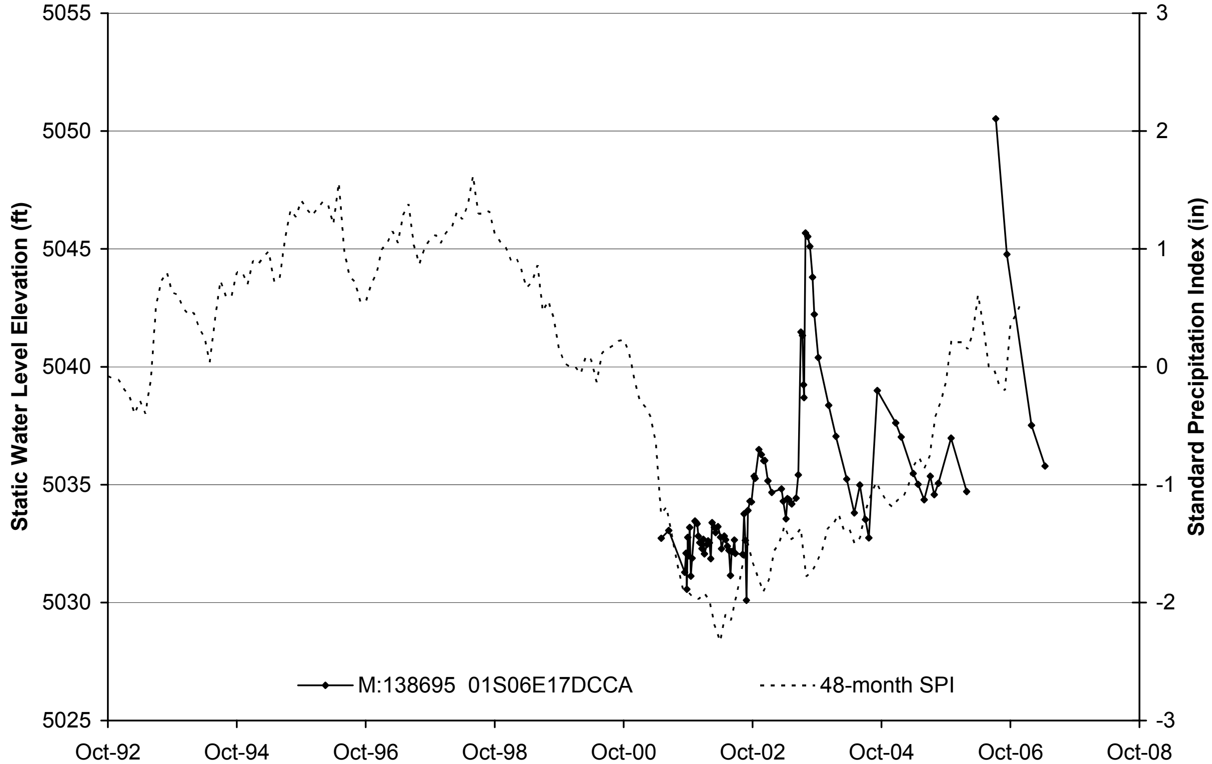


Figure 15. Water levels in well 01S06E17DCCA and 48-month SPI.

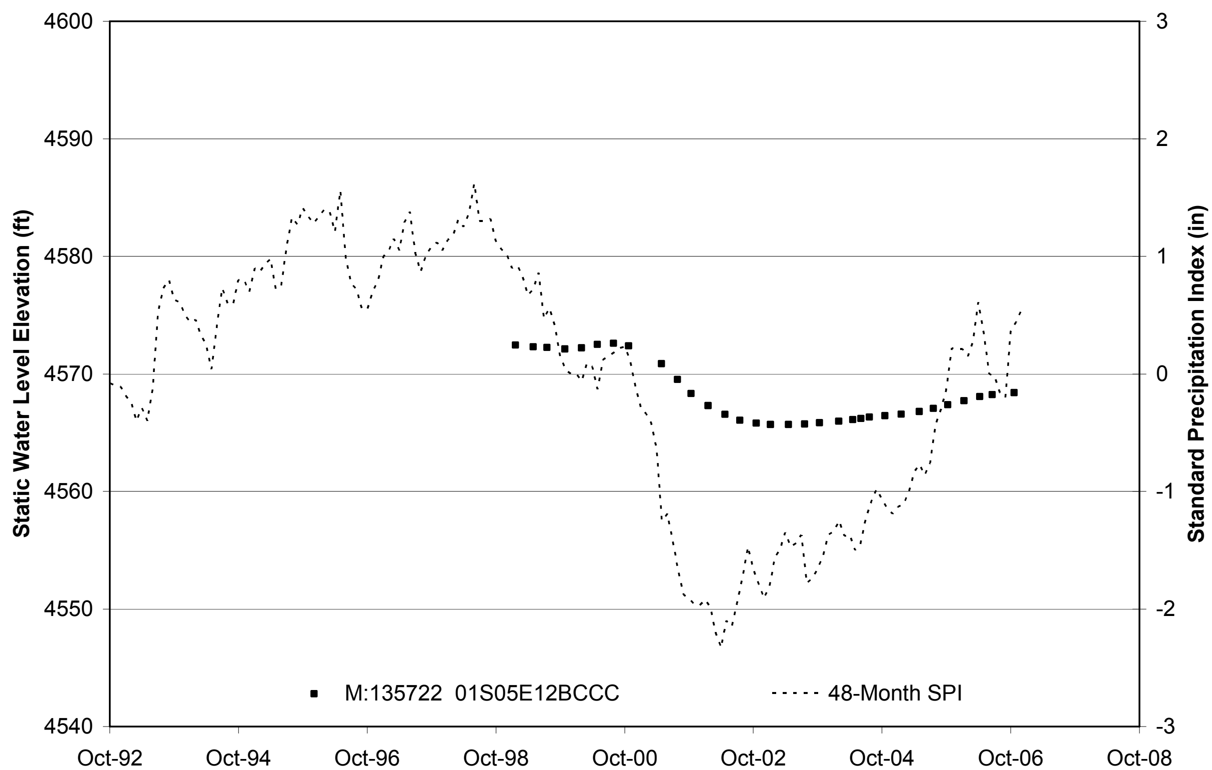


Figure 16. Moving average of water levels in well 01S05E12BCCC and 48-month SPI.

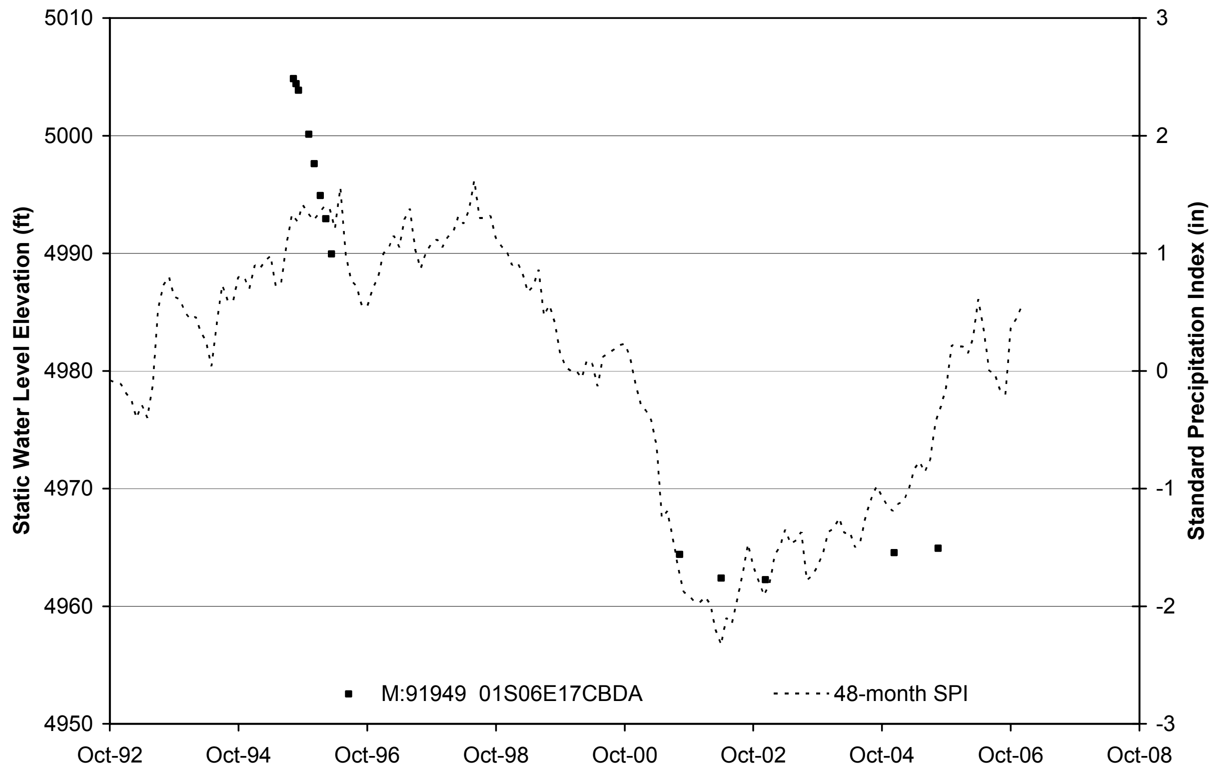


Figure 17. Water levels in well 01S06E17CBDA and 48-month SPI.

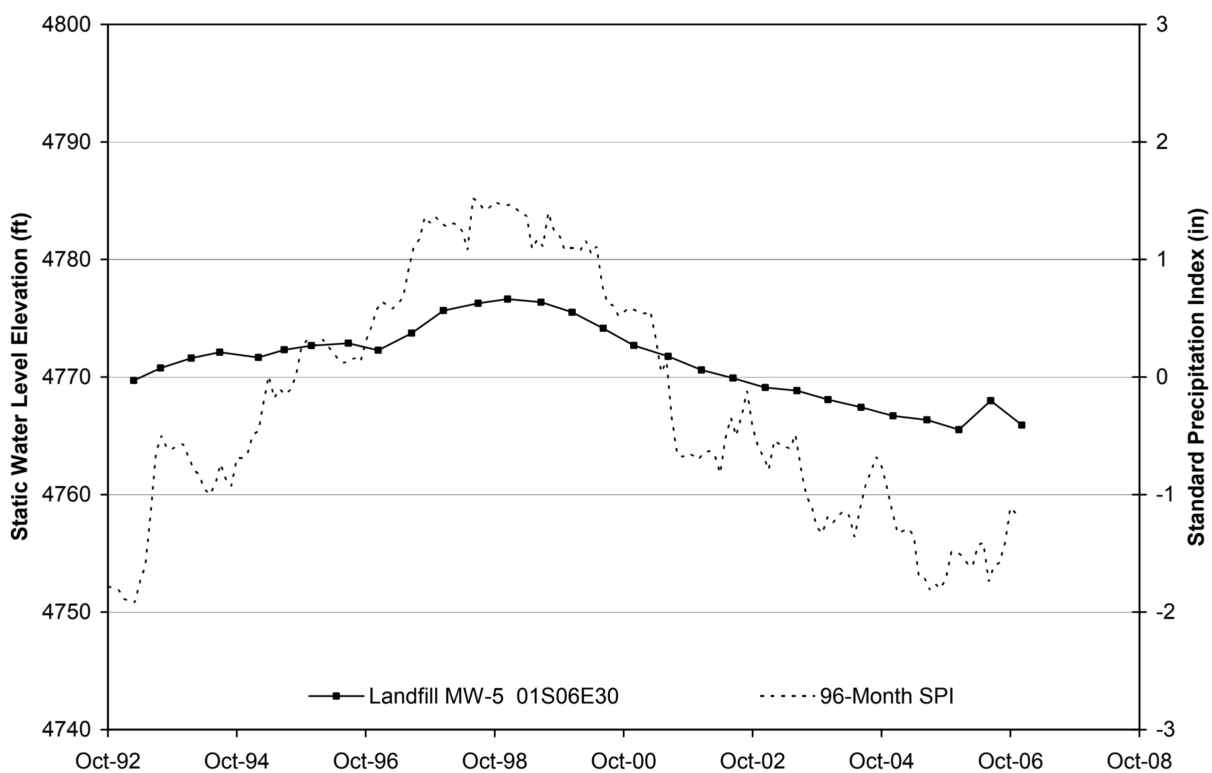


Figure 18. Water levels in well 01S06E30DDAA and 96-month SPI.

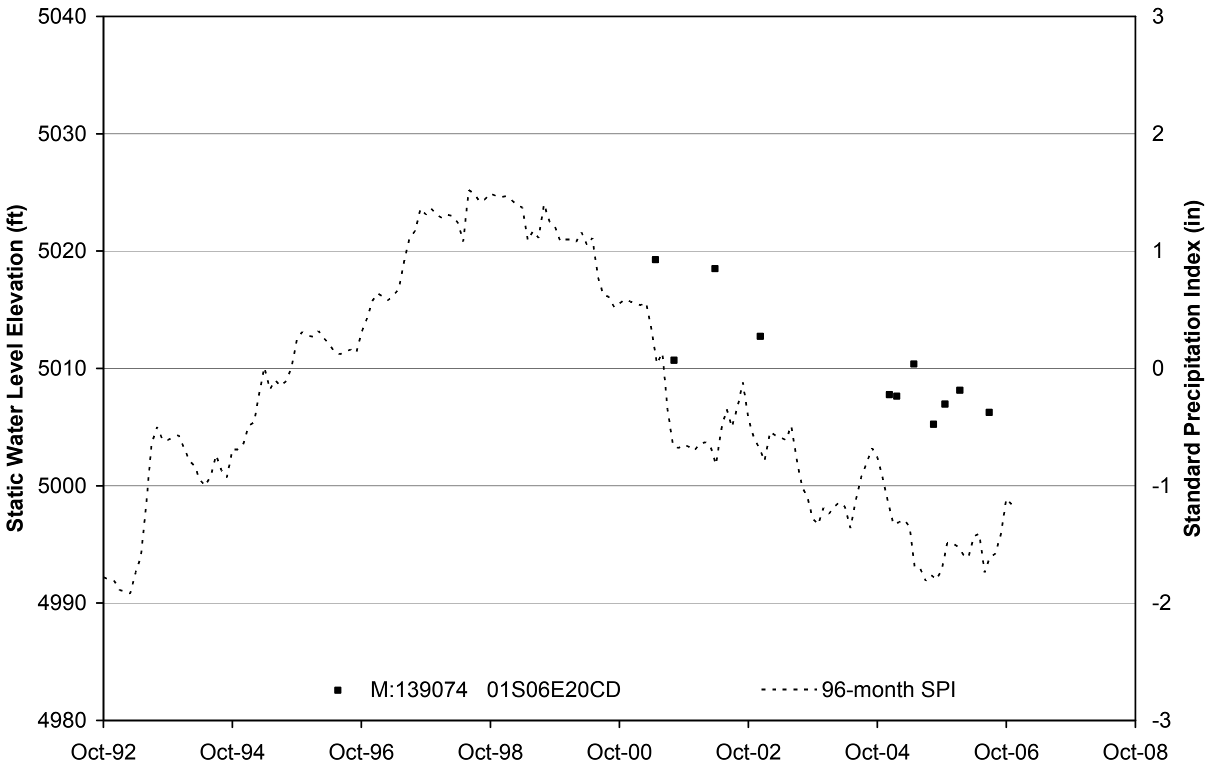


Figure 19. Water levels in well 01S06E20CD and 96-month SPI.

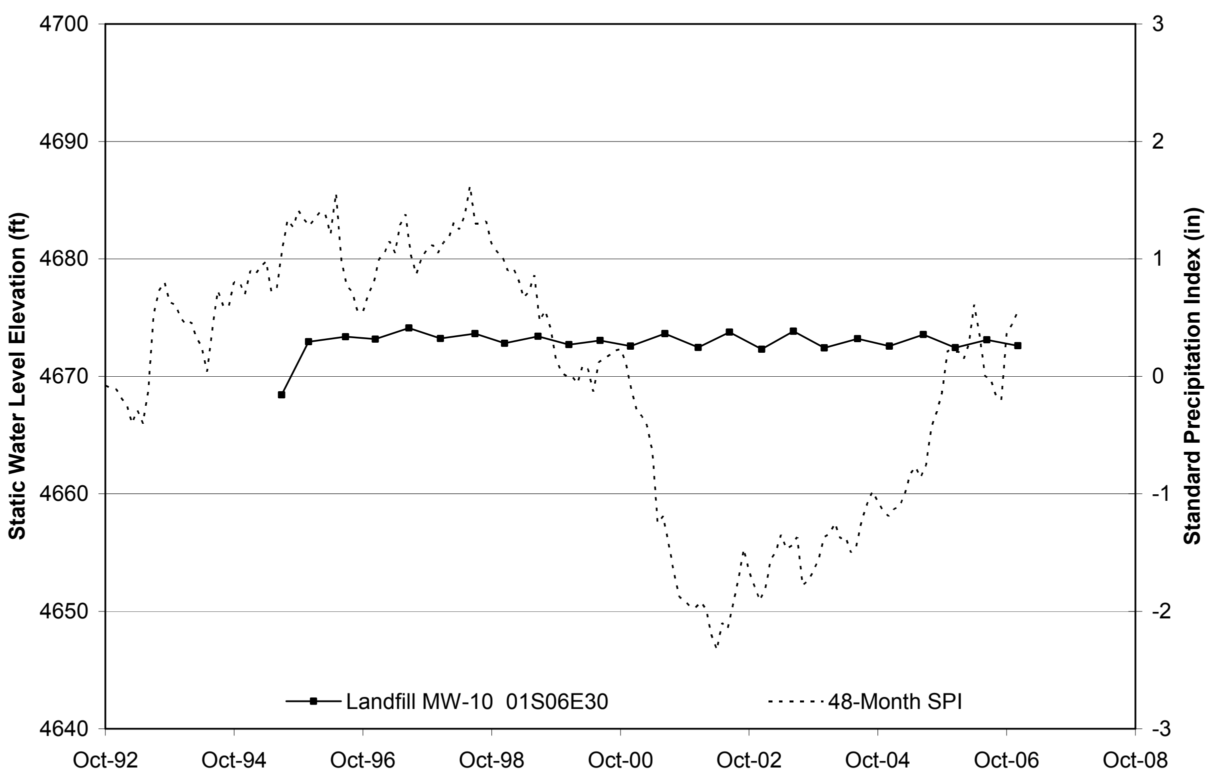


Figure 20. Water levels in well 01S06E30CDCC and 48-month SPI.

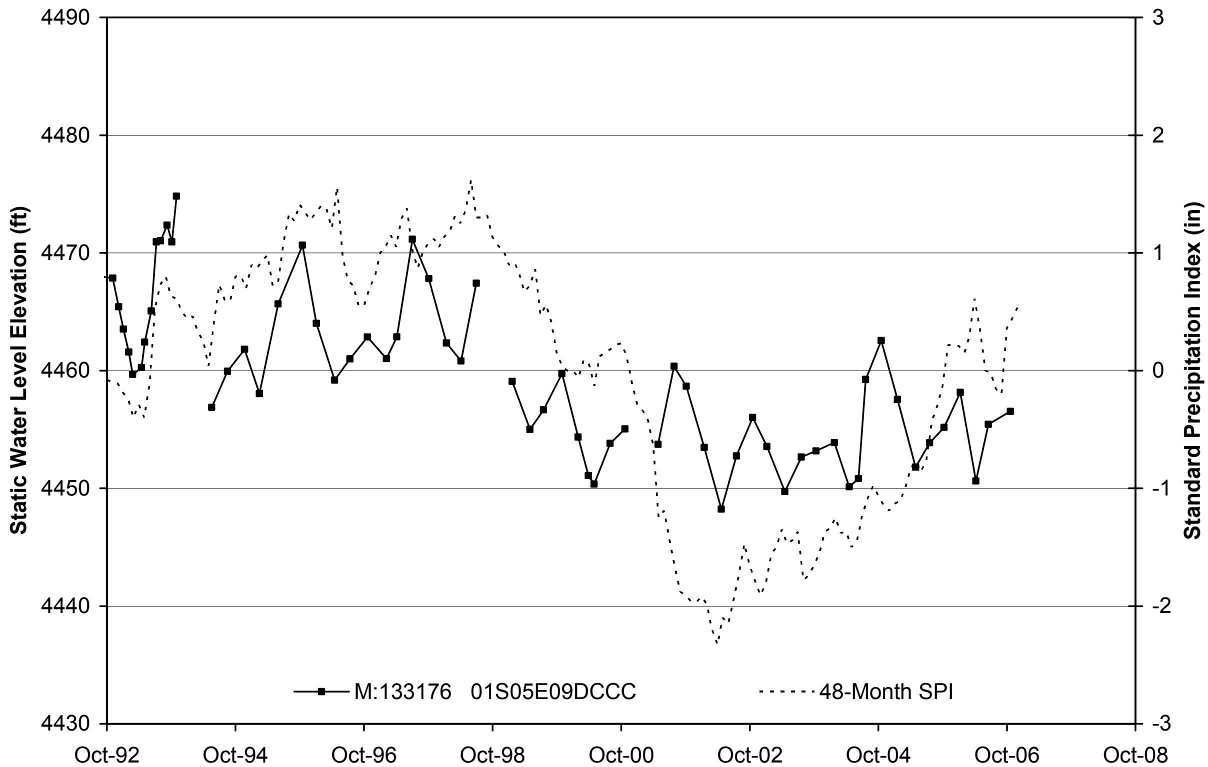


Figure 21. Water levels in well 01S05E09DCCC and 48-month SPI.

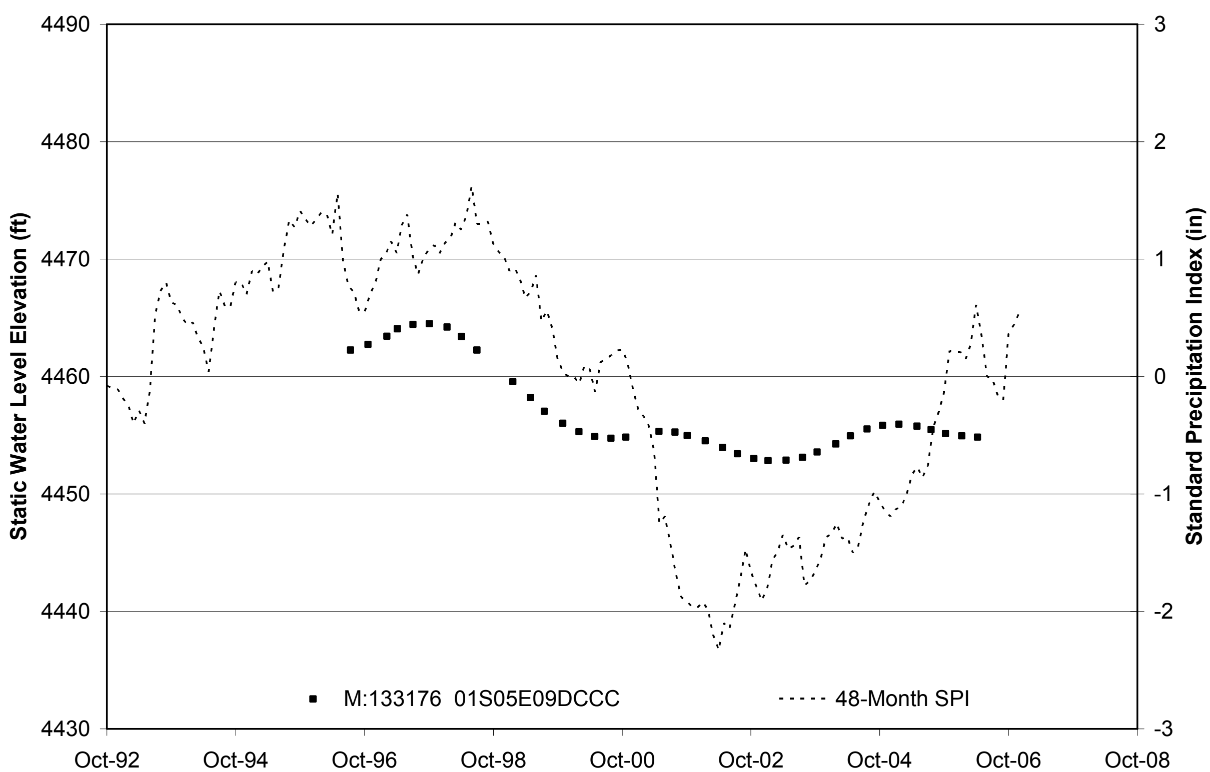


Figure 22. Moving average of water levels in well 01S05E09DCCC and 48-month SPI.

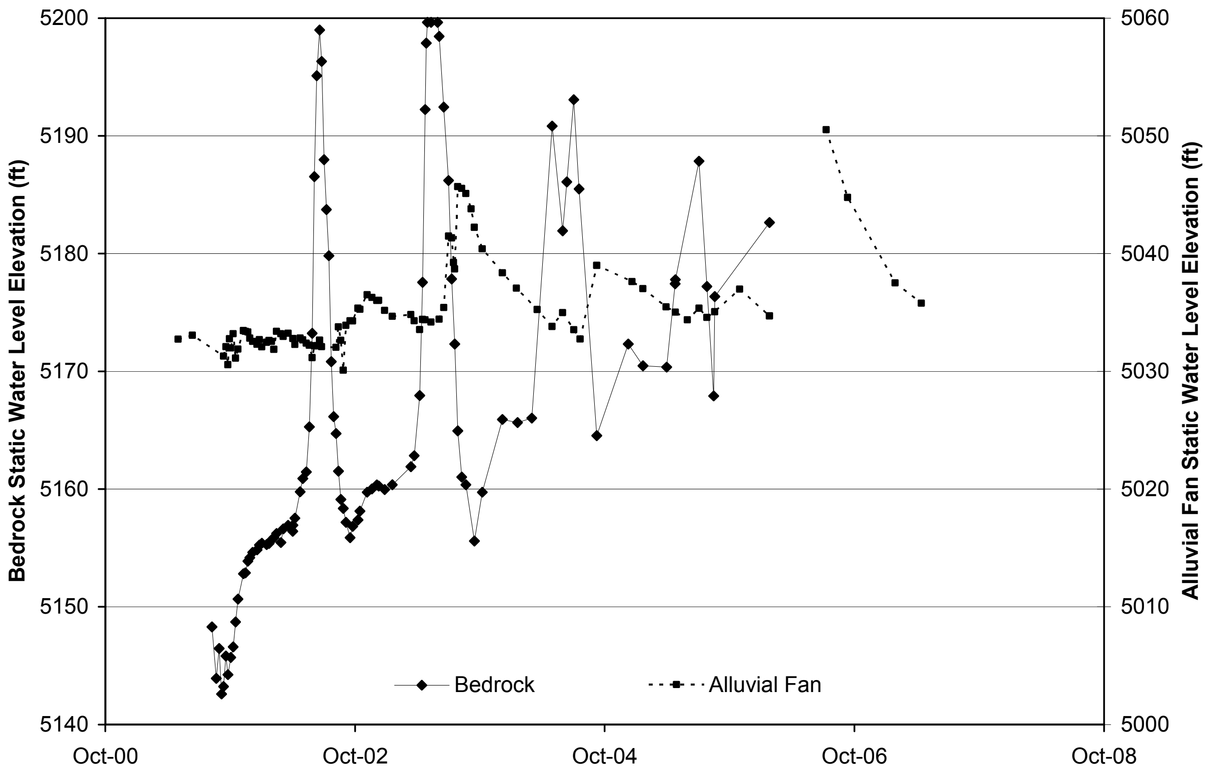


Figure 23. Water levels in bedrock well 01S06E17DCDB and alluvial fan well 01S06E17DCCA.

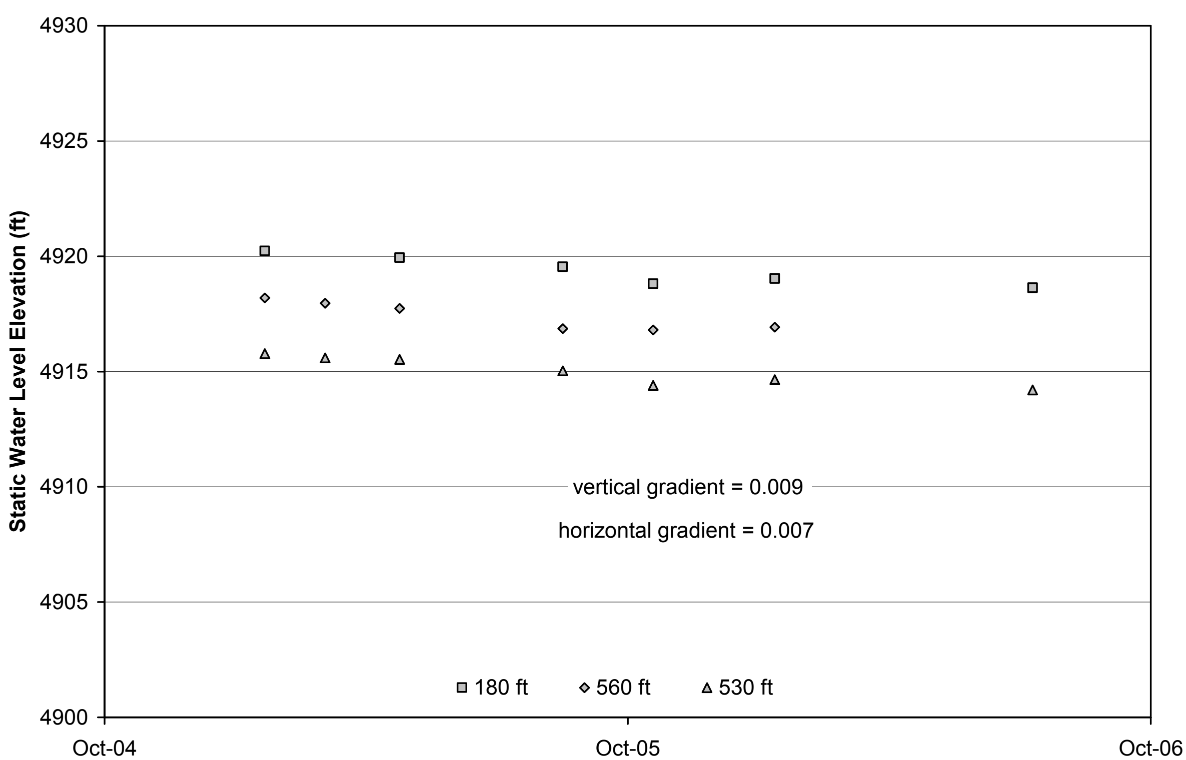


Figure 24. Water levels in wells SCND1, SC2A, and SC2 from Kaczmarek (2001).

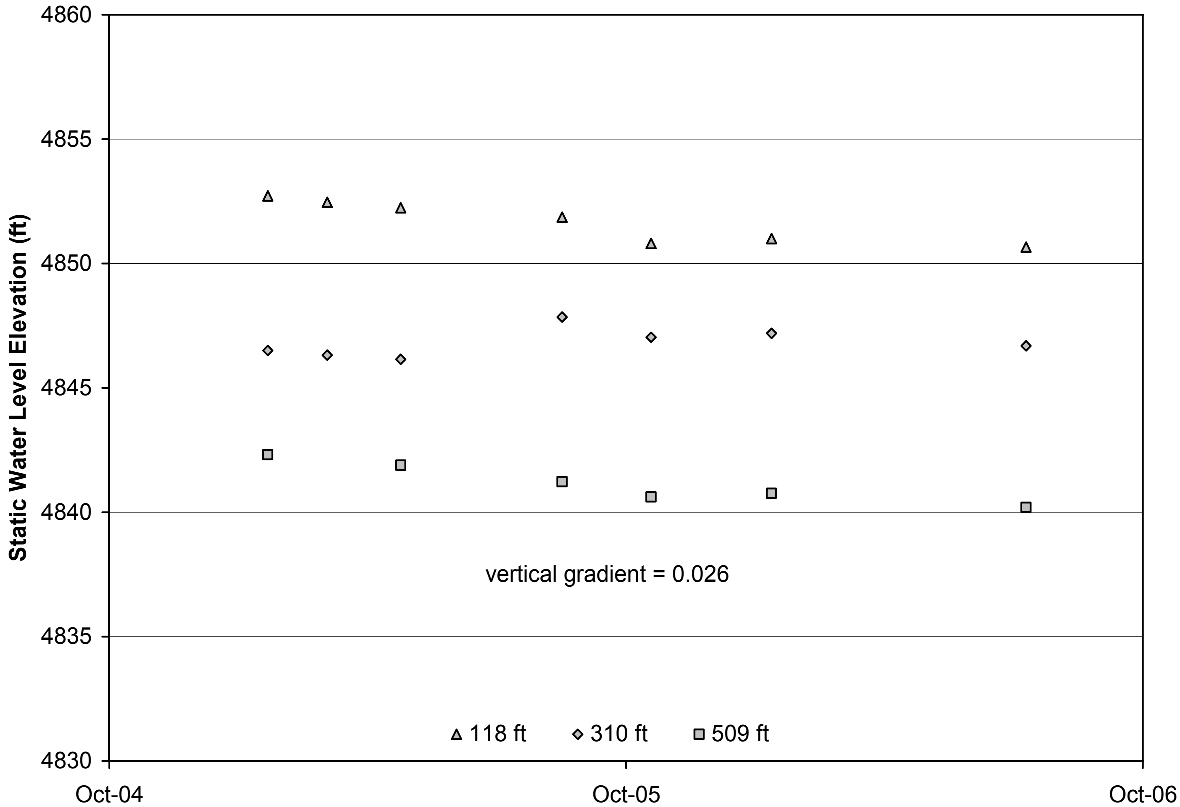


Figure 25. Water levels in wells SC1A, SC1B, and SC1 from Kaczmarek (2001).

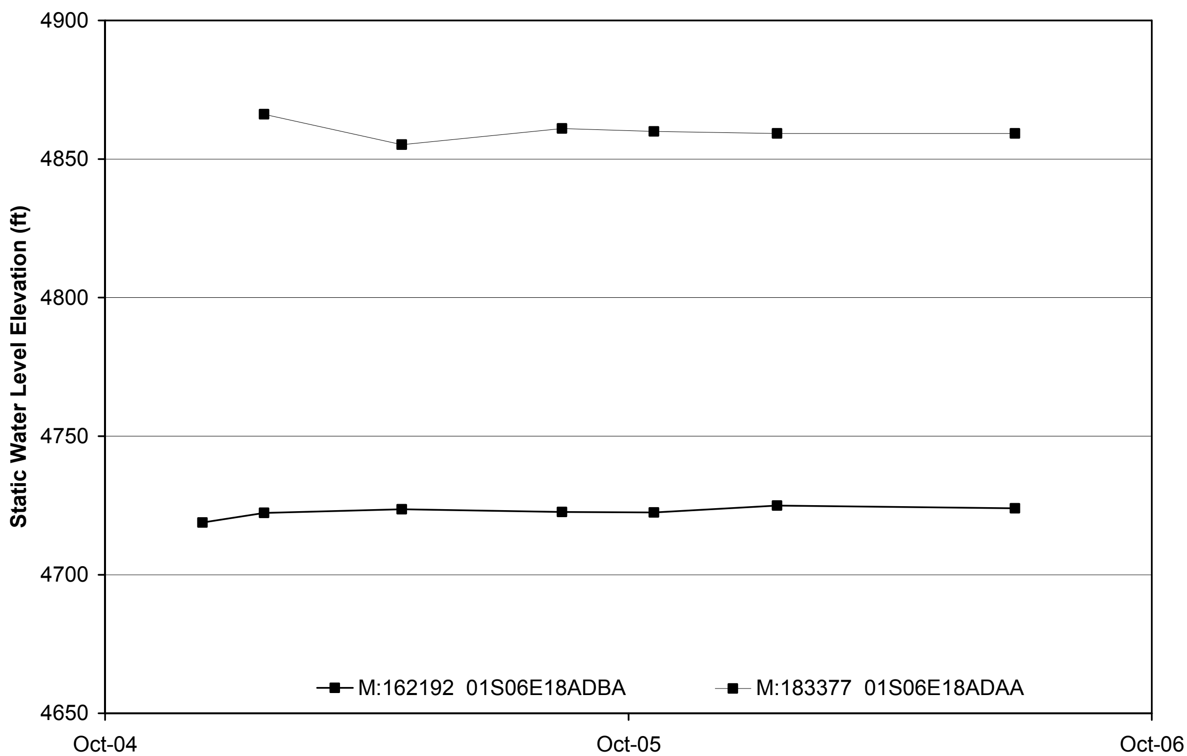


Figure 26. Water levels in wells 01S06E18ADBA and 01S06E18ADAA.

Water Budget

A water budget for the study area shown in Figure 1 provides information for DNRC to evaluate whether withdrawals exceed recharge within the CGWA and for input to the numerical model presented later (Table 4). The recharge components of the water budget considered here include direct infiltration of precipitation and snowmelt on the surface of the alluvial fan, seepage losses from streams that drain the western front of the Bridgers, and inflow from bedrock aquifers in the Bridgers. Discharge components include the consumptive portion of withdrawals from wells and ground-water outflow to alluvium of the East Gallatin River.

Annual precipitation over the alluvial fan portion of the model area is estimated from a GIS coverage derived from point data and a digital elevation model by Daly and Taylor (1998). Precipitation data from this coverage are converted to a grid coverage and interpolated to a 984-foot (300-meter) square grid used for the ground-water flow model to determine recharge from direct infiltration. Total recharge is the sum of ten percent of precipitation for each grid cell multiplied by cell area. Evapotranspiration is taken into account implicitly in estimates of infiltration from precipitation and, therefore, with the exception of areas where phreatophytes take water directly from ground water, it is not included explicitly in the water budget calculation.

Recharge by seepage losses from streams that drain the Bridgers is derived from streamflow measurements by previous investigators (Table 3) and estimates of mean annual flow based on measurements of active channel width following methods described by Parrett et al (1983). Streams that drain the Bridger Range lose virtually all of their flow as they cross alluvial fan sediments (Hackett et al, 1960; Hay, 1997). Therefore, recharge is estimated to be equal to the predicted average annual runoff from streams draining the Bridgers minus consumptive use by evapotranspiration associated with irrigation diversions and phreatophytes along those streams. Irrigated acreage on the fan surface is estimated to be 155 acres from the Water Resource Survey (Montana State Engineers Office, 1953) and area of phreatophytes equal to 193 acres is based on evaluation of color aerial photographs taken in 2005. Plant transpiration of 17 inches per year is assumed in estimates of consumption by evapotranspiration by crops and by phreatophytes.

Estimates of consumption of ground water withdrawn from wells within the model area are based on measurements at Summer Ridge Subdivision, guidelines for typical water use, and information on typical water consumption during household use, lawn and garden irrigation, and wastewater disposal. A technical memorandum to the Colorado State Engineer (Kimsey and Flood, 1987) contains evidence that consumption resulting from indoor household uses is typically 2 percent of the amount diverted. Further, another memorandum to the Colorado State Engineer (Vanslyke and Simpson, 1974) contains evidence that consumption from septic drainfields accounts for an additional 10 percent of the amount diverted for household use. Therefore, total consumption for in-house and waste disposal is considered to be 12 percent of total water diverted for household use. Consumption for lawn and garden irrigation is assumed to be 15.52 inches per year based on net-irrigation demand for pasture grass calculated using the Montana Irrigation Guide (U.S. Soil Conservation Service, 1987). Ground-water outflow from the fan aquifer system is calculated using Darcy’s law and estimates of aquifer transmissivity, aquifer width, and hydraulic gradient.

Table 3. Annual Runoff and estimates of annual recharge for streams within the Sypes Canyon model area.

Stream	Active Channel Width (ft)	Predicted Runoff (ac-ft/yr)	Observed Runoff (ac-ft/yr)			Recharge Estimate (ac-ft/yr)
			Hay (1997)	Hackett (1960)	Other	
East Gallatin River	35			62,912	59,202	--
Bridger Creek	22			25,946	26,493	--
Bostwick Creek	6.2	2,899		3,360		3,226
Schafer Creek	3.1	886	1,075			886
Watts Creek			151			151
Middle Cottonwood Creek	7.7	4,199	4,780	3,365		4,199
Walton Creek	1.7	317	278			228
Sypes Creek	1.7	317	452			317
Deer Creek	1.4	228			180	228
Churn Creek	2.0	419			569	419
Lyman Creek	3.8	1,255			3,760	1,255

The sum of stream loss and ground-water inflow within the study area equals 18,232 acre-feet per year (25 cubic feet per second) (Table 4) compared to an estimate of 37,836 acre-feet per year of precipitation in the contributing area of the Bridgers derived from the GIS coverage by Daly and Taylor (1998). The difference of 19,604 acre-feet is equal to average consumption over the 11,163 acre contributing area of 21.1 inches. This compares to published estimates of general forest consumption of 14.5 to 21 inches (Leaf, 1975). Therefore, the estimate of surface and ground water outflow from the Bridgers appears reasonable based on estimates of precipitation and consumption in the contributing area, with any error likely on the low side.

Table 4. Preliminary water balance for alluvial fan system within model area for Sypes Canyon CGWA.

Recharge (ac-ft/yr)			Discharge (ac-ft/yr)		
Precip.	Small Streams	GW Inflow	Withdrawals	GW Outflow	ET
1,827	10,909	7,323*	466	19,100	493
* calculated as remainder of other terms					

<u>Steady-State Numerical Model</u>

A steady-state numerical model of the Sypes Canyon study area was constructed using MODFLOW 2000 and Groundwater Vistas v4.25. The purpose of the steady-state model is to improve estimates of aquifer properties, recharge, and boundary conditions for use in predicting impacts of future widthdrawals using the transient model described in the subsequent section. The steady-state model consists of 44 rows, 34 columns, and three layers with 2,248 active cells (Figure 27) constructed as follows:

- Cells are 984 feet by 984 feet (300 meters by 300 meters) throughout the model.
- The top layer is 262 feet (80 meters) thick and is designated unconfined and the bottom two layers are 175 feet (60 meters) thick and are designated confined. Layers are designated to provide vertical discretization and are not based on lithologic changes.
- Elevation of the top layer is interpolated to model cells from a digital elevation model using ArcView GIS software and imported into Groundwater Vistas.
- There are 306 cells with individual wells or public water supply wells. Withdrawals from wells in the model equal net consumption of 0.68 acre-feet per-household and are represented by single wells per model cell in layer 2. Net consumption per household is based on 2% of 250 gallons per day (gpd) for in house consumption, 10% of 250 gpd for wastewater consumption, and 15.52 inches irrigation requirement for ½-acre lawn and garden. In-house and wastewater consumption percentages are based on studies (Vanslyke and Simpson, 1974; Kimsey and Flood, 1987) and irrigation requirement is based on the Montana Irrigation Guide (U.S. Soil Conservation Service, 1987) using data from the weather station at Montana State University in Bozeman. Lawn area was estimated by evaluating aerial photographs of a random selection of residences within the study area.
- Seepage from small streams draining the Bridger Range and direct infiltration of precipitation are simulated using the MODFLOW Recharge Package. Recharge estimates from Table 3 are used for recharge from small streams and 10 percent of values from the GIS coverage by Daly and Taylor (1998) are used for precipitation recharge.
- The East Gallatin River and Bridger Creek are simulated using the MODFLOW River Package with channel length and width from the National Hydrography Data Dataset GIS coverage (USGS, 2000).
- Inflow from bedrock in the Bridgers is simulated using injection wells distributed uniformly along the east boundary of the study area in each layer.
- Ground-water inflow from the south and outflow to the north is simulated using general head boundary cells.

- Initial distribution of hydraulic conductivity is designated for zones based on geologic units mapped by Lonn and English (2002) (Figure 5).
- Evapotranspiration of phreatophytes along the East Gallatin River is simulated using the MODFLOW ET Package.
- Water-level elevations measured by GLWQD in wells within and nearby the CGWA are the primary calibration targets. Wellhead elevation was surveyed generally within 0.1 feet for these wells.
- Water-level elevations estimated from static water levels listed on drillers' logs and a digital elevation model are secondary calibration targets outside the main area of interest surrounding the CGWA.
- The model was initially calibrated using measured water-level data, by adjusting hydraulic conductivities and ground-water inflow from the Bridgers. Estimates of hydraulic conductivity from initial calibration are shown in Figure 28. Precipitation and recharge from small streams were not adjusted during calibration.
- The final calibration was attained using pilot points (hydraulic conductivity targets) and the automated calibration program PEST within Groundwater Vistas to adjust hydraulic conductivities for individual cells. Ground-water inflow from bedrock was manually adjusted to refine the calibration obtained using PEST.

Final calibration of the steady-state model resulted in a general match to observed heads. The average and median difference between simulated and measured heads (residual) is near zero (0.07 feet and -1.05 feet respectively); however, many of the residuals remain large with an average absolute value of approximately 15 feet (Figure 29). The main reason for the large residuals is the apparent large variability of hydraulic properties within short horizontal and vertical distances and clustering of observation wells. Smaller residuals could be achieved by using smaller model cells and adjusting hydraulic conductivity cell by cell. However, a more detailed model would still not provide a unique solution or better estimates of water levels throughout the study area even though a better fit to measured data would be achieved. Therefore, the final calibration was deemed adequate for the purpose of conducting transient simulations of future ground-water development and potential impacts on ground-water levels and surface water flows.

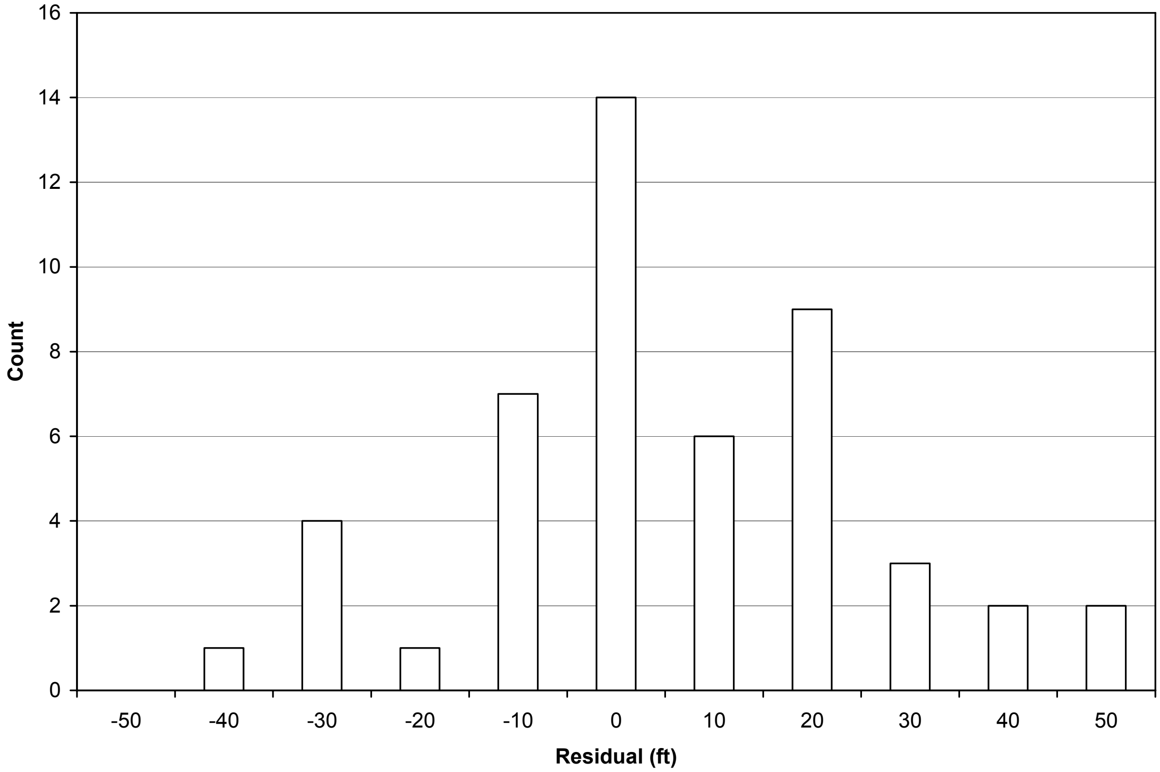


Figure 27. Residual differences between water levels in target wells and water levels calculated by steady state model.

The water balance from the calibrated steady-state numerical model is presented in Table 5. Total recharge to the model is 22,652 ac-ft/yr (31.3 cfs) and net withdrawal (consumption) from wells is 938 ac-ft/yr (1.3 cfs). Over 50 percent of ground-water inflow from bedrock and approximately 80 percent of total recharge to the alluvial fan aquifer system occurs in the upper layer of the model. Note that this water balance is not limited to the CGWA boundary because the area of impact of ground-water withdrawals within the CGWA will extend beyond its boundaries and ground-water withdrawals outside the boundary will impact ground-water levels within the CGWA. In addition, recharge outside the CGWA affects ground-water levels within the CGWA.

Table 5. Water balance for entire model area from steady-state numerical model results.

	Recharge (ac-ft/yr)				Discharge (ac-ft/yr)			
Layer	Precip.	Small Streams	Bridger Ck.	GW In	Wells	E. Gallatin	ET	GW Out
1	2,444	10,626	23	5,030	----	-571	-1,274	-7,104
2	----	----	----	3,952	-938	----	----	-6,447
3	----	----	----	577	----	----	----	-6,321
Total	2,444	10,626	23	9,559	-938	-571	-1,274	-19,872

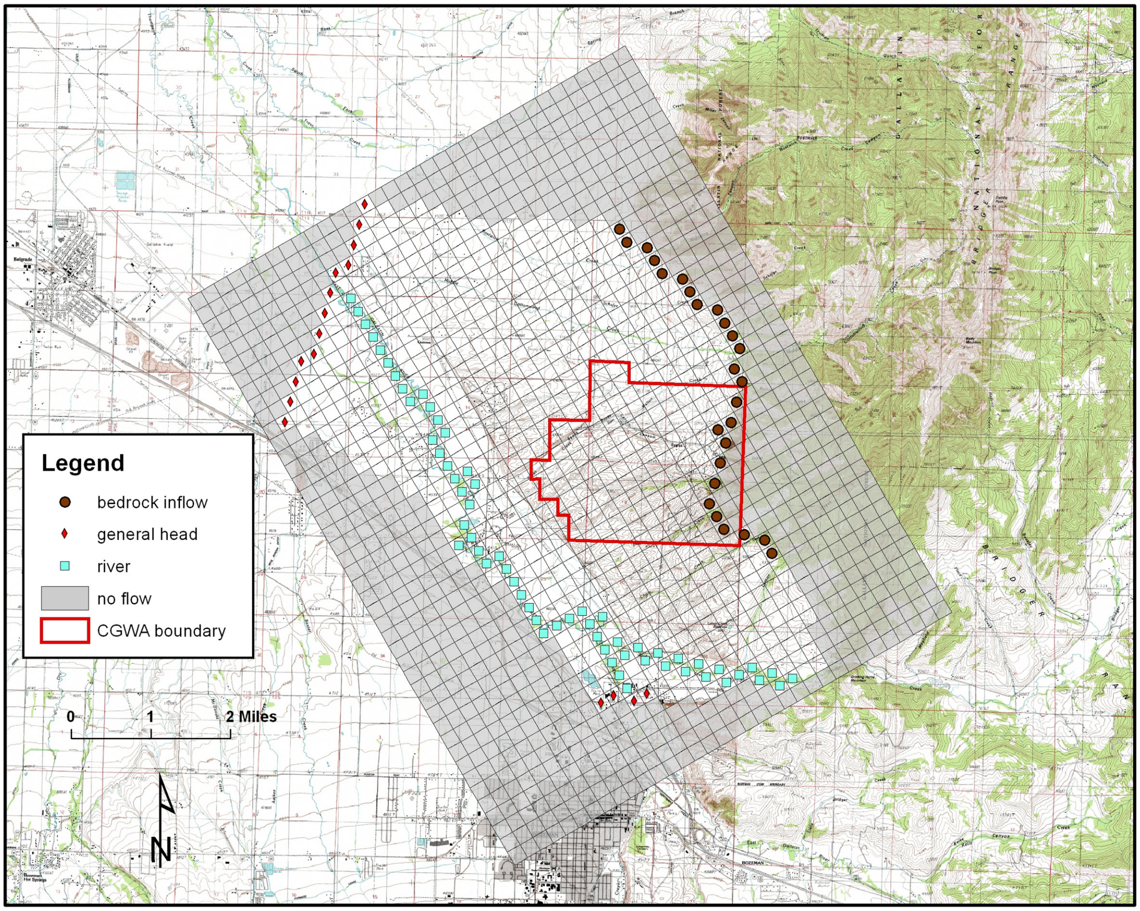


Figure 28. Grid and boundary conditions of numerical models.

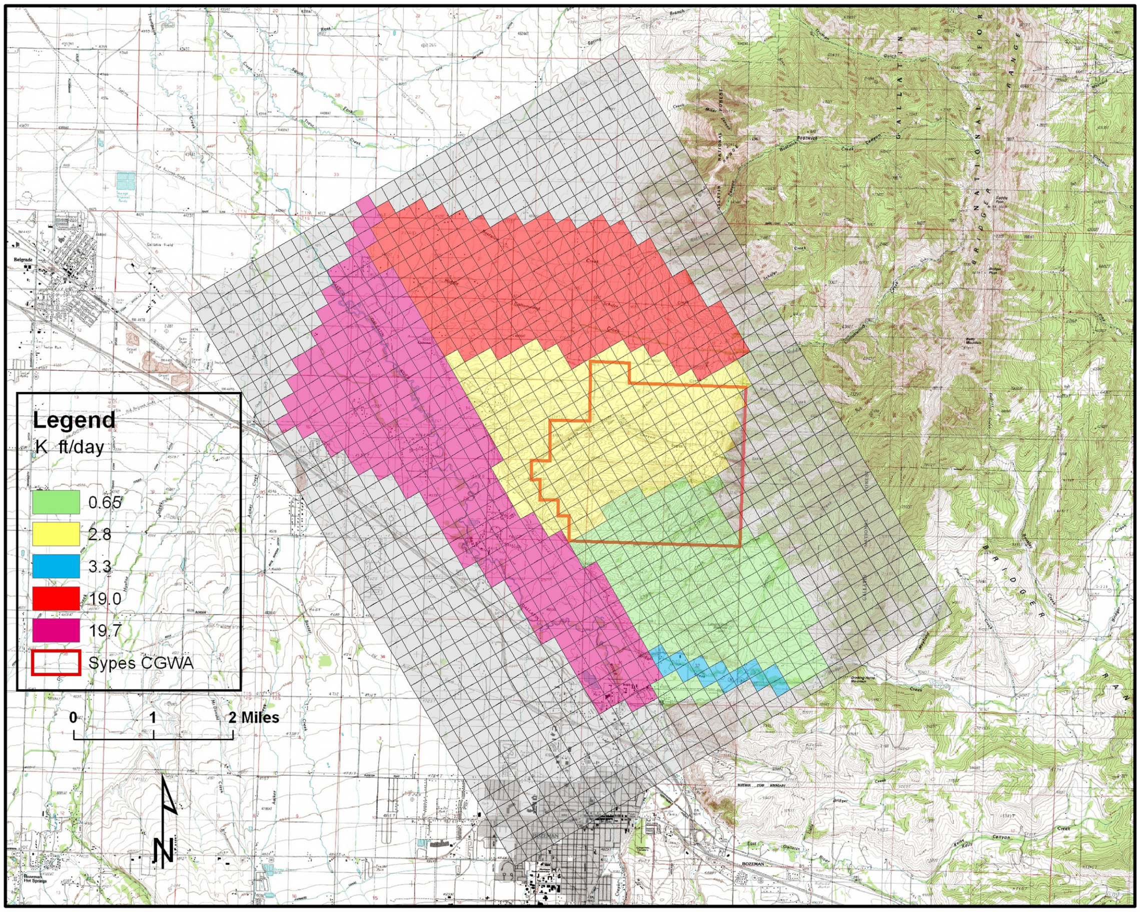


Figure 29. Initial hydraulic conductivity zones for all layers of steady-state numerical model.

Transient Numerical Model

Additional pumping wells were added to the steady-state model to simulate transient drawdown by increased withdrawals of 439 acre-feet per year (248 acre-feet per year consumption) from approximately 450 additional households. The additional wells adjust the overall density to one household per 2.5 acres for the full CGWA. Hydraulic conductivity, recharge, evapotranspiration and aquifer boundaries are retained from the steady-state model. Specific storage and specific yield are set to 0.000015 ft^{-1} (0.00005 m^{-1}) and 0.20, respectively, and initial heads are set to heads calculated from the steady state model. The results of four separate models representing different 50-year duration pumping scenarios, described below, are presented for the purpose of investigating the potential effects of further development on ground water levels within the CGWA.

Transient Model #1 - Withdrawals from additional wells within the Sypes Canyon CGWA are simulated using wells in 41 cells located in layer two (Figure 30) that represent pumping for approximately nine households within each of the 984-foot square cells. Recharge of water that is not consumed and returned to the aquifer system is represented by composite recharge wells in 41 cells in layer one lying immediately above cells containing pumping wells. Both pumping and recharge rates for monthly stress periods vary with seasonal demand and consumption.

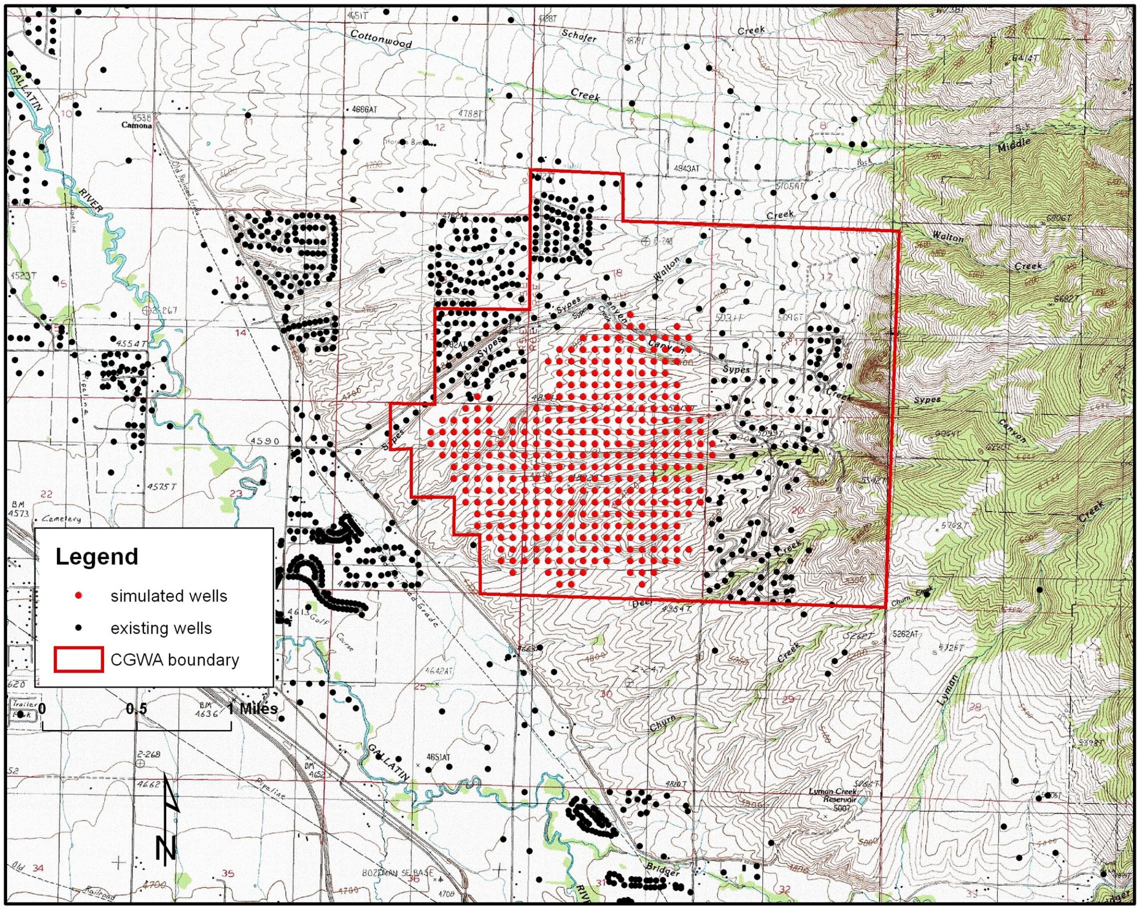


Figure 30. Location of wells simulated in transient models #1 through #3 with approximate locations of existing wells.

Drawdown from pumping the additional wells simulated in transient model #1 emulates the seasonal fluctuations of withdrawals (Figure 31). Drawdown plotted in Figure 31 reaches approximately 80 percent of maximum during the first year and increases gradually year over year as drawdown expands. With time, the rate of progressive increase in drawdown slows as ground water is derived from storage in a greater volume of the aquifer system and flows in the East Gallatin River and Bridger Creek, and evapotranspiration by phreatophytes along the East Gallatin are reduced. Drawdown at the end of the irrigation season of the 50th year is approximately 50 feet within the center of the array of new pumping wells and up to 20 feet in the area of existing wells in Section 20, Township 01 South, Range 06 East (Figure 32). Drawdown in wells monitored by GLWQD is predicted to decline between 0.10 feet in a well in layer one to 45 feet in a well in the Autumn Ridge subdivision within the simulated well field. Excluding the Autumn Ridge wells, drawdown is predicted to exceed five feet in 15 wells with a maximum of 36 feet in well 01S06E20BBBC, located approximately 500 feet from the nearest simulated well.

Transient Model #2 - Simulated pumping wells are moved to layer three and recharge wells are again placed in layer one in transient model #2. The purpose of this model run is to investigate whether drilling new wells to greater depths than most existing wells will significantly reduce drawdown in the existing wells. Results shown in Figure 33 indicate that drawdown in layer two within the simulated well field is about half as large as when the pumping wells are in layer two. However, drawdowns still exceed five feet in 15 wells monitored by GLWQD with a maximum of 22 feet in well 01S06E20BBBC.

Transient Model #3 – Simulated pumping wells are placed in layer three as in transient model #2; however, domestic return flows are eliminated. The purpose of this model run is to investigate the effects of off-site wastewater disposal. Maximum drawdown in layer two within the simulated well field is 36 feet (Figure 34). In addition, drawdown simulated in transient model #3 again exceeds five feet in 15 wells with a maximum of 26 feet in well 01S06E20BBBC.

Transient Model #4 – The uniformly distributed well field from the first three transient models is replaced by five hypothetical public water supply wells in layer three along the west boundary of the CGWA in transient model #4. Recharge from domestic and irrigation return flows are simulated by recharge wells in layer one, also along the west boundary of the CGWA. The purpose of transient model #4 is to investigate whether locating wells farther from existing wells and nearer to the East Gallatin River will reduce drawdown in wells within the CGWA. Maximum drawdown in layer two within the simulated well field is 17 feet (Figure 35) and drawdown in all of the wells monitored by GLWQD is less than five feet.

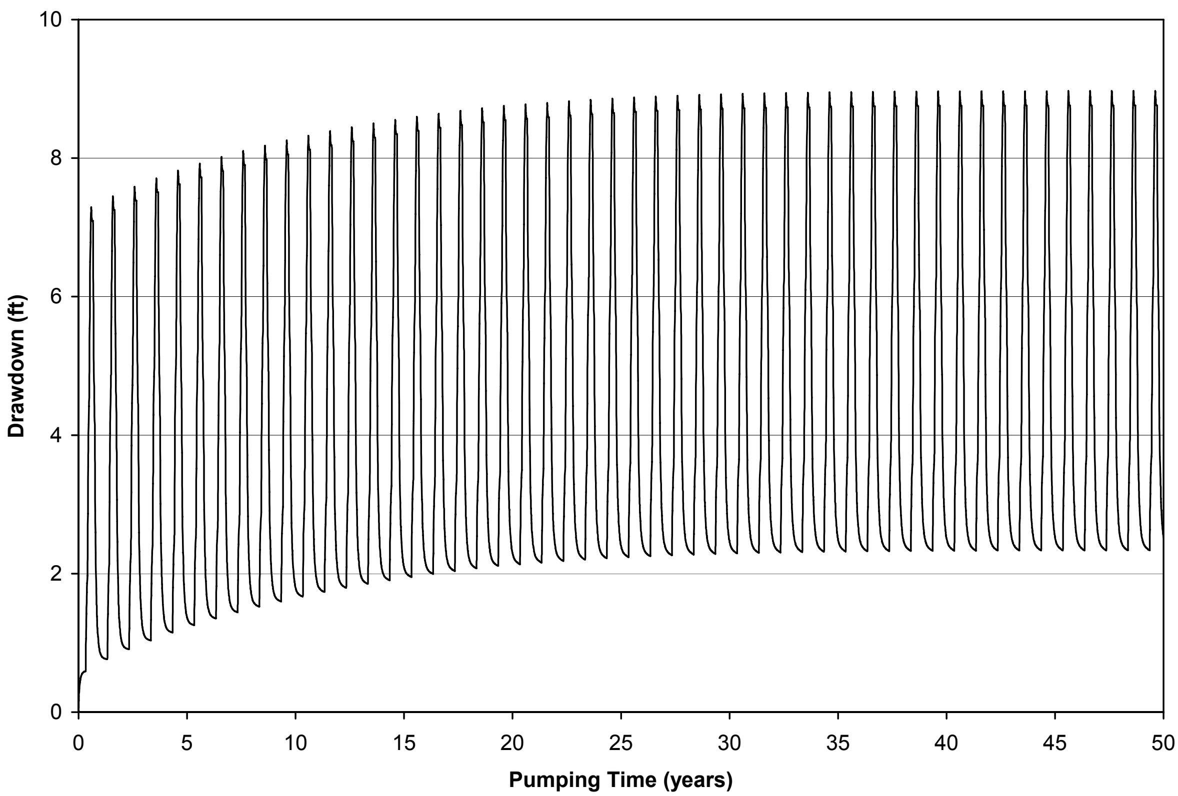


Figure 31. Drawdown in well 01S06E20CCBA from transient model #1.

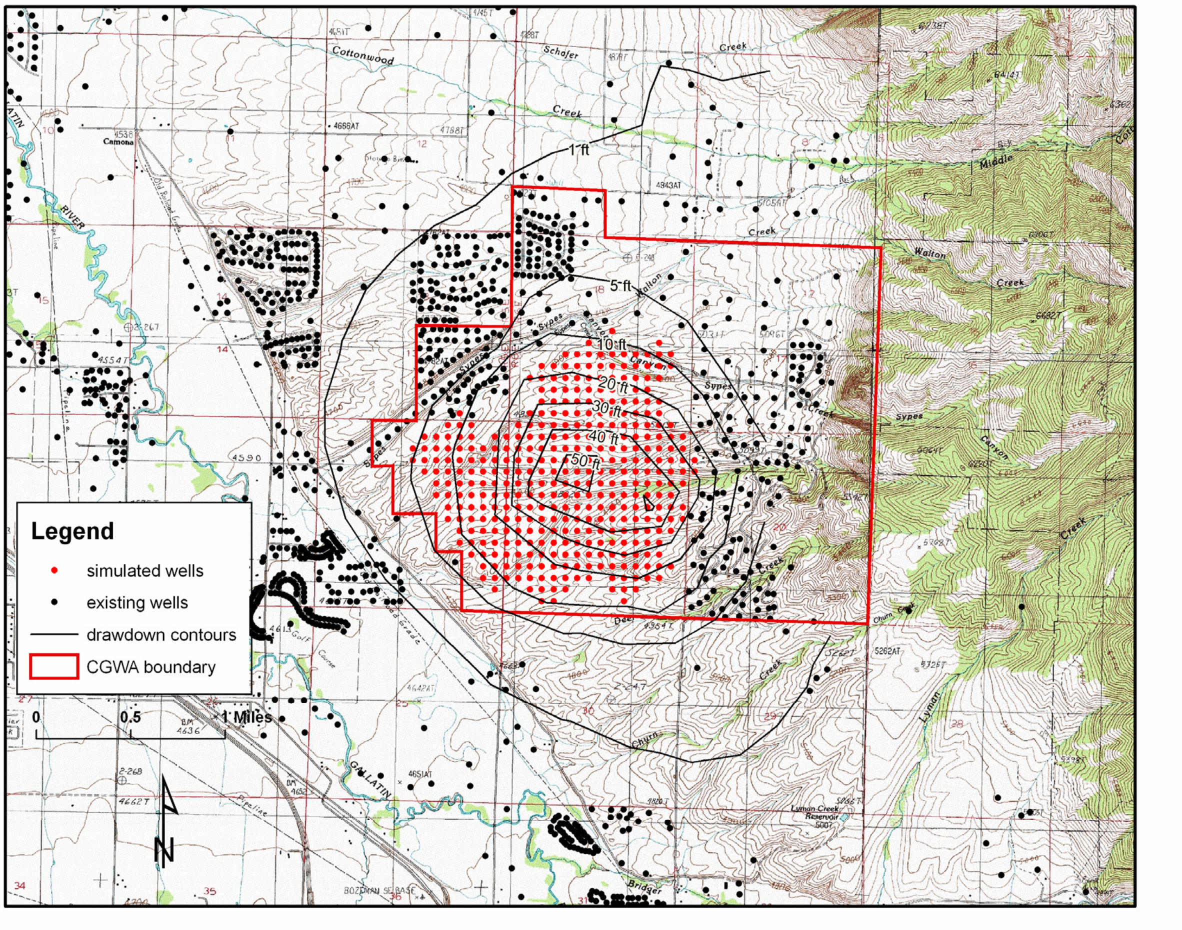


Figure 32. Drawdown after 50 years of pumping from layer two with recharge to layer one calculated from transient model #1.

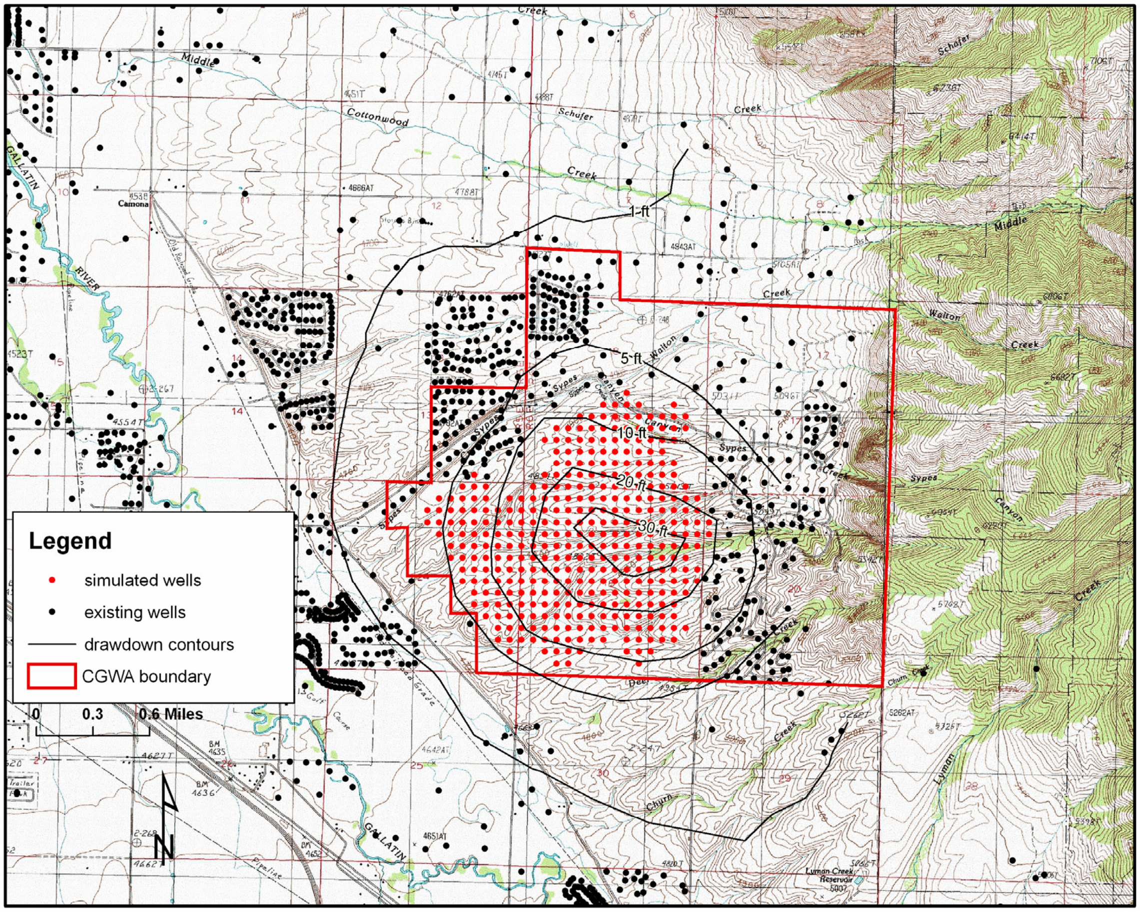


Figure 33. Drawdown after 50 years of pumping layer three with recharge to layer one calculated from transient model #2.

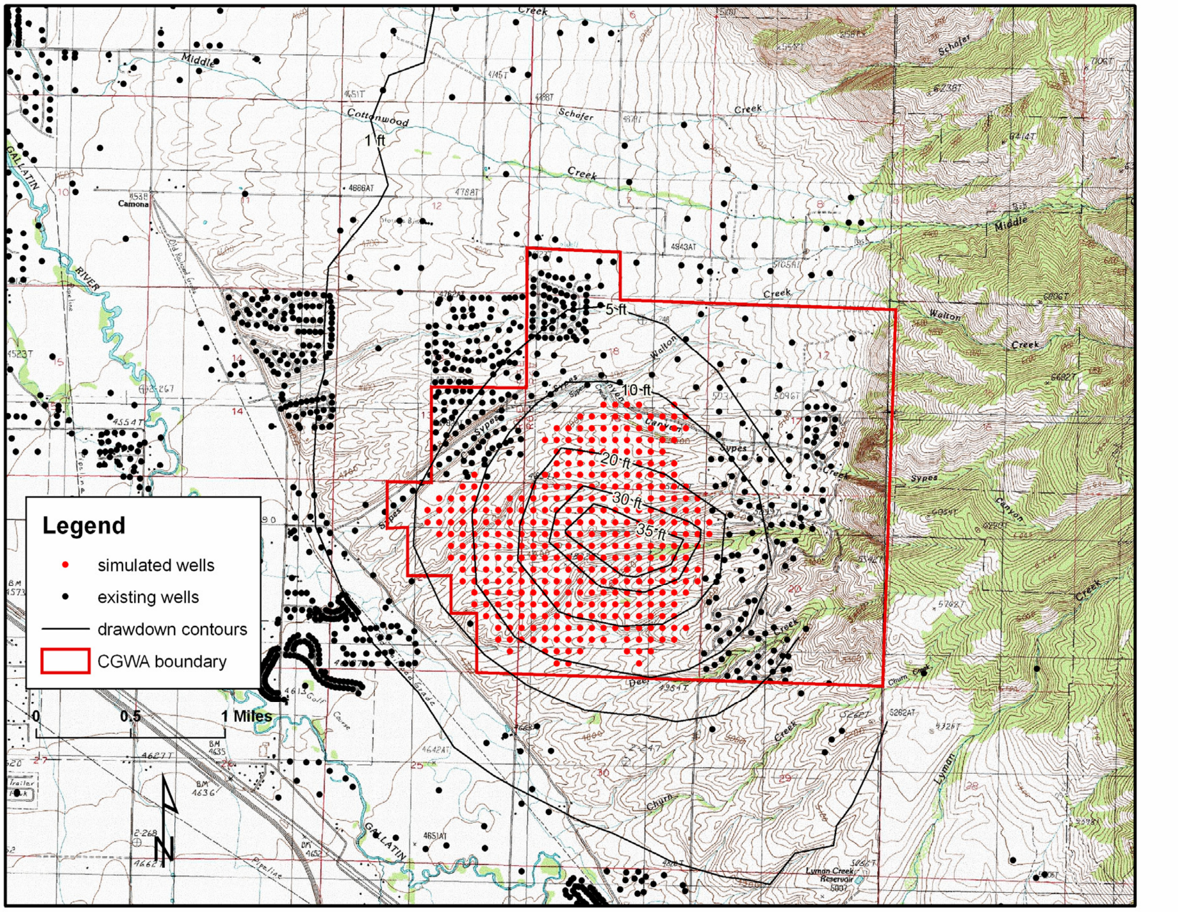


Figure 34. Drawdown after 50 years pumping from layer three without recharge calculated from transient model #3.

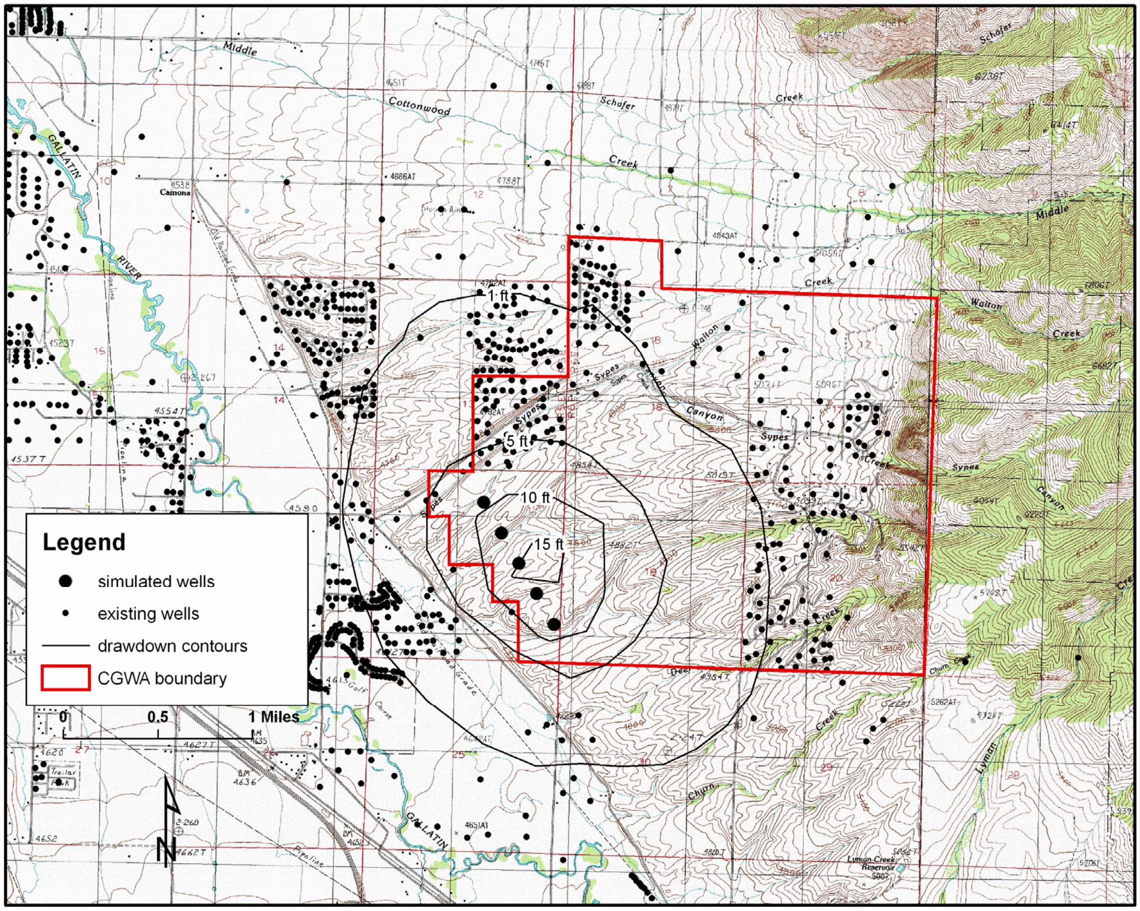


Figure 35. Drawdown after 50 years of pumping public water supply wells in layer three with recharge to layer one calculated from transient model #4.

Surface Water Depletions
Drawdown caused by any new withdrawals within the CGWA will propagate in all directions and will deplete flows in the East Gallatin River and Bridger Creek, and potentially other surface waters in the Gallatin Valley that are hydraulically connected to ground water, by reducing ground-water levels at those streams. Reduced ground-water levels at the East Gallatin River or Bridger Creek will either cause surface water loss (induced infiltration) or reduced ground-water discharge (pre-stream capture). The transient models presented here calculate total net depletion regardless of whether induced infiltration or pre-stream capture occurs.

The rate of depletion simulated by transient models for this investigation fluctuates with the seasonal variation of withdrawals and increases year over year as drawdown increases and propagates away from the simulated pumping wells (Figure 36). Net depletion to the East Gallatin River and Bridger Creek after 50 years of pumping simulated by transient model #2 equals 200.9 acre-feet. Reduced flux out of model #2 at general head boundaries and by evapotranspiration equals 29.9 acre-feet and 4.2 acre-feet respectively. Net depletion of surface water after 50 years for transient model #4, where withdrawals are concentrated closer to the East Gallatin River, equals 237.3 acre-feet. Reduced flux out of model #4 at general head boundaries equals 16.2 acre-feet and reduction of evapotranspiration equals 4.6 acre-feet. The balance of the 248 acre-feet total consumption by well use in models #2 and #4 equal to approximately 10 to 12 acre-feet comes from ground water storage released as drawdown continues to expand. Net depletion to surface water will approach a constant year over year with time as a balance between recharge and discharge is reestablished and the contribution from storage reduces to zero (Theis, 1940) (Figure 37). Reduced flux at general head boundaries is interpreted to represent depletion to surface water within the valley, but outside the model area.

An applicant for a beneficial use permit for greater than 10 acre-feet annually or a maximum rate greater than 35 gallons per minute in the Sypes Canyon area would be required to mitigate depletions to surface water that result in an adverse effect to an existing water user (§85-2-360 MCA). Mitigation generally involves changing the purpose of use of an existing surface-water right to mitigation or aquifer recharge and retiring the historic use (e.g. drying up land previously irrigated). Water from the historic right may have to be diverted and allowed to infiltrate ground water in order to mitigate depletion that occurs outside the historic period of use (e.g. irrigation season) (Bredehoeft and Kendy, 2007). Wells that use less than 10 acre-feet and 35 gallons per minute are exempt from permitting requirements, including mitigation of adverse effects to surface water, in the absence of a controlled ground water area.

<u>Drought and Climate Change</u>
Recharge in the Sypes Canyon area may be affected if temperature, precipitation, and/or timing of runoff change in the future. Ground-water level declines resulting from precipitation approximately 85 percent of the 40-year average are evident from hydrographs for the period between 1998 and 2004 (Figures 9 through 23) and are predicted from the results of a transient simulation for a 10-year drought (Figure 38). Further, a shift to increased summertime precipitation relative to snowfall and higher average temperatures that some predict might occur in the Gallatin Valley (Aber, 2007) could lead to reduced snowpack, early runoff, decreased recharge from small streams draining the Bridger Mountains, and, ultimately, lower ground-water levels.

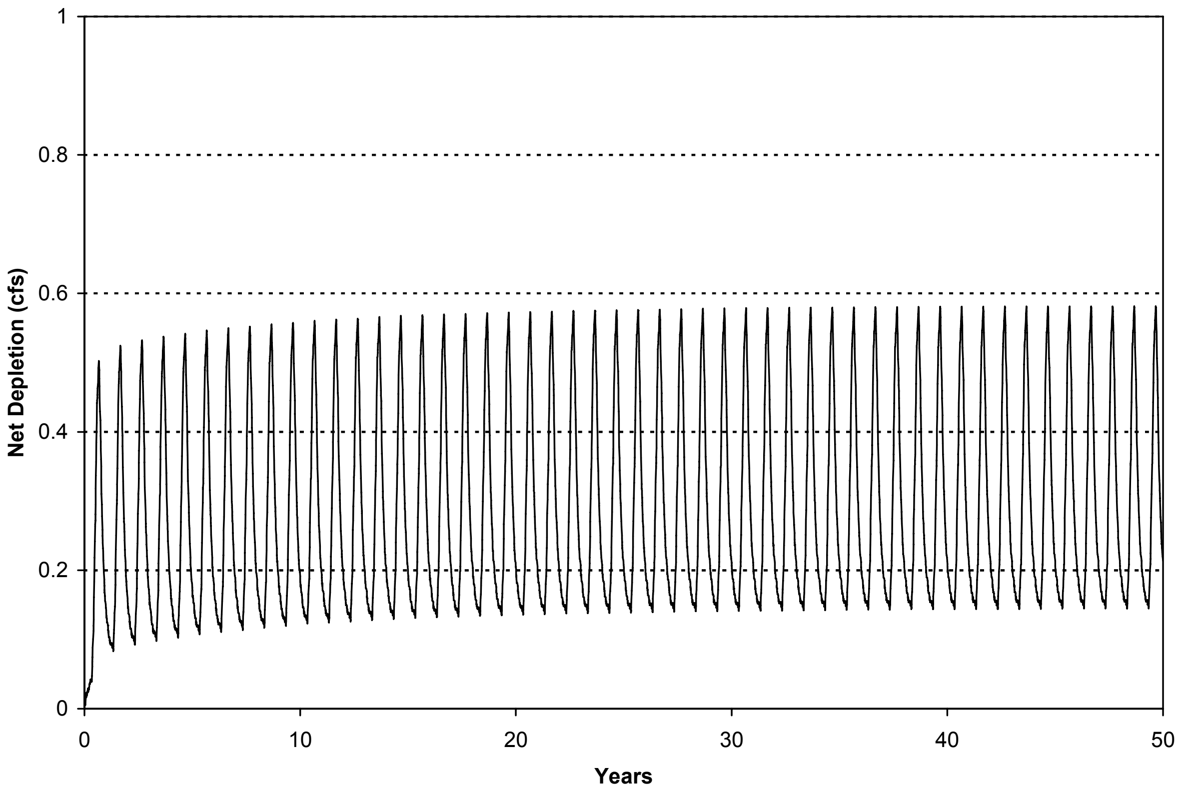


Figure 36. Rate of depletion of surface water calculated by transient model #4.

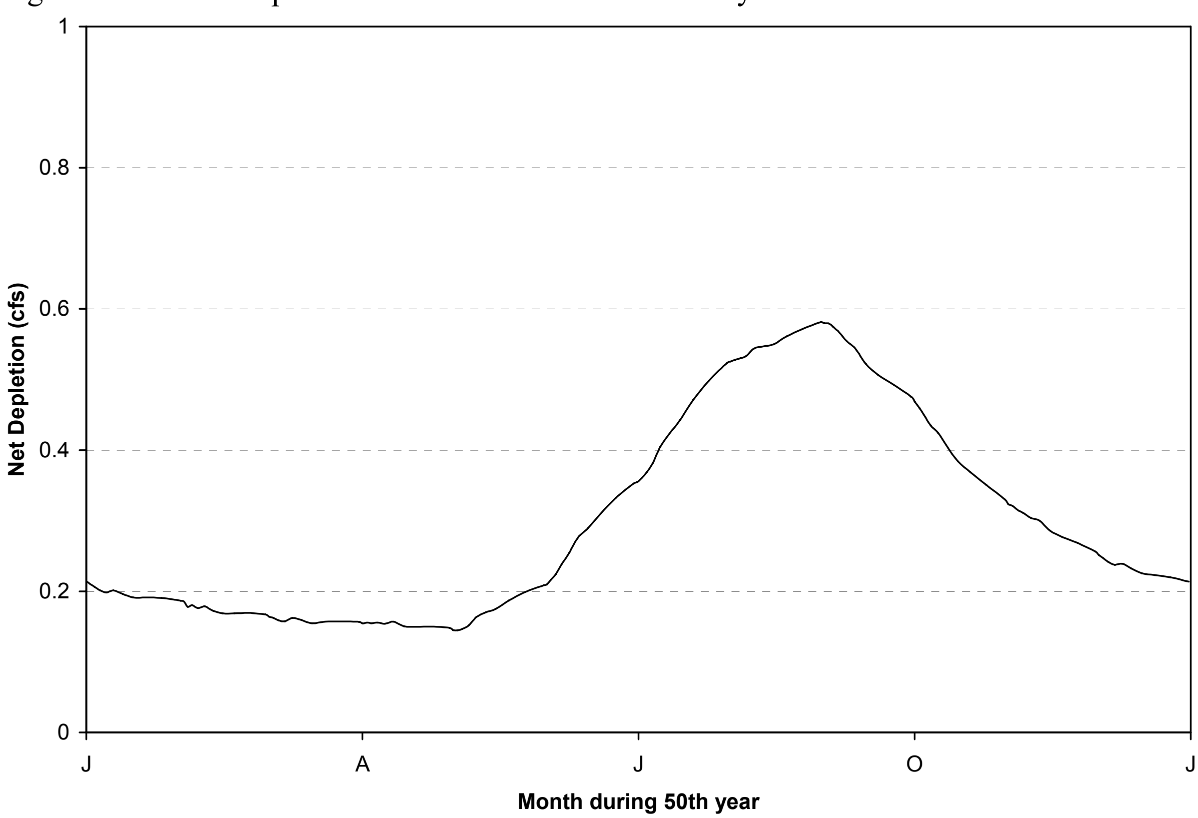


Figure 37. Rate of depletion of surface water from transient model #4 (50th year).

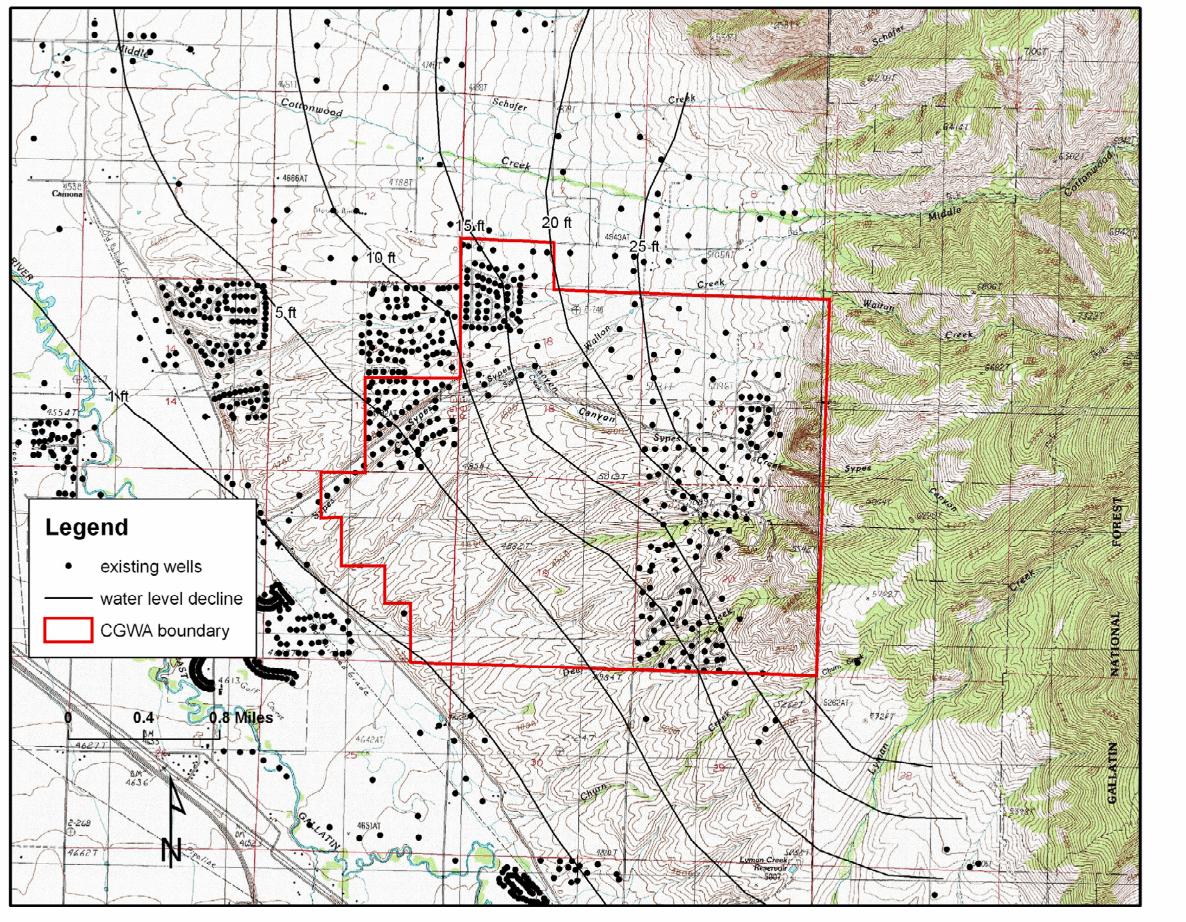


Figure 38. Simulated water-level decline resulting from 10 years of precipitation that is 15 percent less than average.

Summary and Conclusions

DNRC designated a temporary controlled ground water area for the purpose of *"gathering information on aquifer characteristics, aquifer recharge, and aquifer withdrawals to determine if withdrawals exceed recharge and if new wells will impair or substantially interfere with other ground water wells"*. The findings related to the objectives of this report are summarized as follows:

Describe the hydrogeology of the aquifer system in the control area

The Bridger Mountains immediately east of the CGWA consist of folded and faulted steeply dipping Paleozoic- to Mesozoic-age sedimentary rocks and Archean-age metamorphic rocks. Bedrock is down-dropped beneath the CGWA and buried by an undetermined thickness of alluvial fan deposits consisting of discontinuous coarse- and fine-grained sediments. Recharge from bedrock to the alluvial fan is concentrated at shallower depths because water transmission from fractures and faults in the gneiss decreases with depth and increased weight of overlying rock, and because clay in the range-front fault may dam water in some areas.

Describe and evaluate the causes of ground-water level changes

Current ground-water levels in wells completed in the alluvial fan within or near the CGWA generally are 5 to 20 feet lower than approximately 10 years ago. Water levels in wells near the range-front fault generally fluctuate seasonally in response to recharge from small streams and discharge from bedrock aquifers. Seasonal fluctuations of water levels in wells more distant from the primary sources of recharge are dampened and delayed or absent completely. Water levels in wells located near the range-front correlate to 48-month and seasonal precipitation patterns whereas wells located more distant from sources of recharge, or that are completed in poorly connected water-producing intervals, correlate to longer-period precipitation trends. Water-producing intervals at different depths within the alluvial fan aquifer system are hydraulically connected. However, vertical water-level gradients indicate the presence of low hydraulic conductivity layers that create semi-confined conditions. Water levels in alluvium of the East Gallatin have remained relatively constant with small seasonal fluctuations.

Estimate a budget of aquifer recharge and withdrawals

The recharge components of the water budget considered here include direct infiltration of precipitation and snowmelt on the surface of the alluvial fan, seepage losses from streams that drain the western front of the Bridger Mountains, and inflow from bedrock aquifers in the Bridgers. Discharge components include the consumptive portion of withdrawals from wells and ground-water outflow to alluvium of the East Gallatin River. The sum of seepage from small streams draining the Bridgers and ground-water inflow within the study area is estimated to be between approximately 18,000 and 23,000 acre-feet per year (25 to 31 cubic feet per second) from a contributing area of approximately 11,000 acres. Total withdrawal from wells within the model area is estimated to be approximately 1,700 ac-ft/year and total consumption is estimated to be 938 ac-ft/yr (1.3 cfs).

Evaluate the effects of increased withdrawals for future developments

Estimates of the effects of future withdrawals on ground-water levels within and nearby the CGWA are based on simulations conducted using a numerical model. The numerical model is calibrated by adjusting estimates of recharge and aquifer properties using the measured water-level data. The resulting model is not a unique representation of the aquifer system and, therefore, the results should be used carefully. General conclusions that can be made include:

- Continued development at the existing density and at depths similar to existing wells could lower water levels up to 20 feet in some existing wells.
- Pumping from wells at depths greater than depths of existing wells could reduce the effects relative to pumping from shallower depths because of the semi-confined nature of the aquifer system.
- Pumping from individual wells at greater than existing densities would result in proportionally greater drawdown.

- Development of ground-water within the CGWA will deplete flows in the East Gallatin River and Bridger Creek. This depletion ultimately will offset consumption by ground-water use.
- Pumping from public water supply wells located near the East Gallatin River could minimize drawdown within the CGWA.
- Extended drought can reduce ground-water levels in the CGWA up to 30 feet. Changes in temperature and precipitation patterns caused by climate change also may reduce recharge and affect ground-water levels.

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