Hydrogeologic Study
of the
Laramie County Control Area

Prepared for the Wyoming State Engineer's Office

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Errata Sheet

This report is identical to the report of the same name and authorship dated March 2014, with the exception of the following corrections, which have been included for the reader's convenience. There are no modifications of the report analysis or conclusions.

6.4 Transient Calibration Water Budget

p. 37 line 10: "…outflows exceed inflows by 100,000 ac-ft/yr…" was corrected to read "…outflows exceed inflows by 45,000 ac-ft/yr…"

Figures

The y-axis was corrected on Figure 6.14: "Transient Water Budget without Storage Term".

Tables

The water budget values were corrected in Table 6.4: "Transient Water Budget (ac-ft per water year)".

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APPENDICES

1. Introduction

The Laramie County Control Area (LCCA or Control Area) comprises approximately the eastern two-thirds of Laramie County from Cheyenne east to the Nebraska border, south to the Colorado border, and north to Platte and Goshen Counties. Figure 1.1 is a general location map. The High Plains aquifer system underlying most of Laramie County has been heavily appropriated since the 1970s. As a result, the Control Area was established by the Board of Control in 1981. In the Control Area, an application for a new water right or a petition to amend an existing water right may be subject to public notice, objections from existing water right holders, and hearings.

Responding to mounting concerns over increasing development and use of groundwater resources in southeast Wyoming, the State Engineer issued a *Temporary Order Adopting Well Spacing Requirements within the Laramie County Control Area* on April 11, 2012. The Order temporarily limits groundwater development in the Laramie County Control Area. The order establishes well spacing restrictions (horizontally and vertically), as well as use limitations for most new groundwater applications in the Control Area.

Following issuance of the Temporary Order, the Wyoming State Engineer's Office (WSEO) In August 2012, contracted with AMEC Environment & Infrastructure (AMEC), Hinckley Consulting (Hinckley), and HDR, Inc. (HDR) to conduct a hydrogeologic study to inform and provide a scientific basis for future groundwater management decisions. This report presents the results of that study.

The Temporary Order was initially scheduled to remain in effect until October 1, 2013. However, due to time extensions needed to finish the hydrogeologic analysis and to evaluate options for preserving and/or extending the groundwater resources of the area, the Wyoming State Engineer extended the temporary order through March 31, 2014.

This report is a hydrogeologic study of the Laramie County Control Area performed for the WSEO. The study uses existing geologic, hydrogeologic, and water rights information to model the groundwater resources in the Control Area and adjacent areas. Using the results of the modeling, the study evaluates the presence of appropriable water and provides possible alternatives for corrective controls within the Control Area designed to arrest or reverse downward trending water levels.

This report responds to the four primary objectives of the study described by the WSEO in their Request for Proposal No. 0453-V (WSEO, 2012):

1. Compile existing geologic and hydrogeologic information and develop parameters to use in modeling the groundwater resources in the Laramie County Control Area (i.e., the High Plains aquifer system, including the Ogallala, White River and Arikaree Formations). (Report Sections 2 and 3)
2. Evaluate the water rights information and patterns of use to use for modeling the groundwater resources in the Laramie County Control Area. (Report Sections 2 and 3)

3. Re-evaluate (using the information determined under objectives 1 and 2) the boundaries of both the Control Area and the five districts within the Control Area overlying the High Plains aquifer system. This objective may involve re-describing the control area and / or district boundaries. (Report Sections 7 and 8)
4. Develop and evaluate potential corrective control measures designed to arrest, or reverse, downward trending water levels and recommendations relative to developing regulations concerning the spacing, distribution and location of wells in the Control Area. This objective should attempt to correlate the potential control measures to different districts identified under objective 3. (Report Sections 7 and 8)

The keystone of this project is a groundwater flow model reflecting a focused compilation and interpretation of hydrogeologic and water-use data for the study area. The groundwater model was used to evaluate the effects of current and proposed groundwater withdrawals and provide an assessment of the efficacy of various control options at the State Engineer's disposal.

Sections 2 and 3 of this report discuss the hydrogeologic setting and the historical groundwater development and regulation within and around the Control Area. Section 4 describes the process of developing the groundwater model, e.g. sources of data and decisions made regarding domain, parameters, and fluxes. Sections 5 and 6 detail how the steady state and transient simulations were constructed and calibrated. Section 7 presents the specifications and assumptions behind the management scenarios that were run using the calibrated model, and presents the results of the management scenario modeling. Section 8 provides recommendations to the State Engineer based on the results of the modeling.

2. Hydrologic Setting

This section presents an overview of the hydrology and geology of Laramie County, as compiled from existing datasets and literature. The information in this and the following section provides a foundation for the conceptual groundwater model, which is discussed in Section 4, and ultimately the numerical groundwater model, discussed in Sections 4, 5, and 6.

The geohydrology was investigated to inform the development of the groundwater model. The numerical model ("model") uses the widely-applied USGS groundwater modeling code MODFLOW. The model divides the subsurface of Laramie County into grid cells that are 1 km by 1 km in size, with varying vertical thickness based on the cell's location within the model. The model has four vertical layers, each representing a different geologic formation or formations. Recharge (e.g. precipitation, stream losses) enters the modeled aquifer through the top layer, and discharge (e.g. well pumping, underflow, stream gains) exits the aquifer from the top three layers.

2.1 Precipitation

The ultimate source of groundwater in the study area is the infiltration of precipitation, including snowmelt and streamflow losses. Figure 2.1 shows the distribution of average annual precipitation across the area. Annual average measured values vary from 13.4 inches in Cheyenne to 17.5 inches at Albin. Figure 2.2 shows the annual and seasonal variations in precipitation, using the Cheyenne station as an example.

In detail, the proportion of precipitation that infiltrates beyond the root zone to recharge groundwater is a complex function of the seasonal timing, duration, and intensity of precipitation; topography; soil type and condition; evaporation and runoff from the ground surface; and the growth characteristics of surface vegetation. For purposes of generalized groundwater modeling, these variations are subsumed by an average annual recharge as a fixed percentage of precipitation. More detail about how recharge is represented in the model is provided in Sections 4 and 6.

2.2 Geohydrology

"Geohydrology" refers to the characteristics of the subsurface with respect to the storage and transmission of groundwater. Geologic units that provide useful supplies of groundwater are considered to be aquifers; units that serve largely to inhibit the flow of groundwater are considered "aquitards" or "aquicludes". With respect to the present study, aquifers are generally provided by coarse-grained material - sandstones and conglomerates, and aquitards generally occur as fine-grained material - siltstones and shale.

Figure 2.3 presents the surface distribution of the various geologic formations of the study area. Figure 2.4 provides a schematic 3-dimensional view of these formations. The distribution of WSEO groundwater permits across the county (Figure 2.5) reflects the conjunction of water demand and available supplies; it provides a first approximation of the geographic distribution of groundwater availability. The groundwater model representation of the relevant hydrogeologic layers is discussed in Sections 4 and 5, including calibrated hydraulic parameters. A general overview is presented here. From youngest (shallowest) to oldest (deepest), the formations beneath the study area are:

2.2.1 Quaternary Deposits

These Quaternary-age deposits primarily consist of sand and gravel deposited by present and recent-past streams. They occur as narrow and generally thin strips of alluvium along the main streams, but more importantly as extensive terrace deposits in the southeast portion of the study area (see Figure 2.3). Although relatively shallow, where saturated these deposits form some of the most-productive aquifer in the area and have been extensively developed for groundwater irrigation.

Lowry and Crist, 1967 (p. 19) describe the Lodgepole Creek alluvial deposits: “Bjorklund (1959, p. 15) found that the alluvium of Lodgepole Creek valley between the Wyoming State line and Chappell, Nebraska, is relatively thin, averaging about 25 feet, whereas Rapp, Warner, and Morgan (1953, p. 47) stated that the alluvium along Lodgepole Creek in Wyoming is generally thin but is as much as 85 feet thick at some places.”

Lowry and Crist, 1967 describe the terrace deposits as up to 200 ft. thick. (p. 8) and report well-test transmissivities as high as 149,000 gpd/ft. (p. 39). Saturated thickness varies widely, reaching a maximum of approximately 80 ft. in the Carpenter area (Lowry and Crist Fig. 12).

2.2.2 Ogallala Formation

The Ogallala Formation is the primary component of the vast regional aquifer underlying large portions of the high plains from North Dakota to Texas. The Ogallala has been extensively developed for groundwater irrigation. Its declining water levels in many states are nationally famous.

The Ogallala Formation hosts three of the four municipal wellfields for the City of Cheyenne, the industrial wells west of Cheyenne, and most of the domestic wells in the county. It has been developed for groundwater irrigation primarily in the Albin area, particularly in areas where it is locally thicker due to having filled paleochannels as deep as 400 ft., excavated into the underlying Arikaree Fm. (Borchert, 1976).

The Ogallala Formation in Laramie County is a complex aquifer. “The water-bearing beds in the Ogallala consist of lenses, stringers, and irregular masses of sand and gravel which are inter-bedded with silt and clay.” (Lowry and Crist, 1967). Productive wells and unproductive wells occur in close proximity. Different water levels in different individual water-bearing strata are common, as are flowing wells in the western portion of the county. For purposes of county-wide groundwater modeling, however, the formation is generalized as a single aquifer unit. Thus, model results and specific local experience may not be consistent in detail.

2.2.3 Arikaree Formation

Lowry and Crist (1967) describe the Arikaree as, “predominantly a very fine grained to fine-grained massive sandstone that contains beds of siltstone, layers of hard concretionary sandstone, and thin beds of volcanic ash.” The Arikaree Formation is present beneath the Ogallala only across the northeast portion of the county (see Figure 2.4). Although the Arikaree Fm. has been extensively developed for groundwater in Platte, Goshen, and Niobrara Counties, it is generally less productive than the Ogallala and in Laramie County has been most developed where the Ogallala is either absent or unsaturated.

2.2.4 White River Formation (including fractured Brule)

Lowry and Crist (1967) describe the White River Formation as, “of remarkably uniform composition throughout Laramie County and adjacent areas, consisting predominantly of massive brittle argillaceous siltstone containing a few beds of sandstone, conglomerate, and volcanic ash.” Although the formation is commonly subdivided into an upper member - Brule, and a lower member - Chadron, in other areas, these units are not typically differentiated in Laramie County.

From a hydrogeologic perspective, the formation is most usefully divided into a local, highly productive zone formed at the top of the formation (particularly where it is overlain by Quaternary terrace deposits). This unit is here termed “fractured Brule” and it is grouped with the Ogallala layer in the groundwater model. The remainder of the formation is generally only poorly - moderately productive of groundwater. It is this, the great majority of the formation, to which we refer as the “White River” (model layer 3).

The exact nature of the high-permeability in the upper Brule is unclear. It has been described as simply the porous, weathered surface of the formation, as shallow fractures or joint systems, as piping within the weathered siltstones, and as channels of coarse gravel filling the eroded surface of the formation. Lowry and Crist (1967) describe “Surface traces of these fractures, some of which are at least 1 foot wide and 1 mile long.” This highly-productive zone is relatively thin, is not present where the formation is overlain by the Ogallala or Arikaree Formations, and is only locally present otherwise. Thus, it is generally confined to southeast Laramie County and to local areas along the flanks of the Laramie Range. (It is in the latter location that the “fractured Brule” has been developed by Cheyenne’s Federal wellfield.)

Compilation of the "bottom of main water-bearing zone" extracted from the WSEO Statements of Completion (driller reports) for high-yield irrigation wells in SE Laramie County found an average total depth for this “main water-bearing zone” of 170 ft.

Because of the relatively high permeability of the “fractured Brule” and its common association with overlying Quaternary deposits (or terrace deposits), the two are commonly considered and modeled as a single aquifer (e.g. Borchert, 1985; WSEO, 2011). The two units are most commonly developed in concert and communicate readily with respect to recharge and water levels. For the present groundwater model, the “fractured Brule” is assigned to a different layer than the remainder of the White River Fm. and given the same aquifer characteristics as the overlying Quaternary deposits.

The bulk of the White River Fm. is a relatively poor producer of groundwater, although, as with both the Ogallala and Arikaree, local deposits of relatively permeable material provide productive wells in some areas. For example, Lowry and Crist (1967, p. 25) report, “More than half of the test wells drilled in the area by the city were abandoned because of low yields.” Similarly, a detailed study of the White River Fm. on the Belvoir Ranch (SSW of Cheyenne) found thickness variation from 225 to 370 ft. and only one of six exploration borings found enough water to sustain pumping of 8 to 10 gpm (TriHydro, 2009).

For purposes of the present groundwater model, local variations in White River productivity are generalized into a single model layer (with the exception of the fractured Brule) with spatially variable hydraulic conductivity and storage properties.

2.2.5 High Plains Aquifer

The “High Plains Aquifer” is a term coined by the USGS for their Regional Aquifer System Analysis (e.g. Gutentag et al., 1984). It consists of the White River Formation, the Arikaree Fm., the Ogallala Fm., and any water-bearing Quaternary-age deposits. Based on a common geologic age, these formations are also referred to as the “Tertiary Aquifer” (e.g. WSGS, 2014).

The past and continuing regional groundwater modeling of the aquifer by the USGS is based on a single layer, encompassing all the units of the High Plains Aquifer. Previous groundwater modeling specific to Laramie County has also taken a single layer approach, and treated all underlying materials as outside the groundwater domain (e.g. Crist, 1980). Cooley and Crist (1981) provide a detailed fence diagram for Laramie County, on which the individual units of the High Plains Aquifer are distinguished.

2.2.6 Lance/Fox Hills Formations

“The Lance Formation is composed of interbedded tan and gray sandstone, siltstone, gray shale, black carbonaceous shale and thin coal beds.” It varies from “as much as 1500 ft. in the western part of Laramie County” to “only about 200 to 250 ft. thick in the eastern part of the County.” “The Fox Hills Formation is gray to white yellowish-brown friable sandstone interbedded with dark sandy shale. The formation ranges from approximately 40 ft. to over 250 ft. thick in Laramie County.” (Dahlgren, 2005; p. II-5.) These formations have been little developed for groundwater in the county, primarily because shallower (i.e. less expensive to develop) formations commonly provide groundwater of superior quantity and quality.

USGS groundwater modeling has included these with all underlying formations as part of the impermeable base of the useful groundwater system. However, recent exploration suggests the Fox Hills may provide useful water supplies for municipal use (e.g. Dahlgren, 2005), the WSEO 2006 Policy on dual completions distinguishes between the Lance/Fox Hills and the overlying “High Plains” Aquifer (discussed above), and the April, 2012 WSEO order on "Well Spacing

Requirements" directs wells other than for stock, domestic, or miscellaneous use to these lower units.

In addition to the Fox Hills Sandstone, there are discrete water-bearing units within the Lance Formation, and even within the upper Pierre Shale (e.g. encountered in the 1950-ft. well drilled for the Town of Pine Bluffs [Dahlgren, 2005]). Similarly, a moderately productive conglomeratic unit can be found locally in Laramie County at the base of the White River Formation.

Because detailed information on the hydrologic properties, thickness, and distribution of these various units is rare, as is local development experience, the groundwater model developed for the present investigation provides only a generalized representation of their groundwater-production characteristics, via a single model layer of uniform thickness (1,000 ft.) beneath the Control Area and permeability that is generally one to two orders of magnitude lower than the layers comprising the High Plains Aquifer. This layer (Layer 4) represents various sub-White River water-bearing units of potential interest, including the basal conglomerate of the White River Formation (where present), water-bearing sandstones within the Lance Formation, the relatively continuous Fox Hills Sandstone, and water-bearing sandstones in the uppermost Pierre Shale. Actual groundwater production at any specific location will be a function of the thickness and permeability of individual sandstone strata penetrated, and should be preceded by careful, site-specific evaluation. Due to lack of data, this is the only model layer defined by homogeneous hydraulic conductivity and storage properties; however, the model is relatively insensitive to it as a calibration parameter.

2.2.7 “Older Bedrock” Formations

These formations are all of pre-Cambrian, Paleozoic, and Mesozoic age. They form the core of the Laramie Range and the steeply-dipping strata along the east flank of the range. Compositions include granite, limestone, sandstone, siltstone, and shale. Water-bearing characteristics are similarly varied. The outcrops of these formations are all outside (west of) the boundary of the groundwater model developed for the current study. These formations are present at depth beneath the area of interest, but are hydraulically isolated by the thick Pierre Shale, a regional aquitard. The Pierre Shale forms the base of the strata under consideration here, and the base of the groundwater model.

2.3 Hydrology

The major surface drainages of the study area are, from north to south: Horse Creek, Lodgepole Creek, and Crow Creek. Outside the southwest model boundary is Lone Tree Creek. (See Figure 1.1 for locations.) All three have headwaters in the Laramie Range, from which rainfall and snowmelt provide perennial flow where these streams and various tributaries leave the uplands to flow across the developed portions of Laramie County.

Because Horse Creek is at a relatively low elevation with respect to the rest of the county (see Figure 2.6 for a topographic profile; Figure 2.3 for the line of profile) it acts as a drain for the adjacent aquifers to the south, and remains perennial throughout Laramie County. Relatively low permeabilities in the Arikaree Fm. limit this draining effect, however, leaving more of the study area groundwater moving eastward into Nebraska. Southside tributaries of Horse Creek in eastern Laramie County are fed by springs where groundwater in the Ogallala Fm. encounters the lower permeabilities of the Arikaree Fm. and emerges at the surface below that contact (e.g. Little Horse Creek, Bushnell Creek). Horse Creek loses flow to summer irrigation diversions, which can temporarily dry the creek up at specific headgates. Given this natural-boundary relationship with respect to groundwater flow, Horse Creek was selected as the north boundary of the groundwater model.

Little Horse Creek begins at natural springs about 5 miles west of Hwy 85, based on topographic maps and mapped springs on the USGS map (Bartos and Hallberg, 2011). It is perennial to the mouth. The only gage data located for this creek are from a 1986 conveyance loss study. Flows were less than 1 cfs in late summer, rising to 10 cfs after irrigation diversions ceased. Anecdotally, the creek takes on quite a bit of groundwater, probably all from the south, since Horse Creek should capture all the north side groundwater. In the summer the creek is nearly all diverted for irrigation, so groundwater development in this area could have a local impact at the flow vs. no-flow level.

Lodgepole Creek has been mapped as perennial through much of the county (e.g. Figure 1.1), but flow has been greatly reduced due to local groundwater development. Figure 2.7 provides the streamflow records for the Bushnell, Nebraska gage, approximately 9 miles downstream of the Wyoming border, along with the record of Wyoming irrigation well permitting in the upstream basin. This gage suggests the creek was largely dried up, except for stormwater flows, in the 1990s.

There are 40 adjudicated direct flow rights from Lodgepole Creek, including one for 40 cfs at a diversion just east of I-25. These rights were nearly all developed prior to 1900, however. The WSEO Hydrographer/Commissioner for the area, Scott Ross, has observed no significant irrigation from Lodgepole Creek east of I-25 in recent times. He describes the stream as almost always dry at I-25 by mid-June; one diversion between I-25 and Hwy 85 getting a little water in the spring; and no diversions east of Hwy 85, just a few "pockets of life" (e.g. a short reach NW of Hillsdale). He suggests there has been little complaint about creek flows because the irrigation well owners are the same as the surface water-right holders. Aerial photos and field inspection suggest little riparian vegetation fed by shallow groundwater from the creek, and the former stream channel has been largely obliterated east of Burns. There is currently no sign of the “spring” mapped on the standard USGS topographic maps at Pine Bluffs; the creek is dry at the state line.

Lodgepole Creek continues to capture surface runoff from storm events and snowmelt, of course, but Ross reports none of the many small reservoirs along the creek hold water over the winter.

Thus, Lodgepole Creek east of I-25 appears to serve largely as a source for groundwater recharge by flood flows, rather than as an aquifer drain.

The major tributary of Lodgepole Creek is Muddy Creek, which originates in southeast Laramie County without an upland source area. Muddy Creek is currently reported to be perennial from I-80 downstream to a point south of Egbert, a distance of only four miles. This suggests a diminution of flow since the mid-1940s, when the stream was described as perennial down to its northward turn south of Pine Bluffs and as having a "small perennial flow" at the mouth near Pine Bluffs (Rapp et al., 1953).

Crow Creek interactions with groundwater in the study area are complicated by reservoirs in the Laramie Range, water imports from outside the basin, large-scale groundwater development adjacent to the creek for both municipal and irrigation use, and discharge of municipal wastewater to the creek. Upstream of Cheyenne, perennial flow in Crow Creek has generally been dried up by these activities for many years. Flood flows from local runoff, and particularly the urban runoff from Cheyenne, provide substantial intermittent flows.

Crow Creek gains water through the Warren Air Force Base on the west side of Cheyenne to produce a small, but consistent flow at the USGS 19th St. gage in Cheyenne. (USGS gage data show base flow of about 0.5 cfs at 19th St., but with intermittent flows as high as 500 cfs, presumably in response to precipitation events.)

Significant Crow Creek perennial streamflow is established by the discharges from the Cheyenne wastewater treatment plants on the east edge of the city. Discharge rates to the creek over the last ten years have averaged 4.9 and 7.6 cfs from the Crow Creek and Dry Creek plants, respectively. Much of this flow is diverted for surface irrigation of approximately 2,400 acres (including filling irrigation reservoirs) and the remainder is lost to groundwater recharge along approximately 15 miles of Crow Creek downstream of Cheyenne. The creek is normally dry at Carpenter, according to Ross. The absence of riparian vegetation along Crow Creek in the Carpenter area supports reports of streamflow rarely being sustained through that area.

Other small drainages are present in the area. These normally dry washes can fill during storm events and provide recharge to the aquifer.

3. Groundwater Development

Figure 3.1 presents the history of groundwater permit issuance in Laramie County. This figure shows slow growth in permitting activity through approximately 1970, a sharp peak around 1975, then a second peak cresting in approximately 2005. The first of these peaks includes many irrigation wells, reflecting the rapid application of center-pivot technology. The second peak was driven by the proliferation of rural residential and subdivision development in the county.

Figure 3.2 presents the same permits[1], but expressed in terms of cumulative permitted yield[2] rather than simple permit count. This figure shows the overwhelming domination of irrigation in the volumes of groundwater permitted for beneficial use on both a county and control area basis (though other uses may be of critical importance locally). Figure 3.3 shows the location of irrigated acreage in the county, as mapped from 1980s aerial photography and compiled for the 2006 Wyoming Water Development Commission's Platte River Basin Plan (TriHydro, 2006). In addition to approximately 60,000 acres of irrigated cropland, agricultural development in the county includes approximately 300,000 acres of dryland cropping.

Municipal use is almost entirely outside the Control Area, as the Cheyenne municipal wellfields are all west of the Control Area boundary. Industrial use exists at several locations across the county, including various manufacturing and agriculture-related operations. Domestic, stock, and miscellaneous-use wells have been developed throughout the county.

As shown on the figure, growth in groundwater irrigation permitting virtually ceased in 1976. At that point, approximately 83% of the total permitted groundwater yield in the county was for irrigation (93% of the total permitted yield in the Groundwater Control Area). Post-1976 growth in other sectors, primarily domestic wells, has reduced the irrigation percentage to 63% in the county (77% in the Control Area). Although all other use sectors have expanded somewhat since then, the growth in domestic-well permitting is the most conspicuous, particularly outside the Control Area.

Figures 3.4 and 3.5 display the geographic distribution of these two episodes of groundwater development in Laramie County. Although there has continued to be widespread, small-scale groundwater development throughout the county, note the domination of development in the eastern part of the county (irrigation) in the early period, and the domination of development in the Cheyenne area (domestic, subdivision, industrial) in the latter period. The great majority of

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[1] This chart was prepared from the WSEO permit database; "municipal" = any permit with MUN as a listed use; "irrigation" = any remaining permit with "IRR" as a listed use, if >25 gpm; "industrial" = any remaining permit with "IND" as a listed use, if >25 gpm; "miscellaneous" = any remaining permit with "MISC" as a listed use, if >25 gpm; "Domestic and stock" = all other wells. Permits listing both "IND" and "IRR" were further classified based on applicant.

[2] Note that permit yield and actual use may be hugely different, as very few wells are pumped continuously at permit capacity, and, particularly for small wells, considerable excess capacity is routinely permitted.

irrigation extractions (and thus, total extractions) from the aquifers of the county have been in place for more than 35 years.

Comparison with the discussion of hydrogeology, above, suggests drawdown issues in the eastern portion of the county are a function of the long-term impact of large withdrawals from a productive, but relatively shallow aquifer. Drawdown issues in the Cheyenne area are more a function of a proliferation of smaller withdrawals in a less productive, but much thicker aquifer.

3.1 Oil and Gas Exploration/Development

The most recent change in groundwater use in Laramie County is to support oil and gas exploration and development activity, e.g. water for the drilling, completion, and hydraulic fracturing of wells and for related process water and dust control. Based on analysis of WSEO records and staff interviews, it is estimated that oil and gas development has relied upon up to approximately 150 to 300 ac-ft per year of water in Laramie County to meet water needs in the last 2 or 3 years.

Oil and gas exploration activity in Laramie County is primarily associated with the Niobrara Shale. In Laramie County these wells are typically completed by vertical drilling to a depth of approximately 7,000 to 8,000 ft. and drilling horizontally, and completing the wells with multi-stage hydraulic fracturing. The fracturing process of each oil and gas well requires an average of approximately 3 to 4 million gallons of fresh water but the demands can vary (3.5 million gallons = 10.7 ac-ft.). In addition, the drilling of an oil and gas well and dust abatement and construction water can require approximately 300,000 to 500,000 gallons of water. Even at the water demand growth rate of 5-10% per year projected for adjacent parts of the Niobrara Formation in Colorado[3], total use is unlikely to exceed 2,000 ac-ft/yr within 20 years.

As of January 4, 2011, the Wyoming Oil and Gas Conservation Commission (WOGCC) reported that 115 applications for permits to drill (APDs) horizontal wells were approved in Laramie County, 38 wells had been drilled, and 10 of the wells were completed.

Most importantly, the primary source of hydraulic fracturing water within the Laramie County Control Area has been securing existing sources through Temporary Water Use Agreements authorized under W.S. 41-3-110, rather than through the development of new groundwater supplies. The use of temporary water use agreements is well suited to this application because the oil and gas industry demand for water is inherently short-term and local, and the rights used under them revert to their original permitted uses.

The process requires that the oil and gas operator or the water user execute an agreement with an established water rights holder. The holder must give up a portion of their documented

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[3] 2011 Report to the Water Quality Control Commission and Water Quality Control Division of the Colorado Department of Public Health and Environment, Oil and Gas Conservation Commission in accordance with the August 28, 1990 Memorandum of Agreement and Implementing Provisions of Senate Bill 181, February 2012.

historic beneficial use in order to lease an equivalent amount to the water user. The water right holder or well owner must be able to show that they hold an active water right and are willing to forgo the well's current use. WSEO requires documentation of water use in the past 5 years through inspection of aerial photography or other documentation such as well pumping power records or water meter readings. The term of TWUAs is typically one year and the removed acreage is allocated a 1 acre-foot per acre consumption amount unless the appropriator can provide data demonstrating a higher consumptive irrigation requirement[4]. The “1 acre-foot” allowance is approximately the same as the average net pumping assigned to irrigated acreage in the groundwater model (discussed in later sections), demonstrating the appropriate equivalence in the WSEO policy.

All WSEO groundwater permits have an approved instantaneous rate that cannot be exceeded. Newer groundwater permits specify an annual volumetric quantity as well. Less than half a dozen water rights in Laramie County have been enlarged (i.e. rather than just substituting use) to accommodate oil and gas activity.

Thus, groundwater use associated with oil and gas exploration and development activities in the study area is relatively small, and is largely subsumed within estimates of irrigation consumption, which are based on the active acreage from which groundwater is temporarily transferred. Although future expansion of this use may include new “industrial” permits for groundwater development, the continued use of Temporary Water Use Agreements is expected to provide the great bulk of this relatively small study-area demand.

The groundwater-quality concerns associated with hydrocarbon exploration and development in the study area often expressed by members of the public are beyond the scope of this study, and largely deal with deeper strata than are examined here.

3.2 Wells, Geology, and Model Layers

Figures 3.6 and 3.7 present WSEO groundwater permit data superimposed on two rows of the groundwater model (see Fig. 2.3 for row locations). Recall that the groundwater model discretizes the study area into 1 km x 1 km grid cells; these cells are ordered in evenly-spaced rows and columns. Each plot shows the elevation of the various geologic units as rendered in the groundwater model developed for this project. Note that the same layer number may apply to a different geologic unit depending on the location. Also shown are the static water levels and total depths of all water wells permitted in the indicated row (including one model row on either side), as self-reported on the Statements of Completion filed with the WSEO.

The Row 30 diagram shows that nearly all wells along an east-west row through the center of the county are completed in the Ogallala and Arikaree Formations, many only in the Ogallala. While the reported water levels approximately correspond with the model water level, there are

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[4] WSEO Policy Memorandum, 2/24/2012.

two reasons for the differences: 1) water levels in the Ogallala vary substantially between individual water-bearing strata (some even produce water levels above the ground surface); and 2) reported water levels are from different years and different times of year, and are rarely checked for accuracy. The groundwater model provides large-area generalization of groundwater conditions and cannot universally reflect such site-specific details of water levels or geology.

Wells with total depths near the water table are the most vulnerable to small changes in water level, either due to natural variations in recharge, or to the cumulative impact of surrounding groundwater withdrawals. Figure 3.8 summarizes the available drawdown (i.e. the difference between the reported static water level and the reported total depth) for all non-zero-yield groundwater permits in the county. Nearly 2,000 wells (20% of the total) had less than 50 ft. of available drawdown at the time of construction. This potential problem has been addressed in the “North Cheyenne Study Area” by the requirement that all wells be sufficiently deep to provide a minimum saturated thickness of 100 ft. (In other areas, well depth is at the discretion of the owner, although the WSEO generally does not consider regulation for the benefit of wells without “adequate” construction or an ability to withstand reasonable interference.)

The Row 30 diagram shows that the Ogallala has its maximum saturated thickness (i.e. the greatest distance between the water table and the base of the Ogallala) near the western end of this transect. The saturated thickness of the combined Ogallala and Arikaree Formations remains high through the western and central portion of the transect. In these areas, moderate declines in water level do not compromise the overall productivity of the aquifer, and impacts at specific locations may be mitigated by deeper drilling.

At the eastern end of Row 30 this situation changes, as the Ogallala may be unsaturated (water level is below the bottom of the formation), and even the combined Ogallala/Arikaree aquifer is relatively thin. Because of the generally lower permeabilities in the underlying White River Fm. (witness the lack of wells in that layer), drilling deeper is a less viable option for areas experiencing water-level declines. Although there remains a considerable thickness of saturated material above the base of the model, the characteristics of those strata (the White River and Lance/Fox Hills) are not generally conducive to the development of high-capacity wells.

The Row 30 diagram also shows the lack of groundwater development from the White River Formation through most of this transect. The relatively low permeability of the White River generally isolates the Lance/Fox Hills aquifers from groundwater development in the Arikaree and Ogallala. This is the concept reflected in the April, 2012 WSEO order on "Well Spacing Requirements" or miscellaneous use appropriating 25 gpm or less, calling for them to be completed in the Lance/Fox Hills.

The Row 50 transect (Fig. 3.7) presents somewhat different conditions across the southern portion of the study area:

- while the Ogallala is still the primary aquifer along this row, many wells have developed groundwater from the White River in the Cheyenne/Archer area (Columns 30-45), although these are nearly all of fairly low yield;
- the Arikaree Fm. is absent across the west half of the transect, and both the Arikaree and the Ogallala are absent east of Column 81;
- at the east end of the transect, between Egbert and Pine Bluffs, the primary aquifer is the combination of Quaternary terrace deposits and fractured Brule Fm. Although very productive, this aquifer is relatively thin. Saturated thickness above the White River Fm. is small, so there is little room to accommodate declining water tables; and
- scattered wells have been developed in the Lance/Fox Hills strata.

3.3 Regulation

The Wyoming State Engineer has wide authority to administer the state's water resources. All water uses are required to obtain permits, which, at a minimum, specify the priority date of the appropriation, the type and place of use, and the diversion rate. Additional provisions and restrictions may be included on a case-by-case basis. Wyoming’s Legislature enacted the State’s first groundwater statutes in 1945, with considerable refinements of those statutes enacted in 1957 and 1969. Since then, permit requirements include all groundwater use of any kind. WSEO authority includes the careful review and appropriate conditioning of individual permits, and the adoption of corrective controls within designated Groundwater Control Areas.

The WSEO developed “Water Well Minimum Construction Standards” in the early 1970s. These underwent a major revision in 2010, which are the current rules as of this writing.

In addition to the routine implementation of surface and groundwater-right permitting in Laramie County, the study area saw the precursors to the current Groundwater Control Area with designation of the Pine Bluffs and Carpenter "Critical Areas" in 1971 and 1973. Those were consolidated into the current Laramie County Groundwater Control Area, designated in 1981.

Due to growing concerns with well interference in rural subdivisions, the North Cheyenne Study Area (see Fig. 1.1) was subsequently delineated for special groundwater permit conditions. In this area, “wells must be completed with at least 100 feet of water above the uppermost casing perforations.”

The June 27, 2006 WSEO Policy Memo, “DUAL WELL COMPLETIONS IN THE HIGH PLAINS AQUIFER AND LANCE FORMATION, SOUTHEAST WYOMING” adopts the USGS taxonomy in differentiating between the “High Plains Aquifer” and the underlying Lance Formation. Under this policy, completion of water wells in both units is precluded, but co-mingling of the individual water-bearing strata within the High Plains Aquifer is an acceptable method for completion of water-supply wells in this “single aquifer”.

Increasing water demands in the Control Area led to the April 11, 2012 WSEO "Temporary Order Adopting Well Spacing Requirements within the Laramie County Control Area". For wells completed within the High Plains Aquifer, this order limits new stock and domestic wells to one well per developed lot or 10-acre tract, with a maximum annual withdrawal of 1 ac-ft. It also limits new small-yield (less than or equal to 25 gpm) miscellaneous-use wells in the aquifer to a maximum annual withdrawal of 2 ac-ft and requires a minimum spacing of 1 mile with respect to other miscellaneous-use wells.

No other new groundwater wells are allowed to withdraw water from the High Plains Aquifer during the term of the order (currently extended through March 31, 2014). Instead, such wells are directed to the underlying Lance/Fox Hills Aquifer, with a minimum spacing of 1 mile from any existing wells in the aquifer.

4. Model Development

Responding to the need for a scientific tool to inform groundwater management decisions, the WSEO requested that a groundwater model of the aquifers in Laramie County be developed. This section presents the data and specification for the Laramie County Groundwater Model, including modeling platform, model structure, model parameters, conceptual water budget, and calibration data. Section 5 covers the steady state calibration, and Section 6 covers transient model calibration.

4.1 Modeling Platform

MODFLOW-SURFACT version 4.0, an advanced version of the standard and widely applied U.S. Geological Survey (USGS) groundwater modeling code MODFLOW, was used for the groundwater model. The PCG5 solver was used. Groundwater Vistas version 6 served as a graphical user interface to facilitate modeling and visualization. However, the Groundwater Vistas software is not required to run the model.

MODFLOW is a program that uses the finite difference method to solve a three-dimensional groundwater flow equation. The groundwater equation uses transmissivity (in unconfined aquifers this is the product of hydraulic conductivity and saturated thickness), volumetric flux of water, and storage to solve for the change in head over time. MODFLOW solves the groundwater flow equation numerically by dividing the model domain into grid cells and calculating the head at the center of each cell. A complete discussion of the equations used in MODFLOW is available in the USGS open-file report 00-92, “MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process.”

4.2 Model Structure

To solve the groundwater flow equation, it is necessary to define the boundaries of the area of interest. This section discusses the geometry of the groundwater model, which can be thought of as a three-dimensional box that is cut out of the earth and isolated. The domain (edges of the box), cell size (partitions within the box), and layering (levels within the box) were developed in consultation with the USGS and WSEO.

4.2.1 Model Domain

The model domain encompasses 5,477 square kilometers (approximately 2,115 square miles) within and immediately outside Laramie County, Wyoming. General goals for model boundaries were to encompass the relevant groundwater flow system and to minimize the impact of model boundaries on the areas of groundwater-management interest. Where feasible, this was done by extending the model to the geologic termination of the aquifers of interest and following natural lines of no cross-boundary flow. Where no natural boundaries are present, the model boundary was extended sufficiently beyond the area of interest to minimize boundary effects, and boundary conditions were defined to conceptualize the physical reality.

Figure 4.1 presents the grid and boundary of the groundwater model. The Horse Creek channel defines the northern boundary. The creek channel represents a no-flow boundary condition for groundwater, as it is reasonable to assume groundwater flow converges at the creek but does not cross beyond it (see Figure 2.6). The northwest corner of Laramie County and of the LCCA fall outside this boundary, but there is little groundwater development in those areas, no pending aquifer management decisions, and no groundwater issues of a regional nature are anticipated.

Groundwater outflow from the model domain beneath Horse Creek is reflected as a specific flux boundary. At this boundary groundwater leaves the model at a rate of 1,500 ac-ft/yr. The eastern boundary at the Nebraska border is an arbitrary north/south line; groundwater outflow from the model domain is represented as a head-dependent flux boundary in MODFLOW known as a General Head Boundary (GHB). Each model cell along this eastern boundary is assigned a water level elevation; during a model simulation water leaves or enters the model such that the defined water level elevation is maintained along the boundary. In this way the model provides an estimate of the groundwater flux at the boundary and a net amount of groundwater leaving the county and flowing into Nebraska can be determined.

A “buffer” area extends three miles into Nebraska to attenuate boundary impacts on the Wyoming area of interest. The border with Colorado receives similar treatment; a no-flow boundary is applied to this region with a “buffer” area extending three miles into Colorado to attenuate boundary impacts on the Wyoming area of interest. In the case of the Crow Creek area, the extension of the model a short distance into Colorado also serves to approximate the southern termination of the productive Quaternary-age alluvium, terrace and productive areas of the Brule Member of the White River Formation.

The southwest corner of the model domain is bounded by the topographic divide between Crow Creek and Lone Tree Creek. Because this is also the groundwater divide, it is modeled as a no-flow boundary. This area is west of the Laramie County Control Area.

The physical termination of the aquifers of interest (i.e. the High Plains aquifer and the underlying Lance/Fox Hills formation) along the east side of the Laramie Range is the west boundary of the model. This encompasses a swath of the aquifers outside the Control Area, but informs the review of the Control Area boundary and of the potential impacts on the Control Area of groundwater management in the developing areas around Cheyenne.

The bottom of the groundwater model is defined by the contact between the Lance/Fox Hills (model layer 4) and the underlying Pierre Shale.

4.2.2 Grid Size and Orientation

The model has a grid cell size of 1 km x 1 km to be consistent with the USGS’s yet-to-be-released groundwater flow model of the north High Plains aquifer. The grid is oriented north-south and east-west to align with the primary direction of groundwater flow, which is west-to-east. This orientation also conforms to the USGS's groundwater model, although some vertical or horizontal translation would likely be necessary to exactly overlay the two models.

4.2.3 Model Layering

To facilitate evaluation of aquifer management decisions and provide flexibility for the future application of the model, the groundwater model consists of four layers. Individual model cell thickness varies to reflect the local hydrogeologic stratification at a 1-km scale. (The USGS model uses a single layer.) The layering and extent of the formations were derived from isopach maps from the 2008 Laramie County Water Resources Atlas, Cooley and Crist (1981), USGS monitoring well completion logs, and Statements of Completion filed with the WSEO. Contact elevations for the geologic formations were defined using the fence diagram by Cooley and Crist, 1981. Subsequent reports such as the Water Resource Atlas of Laramie County (JR Engineering et al., 2008) and the most recent potentiometric surface map of Laramie County (Bartos and Hallberg, 2011) have relied upon the 1981 research, and it appears to still be the best available resource for geologic layering in Laramie County. Figure 4.2 shows the groundwater model layer discretization profile.

Layer 1 represents the uppermost water-bearing units, including Quaternary-age alluvium and terrace deposits, the Ogallala Formation, and the local, very-productive areas of the uppermost Brule Member of the White River Formation. Although part of a lower formation, hydrogeologically these portions of the Brule have much more in common with the overlying Quaternary deposits. They are commonly developed in concert with the overlying material and communicate readily with respect to recharge and water levels. USGS and WSEO groundwater modeling in the Horse Creek area, for example, has included "fractured Brule" with the overlying alluvial deposits as a single effective aquifer (Borchert, 1985; WSEO, 2011). The top of Layer 1 is the ground surface, which was defined using 10 m Digital Elevation Model files (DEMs) from the USGS (USGS, 2009). These are raster files that are a product of satellite imagery, produced at a 10 m resolution which means that the raster is pixilated in 10 m by 10 m pixels. The DEM was intersected with the model grid and an average surface elevation for each 1 km by 1 km model cell was calculated. The bottom of Layer 1 is the top of Layer 2.

Layer 2 represents the Arikaree Formation. Although aquifer data are less plentiful than for the overlying Ogallala, the Arikaree is understood to be generally less permeable. Thus, aquifer management decisions that are dependent upon correlation of water levels with aquifer productivity will be best informed by recognition that once water levels fall into the Arikaree, productivity may decline substantially. The Arikaree is only present beneath the Ogallala in the northeast portion of the county. To model the absence of the Arikaree, Layer 2 is allowed to "pinch out" to a minimum cell thickness of 1 to 10 m. That is, the cells in Layer 2 are given a thickness of 1 to 10 m and the properties of Layer 3 are assigned to them. Despite the nominal thickness remaining, this assignment effectively terminates the layer. Below the terrace deposits where the Arikaree is absent, Layer 2 also represents the productive portion of the White River Formation known as the fractured Brule. In all cases, the bottom of Layer 2 is the top of Layer 3.

Layer 3 represents the White River Formation. This formation is understood to be substantially less productive than overlying formations, providing a minor aquifer and regional confining layer. The bottom of Layer 3 is the top of Layer 4.

Layer 4 represents the Lance/Fox Hills. Due to the paucity of hydrogeologic information, but growing development interest, this layer is included as something of a place-holder. It represents various sub-White River water-bearing units of potential interest, including the basal conglomerate of the White River Formation (where present), water-bearing sandstones within the Lance Formation, and the relatively continuous Fox Hills Sandstone. Layer 4 was assigned an arbitrary thickness (around 300 m for most of the model, except the area to the west where all formations thin and tilt upward along the eastern flank of the Laramie Range, see Figure 2.4), and the bottom of Layer 4 is a no-flow boundary. Conceptually this represents the contact between the Lance/Fox Hills and the Pierre Shale.

4.2.4 River and Stream Cells

Horse Creek, a model boundary, is represented using “river” cells as it allows the specification of a “river stage” elevation and calculation of an acceptable flux to and from the creek via a conductance parameter. Other streams within the model domain, both perennial and ephemeral, are modeled using “stream” cells. Rather than representing a specified stage, stream cells allow the modeler to assign a flow rate to the upstream cells and to control the gains and losses to the stream cells as that flow travels downstream. Unlike the “river” cells, this allows the “stream” cells to go dry if there is insufficient runoff to sustain both flow and groundwater recharge. Such conditions commonly occur in the Lodgepole and Crow Creek drainages. Figure 4.3 shows the river and stream cells in the model on top of a relief map of the groundwater model, illustrating how the surface topography slopes from high elevations in the west to lower elevations in the east.

Streamflow conditions across the model domain were reviewed in Section 2. The following bullets list how the streams were addressed in the groundwater model.

- Horse Creek – modeled with river cells along the north boundary of the groundwater model. The river bed was defined using the lowest elevation in the DEM within the 1-km cell. Horse Creek is modeled as perennial throughout the model domain. Existing scattered irrigation diversions are not modeled. The Horse Creek river cells are gaining from the mountains to the exit from the model (consistent with potentiometric surface contours from Bartos and Hallberg, 2011), so Horse Creek serves as both a natural boundary and a sink for groundwater.
- Little Horse Creek – modeled with stream cells that begin approximately at the location of natural springs about 5 miles west of Hwy 85, based on topographic maps and mapped springs on the USGS map (Bartos and Hallberg, 2011). At the scale of this regional groundwater model, Little Horse Creek is modeled as a sink for groundwater and none of the scattered irrigation diversions are modeled.

- Lodgepole Creek – modeled with stream cells throughout its length in the model. In the western part of the model, Lodgepole Creek is given a tributary to represent drainage in the Laramie Mountains. In the east, tributaries to Lodgepole Creek include Muddy Creek and other unnamed drainages that were assigned based on channels identified through aerial photography. These stream cells act as a sink for groundwater (gaining streams).
- Crow Creek – modeled with stream cells that start at the western boundary of the model and dip down to the southeast, exiting the model at the Wyoming/Colorado boundary. As with Lodgepole Creek, tributaries to Crow Creek in the west represent drainage in the Laramie Mountains, and tributaries in the east were assigned based on aerial photography. Crow Creek is gaining in most of the cells except for the area east of Cheyenne, where it is a losing stream (per observations).
- Other streams – smaller tributary streams were added to the model during the calibration process, as it became evident that groundwater was pooling above the ground surface. These stream cells are a means of collecting high groundwater and channeling it into natural drainages. Stream cells were placed in areas where surface water drainages exist; these areas were delineated using the DEMs, USGS Topographic Mapping and the National Hydrography Dataset.

The purpose of modeling streams within the domain, in addition to the use of Horse Creek as a model boundary, is to build a picture of recharge to and discharge from the aquifer, as the streams are hydraulically connected to the groundwater at the scale of the model, and there are documented regions of gains and losses. However, the groundwater model does not constitute a model of surface water flows or water rights, it does not attempt to route surface runoff through the model area, and it makes no provisions for surface water diversions. The exception to this statement is along Crow Creek, where evapotranspiration due to surface water irrigated crops in the riparian zone is accounted for as shallow groundwater extractions based on consumptive use for the irrigated acres.

4.3 Model Parameters

Model parameters used to describe the geology are layer thicknesses, hydraulic conductivity, specific yield (in unconfined systems), and specific storage (for confined systems). Parameter values used for this model are sourced from previous hydrogeologic investigations; in cases where there is uncertainty in the parameter value (e.g. hydraulic conductivity), that parameter was adjusted during model calibration.

4.3.1 Hydraulic Conductivity

Hydraulic conductivity is a measure of how freely groundwater can move through a geologic formation. Initial estimates of hydraulic conductivity for the model were taken from the USGS Regional Aquifer System Analysis (RASA) studies and modeling of the 1980s. The general distribution of hydraulic conductivity zones within the model was tied to geologic formations, as shown in Figure 4.4. Hydraulic conductivity values were adjusted during calibration of both the steady state and transient models.

Table 4.1 shows the range of hydraulic conductivity values found in previous studies. These ranges provided minimum and maximum constraints to model calibration.

4.3.2 Specific Yield

Specific yield describes the amount of water than can be drained from the pore space of a soil. For the model, zones of specific yield were defined roughly based on the geologic formations and adjusted during calibration.

Table 4.2 shows the range of specific yield values found in previous studies. This range provided minimum and maximum constraints to the calibration.

4.4 Conceptual Groundwater Budget

Building a water budget is the foundation of the groundwater flow model. The principal data components of a water budget are precipitation, evaporation, evapotranspiration, infiltration or recharge, basin underflow and other sources and sinks such as groundwater pumping (domestic, commercial, municipal, industrial, and agricultural) and incidental recharge from irrigation. The data sources for these components are discussed here in terms of recharge and discharge.

4.4.1 Recharge – Flows into the Aquifer

Recharge is the mechanism by which a portion of the water applied on the land surface infiltrates to the water table and into aquifer storage. There are multiple sources of recharge in Laramie County, including:

- Precipitation
- Underflow due to infiltration at mountain front outcrops
- Stream seepage (losing streams)
- Agricultural returns (percolation)
- Returns from municipal uses (wastewater)

Precipitation

Past estimates of groundwater recharge from precipitation in Laramie County cover a wide range and are indicative of the potential uncertainty associated with this model input. The variability in the recharge estimates exists in part because there are a number of different methods used to estimate recharge and also because some estimates are localized and others are more regional. Table 4.3 shows a compilation of recharge values found in previous studies and the volumes calculated by their application to the area of the active groundwater model domain.

Recharge from precipitation is applied to the model domain as a percentage of the total precipitation falling in each time step in the transient model, and of the 30-year average annual precipitation for the steady-state model. Given the variability that exists in previous estimates of recharge, the precipitation recharge percentage parameters were determined through model calibration.

Thirty-year precipitation normals from the National Climatic Data Center (NCDC) were the starting point for precipitation input for the steady state model. The thirty-year normals were overlain on the model grid, and a single value of precipitation for each model cell was assigned. From there, the percent of that precipitation infiltrating (as recharge) became a steady state calibration parameter. For the transient model, the infiltration percentage determined in the steady state calibration was applied to monthly average precipitation data (aggregated into model time steps) from the Wyoming ET tool (Park and Rasmussen, 2012) which was provided by the WSEO Interstate Streams Division. These data are interpolated from NCDC data and the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset.

Underflow at the Mountain Front (Western Boundary)

From historical and current potentiometric surface maps, it is apparent that groundwater enters the model domain in the west (recharge off the mountains) and leaves the domain in the east (underflow to Nebraska) and north (Horse Creek gains).

Lowry and Crist (1967) estimated recharge from the mountain front to be 10,800 ac-ft/yr. This was used as an initial value for recharge against the western boundary and was adjusted during calibration. Physically, the steep slopes of the mountain range encourage run-off to collect in drainages and streams, so the specified recharge was applied in the uppermost portions of the main streambeds along the western boundary: Lodgepole Creek, Crow Creek, and tributaries (Bear Creek and Lone Tree Creek are outside the model domain). Horse Creek is modeled as a perennial stream with rivers cells which act as constant head cells so mountain front recharge was not explicitly applied, although conceptually the recharge process is the same.

Stream Seepage

Stream seepage into the groundwater model domain occurs via the stream cells. The streambed conductance was qualitatively calibrated to generally match the patterns of reach gains and losses indicated by the potentiometric surface contours and general flow observations discussed above.

Agricultural Returns

Aquifer recharge from groundwater pumping is implicit in the consumptive use numbers that were used for agricultural pumping. By only accounting the “net” pumping as a groundwater withdrawal, any pumping in excess of evapotranspiration that infiltrates back into the aquifer is simply not counted as having been withdrawn in the first place. Aquifer recharge from surface-water flood irrigation likely occurs from near-stream areas along Crow Creek, but is handled by the model the same way, i.e. by only accounting the realized evapotranspiration, water diverted in excess of that amount is effectively left to become groundwater recharge via stream-cell recharge (stream seepage).

Municipal Returns

The City of Cheyenne wastewater treatment plants (WWTPs) discharge to Crow Creek. Figure 4.5 shows the locations of the plants. This discharge is included in the model as a flow into the stream cells representing Crow Creek. Discharge data were provided by the Cheyenne Board of Public Utilities (BOPU). The towns of Albin, Burns, and Pine Bluffs have lined wastewater treatment lagoons and are not considered as sources of recharge.

4.4.2 Discharge – Flows out of the Aquifer

This is the "water out" component of the aquifer mass balance. Simply stated, water out includes:

- Underflow out of the model domain
- Stream seepage (gaining streams)
- Non-irrigated plant evapotranspiration
- Net groundwater withdrawals (pumping and consumption)

Underflows at the Boundary

Underflow out of the county occurs along the Wyoming/Nebraska state line and at the upper northeast corner as groundwater flows north under Horse Creek. As noted above, the southern boundary of the model is considered "no flow". This is consistent with potentiometric surface countouring (e.g. Bartos and Hallberg, 2011), with the exceptions of an area around Crow Creek that indicates underflow out of Wyoming, and an area along the state line south of Muddy Creek that indicates what is considered as an approximately compensating underflow into Wyoming.

Because of this uncertainty and the lack of estimates for the amount of groundwater leaving beneath Crow Creek this underflow was not accounted for and ultimately it was modeled as a no-flow boundary. Table 4.4 shows the outflow estimates that were used as a frame of reference for model calibration. No studies were found citing the underflow from Wyoming to Nebraska across the Laramie County border, so the amount of underflow exiting to Nebraska outside the Lodgepole Creek drainage basin was determined through calibration. The conductance term for the General Head Boundary along the eastern model boundary was adjusted during the calibration process with respect to these outflow estimates and observed water levels.

Stream Seepage (Gaining Streams)

Within the model domain, the gaining streams are Horse Creek (for most of its course from the mountains to the county line), portions of Lodgepole Creek, and portions of Crow Creek (in particular the reach west of Cheyenne). As with the losing stream reaches discussed above, seepage from the aquifer into the streams of the model was qualitatively calibrated to generally match the patterns of reach gains and losses indicated by the potentiometric surface contours and general flow observations.

Non-irrigated Plant Evapotranspiration

Native prairie and non-irrigated croplands also subtract water from the aquifer system. These components are not explicitly modeled, but are included in the large proportion of precipitation that does not become part of the modeled groundwater recharge. There are no significant wetland areas in the model, so groundwater consumption by phreatophytes does not factor into the water budget.

Groundwater Withdrawals

This category of groundwater use was the most complex to quantify and model. Within the model domain, groundwater withdrawals can be classified into the following categories:

- Irrigation
- Industrial
- Municipal
- Domestic
- Stockwater
- Miscellaneous

Each category has a different “level” of data quality associated with it. For example, municipal use in Laramie County includes the City of Cheyenne well fields, which are metered and have historical and current pumping measurements attached to them. Some industrial uses are also metered. On the other hand, domestic, stockwater, miscellaneous, and irrigation uses are generally not metered, and so require simplifying assumptions to estimate the amount of water consumed. Each category of pumping was addressed as follows:

Irrigation

The largest consumptive use of groundwater in the county is for irrigation, but metered records for irrigation pumping are scarce. To develop a transient record of irrigation use, it was assumed that the net withdrawal from the aquifer is equal to the irrigation requirement of the crop, i.e. the amount of water consumed by the plant after accounting for available precipitation. Consumptive use rates were developed for each irrigation season stress period (from May 1994 to September 2010) and applied uniformly across the irrigated acreage in the model. Figure 3.3 shows the location of irrigated acres in the model. Table 4.5 gives the unit consumptive use values for each year. Note that irrigation pumping is only turned on in the irrigation stress period of each year.

Unit consumptive use rates of irrigation water (CUw) for irrigated acreage in Laramie County were developed based on the procedures used in the Platte River Basin Water Plan (2006), which were, in turn, based on the methodology used in the Final Settlement Stipulation (2001) of the Nebraska v. Wyoming Supreme Court lawsuit over North Platte River flows. That methodology uses the Hargreaves equation calibrated to the Penman-Monteith equation for grass reference evapotranspiration using long-term climate data from Scottsbluff, NE. A full description of the methodology behind the values shown in Table 4.5 is provided in the project notebook. In essence, the values calculated for the Basin Plan were extended out to

September 2010 by using additional weather data from weather stations within Laramie County. These rates were applied to areas in the model where irrigated land is located.

Irrigated land in the model was defined using the shapefile from the Platte River Basin Water Plan. This shapefile shows irrigated acreage in the county developed using aerial photographs from the early 1980s. Because growth in irrigation well permits tapered off in the late 1970s, it was assumed that the irrigated areas from the 1980s were more or less the same as the irrigated acres of the present day. The decision was made to keep the spatial coverage constant throughout the transient calibration period. This is supported by the facts that: 1) only a few additional irrigation groundwater permits were approved after 1993; and 2) that small additional irrigated acreage is distributed randomly throughout the county, i.e. there is no one area of concentrated development that would skew model results. Irrigated crops in the model cover approximately 60,000 acres.

No attempt was made to vary irrigation water consumption based on crop type. The modeled discharge coming from groundwater irrigation was applied uniformly over the cells that fall under the mapped agricultural area.

Industrial

Examples of industrial use in Laramie County include quarries (Martin Marietta, Knife River), a chemical manufacturing company (Dyno Nobel), a hog farm (Champ LLC), travel centers (truck stops), and the Army Corps of Engineers. Due to availability of historical and current pumping records and the estimated magnitude of use, industrial pumping was explicitly modeled (rate and location) for only one company, Dyno Nobel, which has three wells within the model domain, near the Lone Tree Creek groundwater divide. Other, small industrial uses are implicit in the “rural domestic” category.

Municipal and Small Community Water Supply

Pumping from the City of Cheyenne well fields was modeled at the historical reported rates. All small community water supply pumping (communities and other centralized water systems) was modeled at the per-capita rates for the three systems for which limited historical data are available, i.e. the towns of Albin, Burns, and Pine Bluffs.

Municipal pumping in the groundwater model is comprised only of pumping from the City of Cheyenne’s well fields, of which the Federal, Bell, and Happy Jack fields fall within the model domain. Pumping records were obtained from BOPU. The location of the wells in the model was determined by a WSEO GIS shapefile showing the names and locations of all the permitted wells within the county and cross-checked with a shapefile from the Laramie County DSS (AMEC, 2013) showing public water supply wells. Figure 4.6 shows the locations of the municipal and small community supply wells in the model.

Small community water supplies are defined as the municipal supplies for towns other than Cheyenne and supplies for select residential developments outside municipal provider limits. These water providers supply communities of a couple dozen to a couple thousand people.

They tend to rely heavily, if not exclusively, on groundwater supplies. For the groundwater model, small community water supply pumping estimates were developed based on available data for the towns of Albin, Burns, Pine Bluffs, and Carpenter, the residential developments of Winchester Hills and Orchard Valley, and the mobile home parks of Hide-A-Way Mobile Village and Avalon. (The latter four of these are not shown on Figure 1.1. All but Winchester Hills are immediately along the southern edge of Cheyenne; Winchester Hills is five miles due south of Cheyenne.)

Electronic pumping records were obtained for the towns of Albin and Burns. Pumping for these towns was placed in the model cells where their physical wells are located and extracted at historical rates, per the records. Pine Bluffs did not have electronic records of pumping, so a ratio of the population of Burns to the population of Pine Bluffs was used to estimate their groundwater extraction. Pine Bluffs wells were placed in the model according to the physical well location, and water production was proportioned among the model cells based on permitted well yields.

Net depletions for Carpenter, Orchard Valley, and Winchester Hills were calculated using the same methodology employed for rural domestic pumping; i.e. a constant “irrigation season” depletion of 85 gallons per capita per day (gpcd) (see full discussion of this value in “Rural Domestic, Stockwater, and ‘Miscellaneous’” paragraphs below).

The mobile home park owners indicated that their parks had very little lawn irrigation, thus the 85 gpcd value was considered too high for these properties. Instead a unit consumptive use requirement for lawn grass was applied to 1 acre (Avalon) and 0.5 acre (Hide-A-Way) to estimate net depletions. For all the small community water supplies, water use inside the home is assumed effectively to be non-consumptive.

A full methodology of the development of small community water supply extractions is given in the project notebook.

Rural Domestic, Stockwater, and “Miscellaneous”

Rural domestic wells serve individual households and are located outside of the service areas for the municipal/small community providers. These wells are not metered so this category of consumptive use was estimated. Rural domestic groundwater consumption was modeled on a “net consumption” basis, recognizing that much of the water pumped by these wells returns to the aquifer via septic system infiltration.

The distribution of rural domestic wells was derived from the WSEO water rights database shapefile, current as of February 2012. All wells listed as domestic, domestic/miscellaneous, domestic/miscellaneous/stock, or domestic/stock (or some permutation thereof) were considered domestic wells. After excluding well permits that had been abandoned, canceled, expired, or rejected, or permits for well enlargements, there were approximately 7,155 domestic wells in the model domain up through the year 2010.

Water consumptive use per household was assumed to be 85 gpcd for the irrigation season and zero gpcd for the winter season. From the literature review, the Platte River Basin Water Plan (TriHydro, 2006) estimates net depletion for rural domestic wells at 75 gallons per capita per day (gpcd), the draft Laramie Decision Support System document (AMEC, 2013) also used 75 gpcd, and the Wyoming Depletion Plan for the Platte River Recovery Implementation Program used 100 gpcd for depletion. The North Cheyenne Master Plan estimates 0.4 ac-ft/yr per residence of net depletion, which works out to 90 gpcd assuming four people per household. Based on this review, 85 gpcd is a reasonable estimate of net depletion from rural domestic wells. The rate of consumption used for rural domestic wells is considered sufficient to cover minor consumptive use under “stock”, “miscellaneous”, and “industrial” use permits that are not captured in the previous categories.

Eighty-five gpcd was multiplied by the proportion of county residents inside the model domain assumed to be on private (domestic) wells, and applied in the model based on the distribution of 1) the location of populations served by EPA-listed public water supplies and 2) WSEO domestic well permits. Rural population was assumed to be geographically distributed in the same manner as the domestic wells. The per capita number is conservative enough to cover any additional non-municipal use such as the miscellaneous uses listed under permits to the WSEO. This pumping occurs in the “irrigation” or “summer” stress period, as winter rural domestic use is assumed to return to the aquifer.

5. Steady State Model Calibration

This section describes how the model framework, parameters, and data presented in Section 4 were calibrated in the numerical groundwater model. Model calibration is the process of "history matching" where the model representations of the hydrogeologic framework, hydraulic properties, and boundary conditions are refined to achieve a desired degree of correspondence between the model simulated values and historical observations of the groundwater flow system (ASTM D5718-95, 2006). The calibration process for the model began with building a "pre-development" steady-state calibration, which was used to refine initial hydrogeologic properties and boundary conditions, and to develop initial heads (groundwater levels) for the transient model calibration. The transient calibration used time-series observations of groundwater levels to further adjust hydraulic parameters and calibrate aquifer storage values. Following calibration, the transient model period can be extended beyond the historical calibration period for predictive simulations.

5.1 Steady State Model Calibration Targets

The steady state simulation ideally would be calibrated to pre-development water levels, meaning water levels measured before any significant groundwater withdrawals from well extraction. In practice this is difficult because before groundwater was being significantly withdrawn, there was little interest in measuring groundwater levels and wells were drilled for use, not observation. With this limitation in mind, the steady state simulation was calibrated to water levels from and before the early 1950s. It is understood that some agricultural withdrawals took place earlier than this, but this time period represents the best available data prior to widespread groundwater development. Given a choice, the earliest water level observation was used. In areas known for early development (e.g. Cheyenne, Carpenter, Pine Bluffs), observations from the non-irrigation season were used in order to avoid the influence of seasonal pumping. Although there are limitations in data availability, a pre-development steady state calibration is preferred because the water budget is simplified without groundwater withdrawals, and the system can more readily be assumed to be in equilibrium for the water balance.

5.1.1 "Pre-development" Potentiometric Surface

A steady state "pre-development" simulation was calibrated to over 450 locations of observed water levels throughout the model domain and from each of the top three model layers. Although the majority of the calibration data is well observations, around 50 DEM elevations from perennial stream locations were used to supplement the water level data. The groundwater observation data were downloaded from the USGS National Water Information System (NWIS) database. The database was queried for well water level data prior to 1955. The observed water level data were used both as observation targets for the model and to generate a "pre-development" potentiometric surface (water level elevation contours) for comparison to model simulated output. This surface is shown in Figure 5.1.

Other data than just the NWIS water levels were used to develop the “pre-development” potentiometric surface. These included the following:

1. Cederstrand and Becker, 1999 – this relatively recent publication uses Gutentag et al., 1984[5], as its data source, and shows the potentiometric surface for the High Plains aquifer in several states. These contours (available in digital format) form the background for the calibration contour set.
2. Lowry and Crist, 1967 – this publication includes a potentiometric surface map for Laramie County based on water level measurements made during 1963 and 1964. There is little difference between the Cederstrand and Becker and Lowry and Crist contours across the majority of the county. The Lowry and Crist water levels are slightly higher in the Carpenter and Pine Bluffs areas. The Cederstrand and Becker water levels were locally modified to incorporate the higher 1964 water levels. Lowry and Crist state that 1963/1964 was one of the driest years of record, and their mapping is more specific to the area.
3. Rapp et al., 1953 – the water levels in this publication precede about 80% of the irrigation well development in the county, but are limited to the Egbert/Pine Bluffs/Carpenter area. The composite surface was compared to the monitoring well data presented in Rapp et al. and modified accordingly.

5.2 Steady State Boundary Conditions

Of the boundary conditions described in Section 4, the parameters that were allowed to vary during calibration were the river bed conductance, the stream bed conductance, and the general head boundary conductance. Conductance is a modeling parameter that controls the interchange between surface water and groundwater. It is primarily a calibration parameter, because as a discrete term it is difficult to measure. Figure 5.2 illustrates the model idealization of riverbed conductance, which is a function of the length of the river (or stream) segment, the width of the river (or stream) channel, and the thickness of the river (or stream) bed. Conductance is also a term used in general head boundary cells to control the interchange between cells to maintain the defined water level elevation.

As discussed in Section 4, there are few measured values to use as calibration targets for stream flow gains and losses and the underflow flux from Laramie County to Nebraska. General estimates were determined from past reports, historical water rights documents, and discussions with WSEO personnel. Table 5.1 presents the steady state fluxes determined during calibration for these boundary conditions. Boundary conditions are illustrated in Figure 5.3.

5.3 Steady State Hydraulic Conductivity

For the steady state model calibration the hydraulic conductivity zones coincide with geologic mapping of the dominant geologic units as shown in Figure 4.3. Initial conductivity values for

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[5] Missing footnote information

steady-state calibration were set based on the literature review discussed in Section 4 and each zone (formation) was assigned a uniform value.

Horizontal conductivities (Kx, Ky) were assumed to be equal (no horizontal anisotropy) and vertical conductivity (Kz) was assumed to be one-tenth the horizontal value. These values were then adjusted as part of model calibration. Table 5.2 presents the calibrated conductivity values for each zone. Note that Table 5.2 has two columns of calibrated values; one labeled “steady state calibration value” and one labeled “final calibration value”. This is because the steady state model was calibrated using a single value for each of the K Zones listed in Table 5.2 (five zones corresponding to the geologic formations), but the final hydraulic conductivity values in the steady state model are from the transient calibration, which refined the distribution in each K Zone through the use of pilot points. The steady state calibrated hydraulic conductivities (“initial K values”) were used as pilot point values for the transient model, and the hydraulic conductivity was again calibrated in the transient calibration but allowing for spatially variable hydraulic conductivity within each K Zone. The hydraulic conductivity distribution resulting from the transient calibration is the “final” distribution (“final K values”), as discussed and illustrated in Section 7. The final K distribution was imported into the steady state model to replace the initial K values that had been derived in the steady state calibration, and the steady state model was re-run with the final K values. The results were nearly identical to those with the initial K values, so the quality of the calibration did not change. The calibration statistics and mass balance presented in this section are all a product of the steady state model run with the final K distribution.

5.4 Recharge

The recharge distribution for the model incorporates three main elements:

1. Mountain front recharge (zone 1) – represents precipitation captured along the mountain front that infiltrates through stream channels along the western boundary of the model. Literature and field observations suggest that the western stream channels typically are perennial west of I-25 and the mountain front recharge zones were set to be consistent with those sources.
2. Distributed areal recharge (zones 2-4) – represents the small percentage of precipitation that infiltrates to the aquifer throughout the model domain. Three zones were delineated based on the 30 yr average annual precipitation distribution presented in the Laramie County Groundwater Atlas (JR Engineering et al., 2008).
3. Low soil permeability (zone 5) – the recharge distribution presented in the Laramie County Groundwater Atlas shows a very low soil permeability zone defined by the La03 fine-loamy soil type[62]. This was delineated as separate recharge zone in the model.

The percentage of precipitation infiltrating to the aquifer system as recharge in each recharge zone was adjusted as a calibration parameter. Initial percentages for the distributed areal recharge zones were set at 5%, consistent with previous modeling and literature values, and for

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[6] Missing footnote information

the low permeability zone a value of 1% was used, consistent with the Laramie County Atlas. The mountain front zone was set to an initial volumetric estimate of 10,800 ac-ft/yr across the entire zone, based on the Lowry and Crist (1967) estimate for mountain front recharge (as discussed in Section 4). The initial annual precipitation value for the distributed areal recharge and the low permeability recharge zones was assumed to be the 30-year average annual precipitation value, as presented in the Laramie County Groundwater Atlas.

The recharge zones are shown in Figure 5.4 and the final calibrated precipitation percentages and amounts are presented in Table 5.3.

5.5 Steady State Calibration Statistics

A model is considered calibrated when observed or estimated hydraulic head or groundwater flow rates are reproduced satisfactorily by the model simulation (ASTM D5718-95, 2006). As previously discussed, the target observations were primarily water levels measured prior to the early 1950s and streambed elevations along perennial stream reaches within the model domain. Because the grid cell size is 1 km x 1 km (0.62 mi x 0.62 mi), a model simulation produces an average water level within the km^2 cell. Also, for comparison with model results, the depths-to-water reported from observation points must be converted to water-level elevations by subtraction from the surface elevation. The surface elevation of each cell is assigned as the average elevation over the km^2 cell domain. This means that all elevations from the DEM falling within a single grid cell were averaged to produce the cell surface elevation (i.e., top of Layer 1). The average range in DEM elevations within a model cell for all the model cells is about 40 m (130 ft). For calibration, this range served as the target maximum allowable deviation between observed and simulated water level measurements.

The automated parameter estimation software PEST (Doherty, 2005) was used to calibrate the model. In PEST, calibration parameters are defined with a starting value and a range of values within which the parameter value will be varied. For example, horizontal hydraulic conductivity was a calibration parameter. For a given zone the initial value could be 2 m/d, and the upper and lower bounds could be 20 m/d and 0.2 m/d, respectively. When available, upper and lower bounds were taken from the literature review values. For the steady state calibration, PEST was allowed to adjust the following parameters by zone or reach:

- Horizontal hydraulic conductivity (Kx and Ky)
- Vertical hydraulic conductivity (Kz)
- Riverbed conductance
- Streambed conductance
- General head boundary conductance

After each PEST run the calibration statistics were analyzed for how well the model matched the observation targets. The difference between the modeled value and the observed value is called the residual. Calibration sought to minimize the sum of squared residuals, within the data and resource constraints of the project. For the head targets in the final steady state model, the average residual was 1.5 m (4.9 ft), and the range of residuals was -30.3 m (-99.4 ft) to 34.9 m (114.5 ft). Note that this meets the “less than 40 m” criteria defined by the average spread of DEM elevations.

In general, the steady state model produced a good match to heads in all layers for which observations were available (Layers 1, 2, and 3). The correlation coefficient R2 for Layers 1 through 3 was greater than 0.99, which is considered very good, considering 1.0 is a perfect match. In the middle and eastern part of the model the average residual was -0.5 m (1.7 ft) in Layer 1 and -1.6 m (5.2 ft) in Layer 2. This indicates that the model slightly underestimates the groundwater levels, although this is an average and the model shows no trend of under- or over-estimating water levels when the calibration points are analyzed collectively (not averaged). In the western part of the model the average residual was somewhat greater; -3.4 m (11.2 ft) in Layer 1 and 2.2 m (7.2 ft) in Layer 2. Reasons for this include more complex geology in the western portion of the model and the greater number of calibration points in the middle-to-eastern area, thereby under-weighting the western part as PEST seeks the minimum residuals. There was no spatial pattern to average residuals in Layer 3; the average for the entire layer was 4.3 m (14.1 ft).

One of the uncertainties in the conceptual model was the amount of underflow leaving Laramie County to Nebraska and potentially to Colorado. General head boundary cells were placed at these boundaries (along the entire state line border on the east) and PEST was allowed to calibrate the amount of flux leaving the model in these cells using the general head boundary conductance term. The underflow beneath Crow Creek is not well known and proved insensitive to calibration, ultimately the entire southern boundary of the model was implemented as a no-flow boundary.

Table 5.4 presents standard calibration statistics for the steady state calibration, and Figure 5.5 shows the relationship between the observed and simulated water levels; a perfect match between observed and simulated water levels would plot directly along a one-to-one line. Figure 5.5 also shows the R2 values for the Layer 1, 2 and 3 observations, indicating that the model calibration accounts for more than 99% of the variation between observed and simulated observations. The calibration quality was further assessed by calculating the normalized root mean square error (RMSE). This was calculated by dividing the RMSE (8.44 m) by the range of observations (678 m) (both values given in Table 5.4); the resulting value of 1.2% indicates that the model does a good job of simulating heads in the aquifer (the industry standard is that a normalized RMSE of 5% or less is considered quite good). Figure 5.6 shows the modeled head contours alongside the estimated pre-development potentiometric surface that served as a calibration target.

A preliminary sensitivity analysis was run using utilities with Groundwater Vistas. Of the various calibration parameters presented above, the principal components controlling the root mean squared error between simulated and observed water level targets was found to be Recharge Zone 2 (high elevation areal distributed recharge), Ogallala horizontal hydraulic conductivity, and Arikaree horizontal hydraulic conductivity, as illustrated in Figure 5.7. The water levels in the model are primarily controlled by the surface topography and the relationship between recharge and hydraulic conductivity. Sensitivity to streambed conductance, and vertical hydraulic conductivities were also tested but are not shown on Figure 5.7 as calibration was relatively insensitive to these parameters.

5.6 Water Budget

The overall water budget for the steady state model is presented in Table 5.5. On average, precipitation accounts for 94,100 ac-ft/yr of recharge to the model. Of this amount, about half (42,900 ac-ft/yr) is attributed to mountain front recharge along the western edge of the model. The steady-state groundwater underflow from Laramie County to Nebraska is calibrated to be about 9,100 ac-ft/yr. Stream and river gains make up the lion's share of "pre-development" outflows from the aquifer, with 93,500 ac-ft/yr flowing into Horse Creek, Lodgepole Creek, Crow Creek, and the smaller tributaries within the model domain. The groundwater flux from Layer 3, the semi-confining White River formation, to Layer 4, the underlying Lance/Fox Hills Formations, is about 53,800 ac-ft/yr. Because the model is finite and at steady state, net flows to Layer 4 are necessarily zero (what comes in from above must go back out). Were the model boundaries larger, the net result would be the same but the location where the flow goes back up to Layer 3 might be outside of Laramie County.

6. Transient Model Calibration

A transient model was built to assess the time-varying aspects of groundwater impacts on a seasonal and annual basis. The steady state model simulation provides results for long-term equilibrium conditions (intended to approximate groundwater conditions before significant development occurred) and does not provide time-dependent results. Developing the transient model involved calibrating to an historical period, which for this model was from 1993 to 2010. This time period includes a series of wet years (i.e. 1990s) and a series of dry years (i.e. early 2000s) while capturing most of the available systematic records of water levels. (The end of the historical period is chosen as 2010 because data later than that may still be provisional, although it could be useful later for model verification.)

Stress periods are used to support representation of change in stress in the model, e.g. when pumping switches on or off, or when there is a strong seasonal signal of precipitation such as heavy infiltration from snowmelt. This model uses an annual "irrigation/non-irrigation" stress period pattern (two stress periods per year) because:

1. irrigation is the largest seasonal component of the aquifer budget,
2. this seasonality is well-aligned with the management issues of this project,
3. this seasonality is well-aligned with the available data, and
4. this is what the USGS is using for their north High Plains aquifer model (personal communication, Steve Peterson, USGS, February 26, 2013).

The conventional irrigation season in Wyoming, based on growing seasons and historical practice, is May 1 – Sept. 30 (This period was also adopted by the USGS for their model). Table 6.1 lists the stress periods and the corresponding time period they represent.

6.1 Transient Model Construction

The transient model required a number of datasets beyond what was needed for the steady state model. It also meant that components of the steady state model needed to be defined or expanded in terms of a time series. The most significant difference between the steady state and the transient model is that groundwater withdrawals are incorporated into the water budget in the latter. The purpose of the transient calibration was to refine estimates of aquifer parameters to achieve a model that accurately represents historically observed water levels.

6.1.1 Groundwater Withdrawals

Recall that the steady state calibration was "pre-development" and did not include groundwater pumping. Groundwater withdrawals are the critical part of the post-development water balance, and their management is a focus of the present investigation. Transient pumping datasets were compiled (see Section 4) for the following groundwater uses: irrigation, municipal, small community water supply, rural domestic, and industrial. Metered pumping records were available for certain industrial and municipal uses. For the other uses estimates were made in terms of the location, timing, and quantity of water extracted from the aquifer. Table 6.2 is a summary of the pumping volume per well per stress period, for all well types. Figure 6.1 shows this summary graphically (note that irrigation pumping is on a secondary vertical axis as it is typically more than an order of magnitude larger).

The following is a summary of the average groundwater consumptive use in the model, as summarized from Table 6.2:

- Irrigation – 54,500 ac-ft per irrigation season (0.93 ac-ft per acre)
- Industrial – 360 ac-ft per year (0.5 cfs, continual)
- Municipal – 4,400 ac-ft per year
- Small Community Water Supply – 600 ac-ft per year
- Domestic – 980 ac-ft per irrigation season (85 gallons per day per person)
- Stockwater – implicit in "Domestic" pumping
- Miscellaneous – implicit in "Domestic" pumping

6.1.2 Recharge

The recharge from the steady state model was expanded into a time-series using the recharge zones and fraction of precipitation determined from the steady state calibration. The precipitation data were derived from PRISM as discussed in Section 4. This dataset originally consisted of interpolated precipitation values across Laramie County for each month of each year of the transient calibration period. The monthly data were averaged for each recharge zone using a grid-based sampling procedure and then converted to average stress period values for each zone. This resulted in two precipitation inputs per year in each recharge zone.

6.1.3 Hydraulic Conductivity

The hydraulic conductivity zones were calibrated with a uniform value for each zone during the steady state calibration. Initial transient runs indicated that based on observed water levels there was significant hydraulic conductivity variability even within the same zone or given geologic unit. To accommodate this variability the hydraulic conductivity distribution was recalibrated with the transient model. For the transient calibration the automated calibration software PEST (Parameter ESTimation) with pilot points was used. Pilot points are simply hydraulic conductivity values assigned to specific locations which are varied up or down by PEST during calibration. The hydraulic conductivity distribution is then interpolated from the pilot point values. Initial pilot point values for each K zone were taken from the steady state calibration. The pilot points were applied on a zone basis so interpolation between pilot points was limited within each zone (i.e. geologic unit). The new calibrated hydraulic conductivity distribution was then also applied to the steady state model to insure it maintained or improved the steady state calibration results, which it did. Figures 6.2 through 6.4 show the calibrated hydraulic conductivity distribution for Layers 1, 2, and 3; Layer 4 was assumed to have a uniform conductivity and was not changed during the transient model calibration.

6.1.4 Specific Yield/Storage

Aquifer storage properties do not apply to a steady state run which, by definition, assumes the system is in equilibrium and there is no change in aquifer storage. Specific yield (the unconfined storage property) and specific storage (the confined storage property) were both used as calibration parameters in the transient model. Initial values were applied based on the range presented in Section 4. These storage properties were calibrated in the same manner as the hydraulic conductivity, i.e. adjusted using the PEST program to achieve satisfactory correspondence with transient-period observations.

6.1.5 Discharge to Streams

Cheyenne municipal waste water returns discharge to two cells in Crow Creek in the transient model. Figure 6.5 presents the discharge that was added to Crow Creek each stress period.

6.2 Transient Model Calibration Targets

There are two sources for the water level targets used in the transient model calibration. The WSEO maintains a set of monitoring wells within Laramie County. A subset of these monitoring wells was used for transient model calibration based on data availability and period of record, shown in Figure 6.6. These monitoring wells represent the primary time-varying targets for model calibration. Examples of the observed versus simulated water levels for these model targets are shown in Figures 6.7-6.10, and the complete set is presented in Appendix A. Another set of water calibration targets was derived from the 2009 potentiometric surface created by the USGS (Bartos and Hallberg, 2011). As with the steady state calibration this potentiometric surface was used for comparison with the transient model's simulated water level contours for 2009. This comparison is shown in Figure 6.11.

Including both head and flux targets in the calibration increases the likelihood of finding a unique solution to the groundwater flow model parameterization. The USGS maintains a stream gage on Crow Creek (19th Street gage, USGS 06755960), which is the only gage in the model domain with a period of record spanning the transient calibration period. For this reason it is the only quantitative flux target. However, qualitative targets were developed as described in Section 4 through interviews with WSEO personnel. These provided a general idea of how the streams in the model should behave for comparison with model results. Figure 6.12 shows the observed and simulated Crow Creek flow at the 19th Street gage (model row 52, column 35).

6.3 Transient Calibration Statistics

Section 5.5 provided a discussion of the meaning and use of calibration statistics. Table 6.3 summarizes the standard calibration statistics for the final calibrated transient model. Figure 6.13 shows the scatterplot of observed and simulated water levels over the entire model domain and transient calibration period. The smaller the difference between simulated and observed values, the more closely the points fall along the one to one line (shown in black). There were fewer wells for the transient calibration (although more data points per well) than for the steady-state calibration, which is why there are more gaps in this scatterplot than for the steady state calibration. Figure 6.13 also shows the R^2 values for the Layer 1 and 2, indicating that the model accounts for more than 99% of all the variation in observed water levels in those layers. There is only a single monitoring well as a transient target in layer 3 so no trend line was established for R^2. The normalized RMSE for the transient calibration is less than one half of one percent, indicating a very good head match across the model. There are no calibration statistics for Layer 4 simply because there were no observations in Layer 4.

6.4 Transient Calibration Water Budget

The water budget for the transient calibration model is presented in Table 6.4. Table 6.5 presents the average annual groundwater withdrawals in the transient model, with the intent of translating the numbers used in the model to familiar units. Figure 6.14 shows the transient water budget each water year in the calibration period. The red line shows the total outflows from the aquifer (underflow, discharge to streams, evaporation, and groundwater pumping), and the blue line shows the inflows (recharge) to the aquifer from sources other than aquifer storage (precipitation, underflow, and leakage from streams). The difference between these two lines is the “change in storage” term – in every year, there is a net change in storage that results in the groundwater table being lowered, as more water is withdrawn from the aquifer than is recharged. If the system were in long-term dynamic equilibrium, there would be years with both positive and negative changes in storage, and the average over the time period would be right around zero. In Figure 6.14 there are no years where inflow exceeds outflow, and on average outflows exceed inflows by 45,000 ac-ft/yr over the 1993 to 2010 calibration period. Physically this manifests in the water level declines that have been observed in places around the county.

When the water budget is analyzed in parts (e.g. western half of the model vs. eastern half of the model), it can be seen that areas in the eastern part of the county have the highest groundwater withdrawals and show a deficit between recharge and withdrawals in most years. Another important observation is how irrigation withdrawals dominate other withdrawals. On average irrigation pumping makes up 92% of the total withdrawals during the irrigation season. In the non-irrigation stress period, City of Cheyenne municipal pumping is the dominant stress, making up about 75% of the withdrawals. Compared to irrigation pumping, however, municipal is a much smaller stress on the aquifer, averaging 2,200 ac-ft/yr of withdrawals compared to 54,500 ac-ft/yr of withdrawals for irrigation. While the eastern half of the model sees the highest groundwater withdrawals, the western half of the model has the highest rate of recharge. Based on the rate at which groundwater moves through the High Plains aquifer, recharge that occurs in the western half of the county could take tens to thousands of years to reach the eastern half.

6.5 Limitations and Recommendations

The objective for the groundwater model was to provide a planning tool for better understanding and managing the water resources of Laramie County. The Control Area is the area of interest and focus of the groundwater model, which is a regional representation of the aquifer system within Laramie County. Given the scale and complexity of the aquifer system and groundwater withdrawals, there are uncertainties in the modeled hydrogeologic properties as well as groundwater use assumptions. The model in its present state is most appropriate for regional-scale analysis, but several areas of refinement have been identified that could reduce model uncertainty and may allow for design of more site-specific modeling.

6.5.1 Recharge

The volume of recharge to the aquifer system was not a tightly constrained parameter, i.e. there was a large range found in the literature review and previous modeling efforts. The lack of site-specific information also meant that the distribution of recharge was broadly applied. Recharge is a very important stress on the aquifer system and model predictions would certainly be improved through a recharge analysis study in Laramie County.

Ideally two approaches, one long-term and one short-term, could be applied to characterize recharge. For the short-term a soil-water-balance model could be developed. This is basically a mass balance approach where a numerical model is developed and inputs are localized around the interface between the ground surface and the water table. The soil-water-balance model would output a spatially variable recharge estimate that could be applied directly to the groundwater model. For the long-term an environmental tracer study could be employed where the evolution of naturally present constituents in the groundwater can be sampled from wells along a flow path to determine groundwater flow rates throughout the aquifer system. Carbon-14 dating for groundwater would yield flow rate, recharge rate, flow paths and would provide a calibration parameter for the groundwater model to constrain travel times using particle flow.

6.5.2 Aquifer Parameters

Significant variability has been observed through the High Plains aquifer system in Laramie County. Two prominent examples of this are pronounced groundwater gradients north of Albin, in the west between Lodgepole and Crow Creek, and the groundwater divide at the southwest edge of the model domain near Lone Tree Creek. These types of gradient deviations can be caused by zones of permeability that differ substantially from surrounding areas. The model presently smoothes out some of the local variability and is more representative of effective regional properties than of specific local properties (i.e. the combination of a high permeability feature with the lower permeability surrounding material or vice versa). Additional water level measurements and aquifer testing (e.g. through installation of monitoring wells) would improve the characterization of these highly variable areas. These data would be utilized in future calibration of modeled hydraulic conductivity and specific yield.

6.5.3 Groundwater Withdrawals

The pumping rates in the model for irrigation, some small public water supply systems, and domestic use were estimated rather than based on direct measurements. Simplifying assumptions were necessary to address these unknown quantities. Groundwater withdrawal data collected via well metering would reduce the uncertainty in this model stress.

6.5.4 Lateral Boundary Flows

The volume of groundwater underflow at model boundaries is estimated. The impacts of the boundaries on nearby areas are called “boundary effects” and are a common problem in numerical models. The model has buffer zones along the east and south boundaries to minimize boundary effects at the areas of interest; however, further characterization of these features would improve the overall quality of model calibration.

For underflow from Wyoming to Nebraska, groundwater level control points on either sides of the state line could be used to refine model calibration. The yet-to-be-released USGS High Plains Aquifer Model is assumed to also provide information on this boundary. For underflow beneath Crow Creek into Colorado, the model could be refined to explicitly represent activities across the border in Colorado, including additional water level targets for model calibration. For the Lone Tree Creek hydraulic divide, borehole logs and aquifer testing in this area could help characterize some of the observed hydrogeologic variability. Many of these data already exist for this area, and a focused calibration could improve overall model calibration. This was not performed for the current study because the Lone Tree Creek area is outside the area of interest, the Control Area.

6.5.5 Discretization

The groundwater model grid cells are 1 km x 1 km, an appropriate scale for a regional planning tool. To apply the model to local questions, such as for evaluation of a specific groundwater well permit, a finer degree of both vertical and horizontal discretization may be appropriate. Vertical discretization would not add more layers to the model, but would involve spot-checking and/or interpolation from borehole logs for geologic contact elevations. This exercise was performed for the current model in the Pine Bluffs and Carpenter area to determine the contact elevation of the fractured Brule, but not for the entire model domain.

6.5.6 Calibration Data

The network of monitoring wells with continuous or monthly water level measurements is not evenly distributed throughout the model domain. Expanding the monitoring well network to target areas of interest for groundwater development, areas with localized hydrogeologic variability, and along critical boundaries of the model, would allow for recalibration of the model and would increase the confidence of model predictions in these areas.

Finally, during model calibration it was noted that the reported water level in the WSEO monitoring well “mxnorth” is much higher than the water level shown on any of the potentiometric surface maps reviewed for this study. Verifying the casing surface elevation and depth to groundwater for this well is recommended.

7. Management Scenarios

This section summarizes the model runs used to evaluate potential groundwater management goals and their resultant effect on the groundwater resource. The general approach to evaluating the efficacy of management scenarios is to evaluate the differences between those scenarios and a Baseline Scenario, which can be thought of as a “business as usual” look into the future. Potential management goals for the groundwater resource in the Control Area fall to three basic categories: 1) a managed rate of future groundwater decline, 2) stabilization of groundwater levels, and 3) recovery of groundwater levels. Scenarios addressing these goals were developed and compared to results from the Baseline.

All model scenarios use a 50-year planning horizon coincident with the City of Cheyenne BOPU Master Planning projections. The transient model input for future years is based on repetition of the average hydrology (recharge and evapotranspiration rates) from the model calibration period. Water demands over this period are consistent with planning projections.

In the following section, the structure, details, and results of the Baseline Scenario and several example management scenarios requested by the WSEO are presented. Note that none of these hypothetical scenarios reflect specific management recommendations of the authors or WSEO. All are presented to provide a general assessment of future possibilities for this groundwater system and a scientific basis for the evaluation of these and other policy options.

7.1 Baseline Scenario

The Baseline Scenario is a transient model run representing a view of future groundwater development that reflects the rate of historical development in the Control Area and in Laramie County. This model run is used to measure changes resulting from the management scenario runs simulating alternative future management strategies. The Baseline Scenario is not a “no growth” scenario, but reflects documented plans for future groundwater development and, where these are not available, a continuation of recent groundwater development patterns or hypothetical future demands suggested by the WSEO. It assumes that the State Engineer’s Temporary Order of April 2012 is lifted and that groundwater development proceeds according to plans and population projections (where available), or as it occurred over the 10 years prior to the Temporary Order (2002 to 2012). Table 7.1 summarizes the Baseline demand assumptions. Figure 7.1 shows the distribution of the three rural densities listed in the table (distribution and density types are from the Laramie County Comprehensive Plan, 2001) and the locations of additional groundwater demands under the Baseline Scenario.

Estimates for future groundwater demands were made for the following uses:

- Municipal and small community water supply
- Rural domestic
- Irrigation
- Industrial and miscellaneous

Municipal and Small Community Water Supply

Baseline demands for the City of Cheyenne ("the City") water service area are derived from the new BOPU Master Plan (HDR et al., 2013), which anticipates 5,000 ac-ft/yr of new groundwater use by 2033. Based on preferences described in the Master Plan, the assumption was made that the first 1,000 ac-ft of this demand will be derived from expansion of the Bell well field, that the next 2,000 ac-ft of this demand will be derived from development outside the model domain, such as the Belvoir Ranch, and that the final 2,000 ac-ft of this demand will be derived from a new well field located north of the City. The Master Plan considers two potential areas for this new well field, one to the northeast of the City (and within the Control Area) where the Ogallala formation is very thick, and one north of the City (outside the Control Area) between Horse Creek and Lodgepole Creek. The Master Plan anticipates that new supplies beyond 2033 will be derived from surface water developments. To account for increased municipal use affecting the outflow from the WWTPs to Crow Creek, discharge to Crow Creek in the model was scaled up by the ratio of historical inflow (at Sherard Water Treatment Plant) to historical outflow (from Dry Creek and Crow Creek WWTPs). Sherard inflow data were provided by BOPU. Municipal groundwater demands were placed in the model beginning in stress periods corresponding to the year in which the demand is assumed to come online:

1) 1,000 ac-ft in the existing Bell wellfield starting in 2018. WWTP discharge increases proportionally.
2) 2,000 ac-ft of development assumed outside the model starting in 2023; no additional demand on groundwater in the model, but WWTP discharge increases proportionally.
3) 2,000 ac-ft of development north of Cheyenne just west (outside) of the LCCA boundary. WWTP discharge increases proportionally.

These demands and increased discharges occur at the time periods noted above and continue through the end of the simulation, in 2060.

Baseline demands for other towns and public water supplies are derived from county population growth projections. Small community water supply demands are applied to the same cells in which they appear in the historical (calibration period) simulation. This category of demand accounts for approximately 260 ac-ft/yr of new demand by the year 2060.

Rural Domestic

Baseline demands for rural domestic use are based on county land use planning and historical per capita use rates. Pumping was apportioned among the three rural densities shown in Figure 7.1 according to the geographic distribution of domestic well permits from the WSEO database. A complete description of how this dataset was developed is included in the project notebook. This category of demand adds 414 ac-ft/yr of new demand by the year 2060.

Irrigation

Baseline demands for irrigation are derived from permitting history over the ten year period prior to the Temporary Order. This history suggests a rate of growth in irrigation permitted yield of about 117 acre-feet per year within the model domain, which was scaled down by the ratio of permitted yield to consumptive use in the historical transient model to arrive at an estimate of 48 ac-ft/yr of additional net groundwater extraction. This translates to about 2,400 ac-ft of new irrigation demand by the end of the 50-year planning period. These demands were placed within and adjacent to existing model cells representing groundwater-irrigated lands in the model domain.

Industrial and Miscellaneous

Baseline demands for industrial and miscellaneous uses are also derived from recent permitting history. This history suggests the addition of about 196 ac-ft of new groundwater use each year within the model domain. Over the 50-year planning period this additional demand could reach nearly 10,000 ac-ft/yr. The WSEO provided specific guidance regarding the location, timing, and quantity of these withdrawals; the amounts of which are shown in Table 7.1.

Results of the Baseline Scenario

Figure 7.2 shows the change in groundwater levels (i.e. “drawdown”) in the model at the end of the transient calibration period (2010) as compared “pre-development” levels which were the initial head distribution used to start the transient run. Figure 7.3 shows the spatial distribution of groundwater withdrawals in the model by 2010, and Figure 7.4 shows the additional groundwater withdrawals (on top of the withdrawals at the end of 2010) in the model by 2060 in the Baseline scenario. These figures show where pumping stresses are imposed in the historical time period and in the future Baseline scenario. Figure 7.5 shows the 2060 drawdown from pre-development at the end of the 50-year future simulation for the Baseline Scenario. All drawdown figures in this and subsequent sections are referenced with the pre-development water levels as the “zero” point. Areas of decline are apparent around the south and west sides of Cheyenne, the Albin area, and the Carpenter and Pine Bluffs areas. Declines south and west of Cheyenne are on the order of 20 to 60 meters (65 to 200 ft) and are largely attributed to the municipal and industrial pumping in the model. In particular, the hypothetical industrial uses at the Campstool Road industrial area (east of Cheyenne and south of I-80), at Terry Ranch (south of Cheyenne and east of I-25), and at Round Top (west of Cheyenne and south of I-80) cause deep, localized declines.

Figures 7.2 and 7.5 reflect the “baseline” condition to which the results of alternative management scenarios will be compared in the following discussion. For purposes of discussion, the five districts within the Control Area are shown on the drawdown figures.

7.2 Management Scenario #1 – Permanent Spacing Order

This management scenario assumes the State Engineer’s Temporary Order of April 2012 is carried forward into the future. It is characterized by the following demands/reductions:

1. No new non-domestic wells in the Control Area
2. Growth of domestic wells as in the Baseline Scenario
3. Growth outside of the Control Area as in the Baseline Scenario

Based on the review of permits issued by the WSEO in the ten years prior to the issuance of the Temporary Order, about 65% of the new irrigation demand (roughly 4,400 ac-ft/yr by 2060) and about 40% of the new industrial and miscellaneous uses (roughly 4,700 ac-ft/yr by 2060) within the model domain would occur within the Control Area. This means that this model run has approximately 9,100 ac-ft/yr less groundwater consumption in 2060 than the Baseline run.

Figure 7.6 shows the drawdown relative to the pre-development condition across the model resulting from Management Scenario #1. The areas of groundwater decline in the northeast (District 5, Albin area) and the southeast (Districts 1 and 2, Carpenter and Pine Bluffs areas) appear in the same locations and to the same depth, although the spread is slightly less in the Management #1 scenario. In terms of spread of drawdown, Management #1 shows a larger gap between the two primary areas of groundwater decline in the model; the area to the west of Cheyenne stemming largely from municipal and industrial pumping, and the area to the east of Cheyenne stemming largely from irrigation pumping. In other words, more of the aquifer within District 3 (and to a lesser extent District 2) looks like pre-development conditions (no drawdown) in Management #1 than in the Baseline Scenario. This result suggests that extension of the Temporary Order would have a degree of success in slowing the spread of water level decline in that area.

7.3 Management Scenario #2 – 50% Reduction in Irrigation Groundwater Use

This management scenario is focused on stabilizing areas within the Control Area that experience the groundwater declines identified in the Baseline scenario. It represents the net effects of a hypothetical program of regulation, rotation, CREP programs, metering and other restrictive regulatory methods to reduce irrigation pumping (recall that irrigation is by far the largest groundwater use in the Control Area). It is characterized by the following demands/reductions:

1. 50% reduction in irrigation pumping within the Control Area
2. Municipal demands increase as in the Baseline scenario
3. Rural domestic demands increase as in the Baseline scenario
4. No new non-domestic groundwater development in the Control Area
5. Demand reductions were fully implemented in the first year of the simulation period

The goal of this scenario was to determine the percentage by which current irrigation groundwater withdrawals would need to be reduced to stabilize groundwater levels at their 2010 condition. Additional runs were contemplated to determine the percent reduction needed to recover water levels to 2000 levels by 2060. However, it became apparent that for a given across-the-board reduction some areas in the model would stabilize and some areas would recover to varying degrees. Therefore, the result of this model run was the percent reduction required to arrest declines in most areas and to produce recovery in some areas. After iterating through a series of irrigation reductions (10% reduction, 20% reduction, etc.), a 50% reduction was chosen as suitable to achieve the stabilization goal for most of the areas around the model.

Figure 7.7 shows the drawdown relative to the pre-development condition across the model resulting from Management Scenario #2. The area where an across-the-board 50% irrigation reduction had the largest impact is the Carpenter/Pine Bluffs area in District 1 and the eastern panhandle of District 2. These areas of decline are very close in depth and spread to the declines seen in 2010, the end of the historical transient simulation. Recovery in the District 5/Albin area was not achieved with a 50% irrigation reduction, as evidenced from the area of decline deepening from 6 to 20 m (20 to 66 ft) to 21 to 100 m (69 to 328 ft) between 2010 and 2060 in Management #2. The areas of drawdown to the west of Cheyenne (outside the Control

Area) are unchanged between the Baseline and the Management #2 runs because the change in pumping was only applied to wells inside the Control Area.

7.4 Management Scenario #3 – Groundwater Use Reduction by District

The goal of this management scenario was also to stabilize the water levels to 2010 levels, but allows the five districts to be treated differently to achieve the objective. This means that the reduction in irrigation pumping can occur at different percentages in each of the districts. This scenario is categorized by the following demands/reductions:

1. Variable reduction in irrigation pumping for each of the five districts within the Control Area
2. Municipal demands increase as in the Baseline scenario
3. Rural domestic demands increase as in the Baseline scenario
4. No new non-domestic groundwater development in the Control Area
5. Demand reductions were fully implemented in the first year of the simulation period

The results of Management Scenario #3 demonstrate that District 5 requires a large reduction in pumping to recover/stabilize water levels, Districts 1 and 2 require somewhat less reduction than the 50% of the previous scenario, and Districts 3 and 4, having no substantial areas of drawdown to begin with, required no reduction. Iteration of the model with varying reduction percentages produced the following estimates to achieve consistent stabilization results across all districts:

- District 1 – 30%
- District 2 – 35%
- District 3 – 0%
- District 4 – 0%
- District 5 – 90%

Figure 7.8 shows the drawdown across the model resulting from Management Scenario #3. Compared to Figure 7.2, drawdown in 2010, the magnitude of drawdown is quite similar. For example, the Carpenter area (roughly the panhandle of District 2) sees drawdowns on the order of 2 to 20 m (6 to 66 ft) in both figures. Similar drawdown magnitudes between 2010 and 2060 are seen in District 5 and in District 1. However, the areas affected by drawdown grow over time even if magnitudes are stabilized. In 2010, with the possible exception of District 1, the areas of decline are tight around cells containing concentrated irrigation pumping. By 2060, even with the reductions, the areas of decline are projected to impact most of Districts 1 and 5.

7.5 Management Scenario #4 - No Growth in Groundwater Use

The intent of this scenario was to model the future impacts of the pumping that is already in existence across the county. This scenario is characterized as follows:

1. No new groundwater extraction of any type anywhere in the model

2. Average irrigation withdrawals from the 1993 to 2010 transient calibration period were repeated every year from 2011 to 2060
3. Average municipal and industrial pumping based on the period from 2005-2010 of the transient calibration period were repeated every year from 2011 to 2060
4. No new domestic withdrawals; locations and pumping rates continued based on the 2010 distribution and rates from the transient calibration

Figure 7.9 shows the drawdown across the model resulting from the Management Scenario #4. Near Cheyenne, there is a noticeable lack of drawdown in the Management #4 run compared to the Baseline scenario; this is because the new municipal and industrial uses in the Baseline scenario were absent from the Management #4 run. The area of decline around the existing Cheyenne municipal wellfields is essentially the same. District 4 shows relatively little drawdown in both the Baseline and the Management #4 scenario, reflecting the fact that the only pumping in this district is rural domestic, a minor demand. Drawdown in District 5 is nearly identical between the Baseline and the Management #4 scenario, which highlights the fact that much of the future drawdown projected in the county will be caused by pumping that is already occurring. This is generally the case in Districts 1, 2, and 3 as well, with the exception of areas of decline in District 3 being less pronounced in the Management #4 scenario. This likely reflects the impact of the new industrial and rural domestic demands around Cheyenne in the Baseline.

7.6 Drawdown in Baseline and Management Scenarios

The yields and thickness of the High Plains aquifer varies depending on location around the county. For example, near Carpenter and Pine Bluffs the productive aquifer is made up of relatively shallow terrace deposits and the thin underlying fractured Brule. While the productive aquifer thickness in this area is limited it represents one of the most transmissive areas of the aquifer and is an area historically characterized by high aquifer yields. As a contrast, in the area north of Cheyenne the Ogallala Fm formation is less productive but much thicker. In the Albin area the productive aquifer is of substantial thickness where deep paleochannels eroded to the Arikaree Fm have filled in with coarse grained material creating high yields that are quite variable locally. Underlying each of these locally productive aquifers is the White River Fm, a relatively competent and uniform siltstone. The majority of the White River is considered a relatively poor producer of groundwater. With this consideration in mind, recognizing when water levels drop below the respective productive aquifer units and into the underlying White River is an important metric for assessing county water resources and yields as they will likely drop considerably at that point. In general, management aimed at sustainable aquifer yield will have to maintain aquifer levels above the White River Contact. Figures 7.10 through 7.14 are hydrographs of simulated water levels in monitoring wells throughout the control area. The ground surface, Ogallala/Arikaree contact (bottom of Layer 1 and top of Layer 2), and Arikaree-fractured Brule/White River contact (bottom of Layer 2 and top of Layer 3) are indicated on the graphs. Figure 7.15 gives the locations of the monitoring wells.

Figure 7.10 is a well in District 1, located in the southeast corner of the county close to the WY/CO state line. Figure 7.11 is a well in District 2, located in the southeast Carpenter area. The response to imposed groundwater withdrawals and the recovery from reductions in groundwater withdrawals at these locations are characteristic of the highly productive and transmissive terrace deposits and underlying fractured Brule. The implications for water resource management in this area due to the aquifer characteristics are as follows:

- The response to groundwater withdrawals is a rapidly declining groundwater level about 6-10 m (18-35 ft) of drawdown in 60 years under the Baseline Scenario.
- The rate of groundwater level decline in this area is of particular concern because the productive aquifer thickness is limited to about 15-20 m (50-65 ft), so the simulated decline is about 40-50% of the total available saturated thickness.
- The recovery response to reductions in groundwater withdrawals is also rapid. Water levels recover and stabilize to 2010 levels within the 60-year planning horizon with a 30% to 35% reduction.

Figures 7.12 and 7.13 are wells located in District 3 and District 4, respectively. These wells are located in an area of the High Plains aquifer where both the Ogallala Fm and the underlying Arikaree Fm are present and have relatively substantial thickness. As previously mentioned there is very little groundwater development for irrigation in these districts so groundwater withdrawals are minimal and related to rural domestic, municipal, and industrial/miscellaneous use. The implications for water resource management in this area due to the aquifer characteristics are as follows:

- The response to groundwater withdrawals in these districts is a maximum of 2 m (6 ft) of drawdown in 60 years under the Baseline Scenario.
- The relatively modest rate of groundwater level decline in these areas is not of immediate concern because the saturated thickness of the productive aquifer units is between 55-90 m (180-300 ft), so the simulated decline is only about 1% of the total available saturated thickness.
- The recovery response to reductions in groundwater withdrawals is minimal because of the limited irrigation withdrawals in these districts. There is very little difference observed between Management Scenario #2 (50% irrigation reduction), Management Scenario #3 (0% irrigation reduction), and the Baseline Scenario.

Figure 7.14 is a well in District 5 located near Albin where extensive groundwater withdrawals have historically taken place. The response to imposed groundwater withdrawals in this area is characteristic of locally productive Ogallala and Arikaree Fms. The Ogallala is generally unsaturated in the Albin area and the majority of the pumping takes place from the Arikaree Fm (relatively less productive) where coarse grained paleochannel deposits are present. While discrete localized features may be very transmissive, the effective properties for this area are generally lower than that of the Ogallala Fm or terrace deposits and fractured Brule. The implications for water resource management in this area due to the aquifer characteristics are as follows:

- The response to groundwater withdrawals in this district is a rapidly declining groundwater level of about 15 m (50 ft) of drawdown in 60 years under the Baseline Scenario.

- The steep rate of groundwater level decline in this area is mitigated by a relatively substantial saturated thickness of about 50 m (165 ft) for the productive aquifer. The simulated decline is less than 30% of the total available saturated thickness.
- The recovery response to reductions in groundwater withdrawals is at slower rate due to the lower transmissivities in this area There is very little difference observed between the Management Scenario #2 (50% irrigation reduction) and the Baseline Scenario over the 50 year planning horizon. Even Management Scenario #3 (90% irrigation reduction in District 5) does not completely recover or stabilize water levels within the 50 year planning horizon. However, this area shows less potential for declines to result in water levels dropping below the Arikaree into the White River Fm.

One implication of this analysis is that the reduction required to stabilize or recover water levels may best be managed on a geographic basis, not only because the current status of groundwater development is spatially variable, but because the hydrogeology is variable. The unique characteristics related to hydrogeology have important implications for management if a sustainable aquifer yield is a long term goal. While none of the example hydrographs (Figures 7.10 through 7.15) show water levels dropping below the White River contact within the 50 year planning horizon, there are locations within the Control Area that do show water level drops below the contact. Figure 7.16 shows an example sequence of water level declines referenced to the White River contact from 2010 to the Baseline Scenario and then simulated recovery of water levels under Management Scenario #2 (50% irrigation reduction). In particular irrigation withdrawals in the Carpenter, Pine Bluffs and Albin areas have potential to lead to water levels dropping below the contact and thus to significant reduction in groundwater yields if no management is implemented.

8. Summary and Discussion

8.1 Conclusions

The three main areas of groundwater decline seen historically and in the modeling are Pine Bluffs/Carpenter, Albin, and around Cheyenne. Spatially, Pine Bluffs and Carpenter are distinct from each other, but they share hydrogeologic characteristics and respond similarly in the model so are discussed together.

Groundwater levels in the Pine Bluffs and Carpenter portion of the county have declined primarily due to the long-term impact of large irrigation withdrawals from a productive, but relatively thin aquifer: the Quaternary-age alluvial/terrace deposits and the immediately underlying fractured Brule Member of the White River Formation. These same aquifer characteristics provide a relative responsive aquifer in terms of arresting or reversing groundwater declines through reduced pumping as shown by the modeling results.

Groundwater levels declines in the Albin area are also largely due to irrigation development, but the aquifer in this area – the Arikaree Formation and locally-saturated Ogallala Formation – is generally less productive and thicker than the aquifer in the southeast portion of the county. Thus, the projected additional declines under baseline conditions (continued development as in the recent past) are relatively large and, through the modeling analyses, were shown not to be easily arrested or reversed by reducing pumping.

Groundwater levels in the area around Cheyenne have been impacted by the cumulative effects of municipal, industrial, and domestic development on an aquifer of modest (and local) productivity, but of substantial thickness. The nature of the aquifer in this area leads to significant local drawdown in response to present and future development, but the most severe drawdown impacts are greatly attenuated and do not spread significantly into the surrounding area or into the LCCA. Future use scenarios indicate that the aquifer in this area may be physically unable to support heavily concentrated development. (Reduced pumping scenarios were not evaluated for this area.)

Over much of the Control Area and the county, i.e. outside the three areas discussed above, the Ogallala and Arikaree Formations have not experienced significant drawdown, nor is significant drawdown projected over the 60 years modeled under continuation of baseline conditions. These areas provide opportunities for limited additional groundwater development without exacerbation of the groundwater declines experienced elsewhere. Water development from the aquifer in these areas is currently less than the expected supplies. While specific amounts of available groundwater were not estimated or quantified within this study, the modeling suggests the presence of groundwater that could be appropriated. The study serves to identify areas of the county where the pre-development resource remains largely intact and where projected future “baseline” development is not likely to significantly change that condition. The study supports the continued close monitoring of existing and additional uses and their long-term effects upon the aquifer across Laramie County both within and outside of the Control Area.

There are groundwater-level effects resulting from annual and long-term changes in precipitation, which is the one of the primary sources of aquifer recharge. These effects are superimposed on the groundwater-development impacts discussed above, serving to either increase or reduce groundwater level changes. Figure 6.14 speaks to this point. The “total outflow” line captures all outflows from the aquifer: underflow, river and stream gains, evaporation, and groundwater pumping. The “inflow minus storage” line captures all inflows to the aquifer that come from a source outside the aquifer itself. The figure shows a decrease in inflow to the aquifer during the early 2000s, which is when the county was experiencing below average precipitation. Starting in 2006 and continuing until 2009 aquifer inflows increased; these are years with increased precipitation recharge in the county. Outflows from the aquifer do not show a similar climatic trend, although pumping tends to increase in years with lower precipitation and vice versa (note the spike in outflows in 2000 and again in 2002) reflecting crop irrigation needs.

The groundwater model that was built and calibrated for this study provides a quantitative tool for assessing the future availability of groundwater within the modeled portions of the Control Area. Summarizing the conclusions from Section 7:

- If groundwater withdrawals continue to increase, expect there to be areas in the county (both localized outside of, and within, the LCCA) where groundwater extraction becomes impractical.
- Absent reductions, pumping in the Control Area that is already in place will continue to lower the water table in the future.
- Groundwater development potential varies across the county and Control Area. Some areas have minimal withdrawals and ample saturated thickness while some areas host substantial withdrawals and have little remaining useful saturated thickness.
- Small withdrawals from the aquifer, such as stock watering and domestic uses, are not substantially adding to the long-term aquifer level declines.

As noted in earlier sections, groundwater withdrawals are difficult to quantify in the absence of contemporary measurements. Approximating the net pumping based on assumed crop consumption or population (e.g. irrigation use, rural domestic use) may overestimate pumping in some areas and time periods and underestimate pumping in others. Like most models, the groundwater model developed for this study could be improved with more data. Installation of additional flow meters on high capacity groundwater wells and consistent enforcement of permit reporting conditions would improve understanding of the water balance. Similarly, installation of additional monitoring wells in the area of the county with sparse monitoring well coverage, e.g. District 4 and north District 3 / southwest District 5, would facilitate the understanding of the local impacts of groundwater withdrawals and future model calibration. Of particular interest in this regard is the Lance/Fox Hills aquifer, to which future development is increasingly being directed and for which there are virtually no systematic groundwater level measurements.

8.2 Control Area Boundaries

The Laramie County Groundwater Control Area is presently divided into five districts. These were based on geographic/political considerations rather than hydrogeology, and, to the extent provided and allowed by Wyoming law, the WSEO may evaluate district area adjustments in the future, as may be needed to implement different groundwater management activities. For example, with minor boundary changes District 5 could be delineated to encompass the area of projected groundwater level declines around Albin (see Figure 7.5). The Pine Bluffs and Carpenter areas are similar in terms of aquifer characteristics, historical groundwater development, and projected declines. As such, the Districts 1 and 2 boundaries could also be adjusted to reflect these hydrogeologic conditions.

The outside boundaries of the Control Area reasonably capture the areas of interest and concern from water development, and serve to closely monitor the nearby areas in the north, east, and south. Modeling results indicate that the areas of groundwater level decline in the Control Area are effectively separated from the impacts of development in the western portion of the county (including around Cheyenne).

8.3 Recommendations

The modeling results suggest that: 1) areas of the LCCA within parts of Districts1, 2, and 5 (as they may be redrawn to facilitate specific management) should establish a long term goal to target the stabilization of aquifer levels; and 2) in the other areas of the LCCA, and the western parts of the county, some additional controlled new uses of groundwater could be allowed from the High Plains Aquifer. In the areas of concern, where continued long-term declines in groundwater levels are likely, there are a number of management strategies that could be pursued and are reflected by the following recommended activities.

1. The WSEO should encourage local water user participation in the development of voluntary demand management programs to reduce the withdrawal of groundwater within the areas of concern identified by the modeling; or within the current or potentially redrawn LCCA district boundaries, such that customized solutions can be implemented in the localized areas of concern to meet the long term goals.

   These voluntary programs could consider and include: local guidance to WSEO on establishing a moratorium on new high capacity wells, metering of high capacity well uses, land-fallowing, continued support of the NRCS Agricultural Water Enhancement Program (AWEP), irrigation rotation and scheduling of withdrawals, expanded use of water conservation practices and investments in efficient irrigation conveyance and distribution systems, and incorporation of weather, crop ET, and related irrigation and groundwater aquifer monitoring data information into irrigation practices.

2. The WSEO, in consultation with the LCCA Advisory Board, should consider a variety of water management tools in the future administration of the groundwater resources of Laramie County
   a. Consider changes to LCCA district boundaries, incorporating the hydrogeologic conditions and projections contained within this study, or otherwise employ management tools tailored to the varying hydrogeologic conditions present within the Control Area.
   b. Consider expansion of the collection, distribution and availability of groundwater monitoring well information to the public.
   c. Consider installing new monitoring wells to add to the existing network of WSEO monitoring wells.

   d. Develop procedural guidelines for how the WSEO will work with groups of water users in the development, review, monitoring and implementation of voluntary water demand management programs.
   e. Evaluate the need and authority to initiate development of possible future geographically targeted rules, policies, guidelines or regulations within the LCCA and county, associated with certain aspects of the water demand management program; including those outlined above in Item 1.
   f. Research possible state, local, or federal funding sources to support implementation of various portions of the water demand management programs.
   g. Establish policies regarding the WSEO's ongoing updating, maintenance, use and public availability of the groundwater model created for WSEO through this study, and how the model may inform the agency's ongoing reviews and analyses leading to permitting decisions for all new high-capacity water appropriations within the county; where the study results suggest adequate groundwater resources exist in the High Plains Aquifer.
   h. Continue to evaluate and support efforts:
      i. to geographically spread out the small capacity stock watering and domestic wells through county based land use authorities, procedures and regulations;
      ii. to evaluate the effectiveness of vertical spacing for groundwater withdrawals;
      iii. to establish minimum static water level conditions for all new groundwater permitting
      iv. to permit and complete new wells in Lance/Fox Hills Aquifers located below the High Plains Aquifers, and to monitor such uses for any hydrogeologic connections between these aquifer systems.
   i. Evaluate possible sources of water that could be developed to increase recharge to the areas of declining groundwater levels in the Carpenter area.

3. The WSEO should establish a timeline for scheduling a public hearing for the presentation of this final technical report and the Agency-adopted recommendations. After public input and if no public plan is forthcoming, the WSEO should consider establishing new policies or guidance for the management of existing water uses, and for new appropriations of groundwater.

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Hydrogeologic Study
of the
Laramie County Control Area

FIGURES

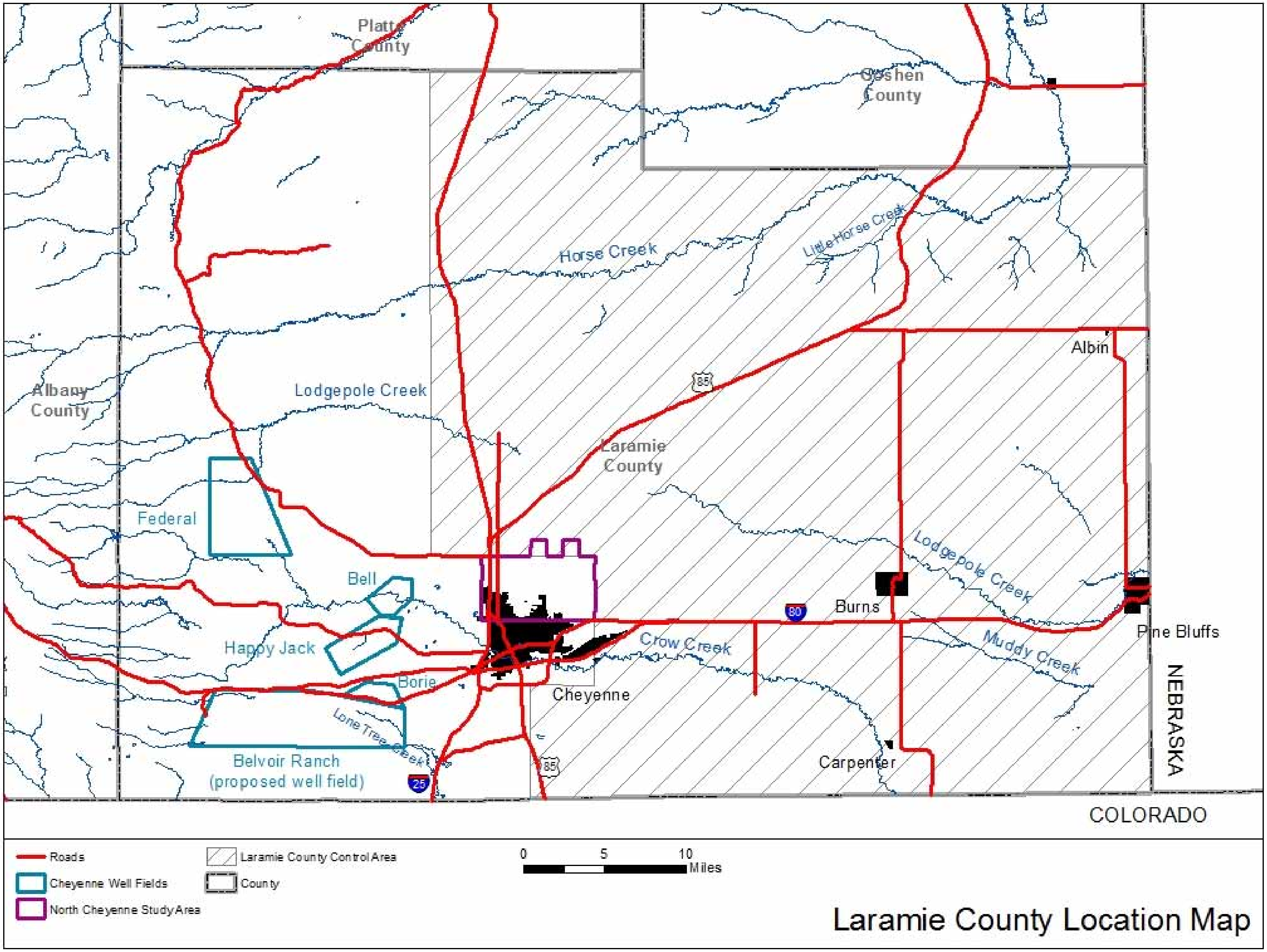


Figure 1.1 Laramie County Location Map

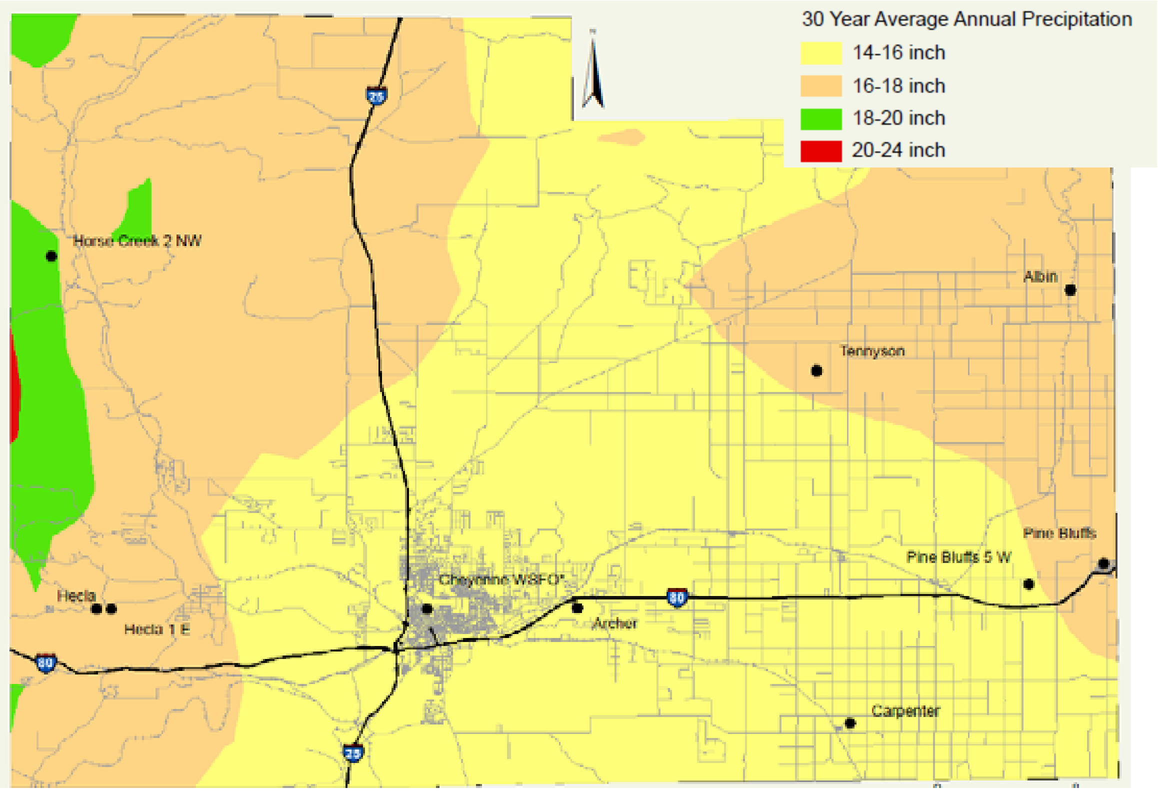


Figure 2.1 Distribution of Precipitation in Laramie County (JR Engineering et al., 2008)

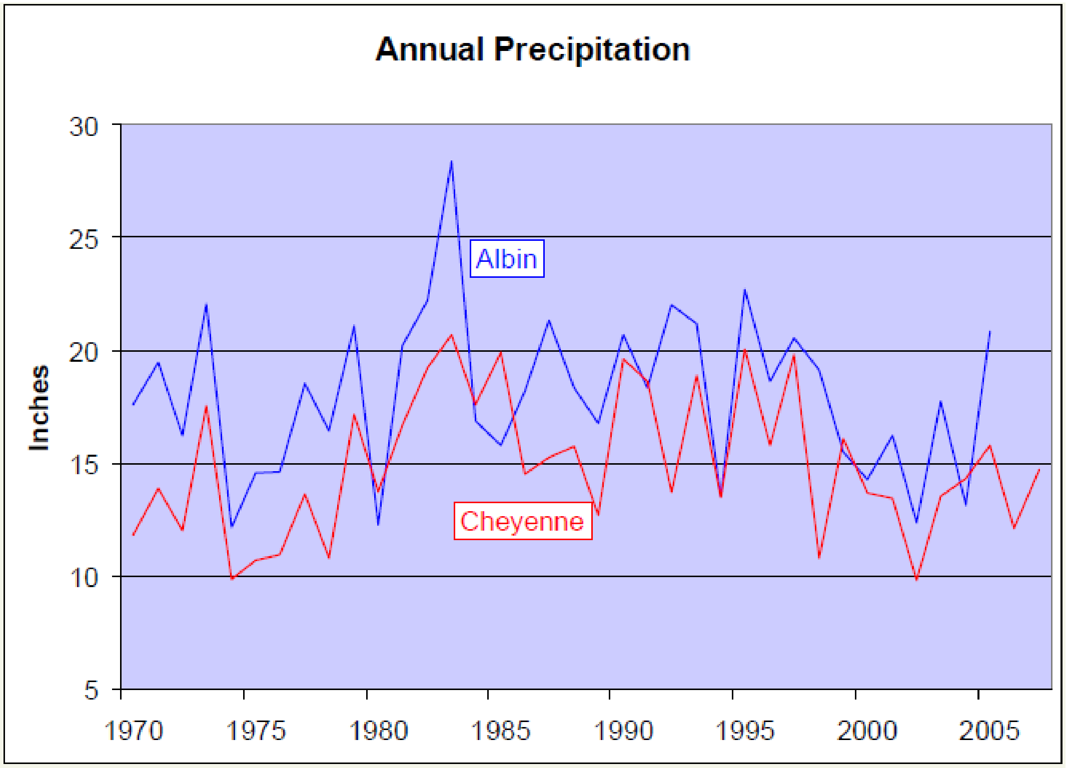


Figure 2.2 Annual and Spatial Variation of Precipitation in Laramie County (JR Engineering et al., 2008)

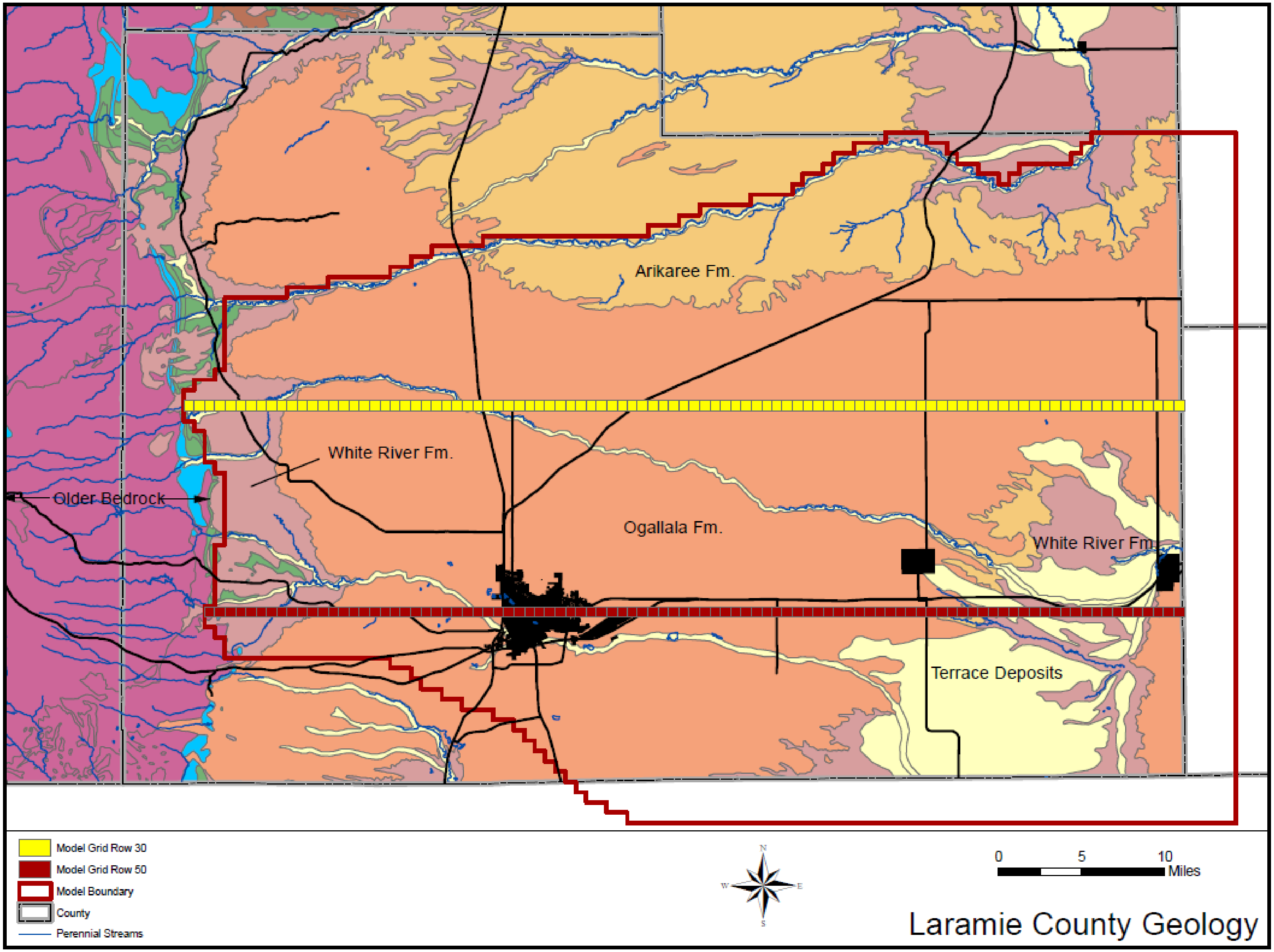
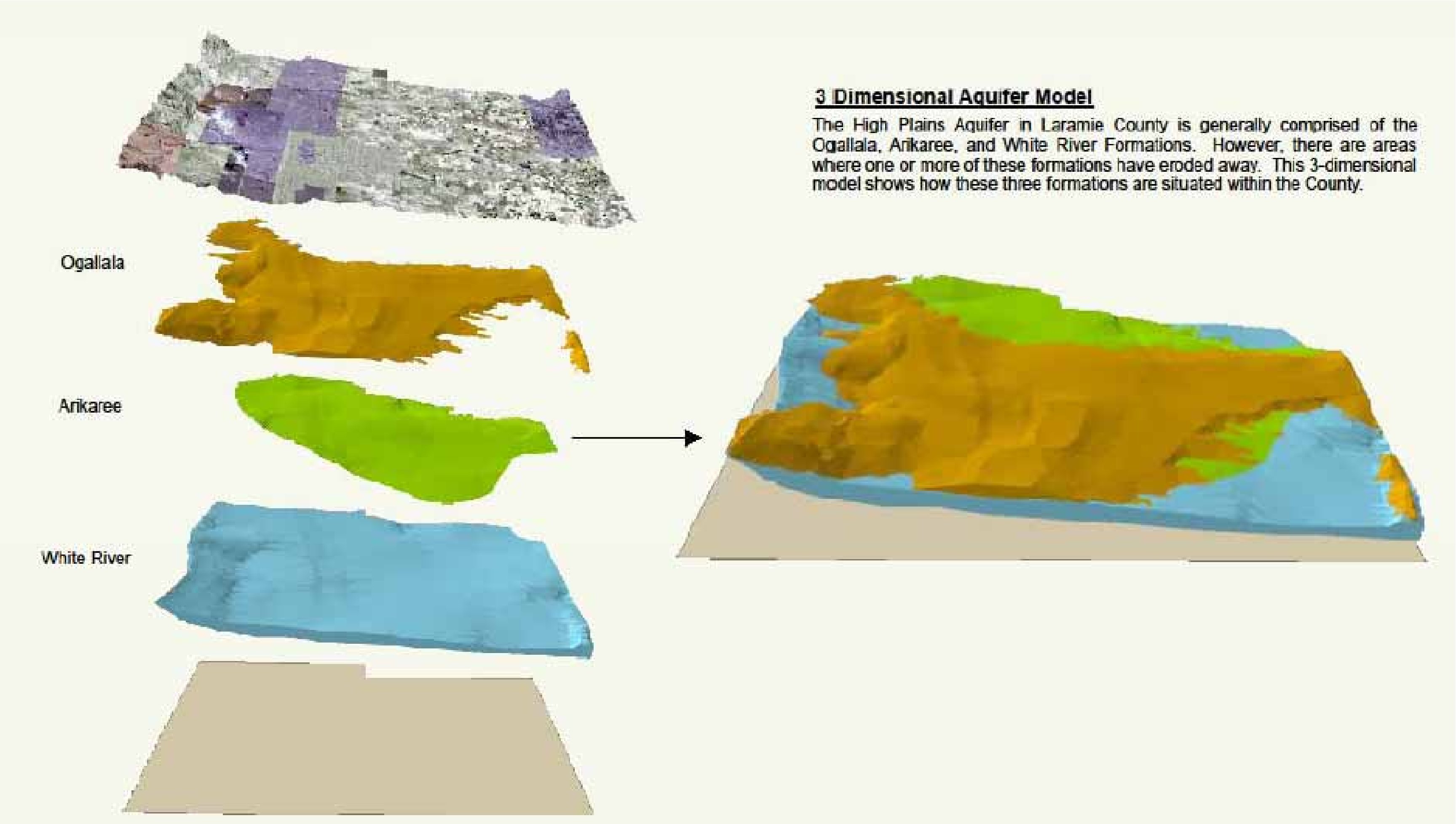


Figure 2.3 Surface Geology in Laramie County



3 Dimensional Aquifer Model

The High Plains Aquifer in Laramie County is generally comprised of the Ogallala, Arikaree, and White River Formations. However, there are areas where one or more of these formations have eroded away. This 3-dimensional model shows how these three formations are situated within the County.

Figure 2.4 Three-Dimensional Aquifer Schematic (JR Engineering et al., 2008)

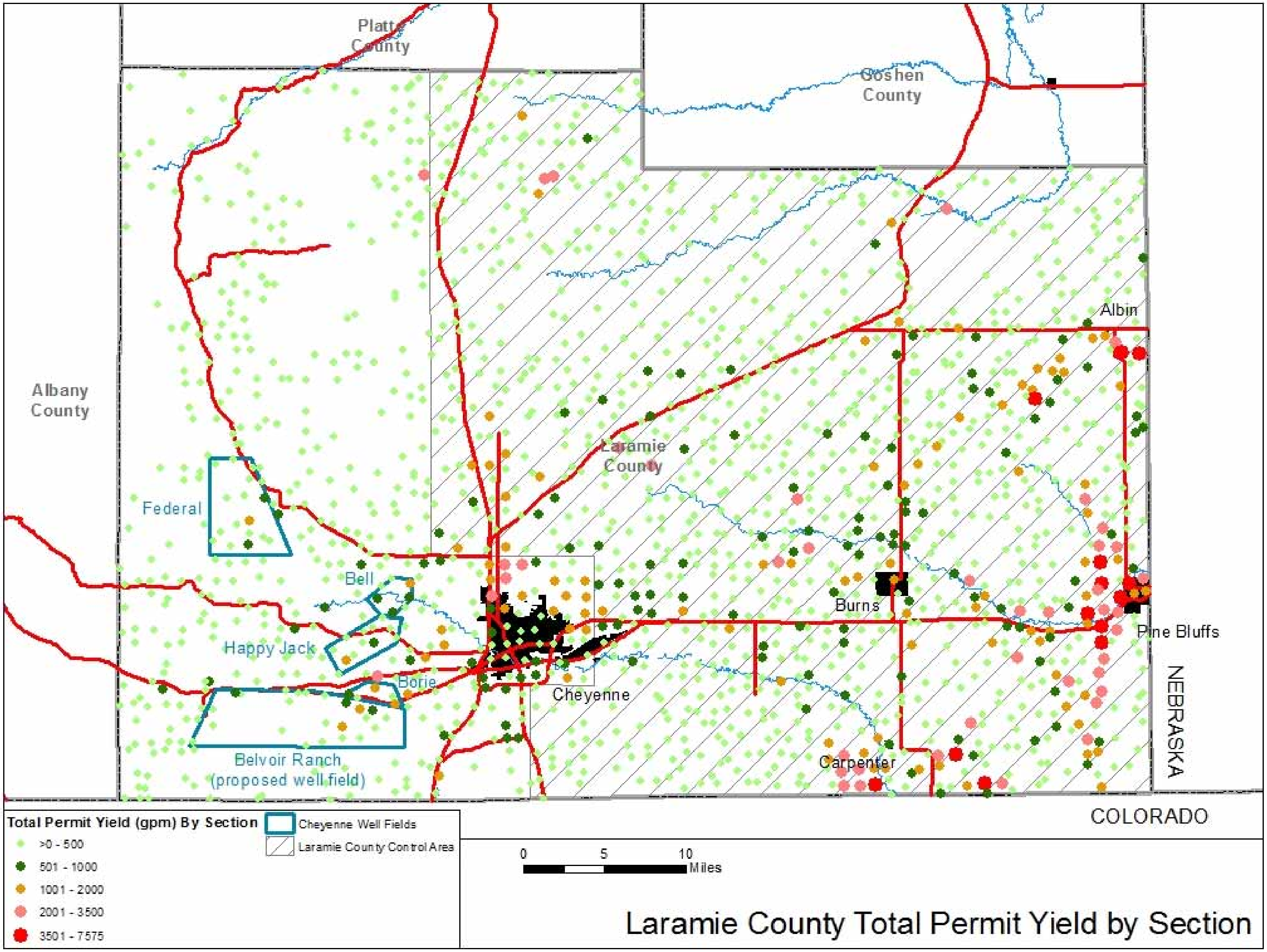


Figure 2.5 WSEO Groundwater Permit Yield by Section

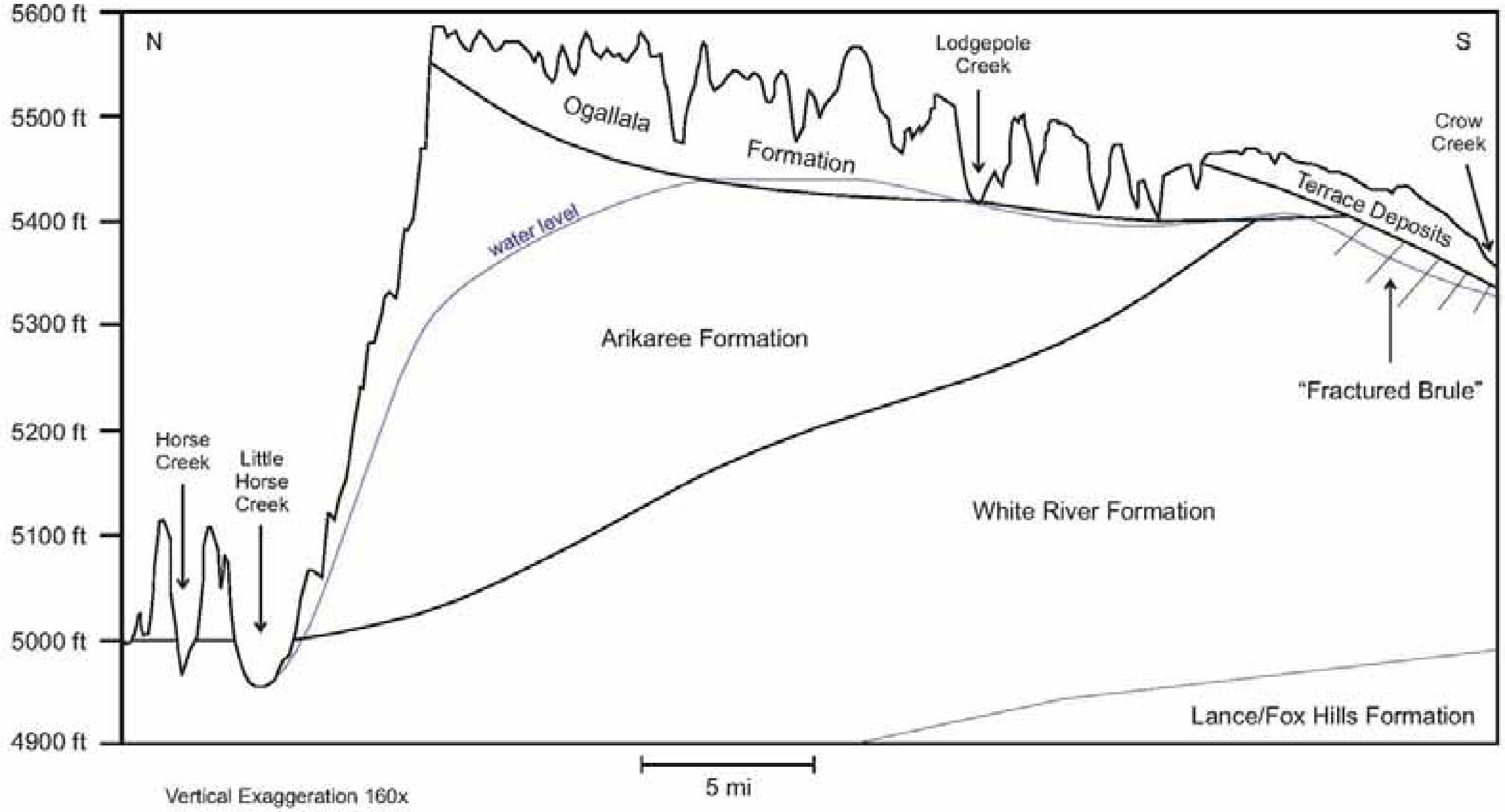


Figure 2.6 Topographic/Geologic Cross-section through Meriden-Burns-Carpenter

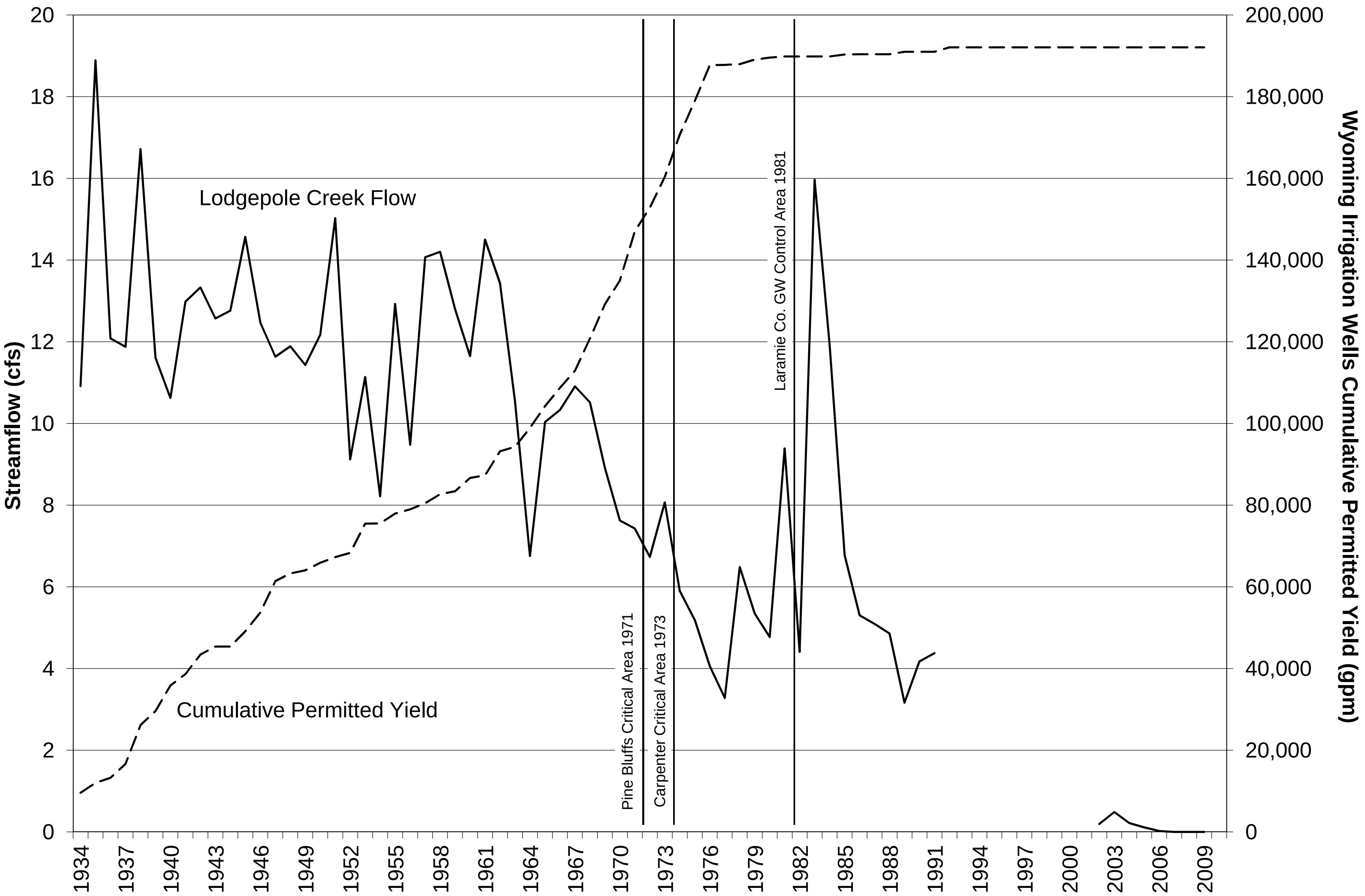


Figure 2.7 Streamflow and Irrigation Well History in Lodgepole Creek Basin, Wyoming

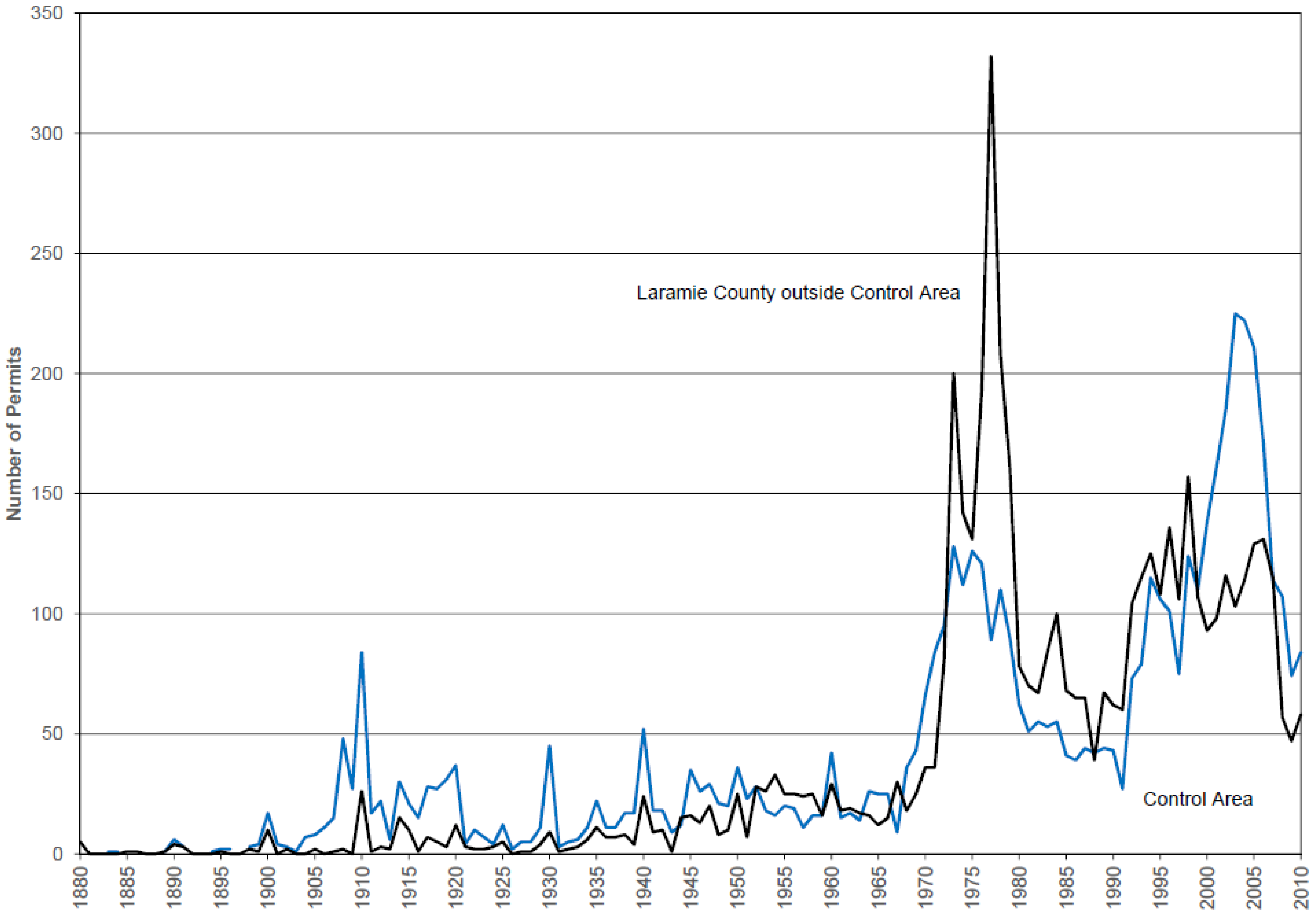
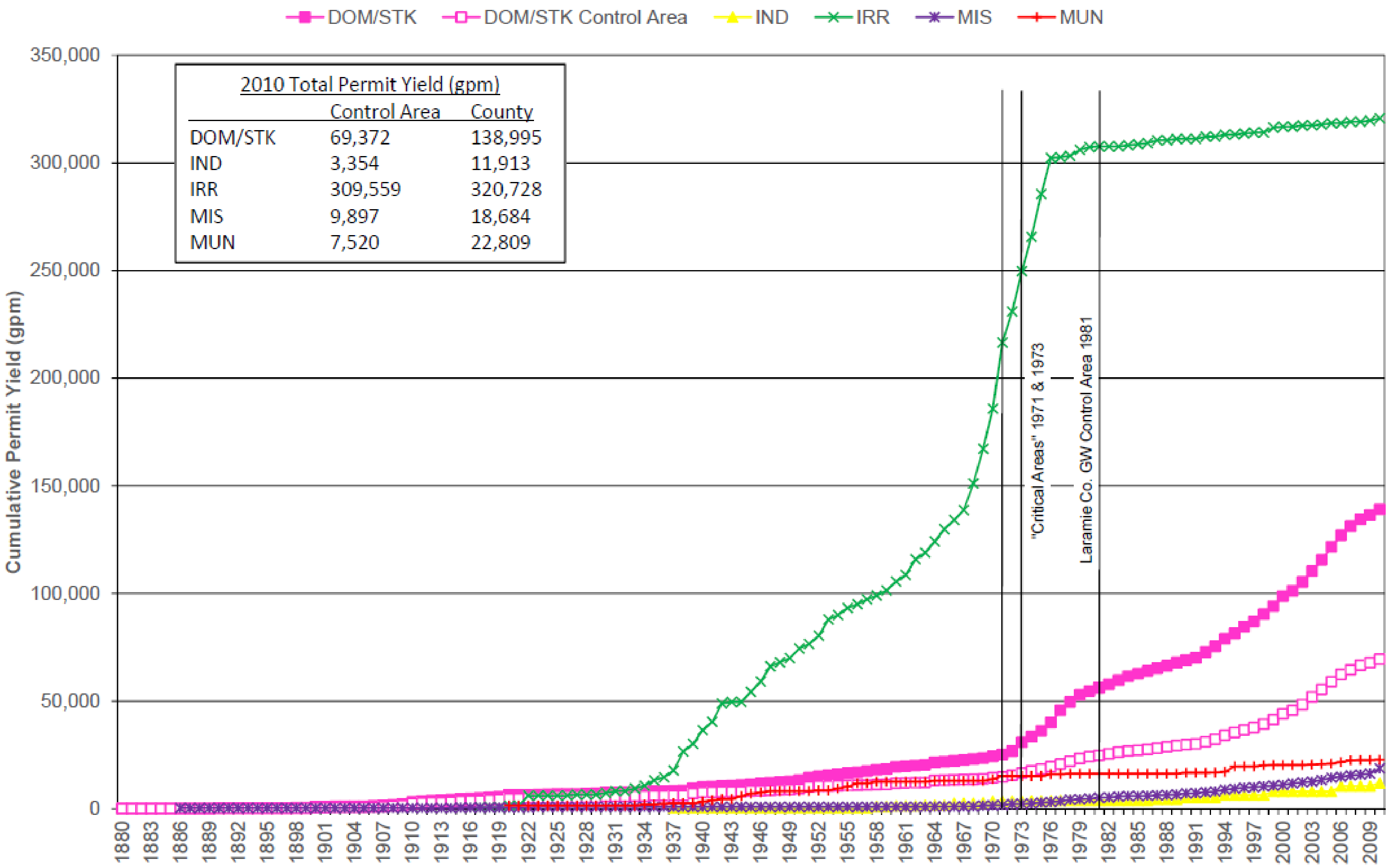


Figure 3.1 Laramie County Groundwater Permitting History



2010 Total Permit Yield (gpm)

	Control Area	County
DOM/STK	69,372	138,995
IND	3,354	11,913
IRR	309,559	320,728
MIS	9,897	18,684
MUN	7,520	22,809

Figure 3.2 Laramie County Cumulative Permit Yield by Use

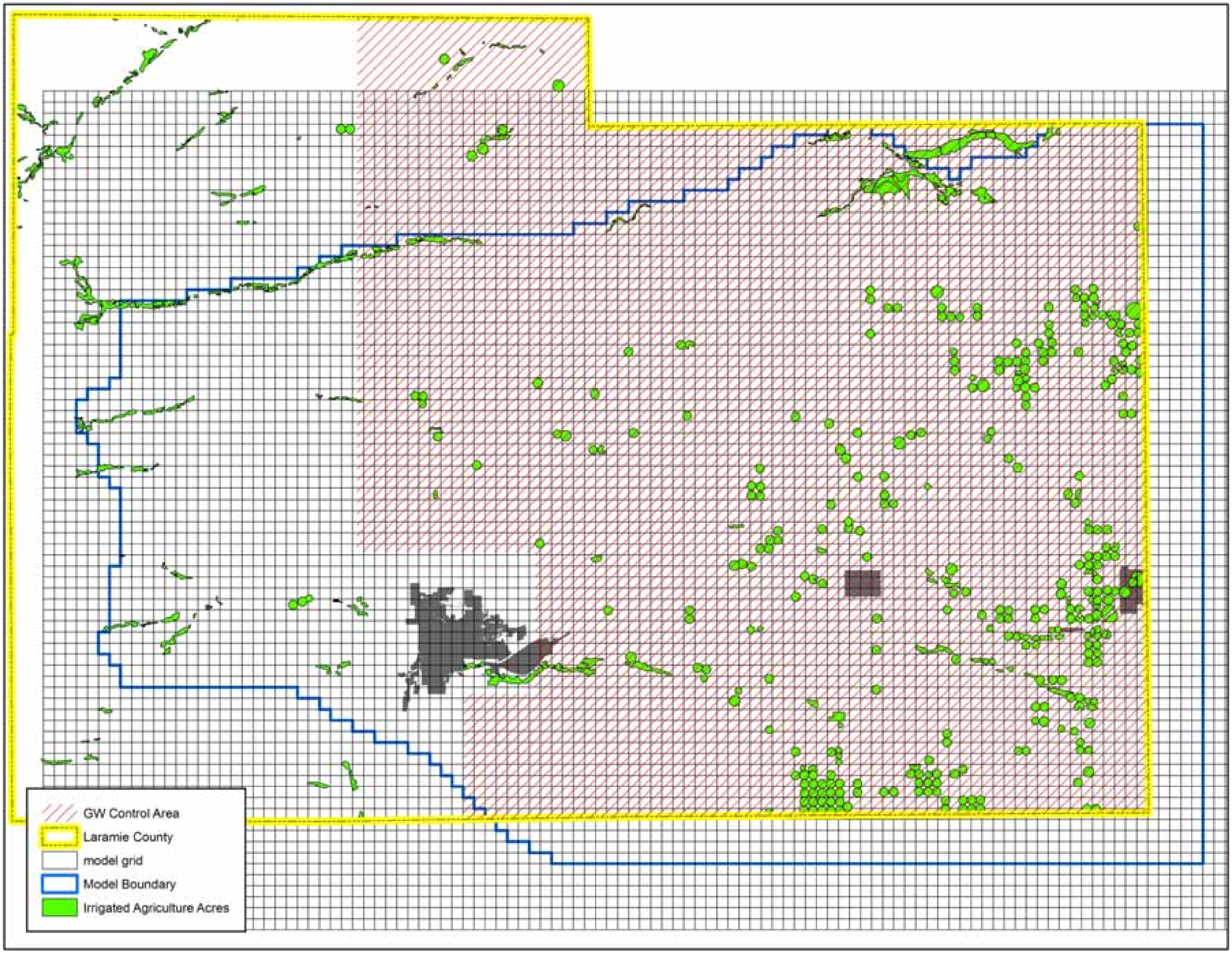


Figure 3.3 Irrigated Land in Laramie County

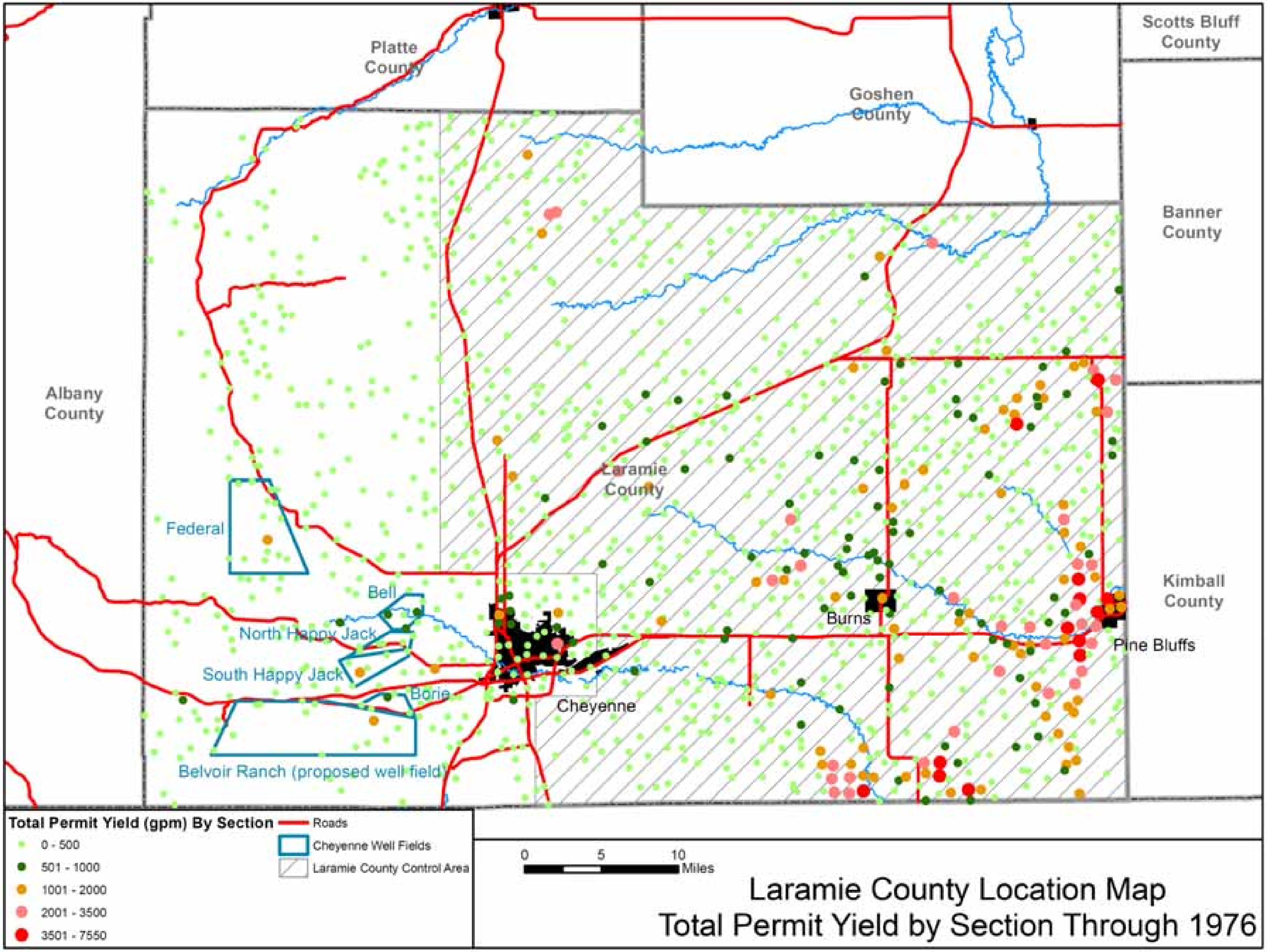


Figure 3.4 Laramie County Location Map Total Permit Yield by Section through 1976

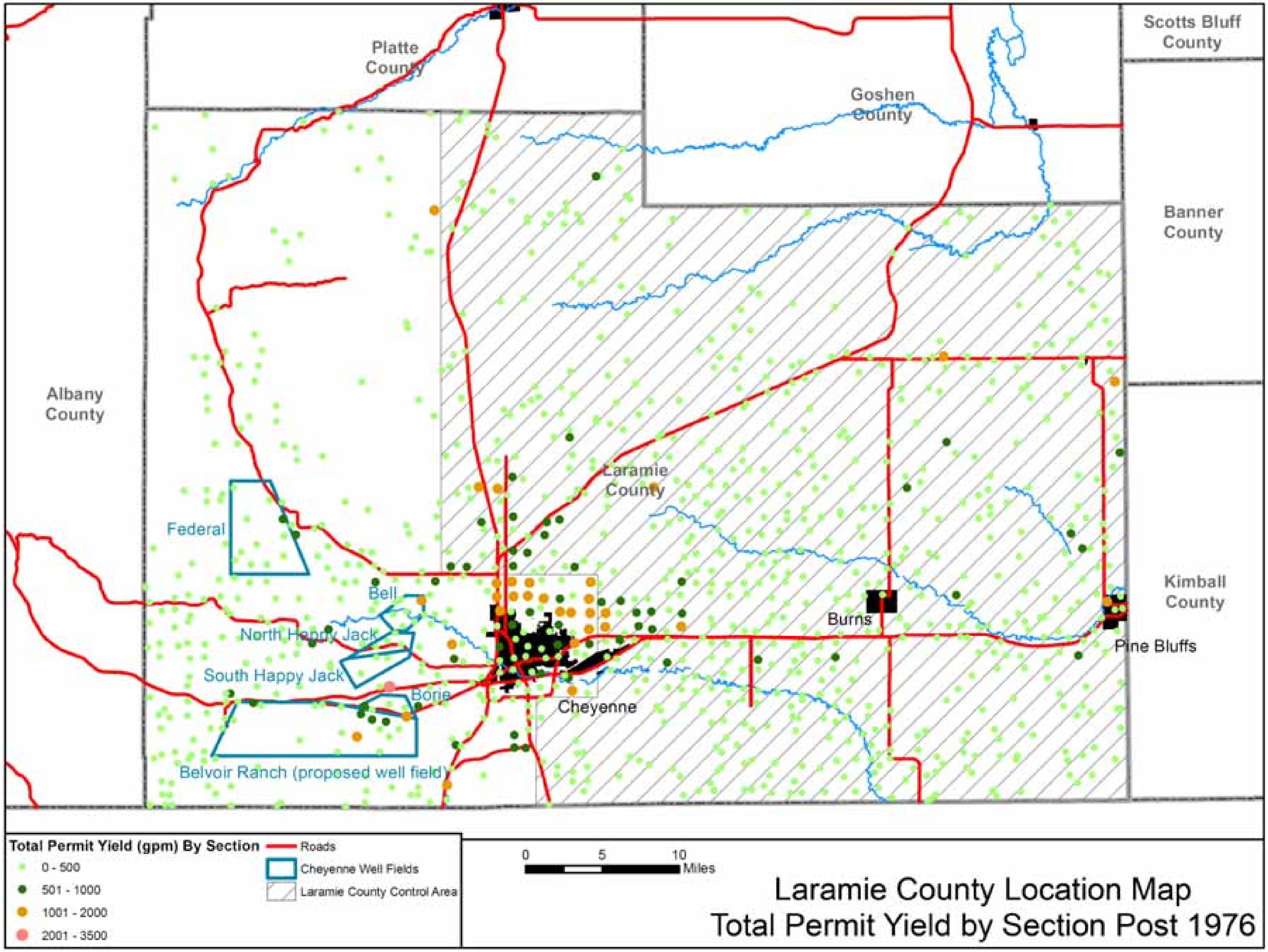


Figure 3.5 Laramie County Location Map Total Permit Yield by Section post-1976

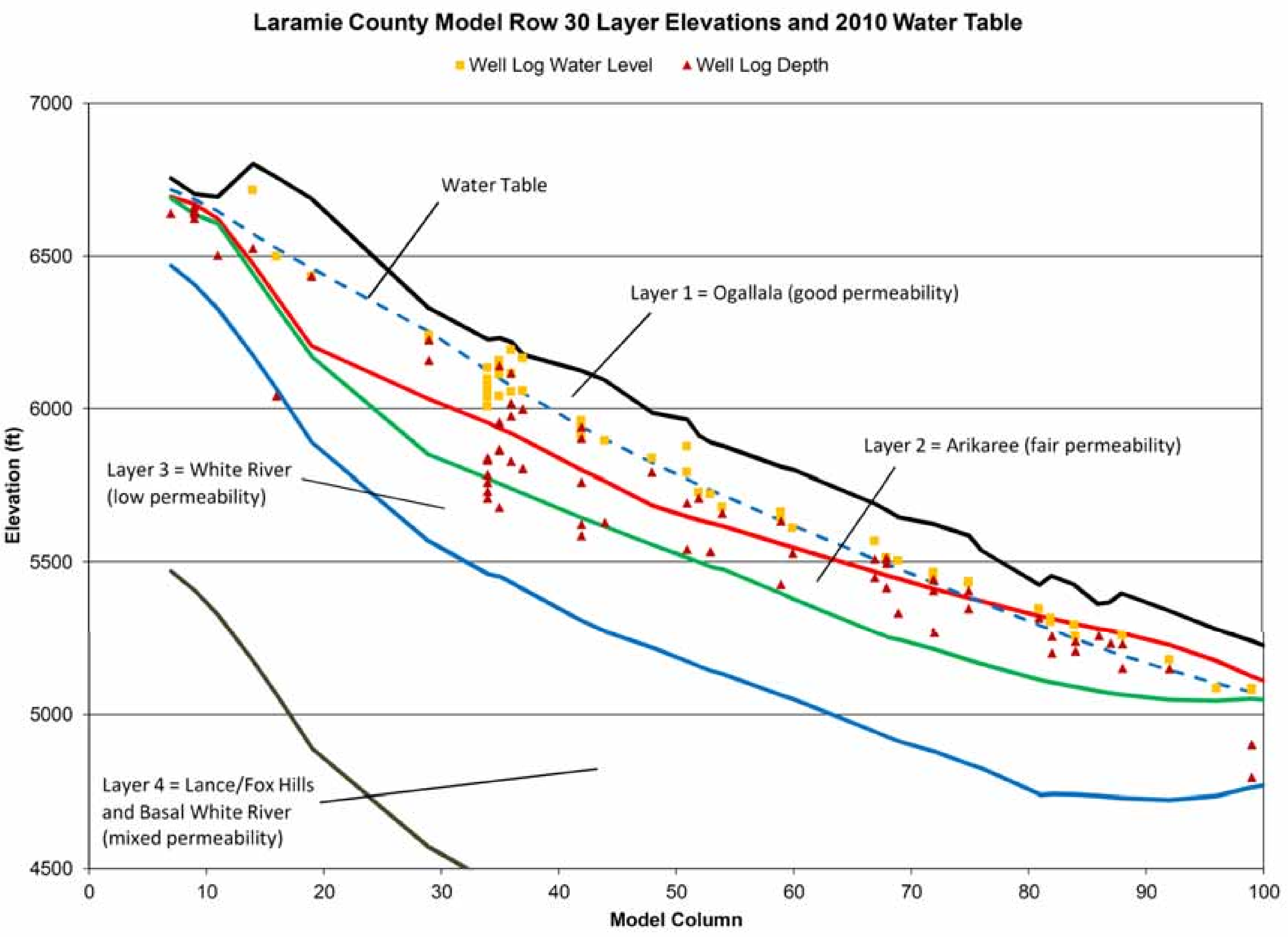


Figure 3.6 Model Row 30 Layer Elevations and 2010 Water Table

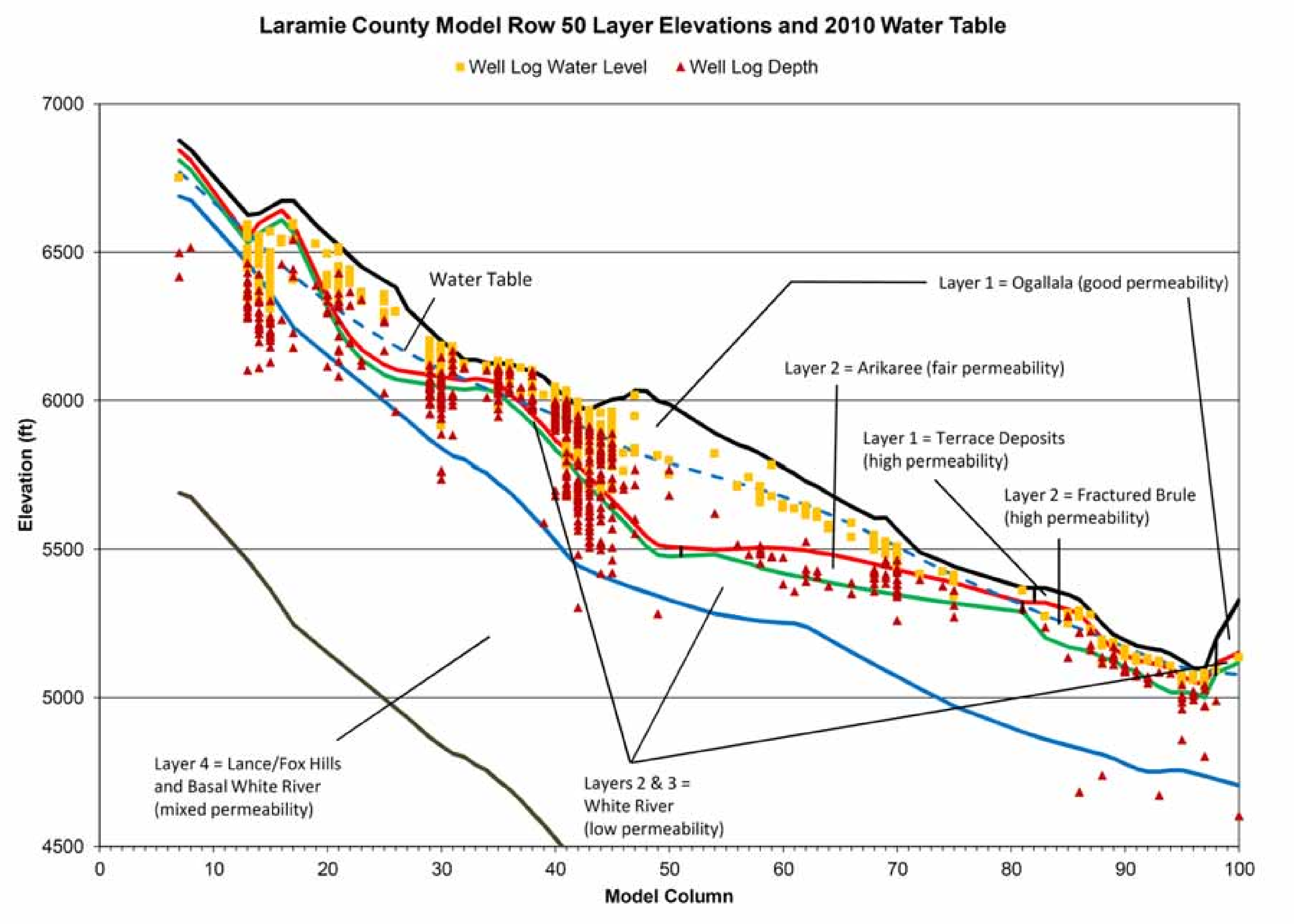


Figure 3.7 Model Row 50 Layer Elevations and 2010 Water Table

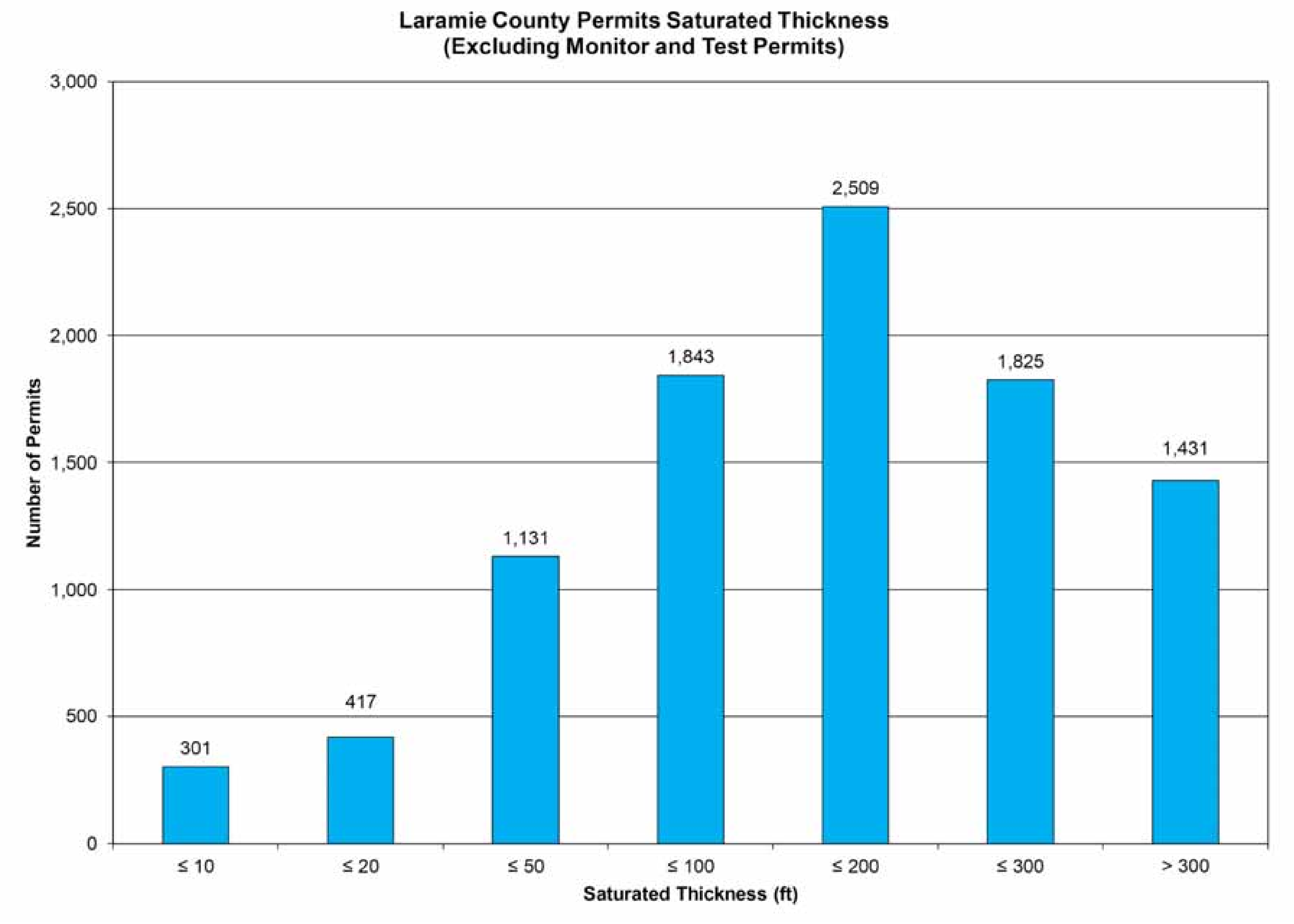


Figure 3.8 Available Drawdown

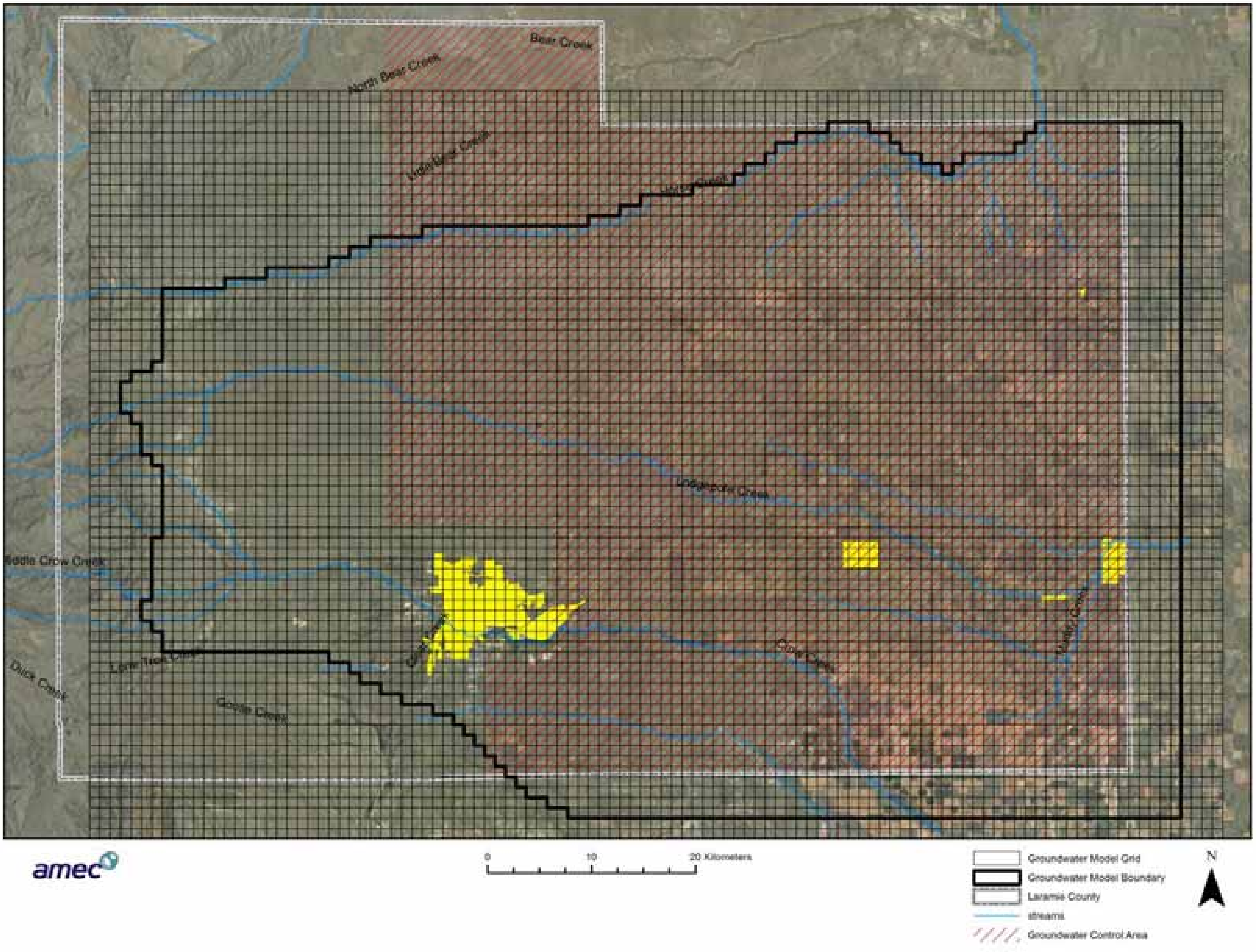
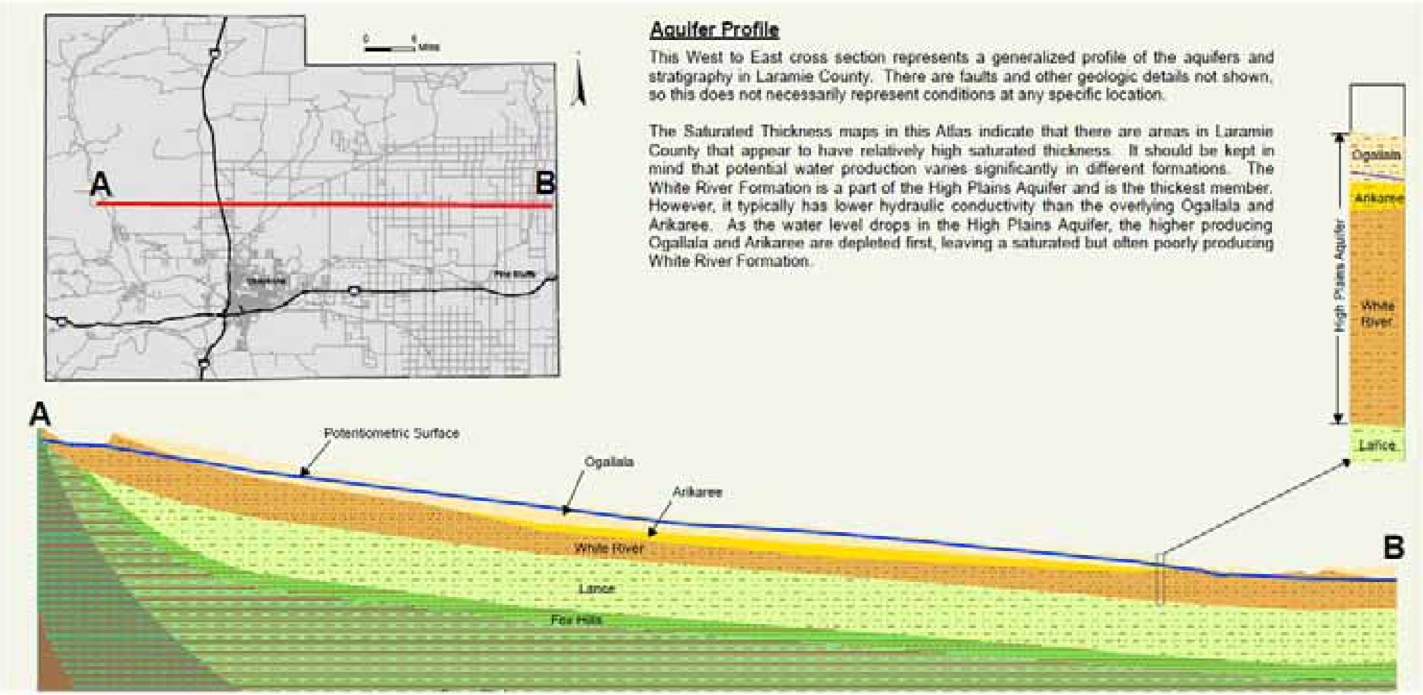


Figure 4.1 Groundwater Model Grid and Boundary

Laramie County Groundwater Atlas Geologic Cross-section



Aquifer Profile

This West to East cross section represents a generalized profile of the aquifers and stratigraphy in Laramie County. There are faults and other geologic details not shown, so this does not necessarily represent conditions at any specific location.

The Saturated Thickness maps in this Atlas indicate that there are areas in Laramie County that appear to have relatively high saturated thickness. It should be kept in mind that potential water production varies significantly in different formations. The White River Formation is a part of the High Plains Aquifer and is the thickest member. However, it typically has lower hydraulic conductivity than the overlying Ogallala and Arikaree. As the water level drops in the High Plains Aquifer, the higher producing Ogallala and Arikaree are depleted first, leaving a saturated but often poorly producing White River Formation.

Groundwater Model Layer Profile Discretization

K Zone	Geologic Formation	Model Layer
🟦	OGLL	1
🟪	ARKR	2
🟥	WRVR	3
🟩	TRRC-Frac-Bruhl	1&2
■	CH-LA-FXH	4

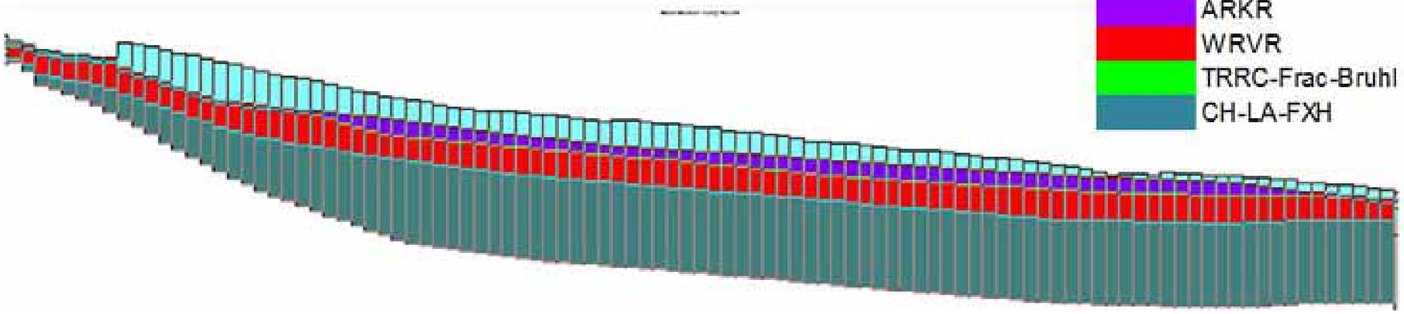


Figure 4.2 Groundwater Model Layers

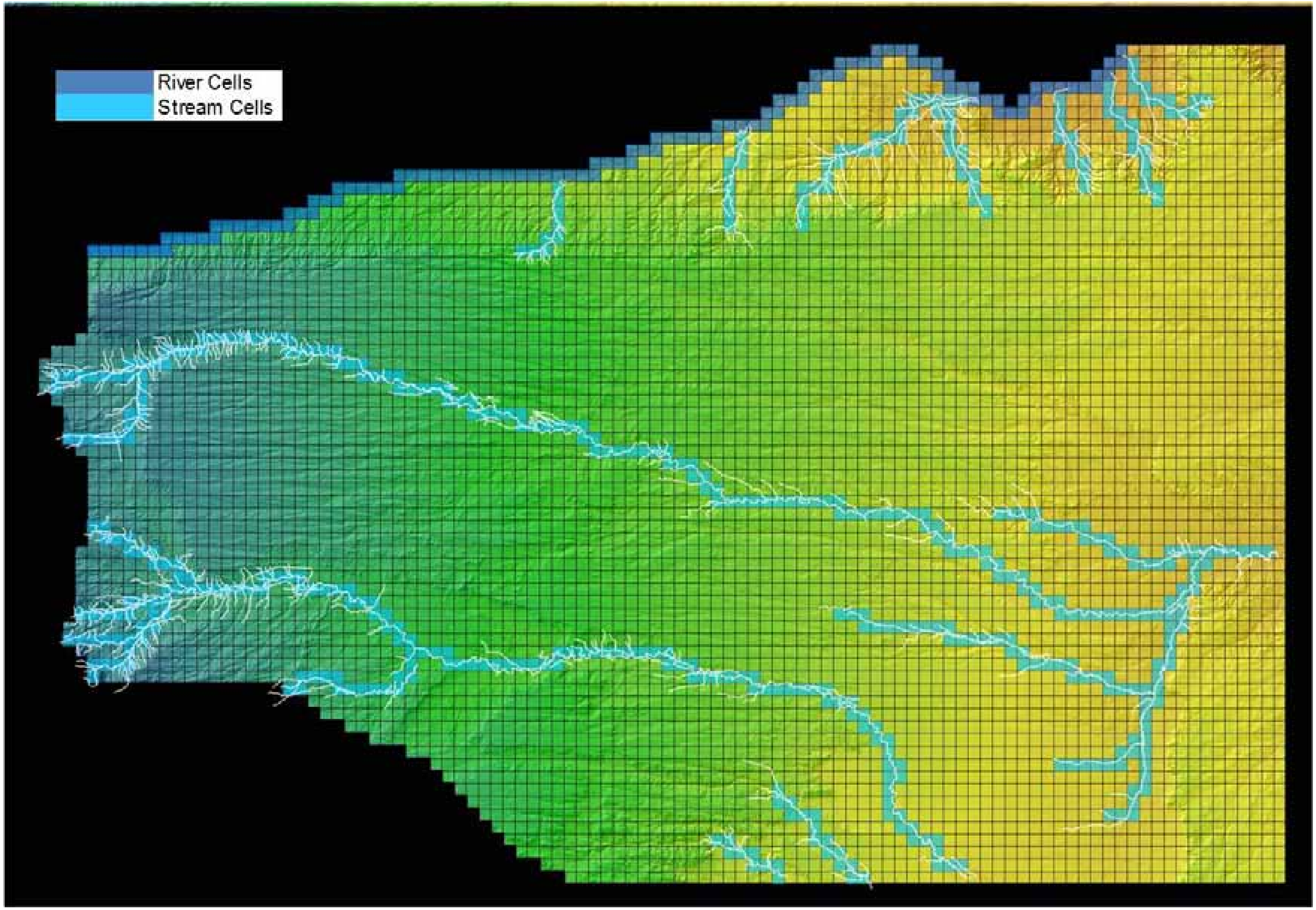


Figure 4.3 River and Stream Cells (Model Boundary Conditions)

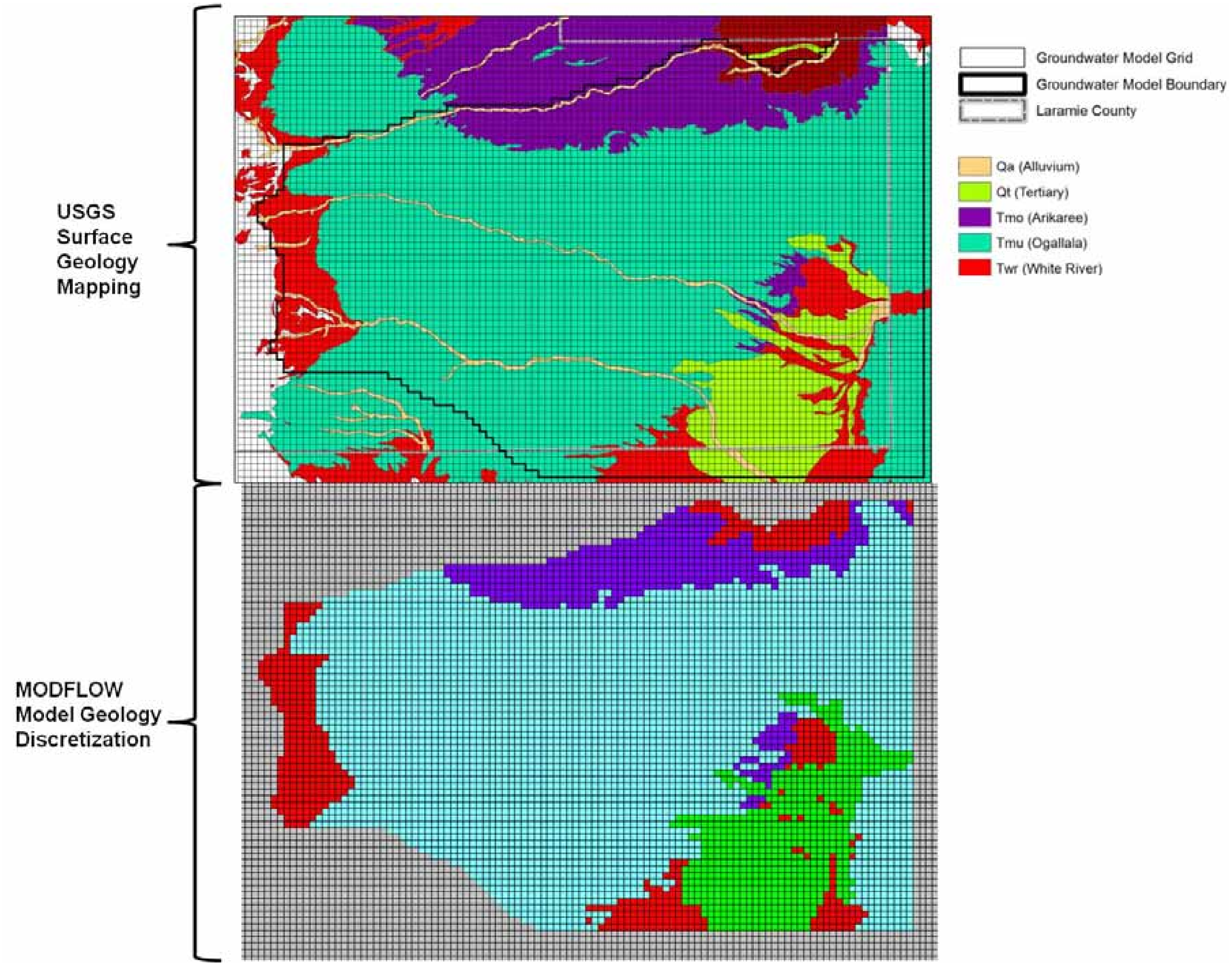


Figure 4.4 General Distribution of Hydraulic Conductivity Zones

Figure 4.5 Cheyenne Wastewater Treatment Plant Locations

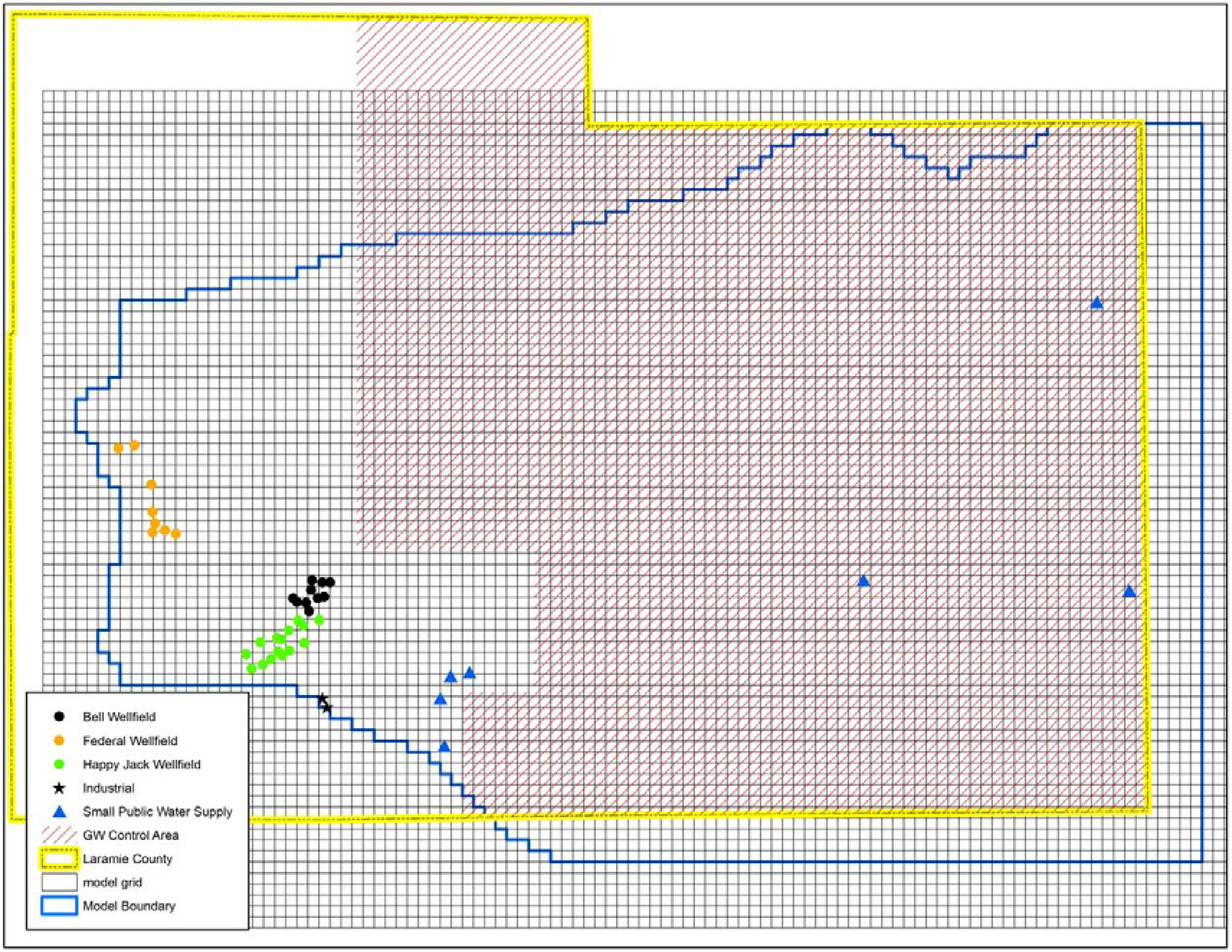


Figure 4.6 Distribution of Municipal and Small Community Supply Wells in Laramie County

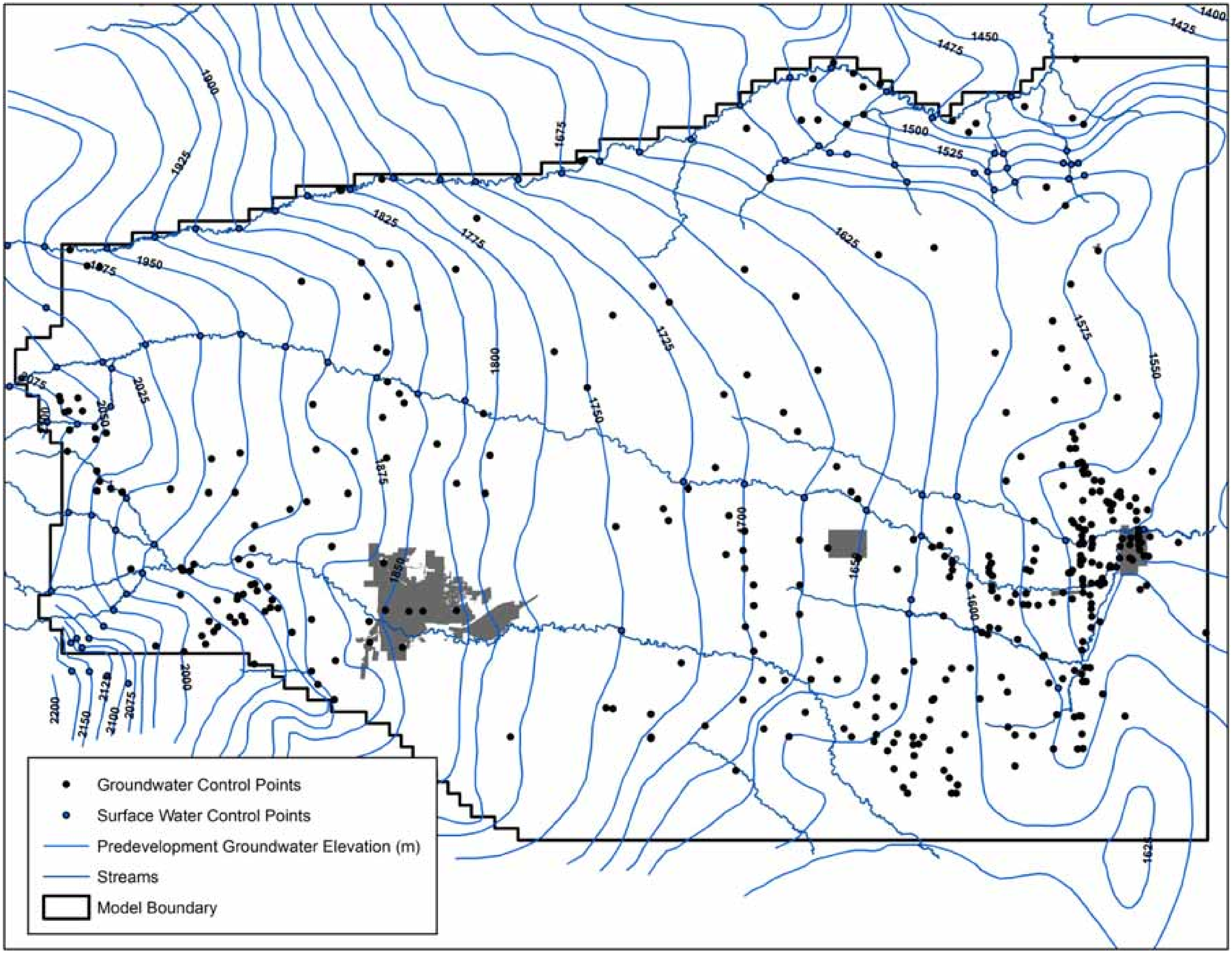


Figure 5.1 "Pre-development" Potentiometric Surface

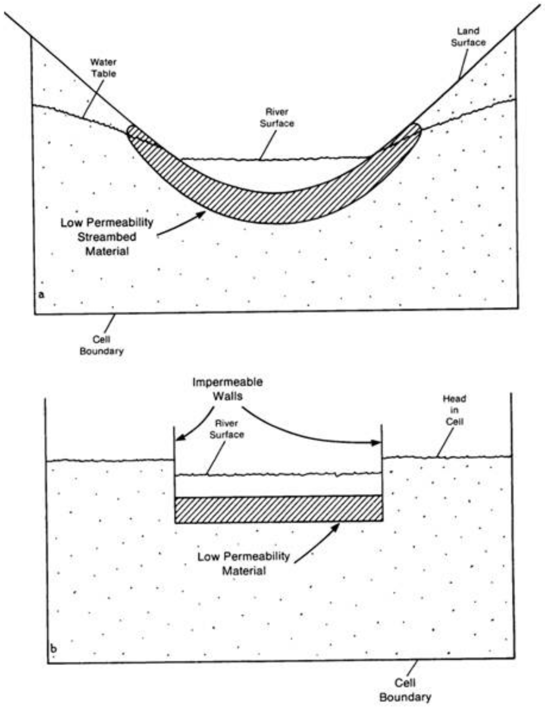


Figure 33.—(a) Cross section of an aquifer containing a stream and (b) Conceptual representation of stream-aquifer interconnection in simulation.

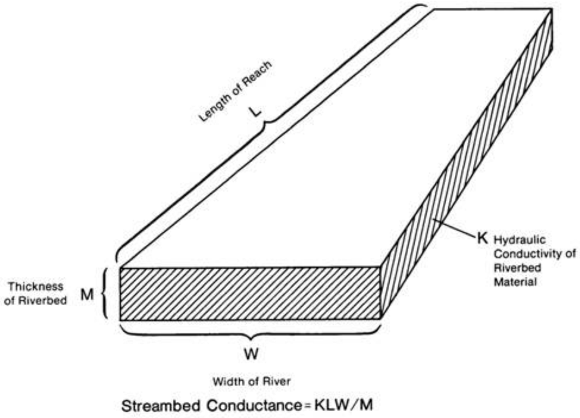


Figure 34.—Idealization of streambed conductance in an individual cell.

6-4

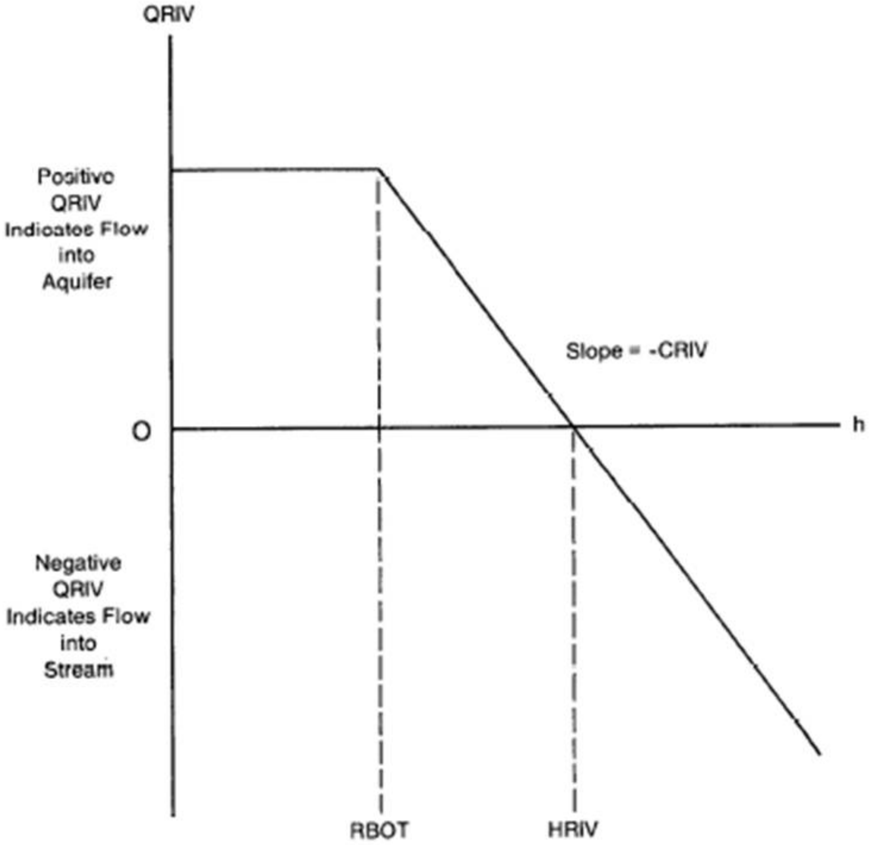


Figure 36.—Plot of flow, QRIV, from a stream into a cell as a function of head, h, in the cell where RBOT is the elevation of the bottom of the streambed and HRIV is the head in the stream.

Figure 5.2 MODFLOW Model Riverbed Conductance Related to Simulated Flux (MODFLOW Documentation, 1988)

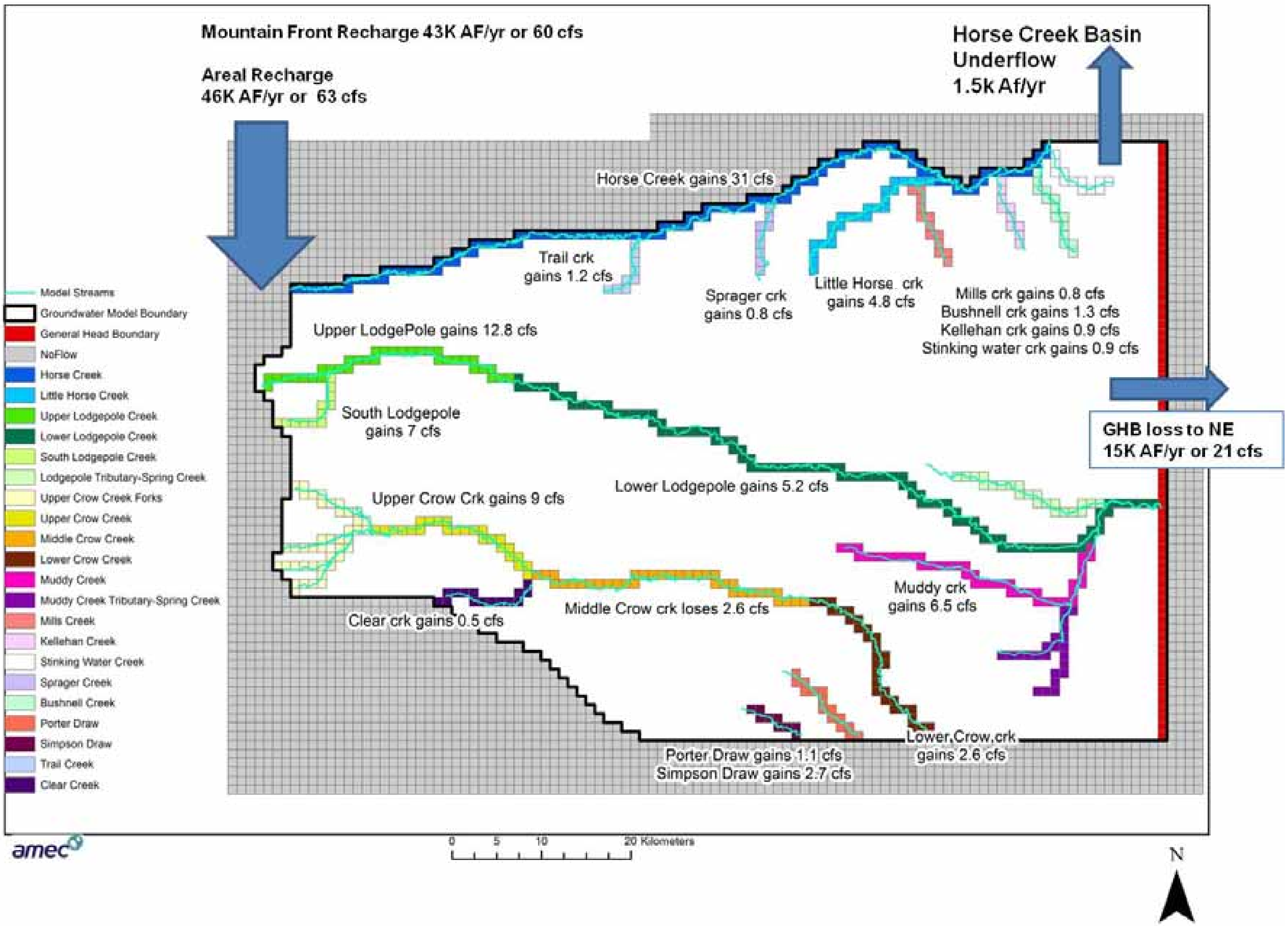
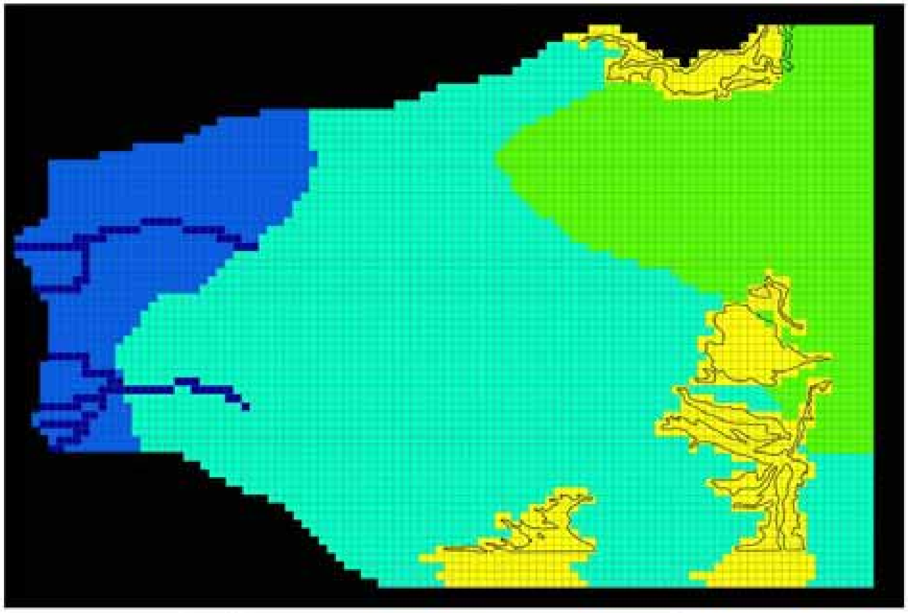


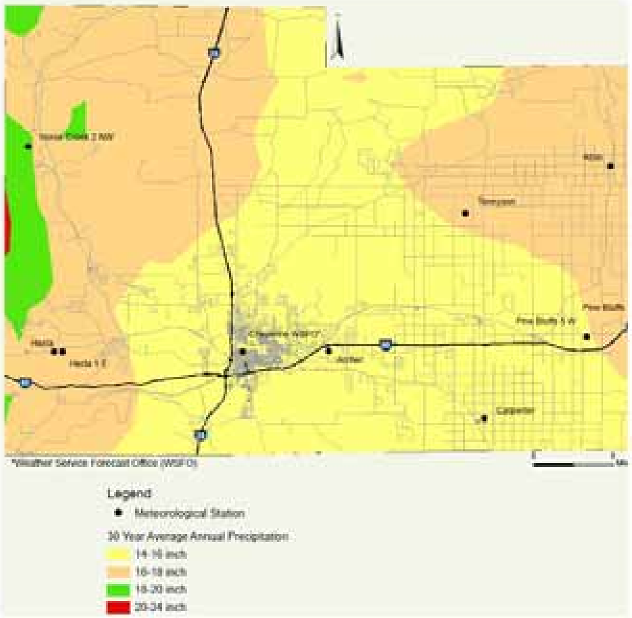
Figure 5.3 Groundwater Model Boundary Conditions and Steady State Mass Balance Fluxes

MODFLOW Model Recharge Zones



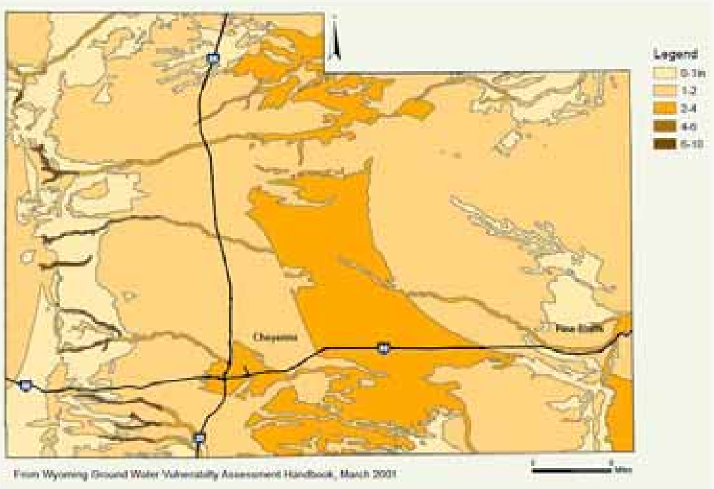
Recharge Zone	Zone	
🟦	1	Mountain Front Recharge
🟦	2	High Elevation Areal Distributed Recharge
🟦	3	Low Elevation Areal Distributed Recharge 1
🟩	4	Low Elevation Areal Distributed Recharge 2
🟨	5	Low Permeability Soil

30yr Annual Average Precipitation Distribution



*Weather Service Forecast Office (WSFO)

Aquifer Recharge Rate by Soil Type



From Wyoming Ground Water Vulnerability Assessment Handbook, March 2001

Figure 5.4 Distribution of Groundwater Model Recharge Zones

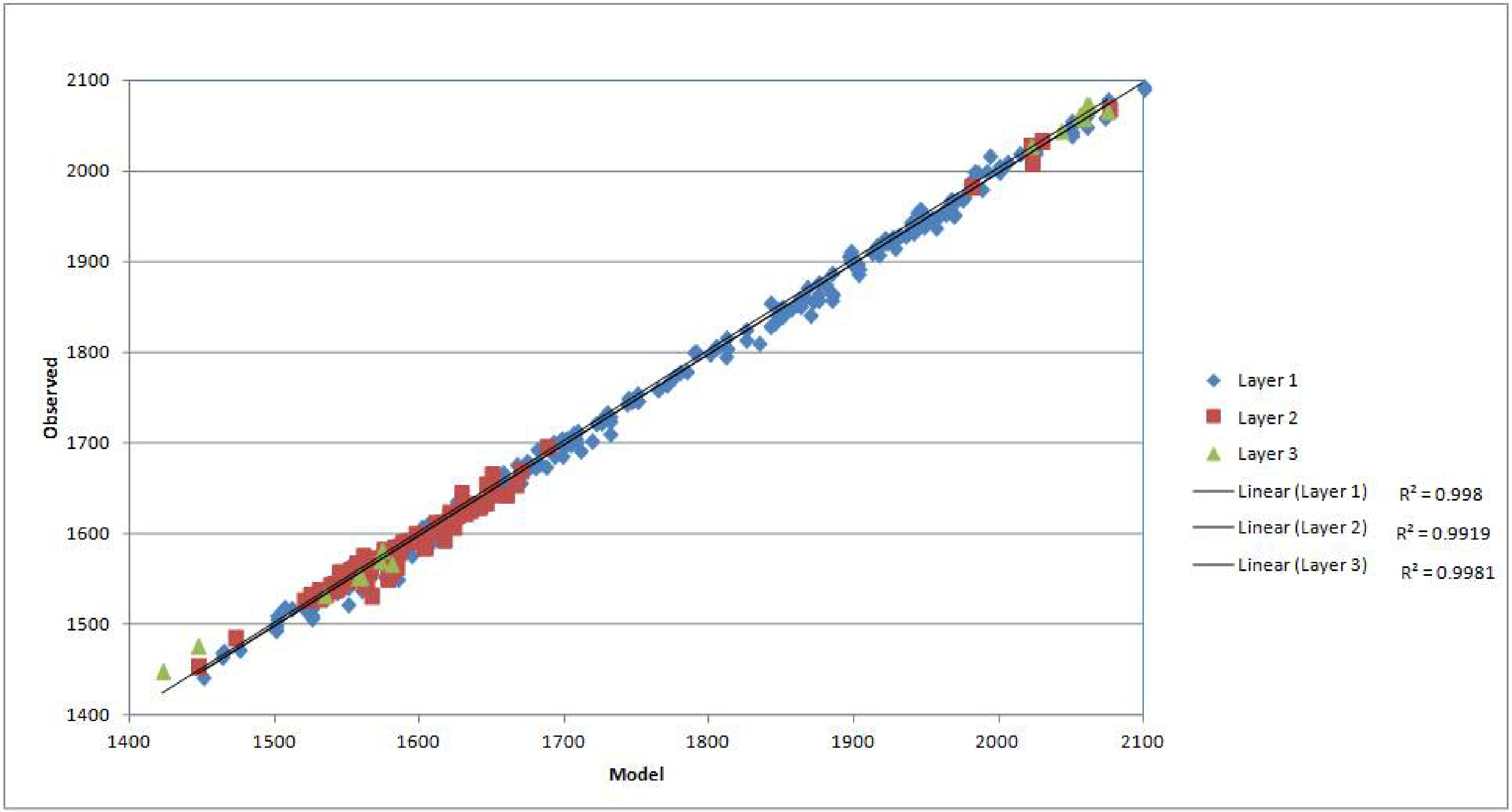


Figure 5.5 Steady State Observed vs. Model Simulated Groundwater Level Calibration Plot

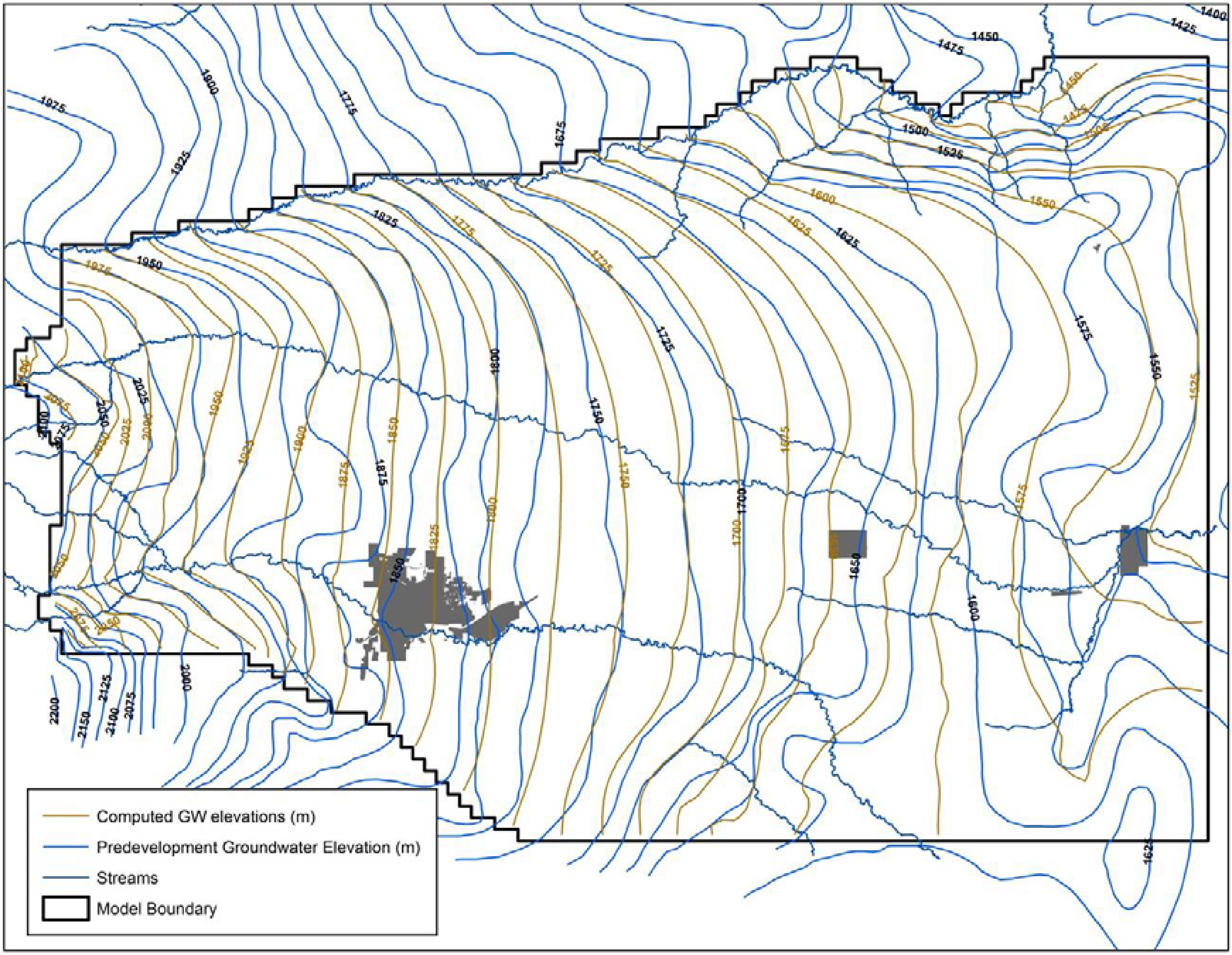


Figure 5.6 Steady State “Pre-development” Potentiometeric Surface Comparison

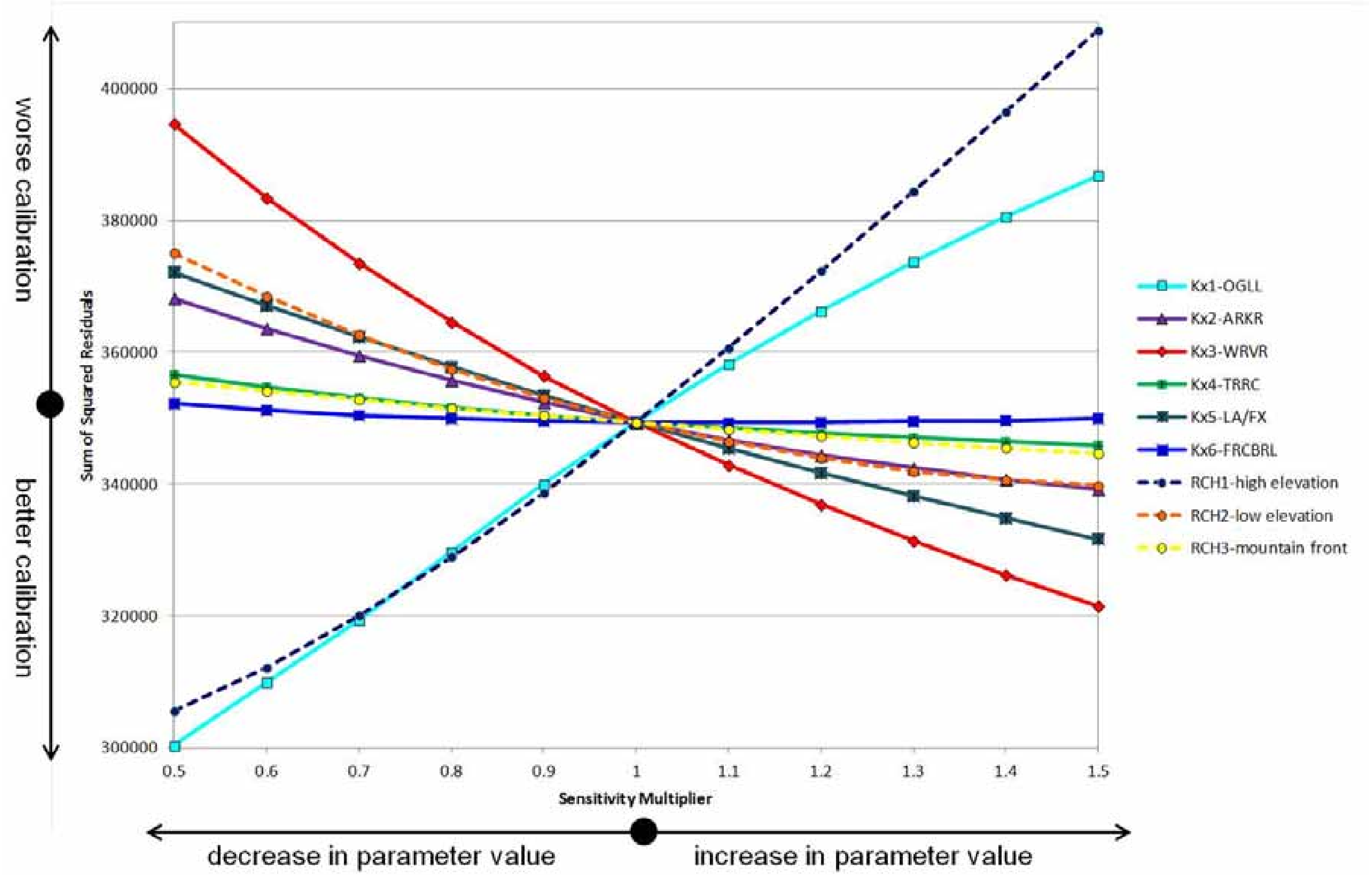


Figure 5.7 Steady State Sensitivity Analysis

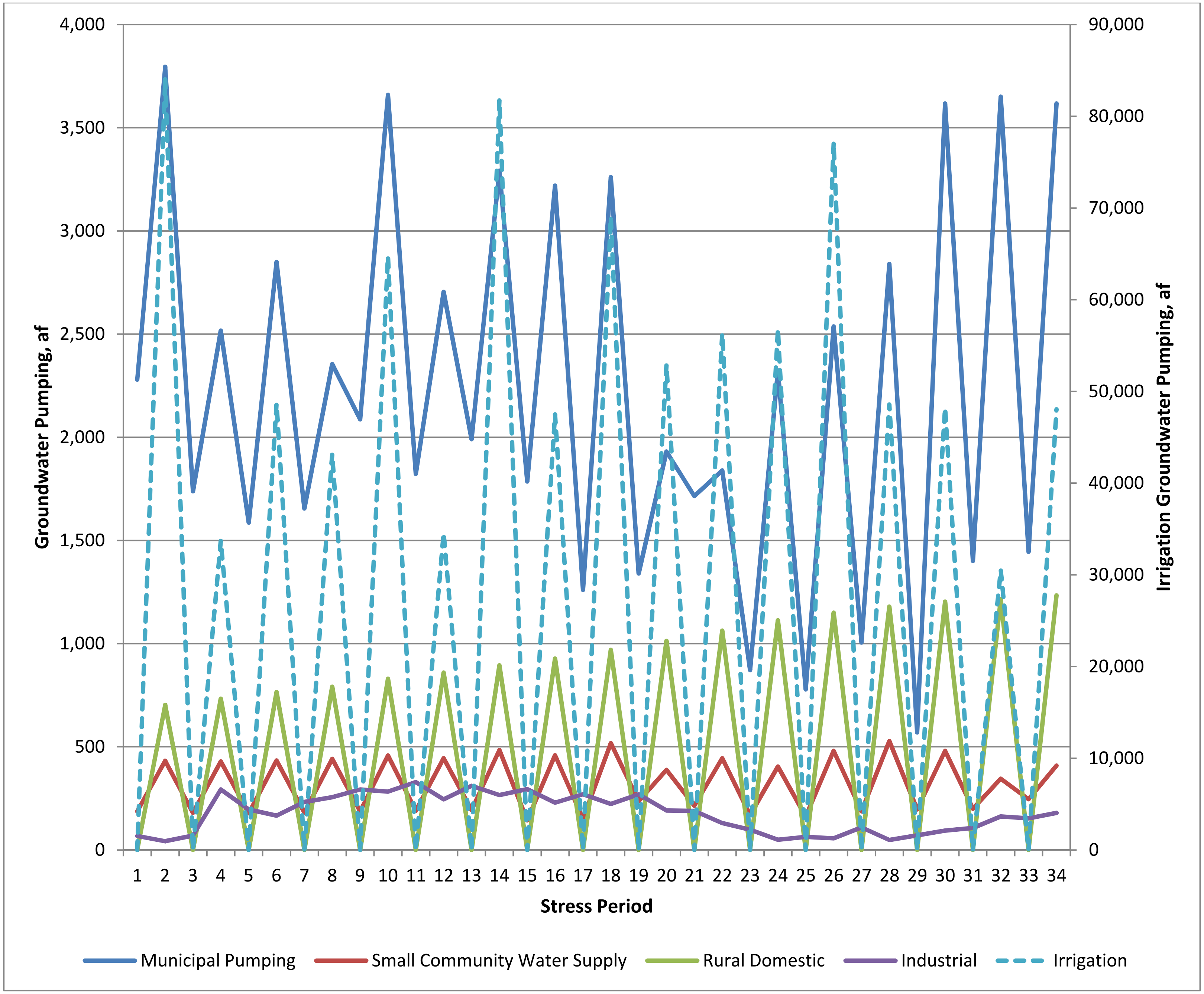


Figure 6.1 Pumping Summary

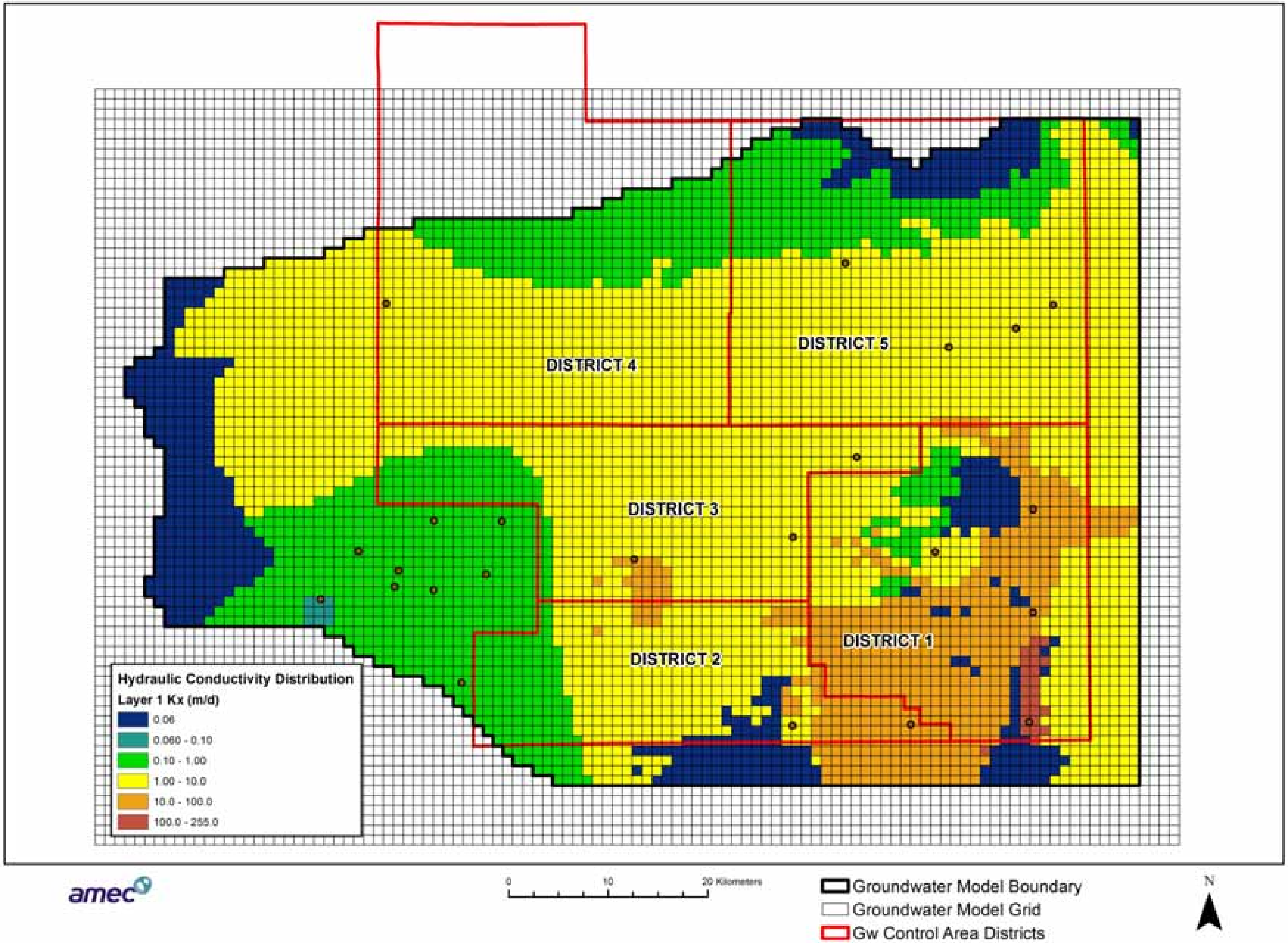


Figure 6.2 Hydraulic Conductivity Layer 1 Distribution

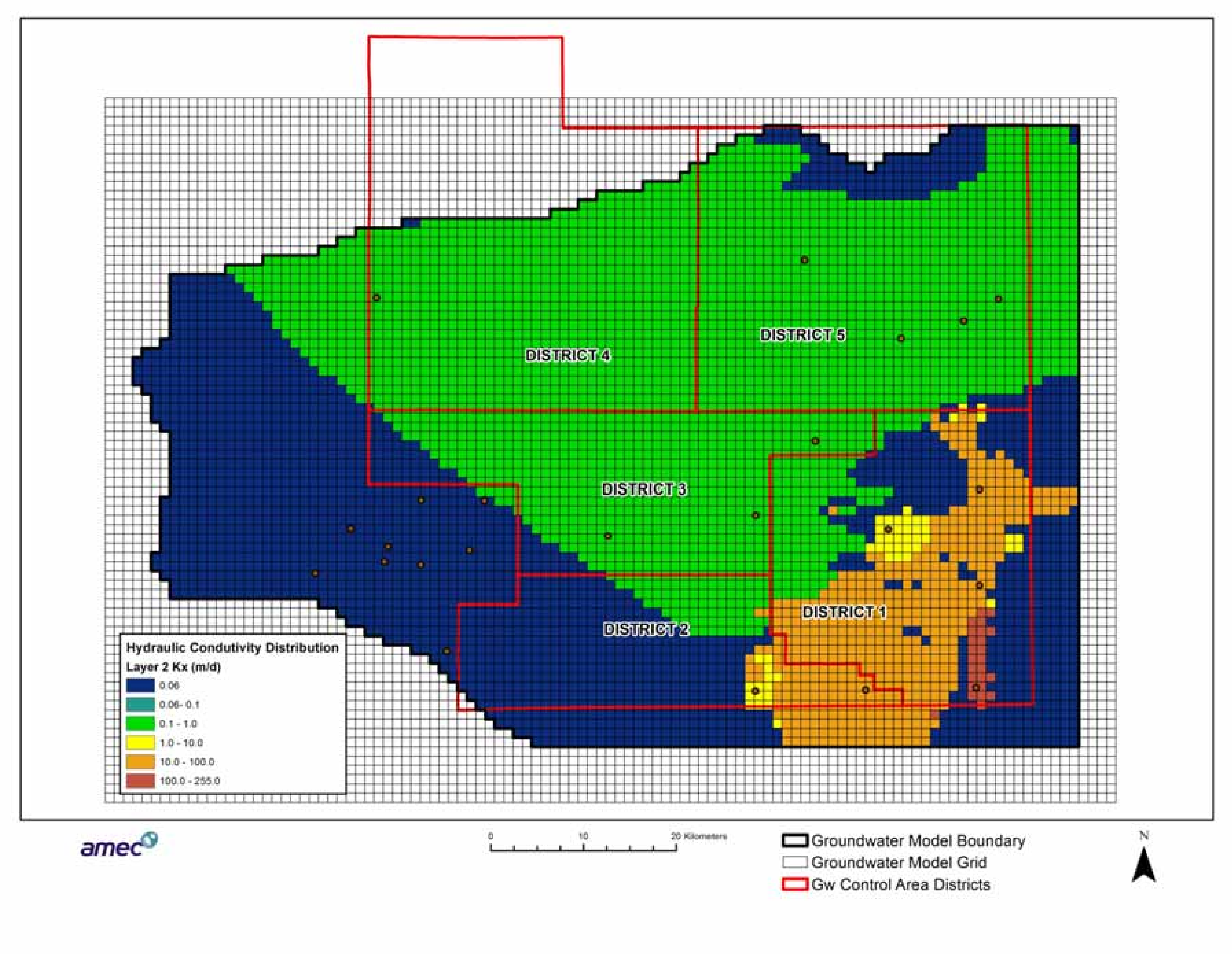


Figure 6.3 Hydraulic Conductivity Layer 2 Distribution

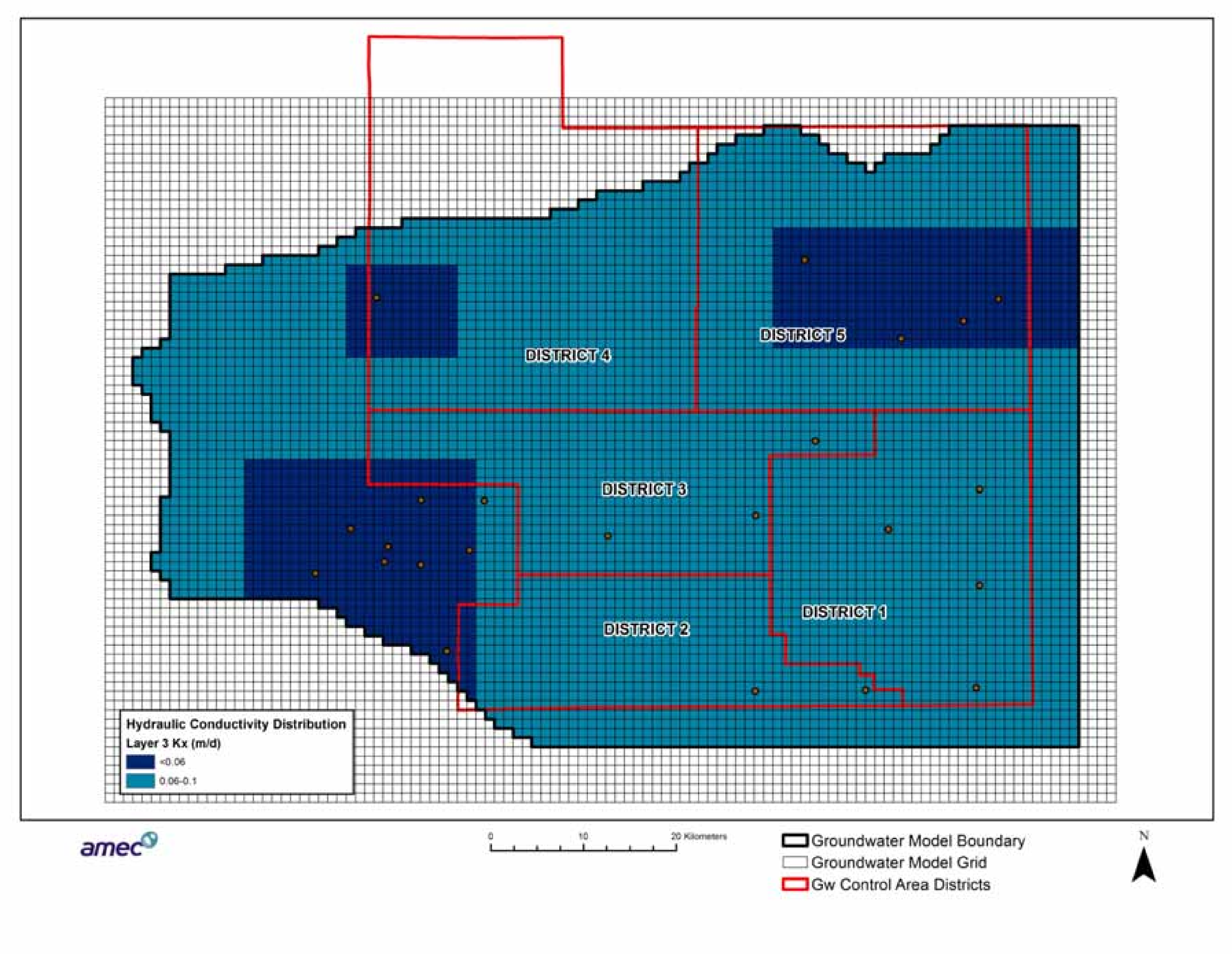


Figure 6.4 Hydraulic Conductivity Layer 3 Distribution

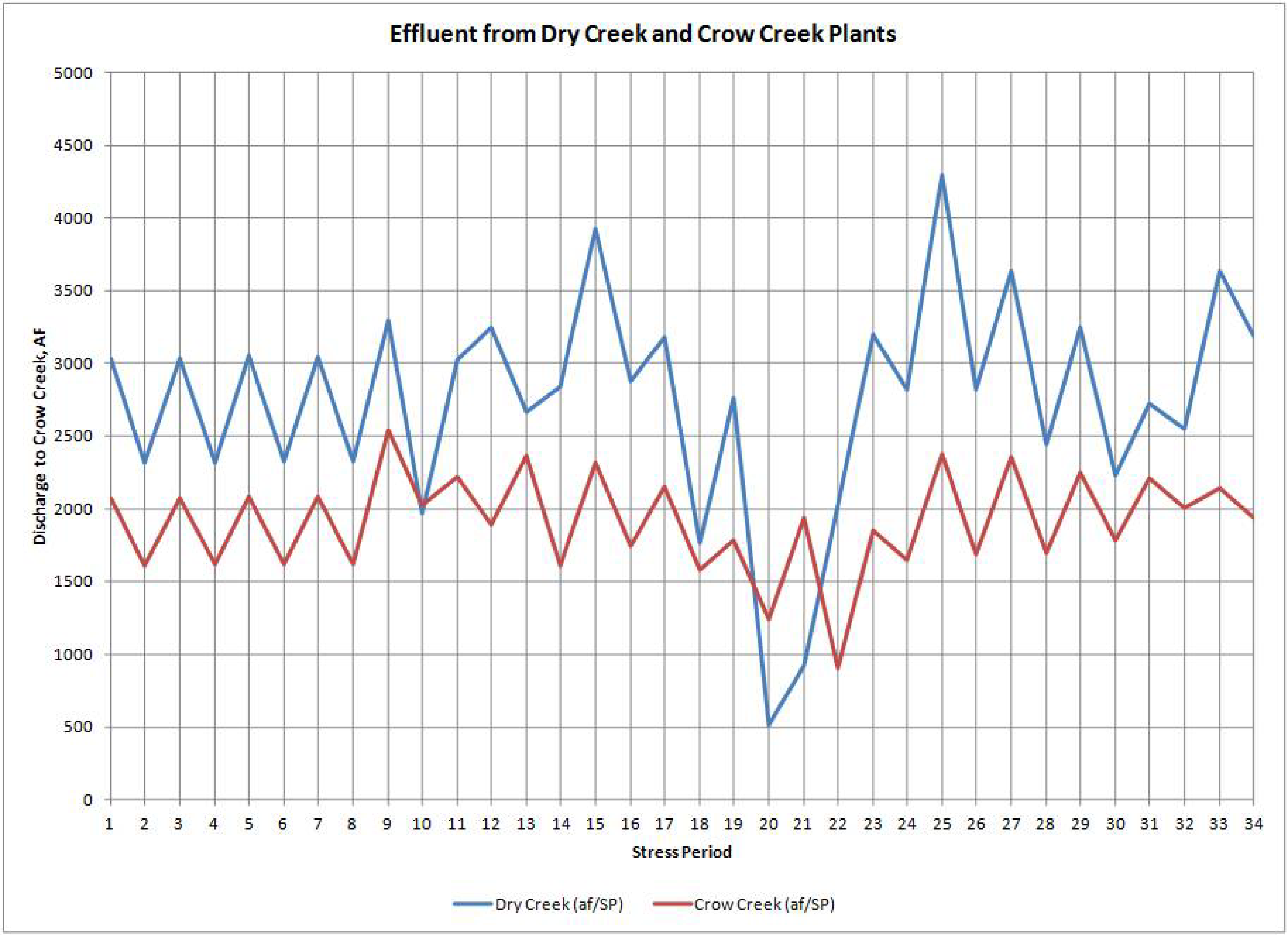


Figure 6.5 Streamflow Inputs for Wastewater Treatment Plant Discharge

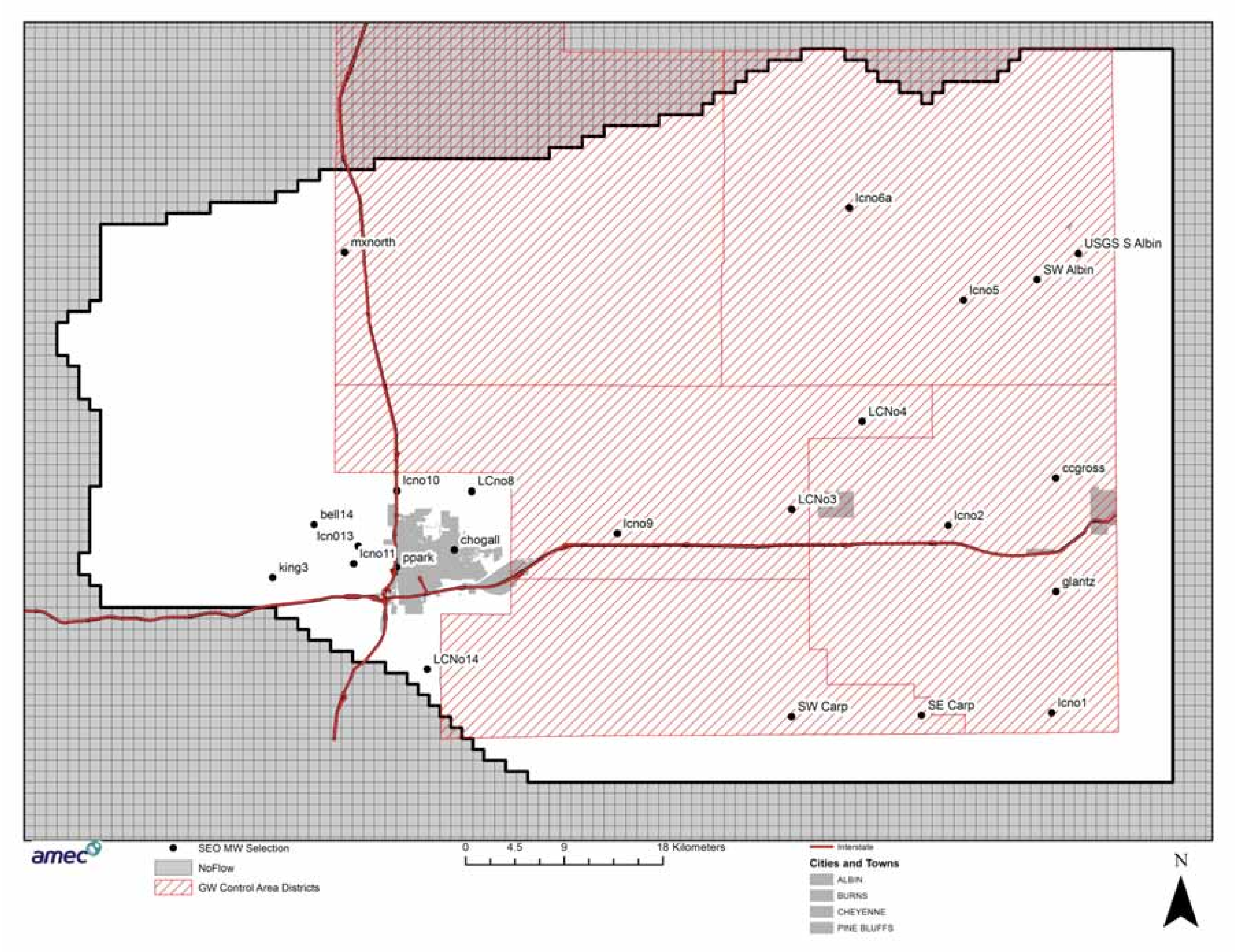


Figure 6.6 WSEO Monitoring Wells Used in Transient Calibration

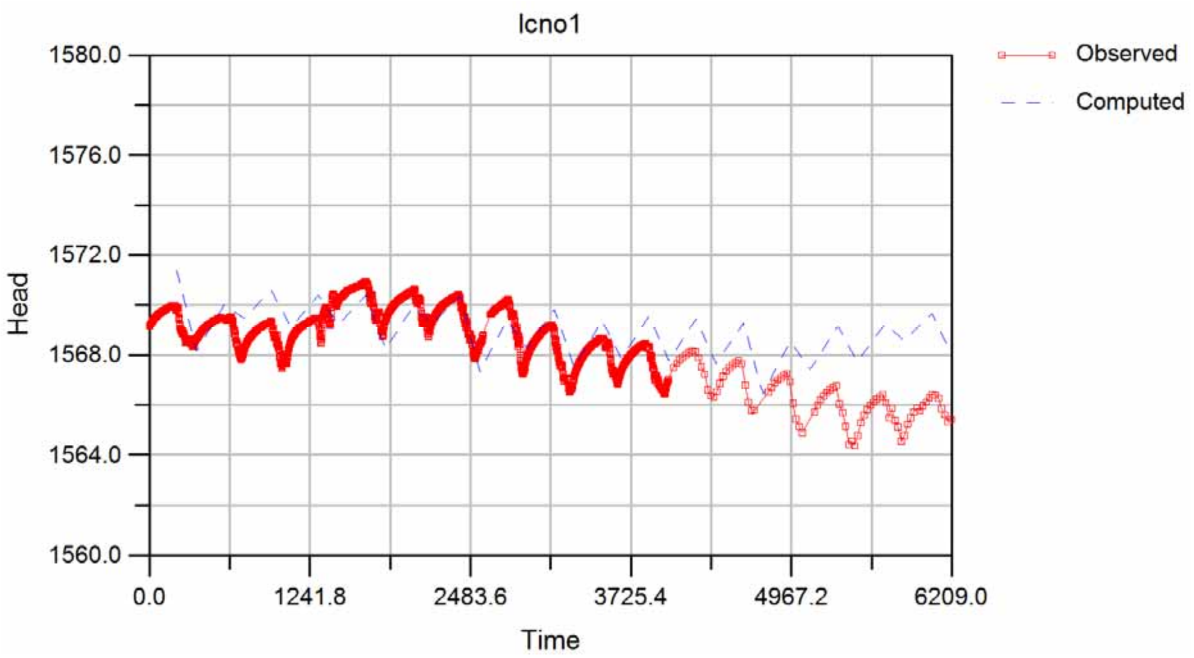


Figure 6.7 Observed vs Model Computed Water Levels for WSEO Monitoring Well (LCN01)

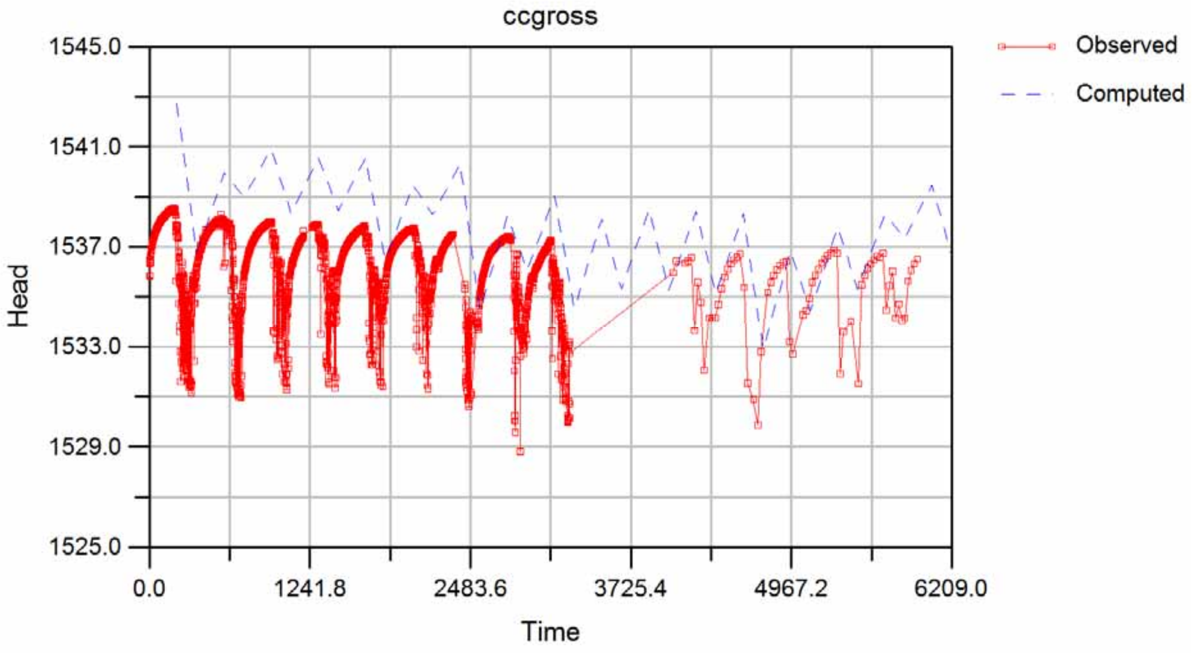


Figure 6.8 Observed vs Model Computed Water Levels for WSEO Monitoring Well (CCGROSS)

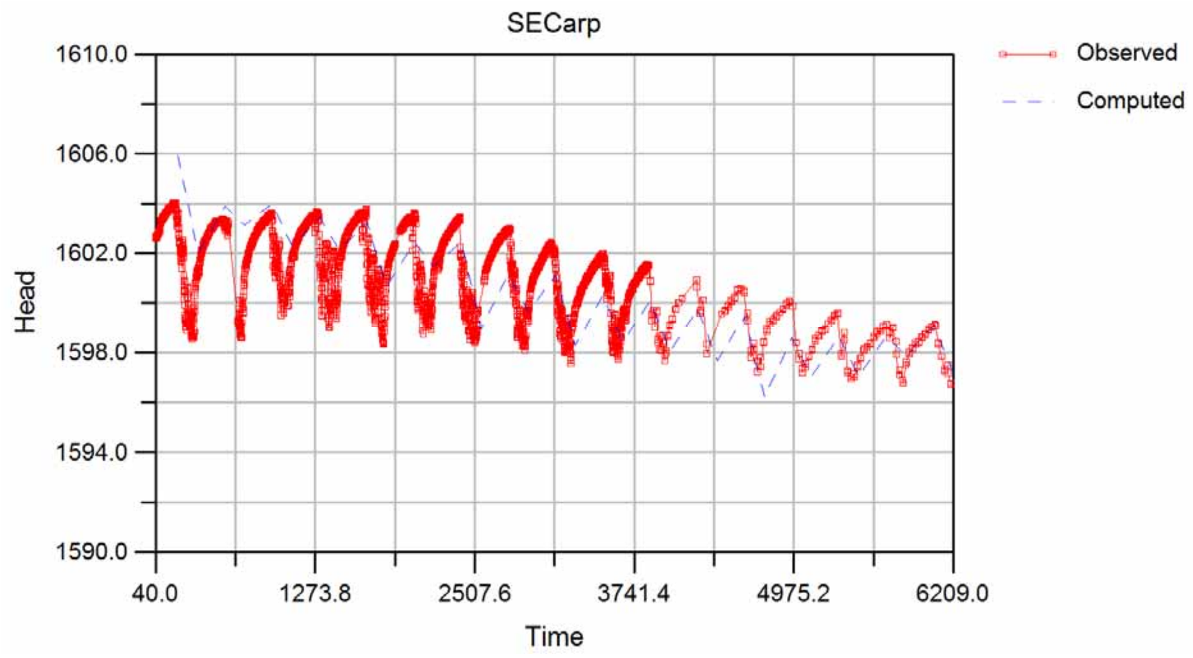


Figure 6.9 Observed vs Model Computed Water Levels for WSEO Monitoring Well (SECARP)

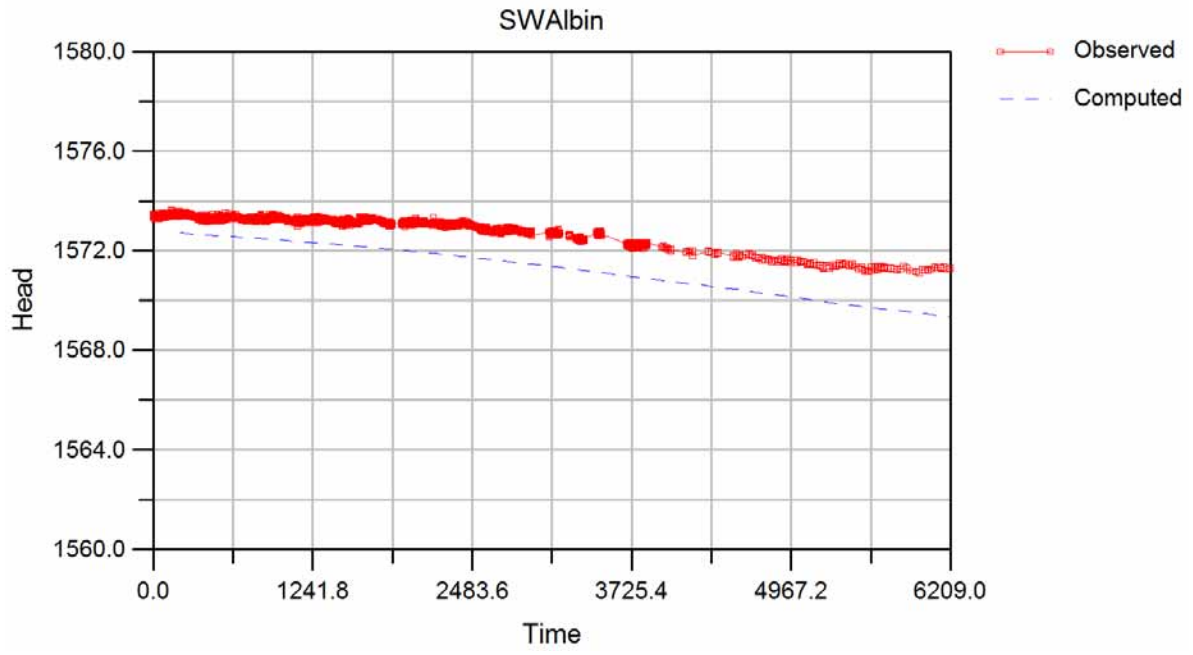


Figure 6.10 Observed vs Model Computed Water Levels for WSEO Monitoring Well (SWAlbin)

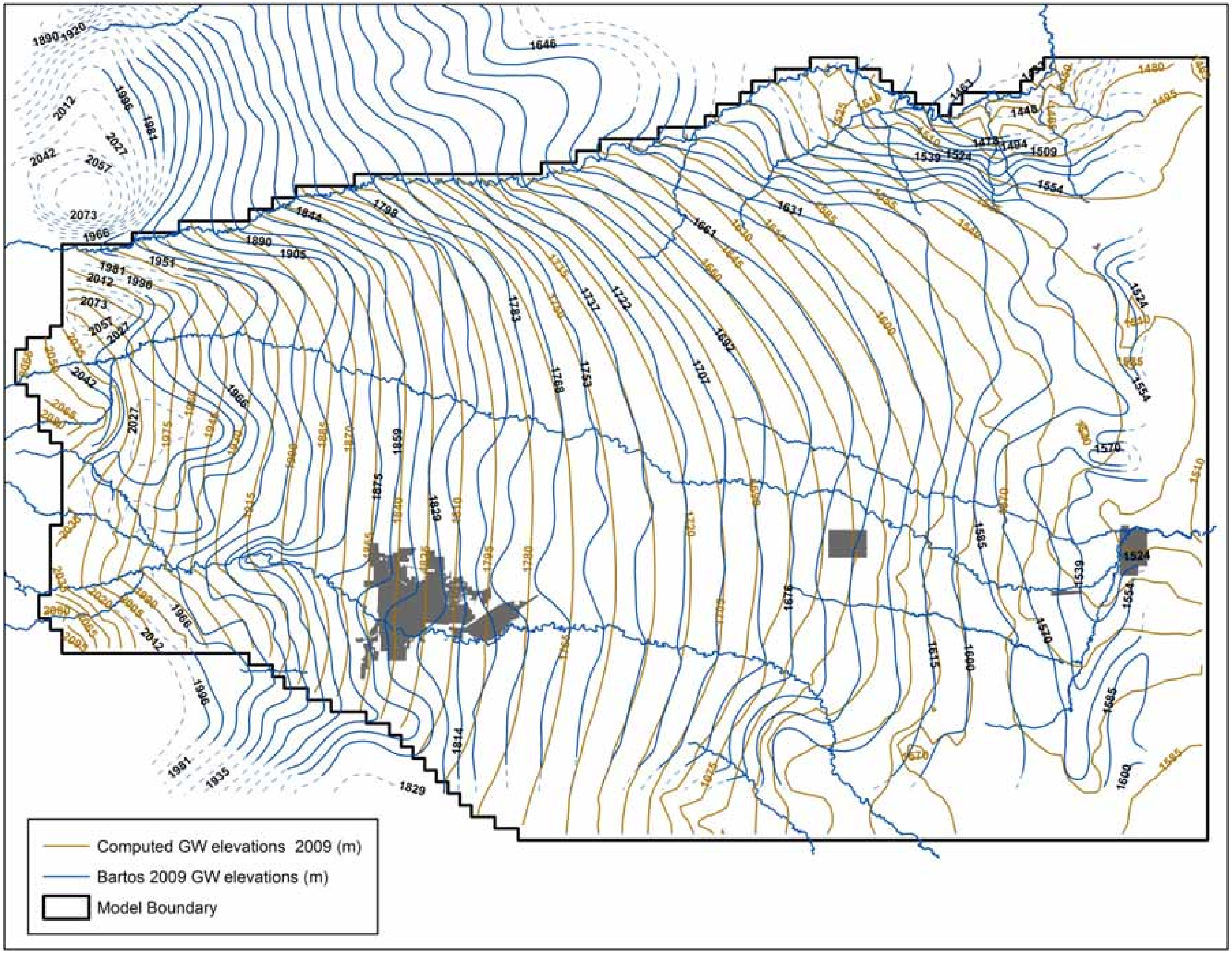


Figure 6.11 Transient Potentiometeric Surface Comparison

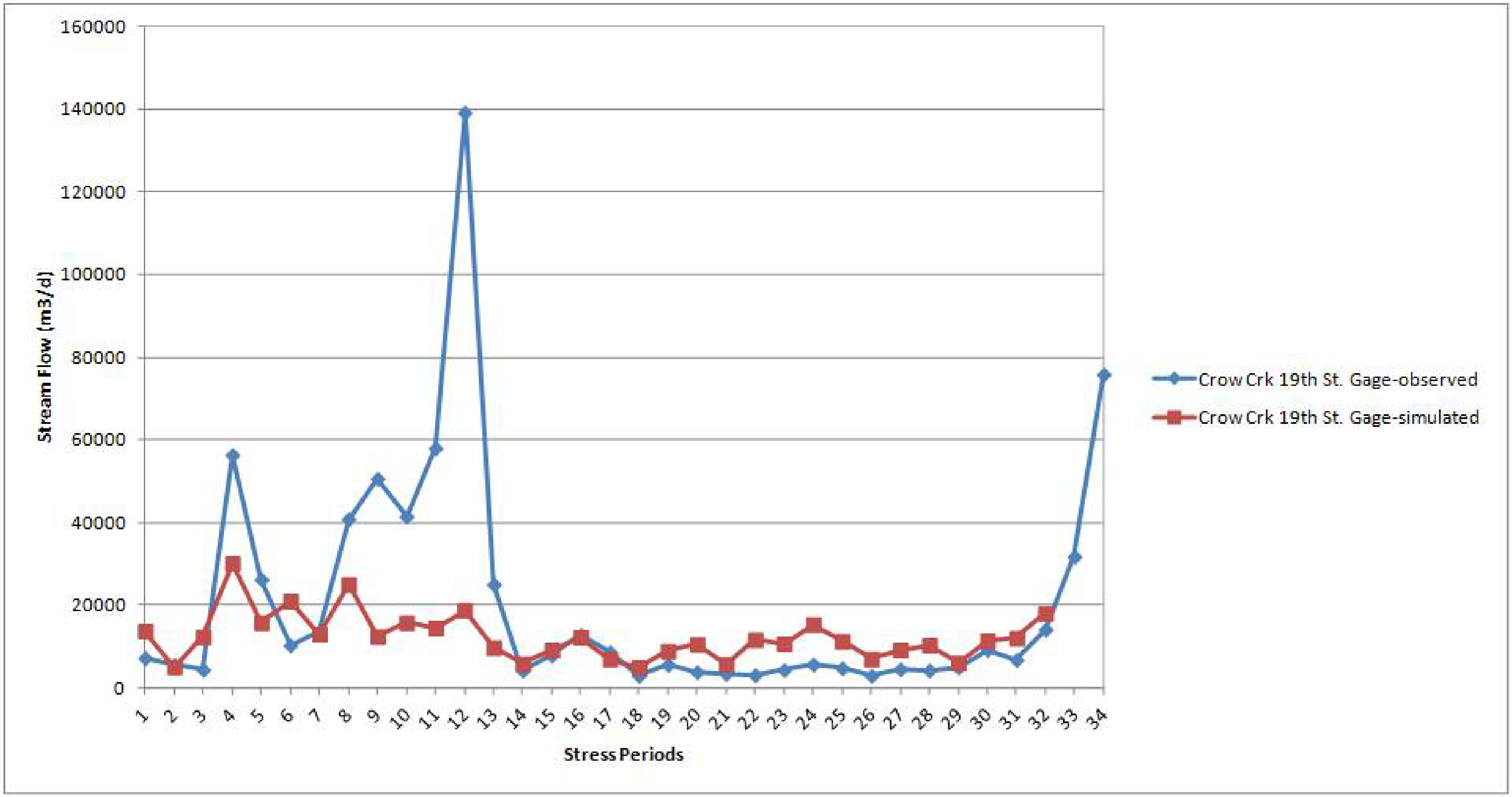


Figure 6.12 Crow Creek 19th St. Gage Observed vs. Simulated Streamflow

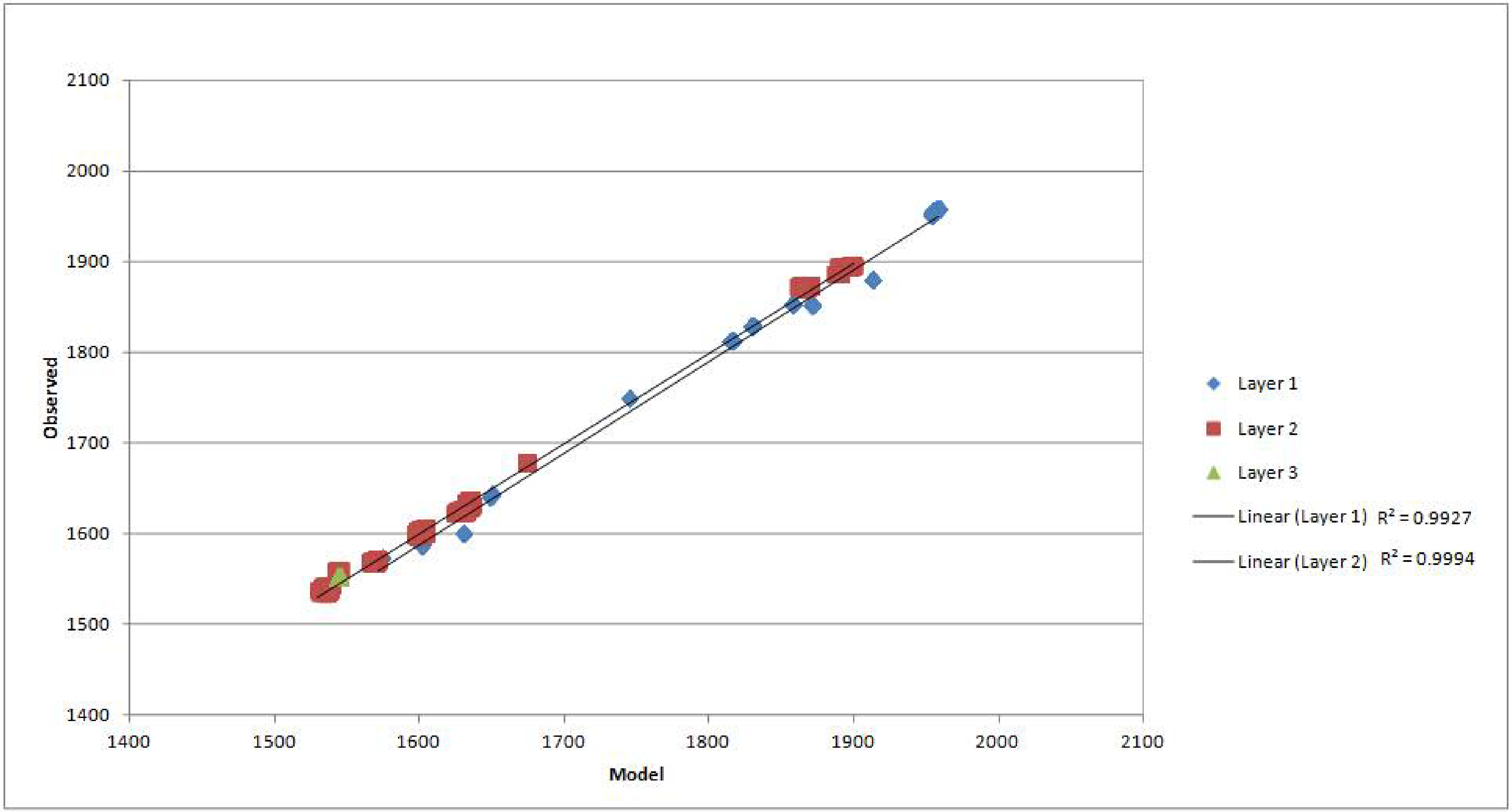


Figure 6.13 Transient Observed vs. Simulated Groundwater Level Calibration Plot

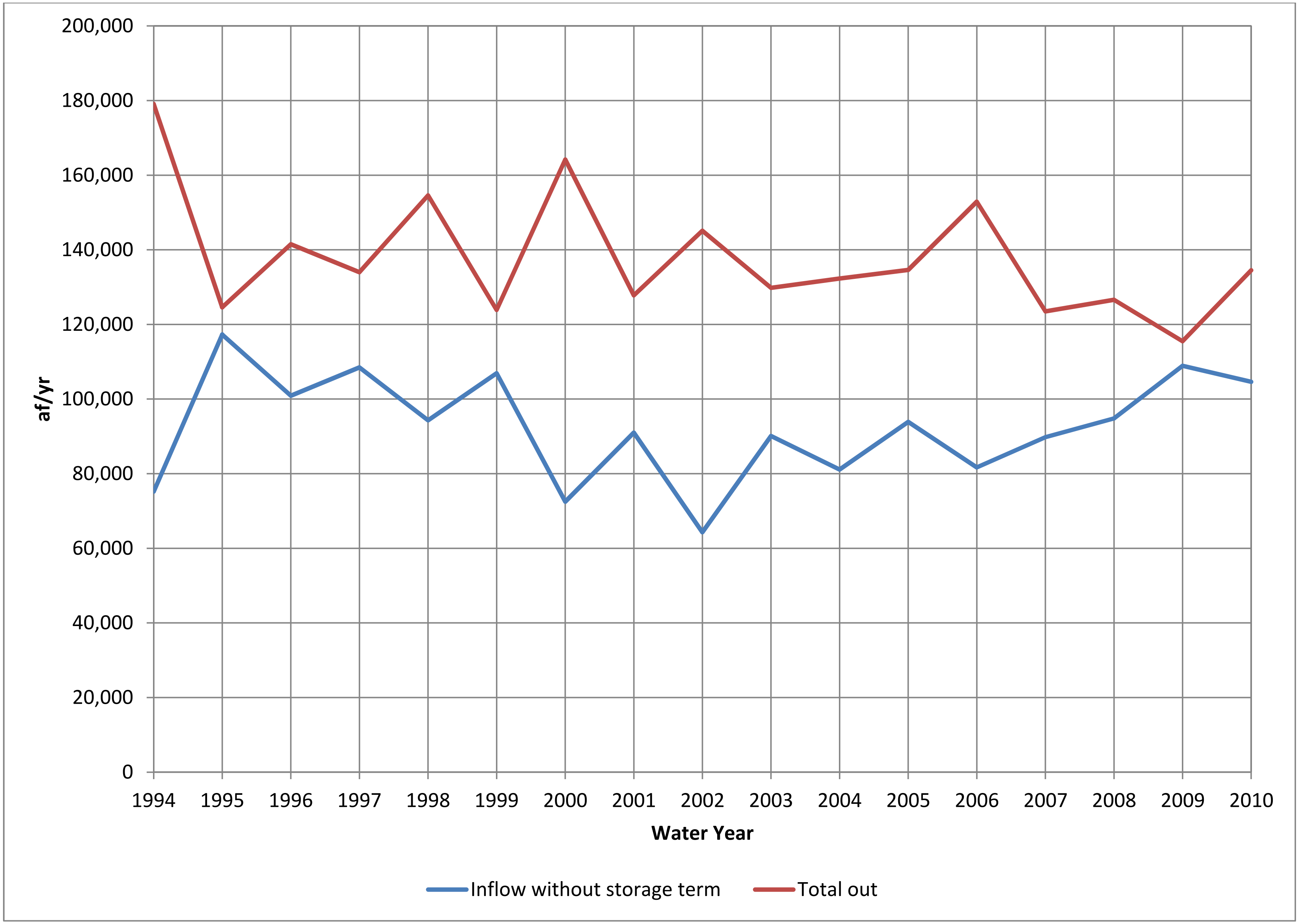


Figure 6.14 Transient Water Budget without Storage Term

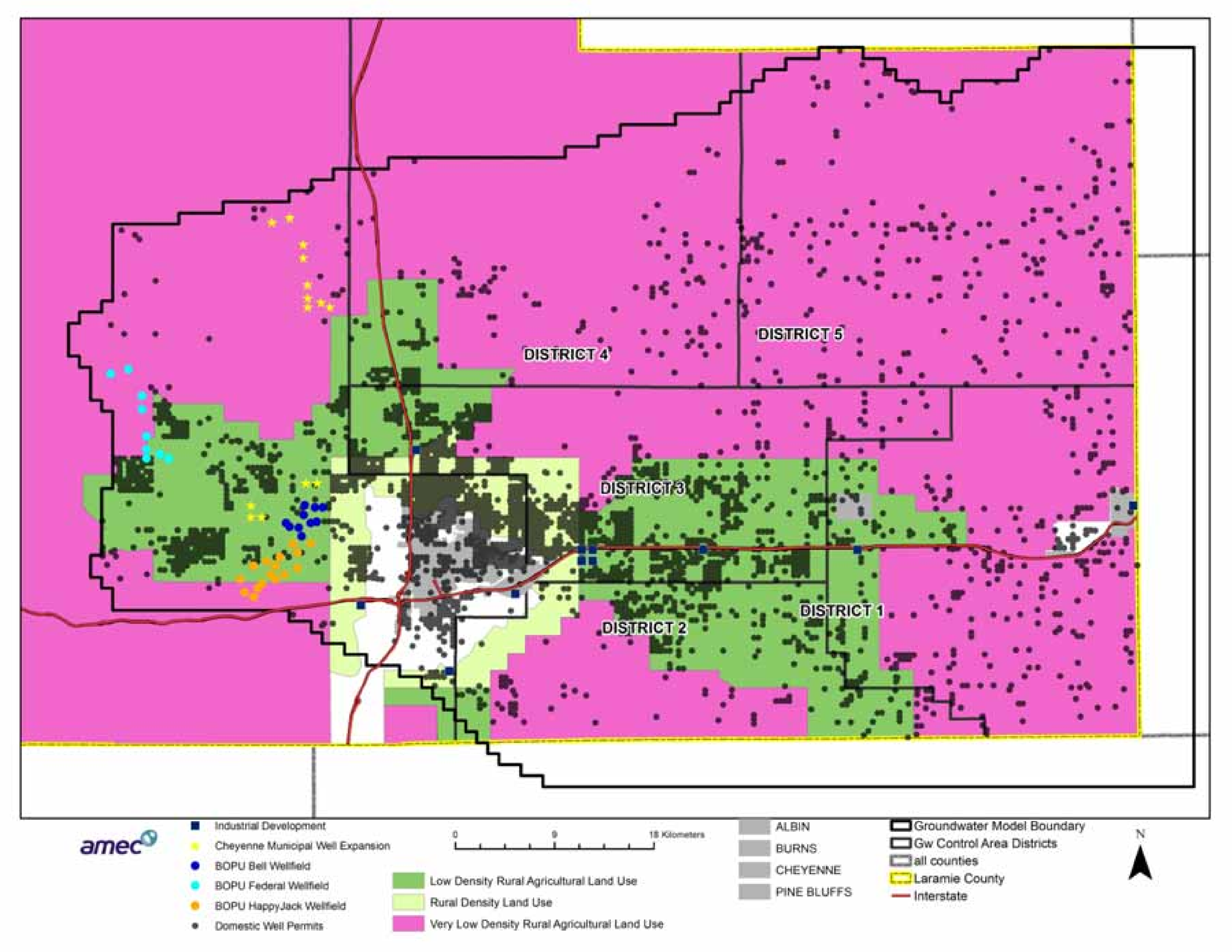


Figure 7.1 Rural Densities in Laramie County (modified from Laramie County Comprehensive Plan, 2001)

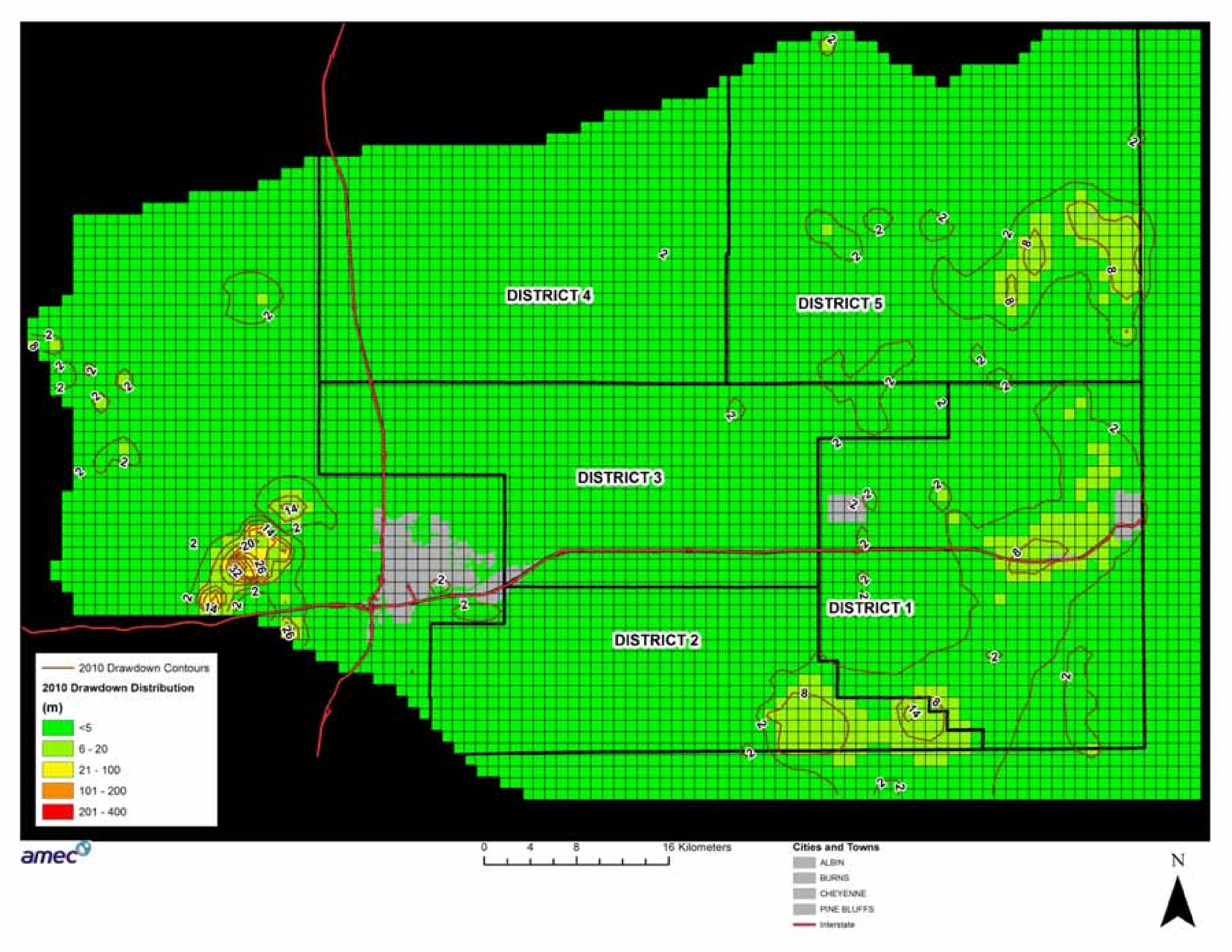


Figure 7.2 Water Level Declines in 2010

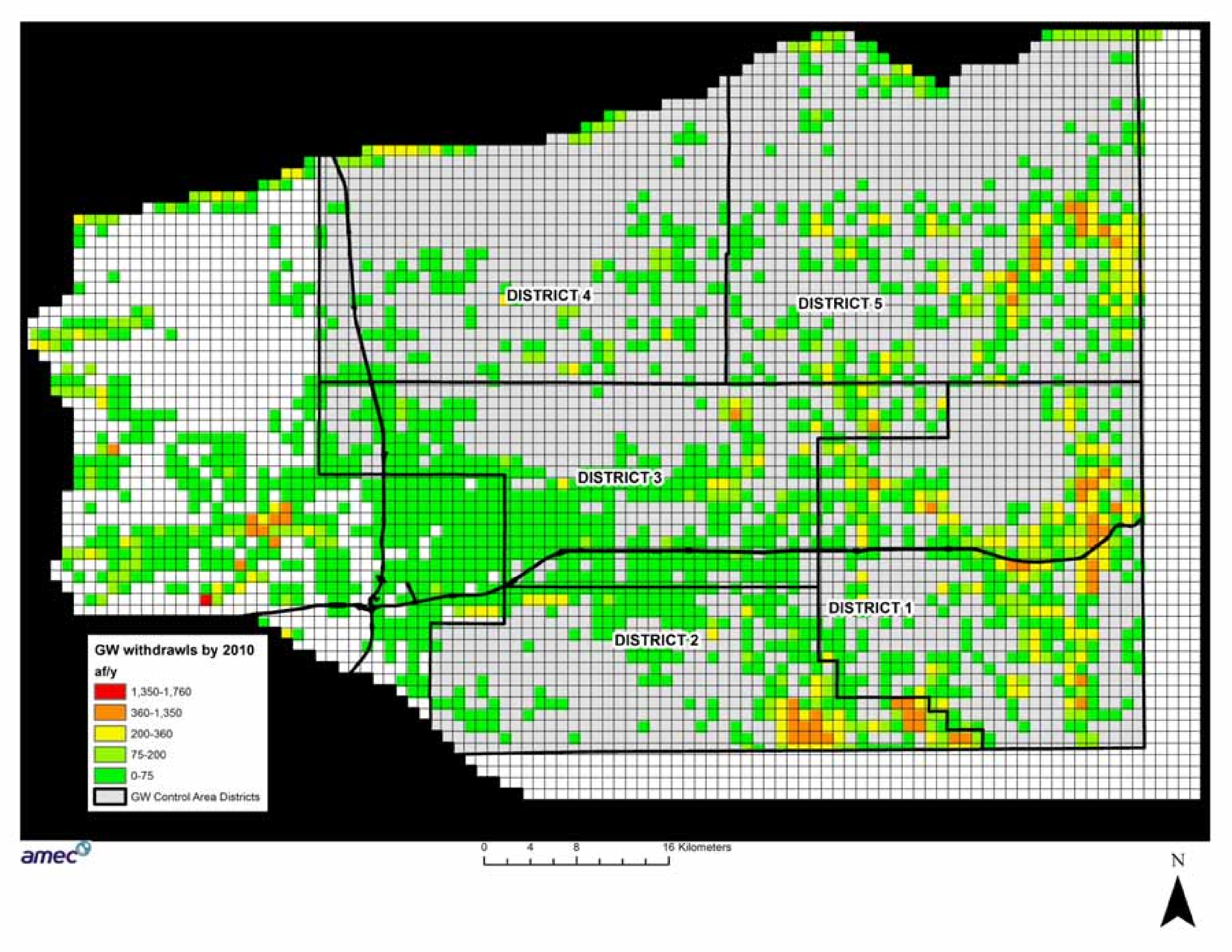


Figure 7.3 2010 Distribution of Model Groundwater Withdrawals

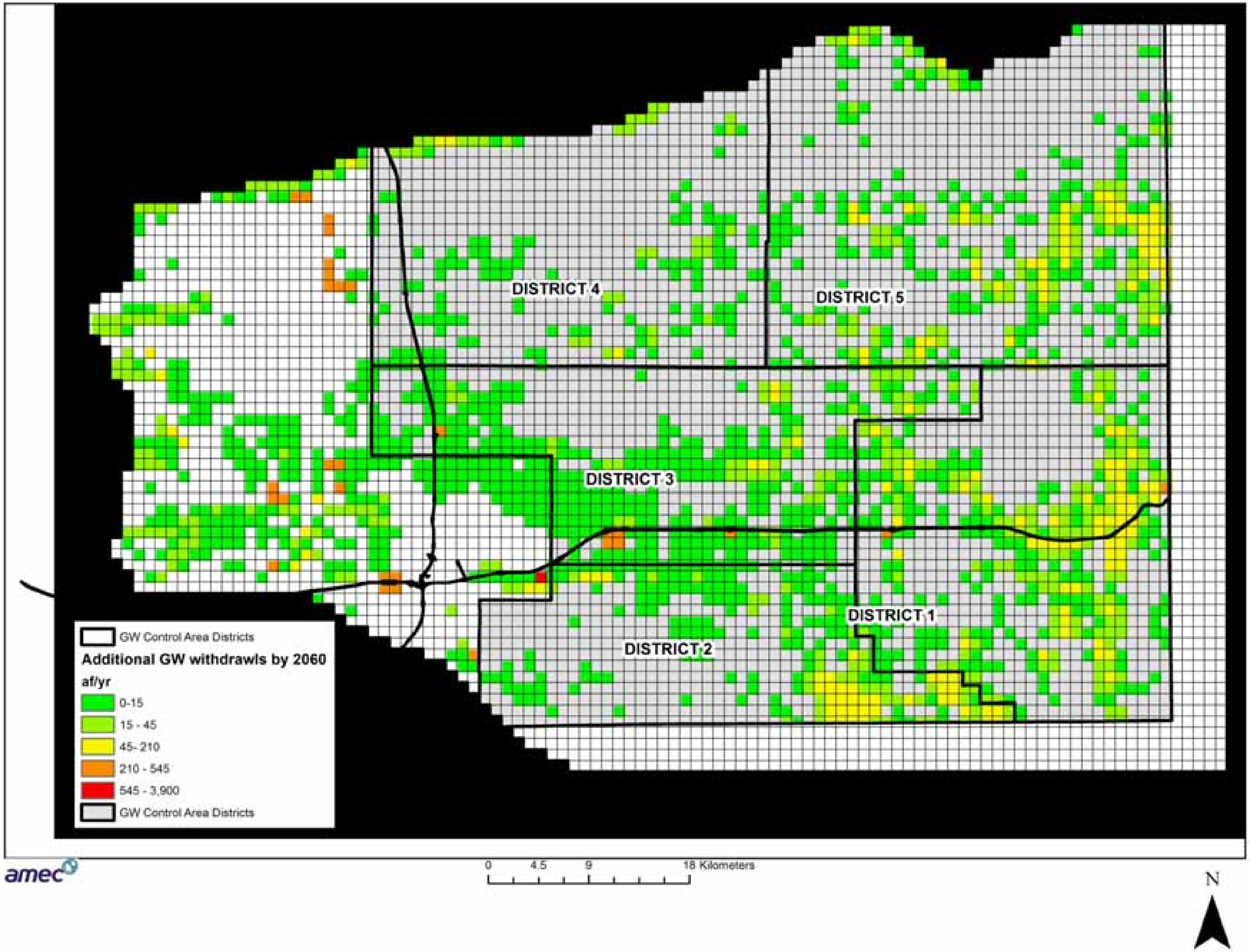


Figure 7.4 Distribution of Additional Model Groundwater Withdrawals by 2060 Relative to 2010

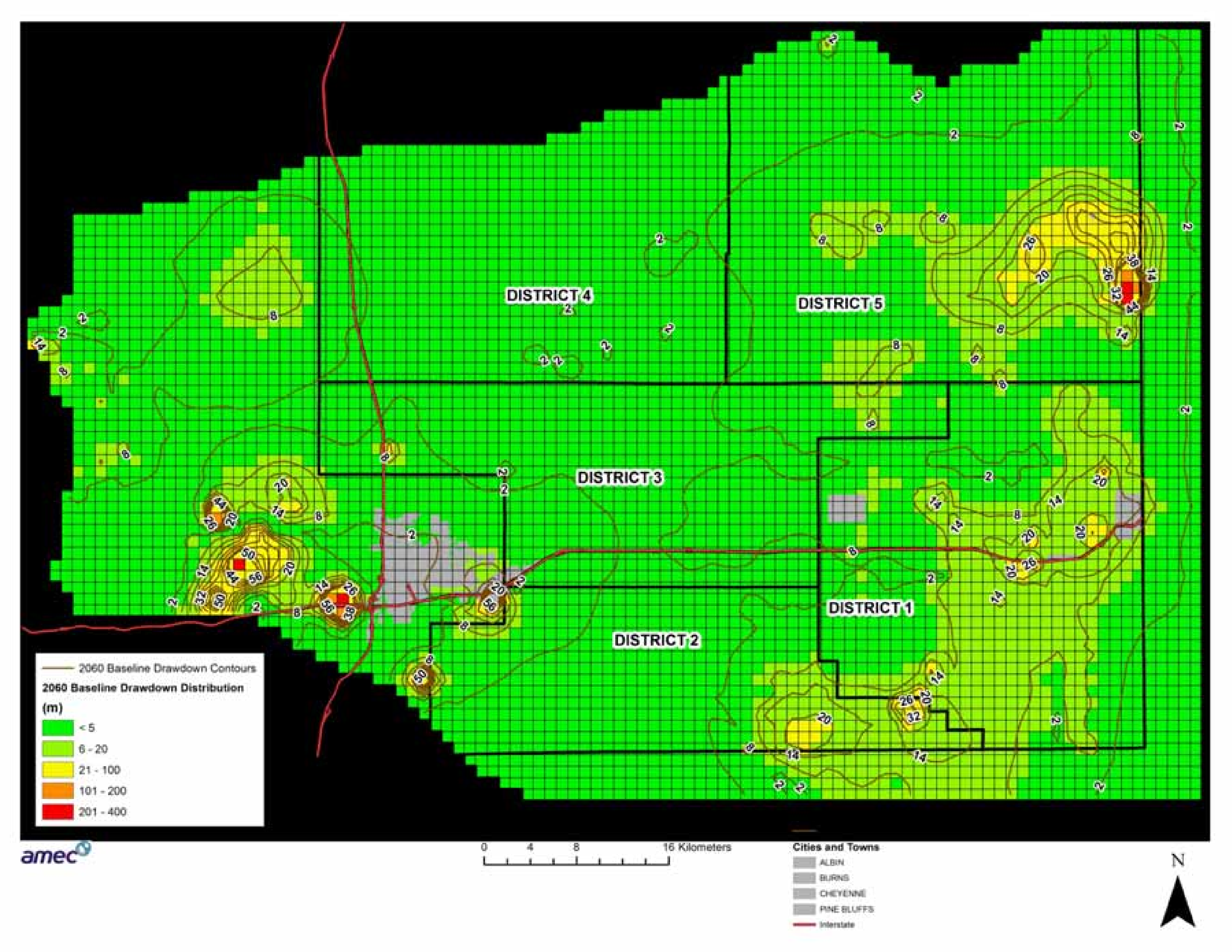


Figure 7.5 Baseline Scenario Water Level Declines 2060

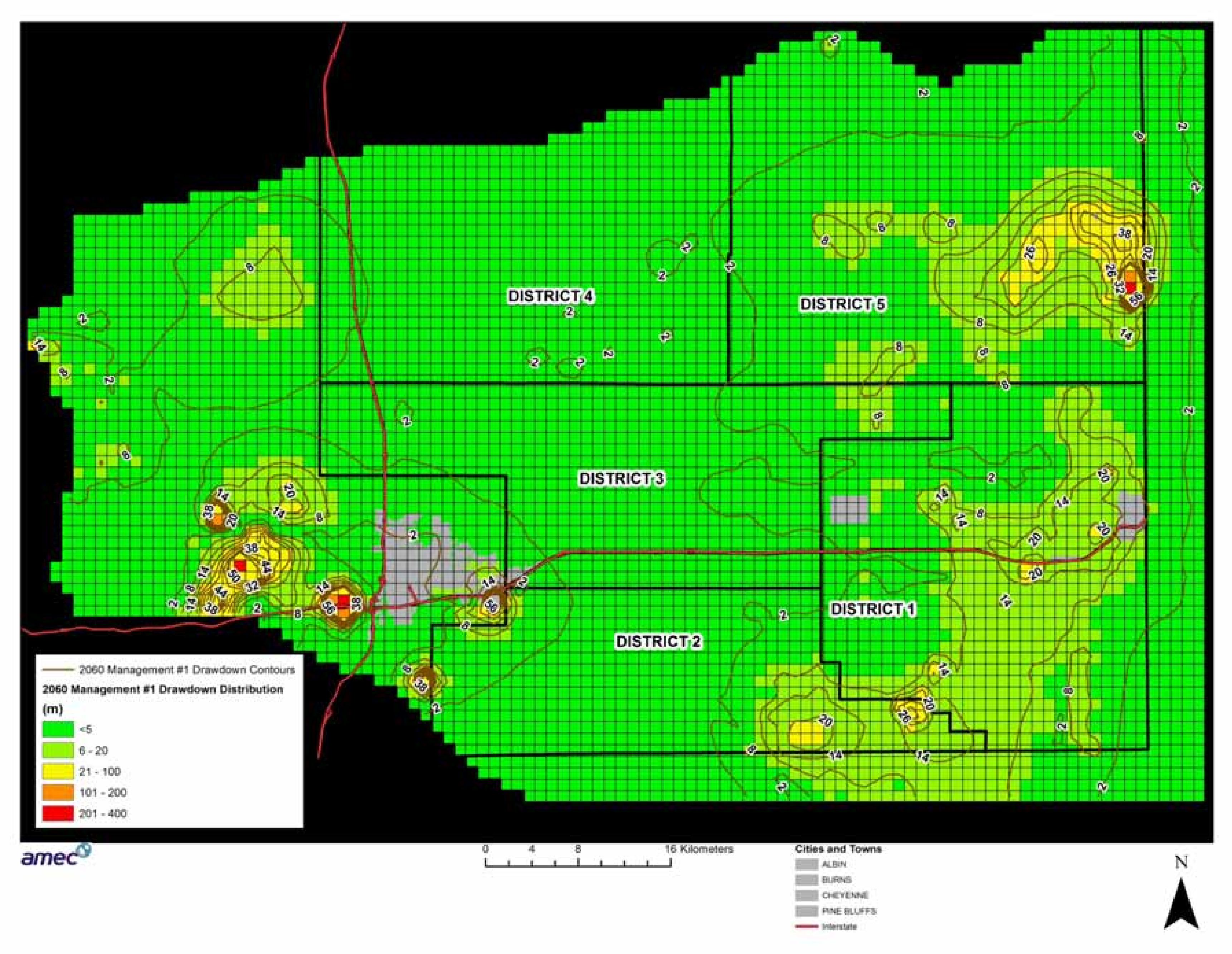


Figure 7.6 Management Scenario #1 Water Level Declines 2060

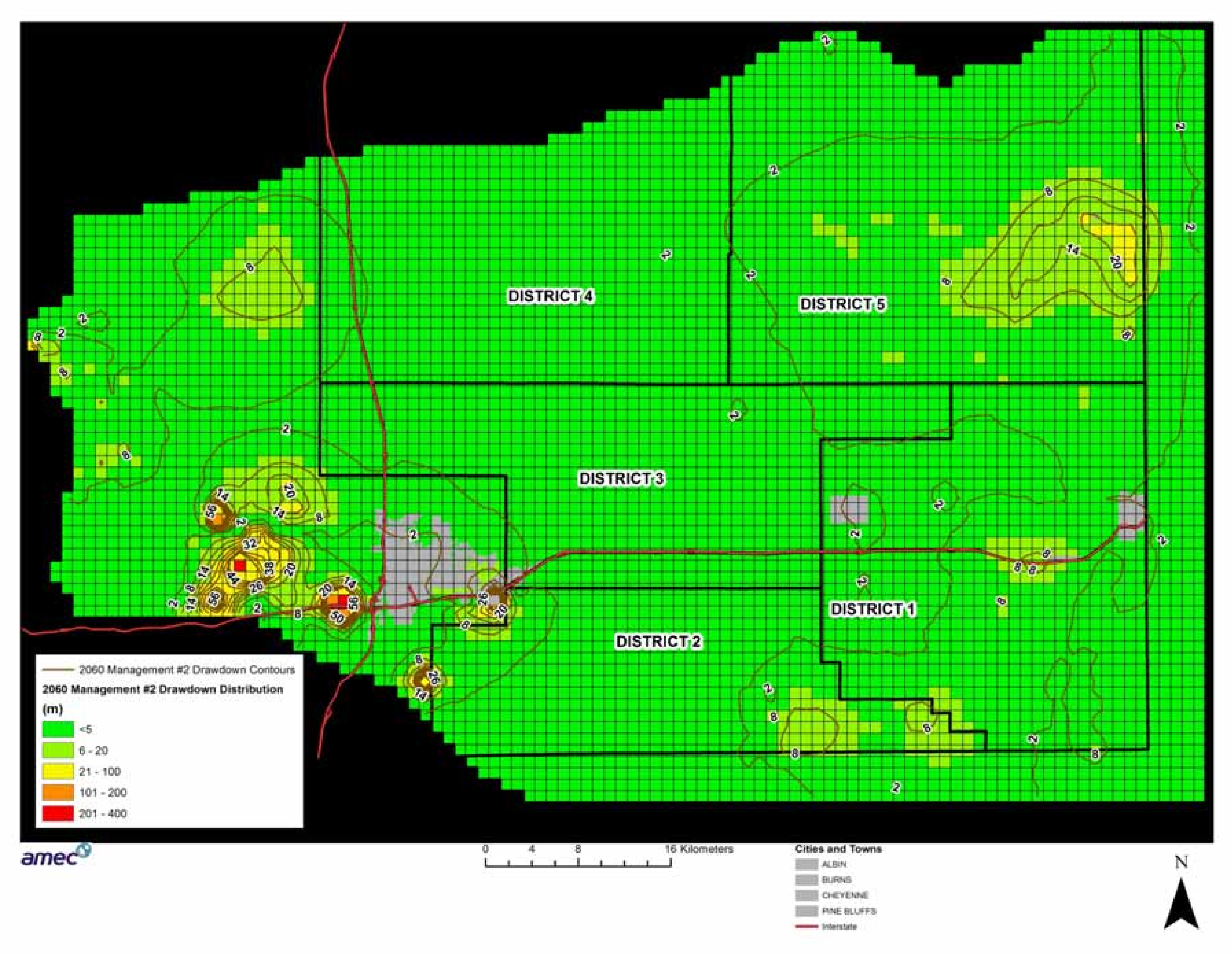


Figure 7.7 Management Scenario #2 Water Level Declines 2060

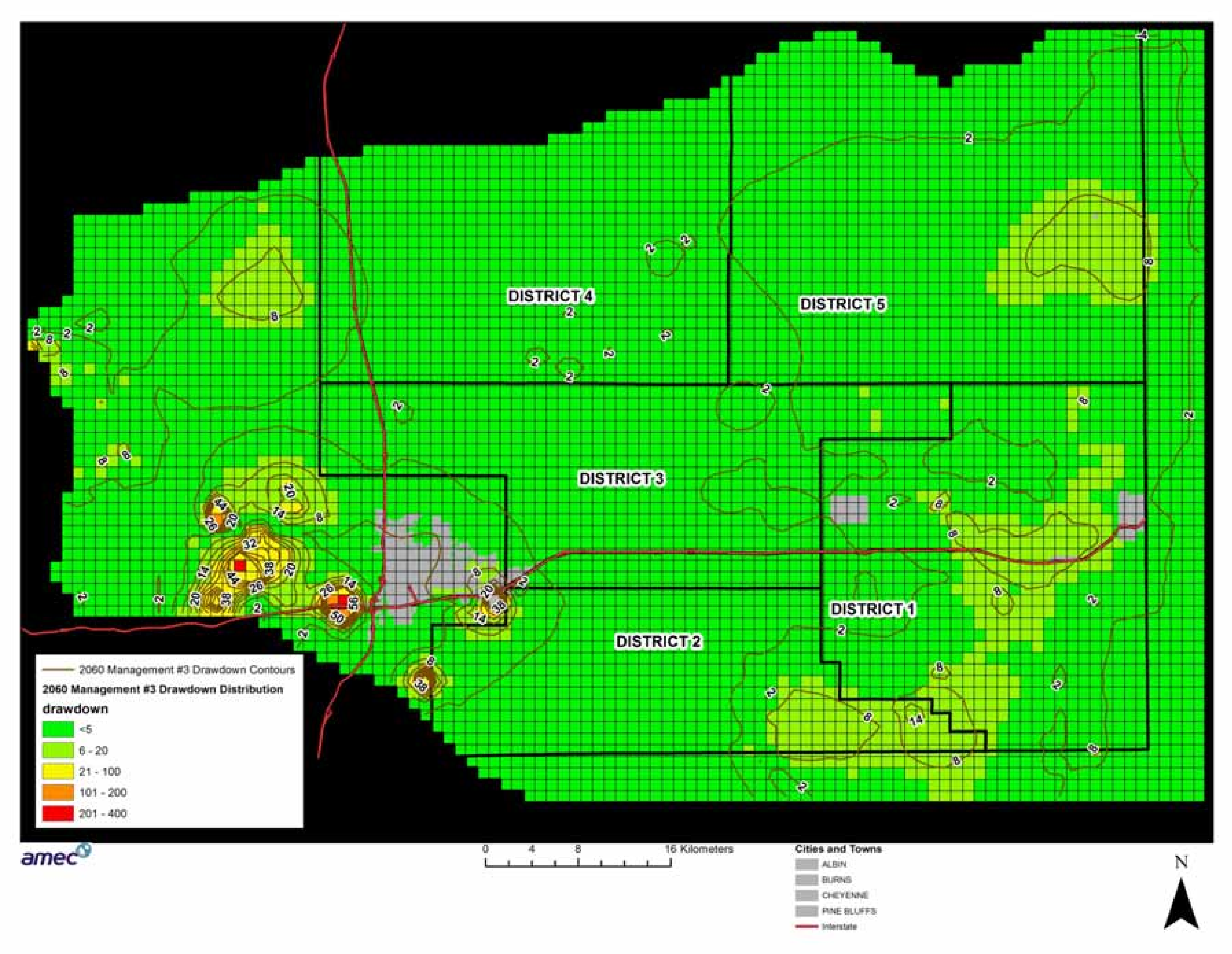


Figure 7.8 Management Scenario #3 Water Level Declines 2060

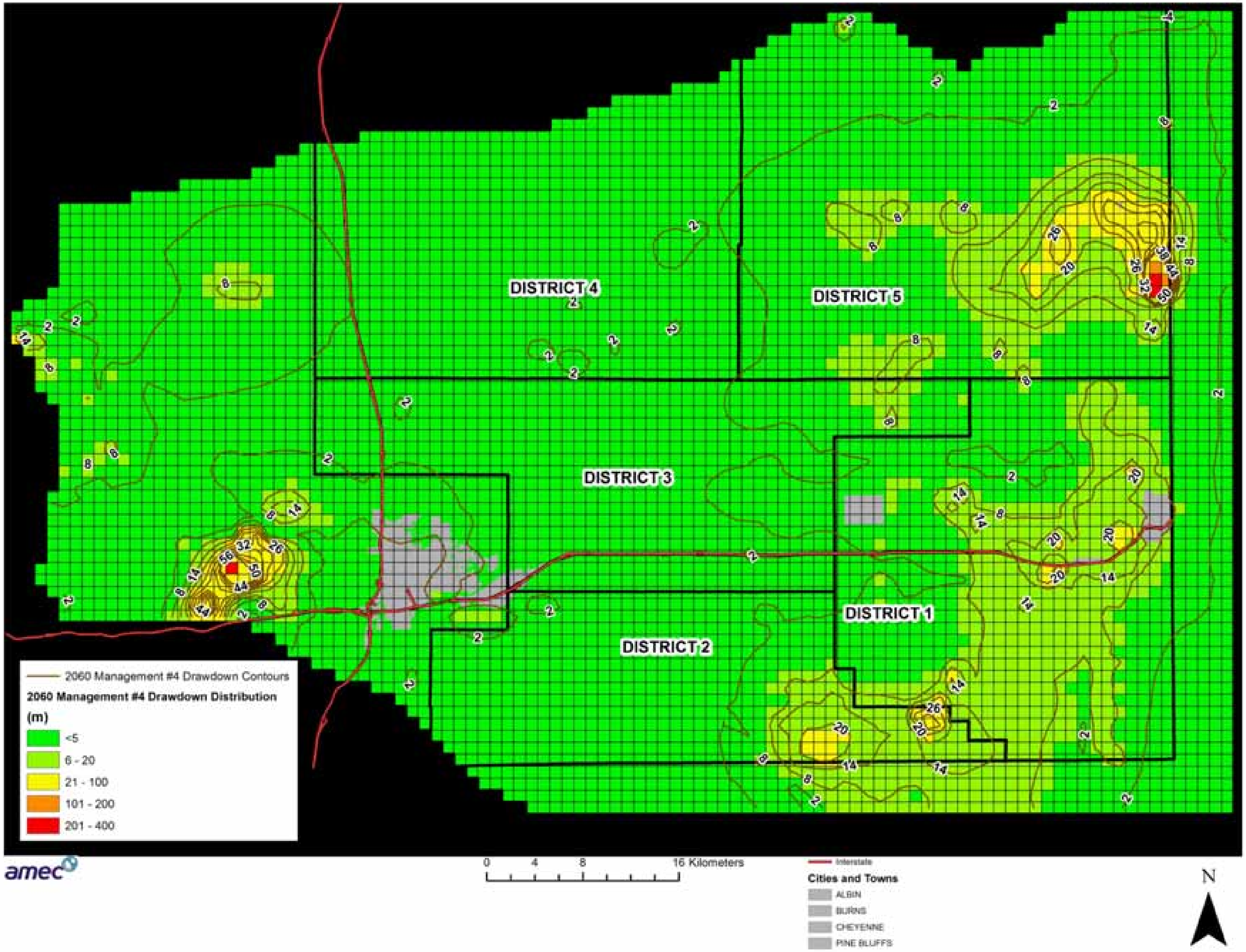


Figure 7.9 Management Scenario #4 Water Level Declines 2060

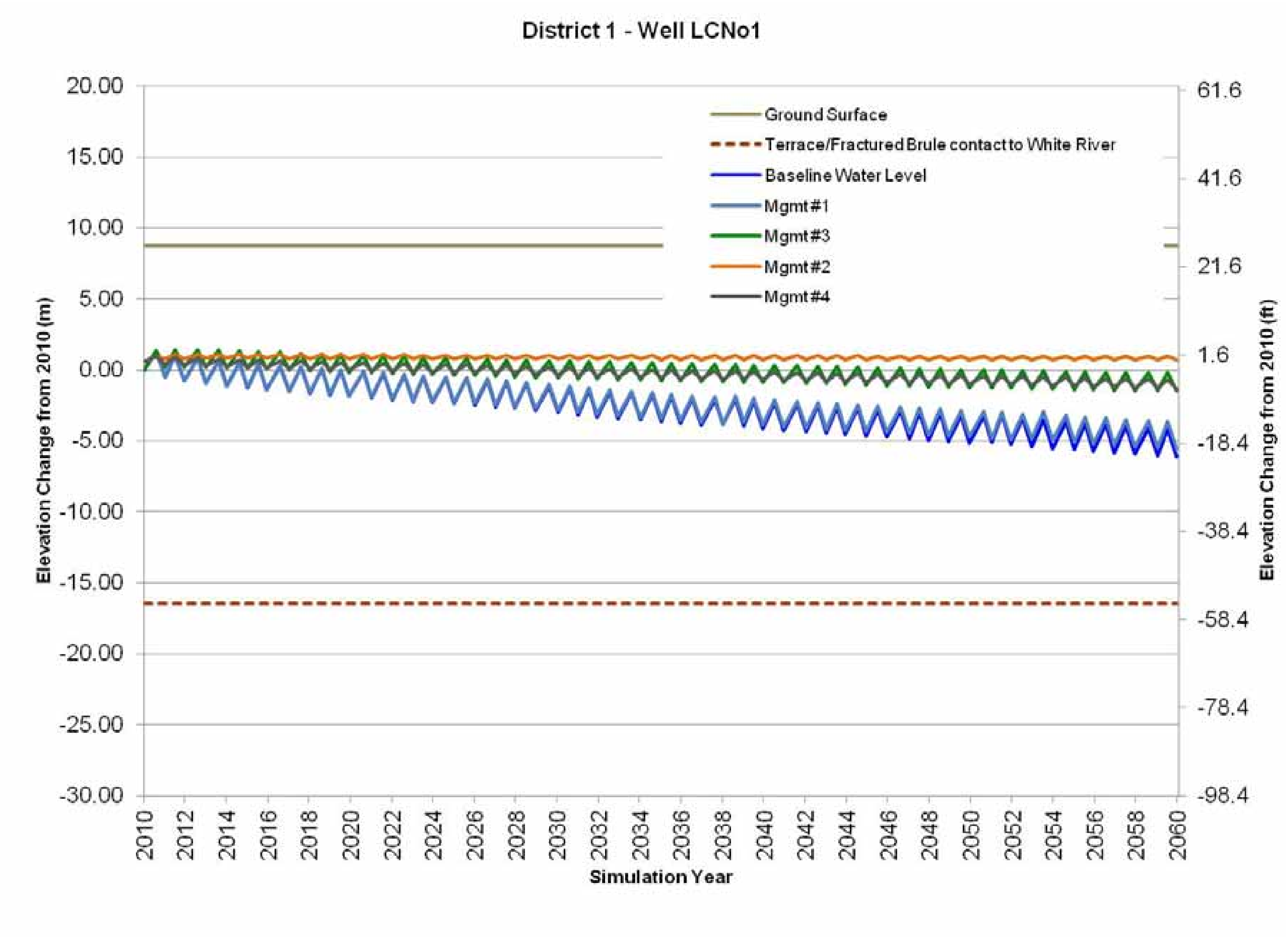


Figure 7.10 District 1 Hydrograph

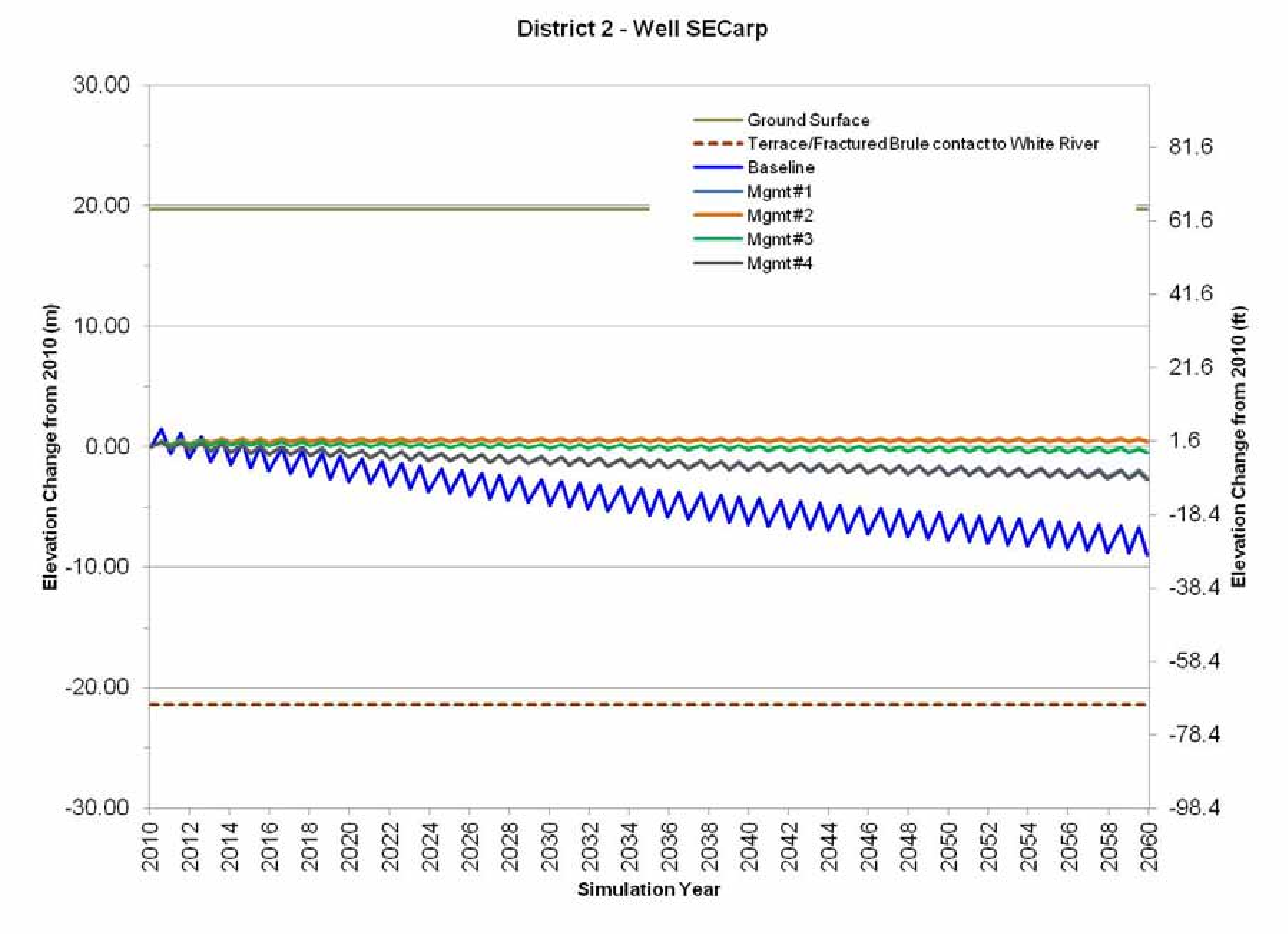


Figure 7.11 District 2 Hydrograph

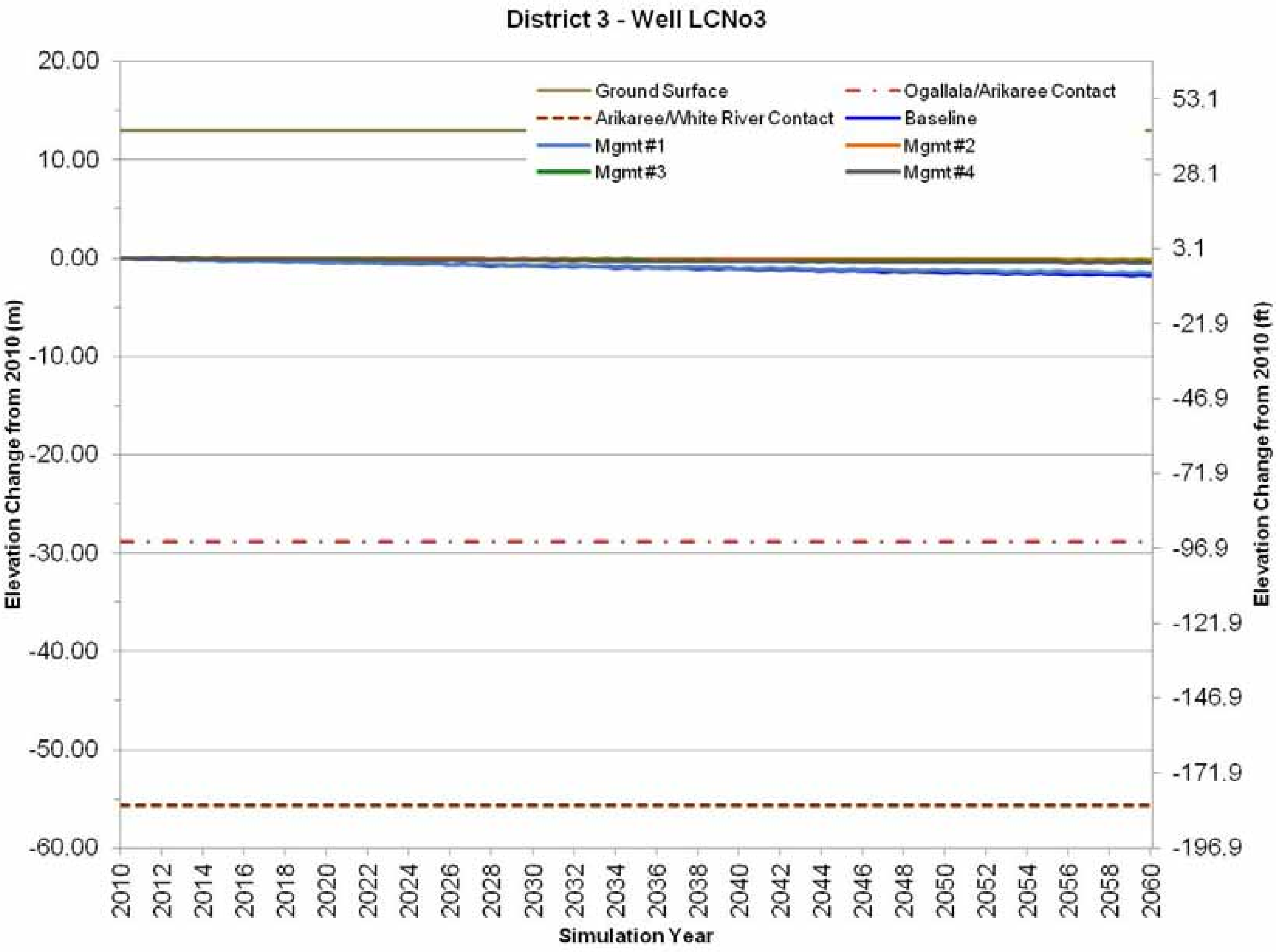


Figure 7.12 District 3 Hydrograph

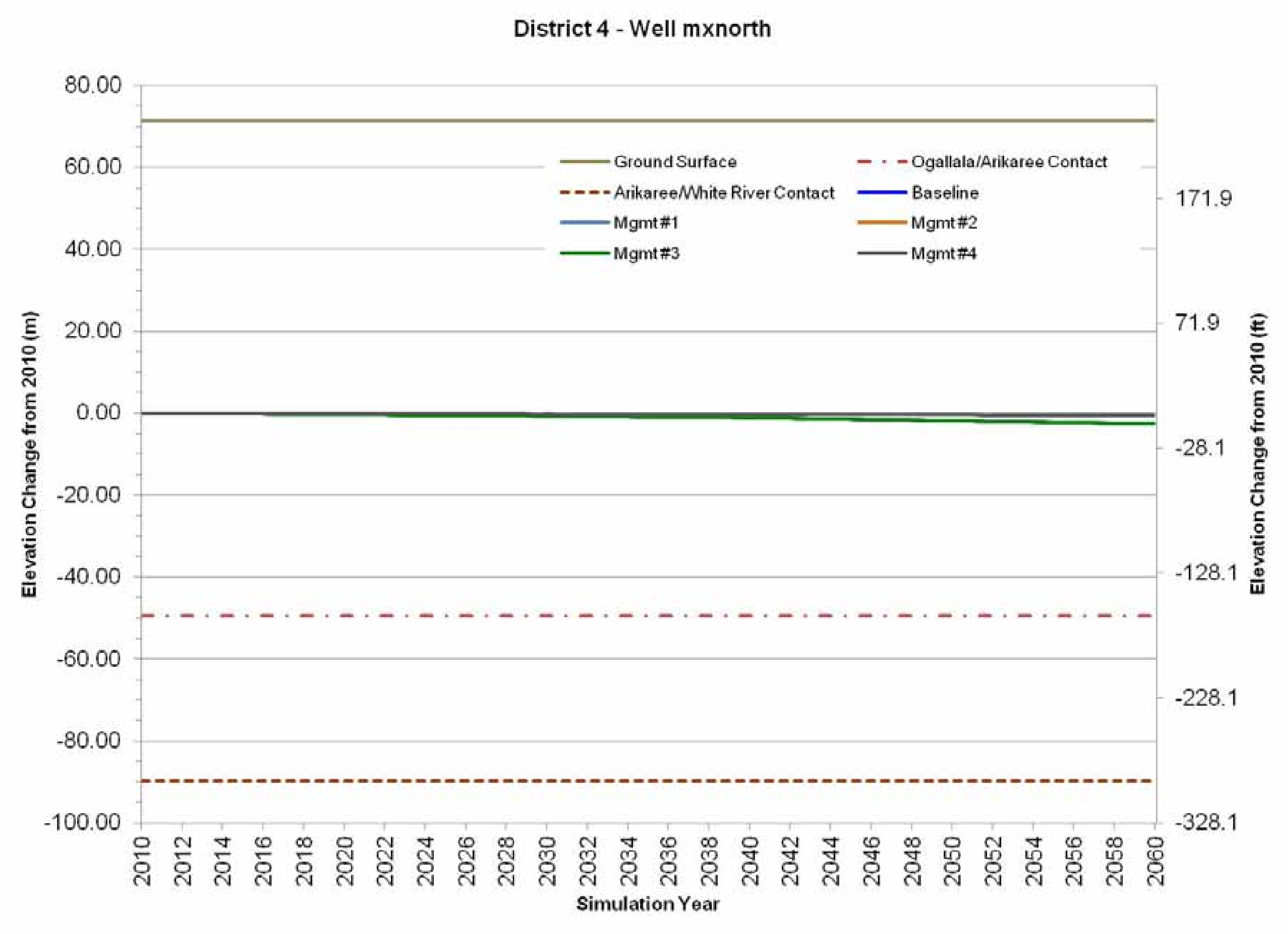


Figure 7.13 District 4 Hydrograph

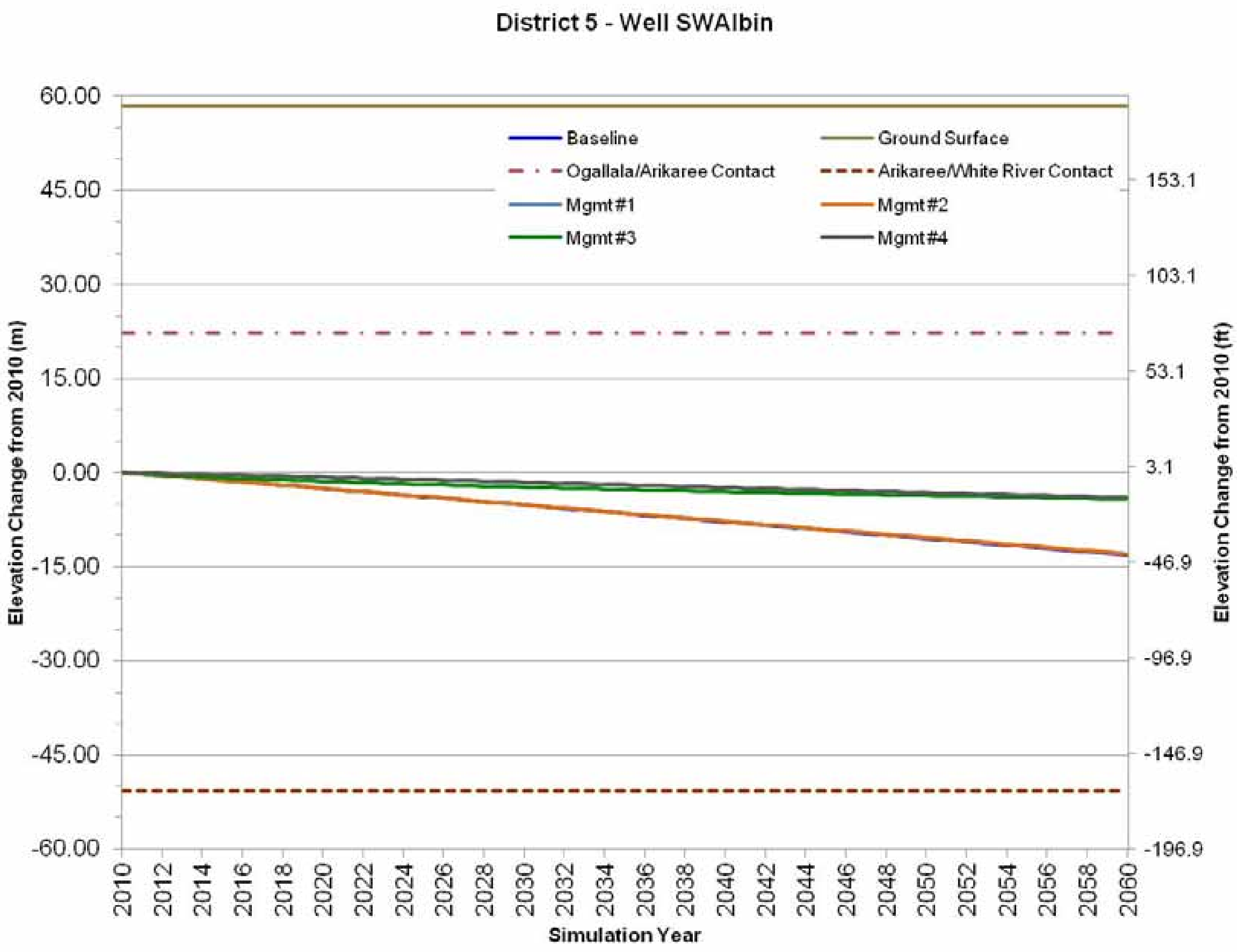


Figure 7.14 District 5 Hydrograph

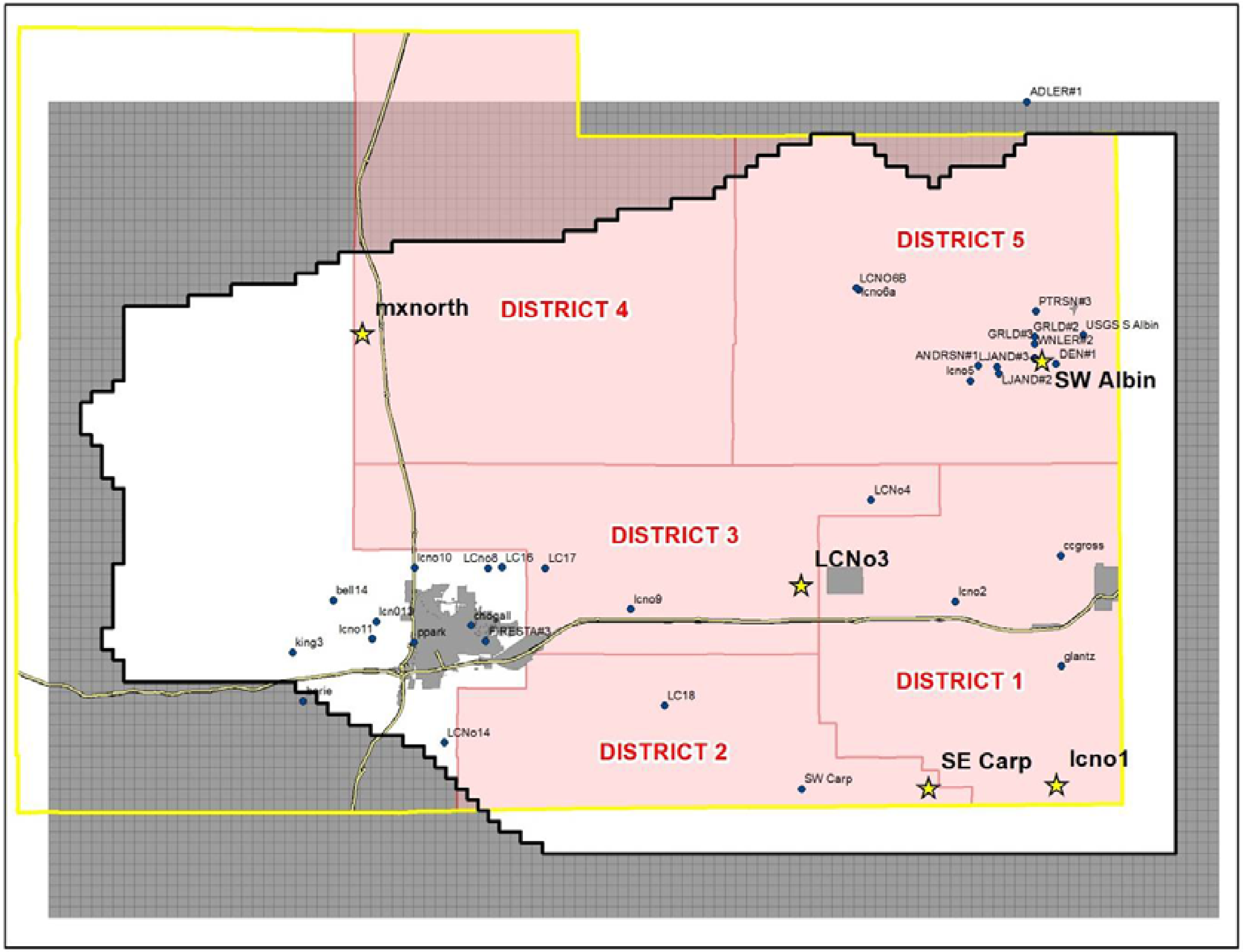


Figure 7.15 Monitoring Well Locations

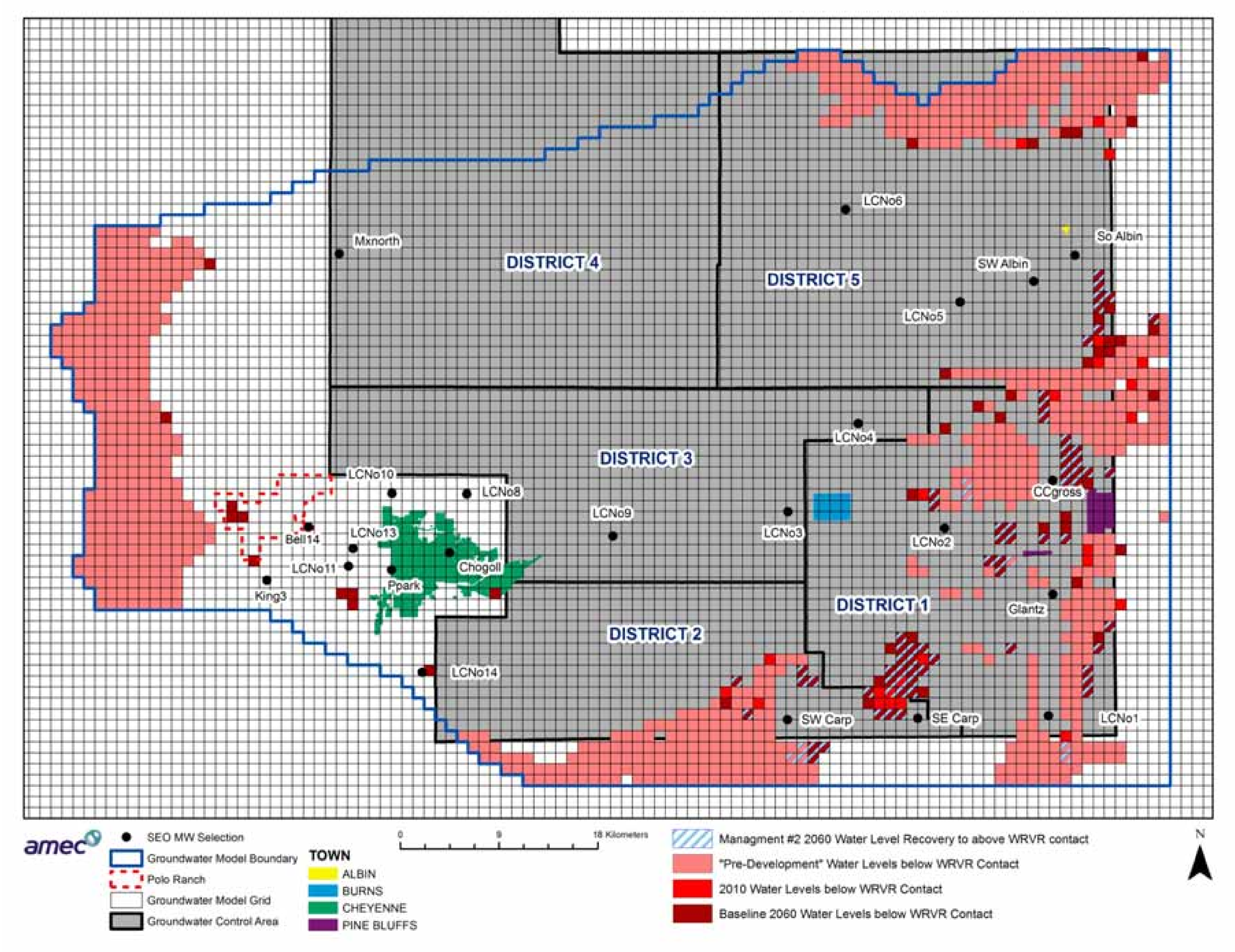


Figure 7.16 Groundwater Level Declines below White River Contact

Hydrogeologic Study
of the
Laramie County Control Area

TABLES

Table 4.1. Range of Hydraulic Conductivity within Laramie County

Geologic Unit / Aquifer	Hydraulic Conductivity (ft/day)	Source
High Plains Aquifer, Laramie County	0.0864 to 432	Crist, 1980 – groundwater model calibration values
High Plains Aquifer, Wyoming	36	Gutentag et al., 1984 – RASA model
Ogallala Fm.	21 to 534	Libra et al., 1981; Wireman, Anctil and Frederick, 1994
Arikaree Fm.	0.17 to 50	
White River Fm.	0.005 to “siltstone”*	Lowry and Crist, 1967

*a typical range of hydraulic conductivity for siltstone is 3x10^{-6} to 0.004 ft/day (Heath, 1983).

Table 4.2. Range of Specific Yields within Laramie County

Specific Yield	Source
0 – 25%; highest values between Cheyenne and Albin and near Carpenter	JR Engineering et al., 2008; Gutentag et al., 1984

Table 4.3. Compilation of Recharge Values from Previous Studies

Recharge Rate (in/yr)	% Annual Precip.	Recharge Volume in the Model Area* (af/yr)	Recharge Estimate Method	Source
0.06	N/A	6,800	Silt loam soil type infiltration rate	Luckey (1986). RASA model of the northern High Plains Aquifer, recharge rate for Laramie Co.
0.17	2%	19,200	Computer-model analysis	Borchert (1977). Arikaree Formation, Central WY
0.25-0.5	5%	28,200 to 56,400	Soil water balance model	Dugan (2000). Great Plains regional contour maps, recharge rate for Laramie Co.
0.53	N/A	59,800	Base Flow Index	USGS (Wolock) (2003) estimated mean annual natural groundwater discharge for U.S. This is the recharge rate for the Laramie Co. area.
0.56	3.60%	63,200	Water budget	Crist (1977) High Plains Aquifer, Niobrara Co., WY
0.24-0.6	N/A	27,100 to 67,700	Vertical gradients in groundwater age	McMahon (2007). Long term average for High Plains Aquifer, study site in Lincoln and McPherson Counties, NE
0.75	5%	84,600	Direct infiltration (5% precip.) + 5,000 ac-ft from streamflow infiltration	Lowry and Crist (1967). Laramie Co., WY
0.83	5.50%	93,600	Water budget	Rapp (1953). Egbert-Pine Bluffs-Carpenter area, WY
0.6-1.0	N/A	67,700 to 112,800	Soil Water Balance Model	USGS (2011). High Plains Aquifer Water Budget Components report, recharge rate for Laramie Co.
~2.0	N/A	~225,600	Soil type infiltration rates	WY GW Vulnerability Assessment Handbook (1998), used in the WY GW Atlas (JR Engineering et al., 2008)

*The model domain is 5,477 km^2

Table 4.4. Estimates of Outflow for the Groundwater Model		
Boundary	Outflow estimate (af/yr)	Source
Laramie County to Horse Creek basin	1,500	Hinckley and AMEC, 2011
Laramie County to Nebraska within Lodgepole Creek drainage basin (not entire eastern boundary)	9,050	Bjorklund, 1959

Table 4.5 Annual Unit CUw for Laramie County Model Area	
Year	Average Unit CUw (ft)
1993	0.75
1994	1.44
1995	0.58
1996	0.83
1997	0.74
1998	1.11
1999	0.59
2000	1.40
2001	0.81
2002	1.18
2003	0.91
2004	0.96
2005	0.97
2006	1.32
2007	0.83
2008	0.82
2009	0.52
2010	0.82
Average	0.93

*1993 not included in average because model starts on 10/1/1993, after the 1993 irrigation season

Table 5.1. Steady State Mass Balance Fluxes for Boundary Conditions

Boundary Condition - Streams

Segment	Name	Flux, CFS	Gaining or Losing Segment?
1	Little Horse Creek	-4.8	Gaining
2	Upper Lodgepole	-12.7	Gaining
3	Lower Lodgepole	-5.2	Gaining
4	Upper Crow	-9.1	Gaining
5	Middle Crow nr WWTP, upstream seg.	-0.3	Gaining
6	Middle Crow nr WWTP, downstream se	1.6	Losing
7	Middle Crow Creek	1.0	Losing
8	Lower Crow Creek	-2.6	Gaining
9	Trib. to Upper Lodgepole	-7.0	Gaining
10	Trib. to Upper Crow	-3.3	Gaining
11	Trib. to Upper Crow	-6.1	Gaining
12	Trib. to Upper Crow	-4.4	Gaining
13	Muddy Creek	-6.5	Gaining
14	Trib. to Upper Crow	-1.3	Gaining
15	Mills Creek	-0.8	Gaining
16	Bushnell Creek	-0.9	Gaining
17	Kellehan Creek	-1.3	Gaining
18	Trib. to Lower Lodgepole	-4.5	Gaining
19	Trib. to Muddy	-4.5	Gaining
20	Trib. to Muddy	-0.1	Gaining
21	Stinking Water Creek	-0.9	Gaining
22	Simpson Draw	-1.1	Gaining
23	Porter Draw	-2.7	Gaining
24	Sprager Creek	-0.8	Gaining
25	Trail Creek	-1.2	Gaining
26	Clear Creek	-0.5	Gaining

Boundary Condition - River

Segment	Name	Flux, CFS	Gaining or Losing Segment?
1	Horse Creek	-31.3	Gaining

Boundary Condition - General Head Boundary (Underflow to Nebraska)

Segment	Name	Flux, ac-ft/yr	Entering or Leaving Wyoming?
1	Underflow north of Lodgepole Creek	-6,404	Leaving
2	Underflow south of Lodgepole Creek	-468	Leaving

Table 5.2. Hydraulic Conductivity Calibrated Values

K Zone	Geologic Formation	Model Layer	Steady State Calibration (m/d)	Steady State Calibration (ft/d)	Final Calibration (m/d)	Final Calibration (ft/d)
🟦	Ogallala (OGLL)	1	2	6.6	0.1-35	0.3-115
🟪	Arikaree (ARKR)	2	1	3.3	0.5-35	1.6-115
🟥	White River (WRVR)	3	0.06	0.20	0.000006-0.06	0.00002-0.2
🟩	Terrace/Fractured Brule (TRRC-Frac-Bruhl)	1&2	35	114.8	2.5-255	8-836
🟦	Lance/Foxhills (CH-LA-FXH)	4	0.3	1.0	0.5	1.6

Table 5.3. Recharge Zones and Calibrated Precipitation Percentages

Recharge Zone	Zone	Description	Annual Average Precipitation (in/yr)	Precipitation Percentage	Steady State Rate (in/yr)
🟦	1	Mountain Front Recharge	17	100%	17
🟦	2	High Elevation Areal Distributed Recharge	17	4.47%	0.76
🟦	3	Low Elevation Areal Distributed Recharge 1	15	3.35%	0.50
🟩	4	Low Elevation Areal Distributed Recharge 2	15	3.06%	0.46
🟨	5	Low Permeability Soil	15	<1%	<0.1

Table 5.4 - Steady State Calibration Statistics
(Head Targets)

Residual Mean (m)	1.5
Residual Standard Deviation (m)	8.31
Absolute Residual Mean (m)	6.04
Residual Sum of Squares (m^2)	33800
RMS Error (m^2)	8.44
Minimum Residual (m)	-30.25
Maximum Residual (m)	34.9
Range of Observations (m)	678
Number of Observations	474

Table 5.5 Steady State Water Budget

Long-term Average Inflows	*af/yr*
Precipitation	
from the mountains	42,900
across the surface of the model area	51,200
Groundwater underflow into the model	2,200
Infiltration of streamflow	12,800
Total in	*109,100*
Long-term Average Outflows	*af/yr*
Groundwater underflow out of the model	
to Nebraska	9,100
to Horse Creek basin (Goshen Co.)	1,500
Streamflow gains from the aquifer	93,500
Surface runoff	5,000
Total out	*109,100*
Inter-layer flows	*af/yr*
Between Layer 1 and Layer 2 (net)	6,000
Between Layer 2 and Layer 3 (net)	4,100
Between Layer 3 and Layer 4 (net)	0
From Layer 3 to Layer 4 (one way)	53,800

Table 6.1 Stress Periods

Stress Period	Tag	Start Date	End Date	Period Length (Days)	Water Year
		Calibration Period			
1	1994-ni	10/1/1993	4/30/1994	212	1994
2	1994-irrig	5/1/1994	9/30/1994	153	1994
3	1995-ni	10/1/1994	4/30/1995	212	1995
4	1995-irrig	5/1/1995	9/30/1995	153	1995
5	1996-ni	10/1/1995	4/30/1996	213	1996
6	1996-irrig	5/1/1996	9/30/1996	153	1996
7	1997-ni	10/1/1996	4/30/1997	212	1997
8	1997-irrig	5/1/1997	9/30/1997	153	1997
9	1998-ni	10/1/1997	4/30/1998	212	1998
10	1998-irrig	5/1/1998	9/30/1998	153	1998
11	1999-ni	10/1/1998	4/30/1999	212	1999
12	1999-irrig	5/1/1999	9/30/1999	153	1999
13	2000-ni	10/1/1999	4/30/2000	213	2000
14	2000-irrig	5/1/2000	9/30/2000	153	2000
15	2001-ni	10/1/2000	4/30/2001	212	2001
16	2001-irrig	5/1/2001	9/30/2001	153	2001
17	2002-ni	10/1/2001	4/30/2002	212	2002
18	2002-irrig	5/1/2002	9/30/2002	153	2002
19	2003-ni	10/1/2002	4/30/2003	212	2003
20	2003-irrig	5/1/2003	9/30/2003	153	2003
21	2004-ni	10/1/2003	4/30/2004	213	2004
22	2004-irrig	5/1/2004	9/30/2004	153	2004
23	2005-ni	10/1/2004	4/30/2005	212	2005
24	2005-irrig	5/1/2005	9/30/2005	153	2005
25	2006-ni	10/1/2005	4/30/2006	212	2006
26	2006-irrig	5/1/2006	9/30/2006	153	2006
27	2007-ni	10/1/2006	4/30/2007	212	2007
28	2007-irrig	5/1/2007	9/30/2007	153	2007
29	2008-ni	10/1/2007	4/30/2008	213	2008
30	2008-irrig	5/1/2008	9/30/2008	153	2008
31	2009-ni	10/1/2008	4/30/2009	212	2009
32	2009-irrig	5/1/2009	9/30/2009	153	2009
33	2010-ni	10/1/2009	4/30/2010	212	2010
34	2010-irrig	5/1/2010	9/30/2010	153	2010
Stress Period	**Tag**	**Start Date**	**End Date**	**Period Length (Days)**	**Water Year**
		Projection Period			
35	2011-ni	10/1/2010	4/30/2011	212	2011
36	2011-irrig	5/1/2011	9/30/2011	153	2011
37	2012-ni	10/1/2011	4/30/2012	213	2012
38	2012-irr	5/1/2012	9/30/2012	153	2012
39	2013-ni	10/1/2012	4/30/2013	212	2013
40	2013-irr	5/1/2013	9/30/2013	153	2013
41	2014-ni	10/1/2013	4/30/2014	212	2014
42	2014-irr	5/1/2014	9/30/2014	153	2014
43	2015-ni	10/1/2014	4/30/2015	212	2015
44	2015-irr	5/1/2015	9/30/2015	153	2015

Table 6.1 Stress Periods, continued

Stress Period	Tag	Start Date	End Date	Period Length (Days)	Water Year
45	2016-ni	10/1/2015	4/30/2016	213	2016
46	2016-irr	5/1/2016	9/30/2016	153	2016
47	2017-ni	10/1/2016	4/30/2017	212	2017
48	2017-irr	5/1/2017	9/30/2017	153	2017
49	2018-ni	10/1/2017	4/30/2018	212	2018
50	2018-irr	5/1/2018	9/30/2018	153	2018
51	2019-ni	10/1/2018	4/30/2019	212	2019
52	2019-irr	5/1/2019	9/30/2019	153	2019
53	2020-ni	10/1/2019	4/30/2020	213	2020
54	2020-irr	5/1/2020	9/30/2020	153	2020
55	2021-ni	10/1/2020	4/30/2021	212	2021
56	2021-irr	5/1/2021	9/30/2021	153	2021
57	2022-ni	10/1/2021	4/30/2022	212	2022
58	2022-irr	5/1/2022	9/30/2022	153	2022
59	2023-ni	10/1/2022	4/30/2023	212	2023
60	2023-irr	5/1/2023	9/30/2023	153	2023
61	2024-ni	10/1/2023	4/30/2024	213	2024
62	2024-irr	5/1/2024	9/30/2024	153	2024
63	2025-ni	10/1/2024	4/30/2025	212	2025
64	2025-irr	5/1/2025	9/30/2025	153	2025
65	2026-ni	10/1/2025	4/30/2026	212	2026
66	2026-irr	5/1/2026	9/30/2026	153	2026
67	2027-ni	10/1/2026	4/30/2027	212	2027
68	2027-irr	5/1/2027	9/30/2027	153	2027
69	2028-ni	10/1/2027	4/30/2028	213	2028
70	2028-irr	5/1/2028	9/30/2028	153	2028
71	2029-ni	10/1/2028	4/30/2029	212	2029
72	2029-irr	5/1/2029	9/30/2029	153	2029
73	2030-ni	10/1/2029	4/30/2030	212	2030
74	2030-irr	5/1/2030	9/30/2030	153	2030
75	2031-ni	10/1/2030	4/30/2031	212	2031
76	2031-irr	5/1/2031	9/30/2031	153	2031
77	2032-ni	10/1/2031	4/30/2032	213	2032
78	2032-irr	5/1/2032	9/30/2032	153	2032
79	2033-ni	10/1/2032	4/30/2033	212	2033
80	2033-irr	5/1/2033	9/30/2033	153	2033
81	2034-ni	10/1/2033	4/30/2034	212	2034
82	2034-irr	5/1/2034	9/30/2034	153	2034
83	2035-ni	10/1/2034	4/30/2035	212	2035
84	2035-irr	5/1/2035	9/30/2035	153	2035
85	2036-ni	10/1/2035	4/30/2036	213	2036
86	2036-irr	5/1/2036	9/30/2036	153	2036
87	2037-ni	10/1/2036	4/30/2037	212	2037
88	2037-irr	5/1/2037	9/30/2037	153	2037
89	2038-ni	10/1/2037	4/30/2038	212	2038
90	2038-irr	5/1/2038	9/30/2038	153	2038
91	2039-ni	10/1/2038	4/30/2039	212	2039

Table 6.1 Stress Periods, continued

Stress Period	Tag	Start Date	End Date	Period Length (Days)	Water Year
92	2039-irr	5/1/2039	9/30/2039	153	2039
93	2040-ni	10/1/2039	4/30/2040	213	2040
94	2040-irr	5/1/2040	9/30/2040	153	2040
95	2041-ni	10/1/2040	4/30/2041	212	2041
96	2041-irr	5/1/2041	9/30/2041	153	2041
97	2042-ni	10/1/2041	4/30/2042	212	2042
98	2042-irr	5/1/2042	9/30/2042	153	2042
99	2043-ni	10/1/2042	4/30/2043	212	2043
100	2043-irr	5/1/2043	9/30/2043	153	2043
101	2044-ni	10/1/2043	4/30/2044	213	2044
102	2044-irr	5/1/2044	9/30/2044	153	2044
103	2045-ni	10/1/2044	4/30/2045	212	2045
104	2045-irr	5/1/2045	9/30/2045	153	2045
105	2046-ni	10/1/2045	4/30/2046	212	2046
106	2046-irr	5/1/2046	9/30/2046	153	2046
107	2047-ni	10/1/2046	4/30/2047	212	2047
108	2047-irr	5/1/2047	9/30/2047	153	2047
109	2048-ni	10/1/2047	4/30/2048	213	2048
110	2048-irr	5/1/2048	9/30/2048	153	2048
111	2049-ni	10/1/2048	4/30/2049	212	2049
112	2049-irr	5/1/2049	9/30/2049	153	2049
113	2050-ni	10/1/2049	4/30/2050	212	2050
114	2050-irr	5/1/2050	9/30/2050	153	2050
115	2051-ni	10/1/2050	4/30/2051	212	2051
116	2051-irr	5/1/2051	9/30/2051	153	2051
117	2052-ni	10/1/2051	4/30/2052	213	2052
118	2052-irr	5/1/2052	9/30/2052	153	2052
119	2053-ni	10/1/2052	4/30/2053	212	2053
120	2053-irr	5/1/2053	9/30/2053	153	2053
121	2054-ni	10/1/2053	4/30/2054	212	2054
122	2054-irr	5/1/2054	9/30/2054	153	2054
123	2055-ni	10/1/2054	4/30/2055	212	2055
124	2055-irr	5/1/2055	9/30/2055	153	2055
125	2056-ni	10/1/2055	4/30/2056	213	2056
126	2056-irr	5/1/2056	9/30/2056	153	2056
127	2057-ni	10/1/2056	4/30/2057	212	2057
128	2057-irr	5/1/2057	9/30/2057	153	2057
129	2058-ni	10/1/2057	4/30/2058	212	2058
130	2058-irr	5/1/2058	9/30/2058	153	2058
131	2059-ni	10/1/2058	4/30/2059	212	2059
132	2059-irr	5/1/2059	9/30/2059	153	2059
133	2060-ni	10/1/2059	4/30/2060	213	2060
134	2060-irr	5/1/2060	9/30/2060	153	2060

Table 6.2. Groundwater Pumping per Stress Period (values in cubic meters per day unless otherwise noted)

Stress Period:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Days per stress period:	212	153	212	153	213	153	212	153	212	153	212	153	213	153	212	153	212
Municipal Pumping																	
Well name & field																	
Bailey 05 - Happy Jack	0	0	0	0	0	25	32	114	0	29	0	32	0	75	0	65	4
Conrey 01 - Happy Jack	398	981	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eddy 02 - Happy Jack	13	326	177	16	735	89	97	925	1,004	1,312	155	771	45	1,017	1,362	1,089	330
Elkar 01 - Happy Jack	200	184	31	33	0	71	882	445	12	245	42	195	0	7	0	43	1
Elkar 05 - Happy Jack	1,468	2,481	2,461	2,681	1,617	1,605	108	1,764	1,793	1,718	665	2,024	1,131	1,536	0	354	0
Happy Jack 03 - Happy Jack	66	800	0	355	0	907	8	10	0	0	1	30	0	409	0	445	50
Holman 01 - Happy Jack	706	995	303	0	0	3	1,107	532	1	0	0	446	31	582	0	641	313
King 01 - Happy Jack	0	0	0	0	0	11	2	272	0	375	0	660	54	414	0	285	6
King 02 - Happy Jack	0	132	0	325	0	347	1	122	0	144	0	0	0	0	0	0	0
King 04 - Happy Jack	0	264	1	890	0	385	1,711	646	343	1,194	179	1,263	169	1,157	250	980	50
King 05 - Happy Jack	120	714	0	648	0	559	9	0	0	617	10	244	0	71	0	167	6
Koppes 01 - Happy Jack	20	356	212	751	873	373	703	1,507	136	1,306	728	589	341	581	1,542	1,432	287
Koppes 02 - Happy Jack	1,376	1,640	1,628	1,780	1,736	3,843	1,454	458	2,027	2,535	1,880	2,098	501	2,380	0	2,157	1,676
Koppes 03 - Happy Jack	558	968	819	1,086	1,130	1,003	616	749	601	470	159	1,713	140	696	32	1,040	461
Koppes 04 - Happy Jack	20	754	0	729	560	927	850	457	0	583	84	236	0	451	254	920	518
Koppes 06 - Happy Jack	405	756	643	415	653	434	314	246	0	418	1	173	304	423	0	313	25
Merritt 05 - Federal	0	352	0	616	102	690	11	703	11	207	0	399	378	380	0	268	5
Merritt 06 - Federal	477	626	247	650	50	714	18	532	22	740	93	361	99	1	0	461	8
Merritt 08 - Federal	1,314	1,586	915	1,569	151	1,464	40	688	847	1,039	775	229	3,798	696	1,224	690	1,400
Merritt 09 - Federal	639	969	204	402	96	532	28	184	8	168	0	0	0	305	1,786	319	12
Merritt 14 - Federal	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Merritt 15 - Federal	68	949	228	575	111	489	53	1,071	75	773	0	604	45	636	0	698	58
State 01 - Federal	164	158	44	47	62	68	4	0	0	124	1,783	0	0	0	0	0	0
State 02 - Federal	1,084	1,511	486	410	146	949	45	395	26	885	282	341	0	0	0	494	34
Bell 05 - Bell	417	888	466	530	163	323	256	577	230	675	395	754	17	524	0	1,163	690
Bell 06 - Bell	0	1,499	2	518	0	580	0	213	499	1,620	419	455	912	1,796	1,676	1,505	44
Bell 08 - Bell	0	317	0	160	0	169	0	183	433	1,636	296	1,392	1,704	1,276	0	1,361	141
Bell 10 - Bell	228	678	5	164	0	175	0	196	43	848	241	981	91	868	0	367	4
Bell 11 - Bell	2,843	2,408	30	1,006	0	1,715	0	1,356	1,717	2,644	1,788	196	682	2,515	1,272	2,737	320
Bell 12 - Bell	38	1,826	3	580	0	1,017	0	699	0	1,504	0	1,200	86	1,581	0	1,580	57
Bell 17 - Bell	34	1,584	2	460	0	568	0	575	636	1,530	366	1,095	429	1,570	0	1,145	53
Federal 16 - Bell	525	1,934	686	1,639	878	1,495	792	1,878	1,051	2,263	169	2,295	541	2,349	9	1,504	82
Federal 24 - Bell	4	317	0	160	0	169	0	183	0	344	0	196	17	524	0	321	4
Federal 25 - Bell	75	1,638	474	1,097	125	1,274	487	1,306	628	1,557	97	830	17	1,725	982	1,410	695
Subtotal, Municipal Pumping	*13,262*	*30,597*	*10,114*	*20,292*	*9,189*	*22,972*	*9,629*	*18,982*	*12,143*	*29,504*	*10,605*	*21,804*	*11,529*	*26,543*	*10,388*	*25,955*	*7,333*
Subtotal in ac-ft per stress period	*2,279*	*3,795*	*1,738*	*2,517*	*1,587*	*2,849*	*1,655*	*2,355*	*2,087*	*3,660*	*1,823*	*2,704*	*1,991*	*3,292*	*1,785*	*3,219*	*1,260*

Table 6.2. Groundwater Pumping per Stress Period, continued

Stress Period:	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Days per stress period:	153	212	153	213	153	212	153	212	153	212	153	213	153	212	153	212	153
Municipal Pumping Well name & field																	
Bailey 05 - Happy Jack	3	0	0	0	0	0	0	0	0	0	2,076	0	0	0	0	0	0
Conrey 01 - Happy Jack	0	0	0	0	0	0	0	0	0	0	0	0	49	0	0	0	0
Eddy 02 - Happy Jack	1,198	1,067	737	957	977	518	338	28	649	121	0	0	431	0	0	0	189
Elkar 01 - Happy Jack	181	0	8	0	0	0	0	0	0	0	362	0	355	0	0	31	26
Elkar 05 - Happy Jack	285	190	275	0	258	16	1,176	141	1,585	154	617	0	354	147	5,236	738	892
Happy Jack 03 - Happy Jack	148	7	739	164	905	552	602	755	855	57	881	921	631	257	769	35	616
Holman 01 - Happy Jack	732	0	246	0	1	4	0	0	8	0	0	0	0	0	4,252	2,430	1,099
King 01 - Happy Jack	367	0	16	0	0	0	0	0	0	0	309	0	413	502	513	12	438
King 02 - Happy Jack	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
King 04 - Happy Jack	1,199	667	1,010	848	1,175	736	1,287	398	1,459	563	1,649	1,631	1,047	745	1,320	535	1,033
King 05 - Happy Jack	124	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	5,954
Koppes 01 - Happy Jack	675	254	802	0	904	1,784	1,330	0	680	26	1,011	0	1,073	679	708	137	46
Koppes 02 - Happy Jack	1,888	1,172	1,435	1,532	1,909	510	1,168	1,777	1,990	1,876	1,673	458	1,261	661	0	525	1,654
Koppes 03 - Happy Jack	949	38	703	801	230	0	0	0	0	0	0	0	0	0	0	0	0
Koppes 04 - Happy Jack	1,052	0	476	743	19	42	1,068	149	1,690	623	1,366	128	1,481	1,145	1,389	1,359	857
Koppes 06 - Happy Jack	0	0	17	1	0	0	105	0	0	0	0	0	0	0	0	0	189
Merritt 05 - Federal	19	0	0	1,778	28	4	407	0	625	32	397	0	152	0	383	0	333
Merritt 06 - Federal	520	1	180	31	307	160	339	22	499	89	507	30	682	157	463	40	283
Merritt 08 - Federal	1,406	1,427	881	15	3	6	2,687	16	768	147	892	0	735	0	926	0	1,105
Merritt 09 - Federal	135	11	15	0	0	0	0	0	0	0	0	0	2,263	0	382	0	256
Merritt 14 - Federal	176	0	0	7	0	18	104	10	278	68	119	0	237	21	250	0	107
Merritt 15 - Federal	132	0	22	0	8	0	2	3	674	35	824	0	580	87	1,186	0	595
State 01 - Federal	0	0	0	0	0	0	0	0	0	0	0	0	1,356	0	0	0	152
State 02 - Federal	1,069	143	282	0	691	9	599	21	731	132	868	0	419	192	1,149	63	836
Bell 05 - Bell	1,507	632	162	568	416	377	726	0	279	0	839	0	682	795	1,384	840	1,376
Bell 06 - Bell	1,537	113	1,242	564	1,178	148	380	0	415	0	165	0	279	0	309	158	1,498
Bell 08 - Bell	1,265	0	162	0	176	34	179	0	164	0	165	4	1,070	705	769	12	1,042
Bell 10 - Bell	424	0	161	0	176	0	159	1	913	124	1,061	125	1,196	607	1,264	870	1,415
Bell 11 - Bell	3,510	1,077	2,442	1,628	2,491	111	2,590	996	2,206	1,602	4,425	0	1,694	441	2,321	82	2,296
Bell 12 - Bell	1,463	143	1,209	0	978	4	751	95	1,222	0	737	1	726	800	892	497	1,406
Bell 17 - Bell	1,488	142	970	292	915	14	533	1	695	3	638	0	545	120	699	42	838
Federal 16 - Bell	575	133	536	0	632	13	1,105	58	1,176	105	817	0	1,098	43	1,290	0	1,135
Federal 24 - Bell	424	0	161	0	176	0	159	0	164	0	165	0	7,377	0	309	0	519
Federal 25 - Bell	1,837	578	666	0	275	15	938	57	728	91	334	0	978	43	1,273	0	977
Subtotal, Municipal Pumping	*26,288*	*7,795*	*15,566*	*9,930*	*14,829*	*5,074*	*18,731*	*4,527*	*20,453*	*5,849*	*22,897*	*3,298*	*29,164*	*8,149*	*29,434*	*8,406*	*29,164*
Subtotal in ac-ft per stress period	*3,261*	*1,340*	*1,931*	*1,715*	*1,839*	*872*	*2,323*	*778*	*2,537*	*1,005*	*2,840*	*570*	*3,617*	*1,401*	*3,651*	*1,445*	*3,618*

Table 6.2. Groundwater Pumping per Stress Period, continued

Stress Period:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Days per stress period:	212	153	212	153	213	153	212	153	212	153	212	153	213	153	212	153	212
Small Community Water Supply																	
Well name																	
Albin-1	102	146	67	128	59	146	73	182	101	282	116	200	128	209	142	318	125
Albin-2	30	44	20	38	18	44	22	55	30	84	35	60	39	63	43	95	37
Albin-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Burns	214	643	214	643	213	643	214	643	214	643	214	643	213	711	145	635	160
PineBluffs-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PineBluffs-2	444	1,316	444	1,316	442	1,293	444	1,293	444	1,293	444	1,293	442	1,435	302	1,276	333
PineBluffs-3	167	495	167	495	166	524	167	524	167	524	167	524	166	577	114	517	125
PineBluffs-4	132	391	132	391	131	384	132	384	132	384	132	384	131	426	90	379	99
Orchard Valley Water	0	129	0	129	0	129	0	129	0	129	0	129	0	129	0	129	0
Winchester Hills-1	0	227	0	227	0	227	0	227	0	227	0	227	0	227	0	227	0
Winchester Hills-2	0	75	0	75	0	75	0	75	0	75	0	75	0	75	0	75	0
Carpenter	0	0	0	0	0	16	0	32	0	32	0	32	0	32	0	32	0
Hide-A-Way Mobile Village	0	6	0	6	0	6	0	6	0	6	0	6	0	6	0	6	0
Avalone Mobile Village	0	13	0	13	0	13	0	13	0	13	0	13	0	13	0	13	0
Subtotal, Small Community Pumping	1,089	3,483	1,045	3,460	1,029	3,498	1,052	3,562	1,088	3,692	1,108	3,586	1,120	3,903	836	3,702	880
Subtotal in ac-ft per stress period	*187*	*432*	*180*	*429*	*178*	*434*	*181*	*442*	*187*	*458*	*190*	*445*	*193*	*484*	*144*	*459*	*151*
Rural Domestic																	
Total rural domestic	0	5,663	0	5,912	0	6,167	0	6,381	0	6,691	0	6,933	0	7,214	0	7,480	0
Subtotal in ac-ft per stress period	*0*	*702*	*0*	*733*	*0*	*765*	*0*	*792*	*0*	*830*	*0*	*860*	*0*	*895*	*0*	*928*	*0*
Industrial																	
DynoNobel	395	343	406	2,365	1,137	1,341	1,355	2,064	1,705	2,281	1,913	1,980	1,803	2,145	1,715	1,849	1,572
Subtotal in ac-ft per stress period	*68*	*42*	*70*	*293*	*196*	*166*	*233*	*256*	*293*	*283*	*329*	*246*	*311*	*266*	*295*	*229*	*270*
Irrigation																	
Total irrigation pumping	0	677,516	0	271,702	0	392,174	0	347,947	0	521,747	0	278,619	0	659,269	0	382,918	0
Subtotal in ac-ft per stress period	*0*	*84,038*	*0*	*33,702*	*0*	*48,645*	*0*	*43,159*	*0*	*64,717*	*0*	*34,560*	*0*	*81,775*	*0*	*47,497*	*0*
Total pumping per stress period, m3/d	14,746	717,601	11,565	303,730	11,356	426,152	12,035	378,937	14,936	563,914	13,626	312,922	14,451	699,075	12,939	421,904	9,784
Total pumping per stress period, ac-ft	2,534	89,011	1,988	37,674	1,961	52,859	2,069	47,003	2,567	69,947	2,342	38,815	2,495	86,713	2,224	52,333	1,682

Table 6.2. Groundwater Pumping per Stress Period, continued

Stress Period:	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Days per stress period:	153	212	153	213	153	212	153	212	153	212	153	213	153	212	153	212	153
Small Community Water Supply																	
Well name																	
Albin-1	326	164	241	121	199	101	201	102	201	102	201	79	0	0	0	0	0
Albin-2	98	49	72	36	60	30	60	30	60	30	60	40	155	78	155	78	155
Albin-3	0	0	0	0	0	0	0	0	0	0	0	13	107	54	107	54	107
Burns	738	259	530	242	643	191	570	180	707	214	792	225	706	230	464	290	578
PineBluffs-1	0	0	0	0	0	0	0	0	0	0	0	0	141	48	91	60	114
PineBluffs-2	1,490	538	1,057	503	1,278	397	1,127	375	1,716	541	1,930	568	1,612	547	1,036	689	1,306
PineBluffs-3	598	202	435	189	543	149	487	141	708	203	788	213	669	206	452	259	554
PineBluffs-4	443	160	314	150	380	118	335	111	0	0	0	0	0	0	0	0	0
Orchard Valley Water	129	0	129	0	129	0	129	0	129	0	129	0	129	0	129	0	129
Winchester Hills-1	227	0	227	0	227	0	227	0	227	0	227	0	227	0	227	0	227
Winchester Hills-2	75	0	75	0	75	0	75	0	75	0	75	0	75	0	75	0	75
Carpenter	32	0	32	0	32	0	32	0	32	0	32	0	32	0	32	0	32
Hide-A-Way Mobile Village	6	0	6	0	6	0	6	0	6	0	6	0	6	0	6	0	6
Avalone Mobile Village	13	0	13	0	13	0	13	0	13	0	13	0	13	0	13	0	13
Subtotal, Small Community Pumping	4,174	1,373	3,131	1,241	3,584	986	3,262	939	3,874	1,091	4,253	1,137	3,871	1,163	2,785	1,430	3,295
Subtotal in ac-ft per stress period	*518*	*236*	*388*	*214*	*445*	*169*	*405*	*161*	*481*	*187*	*528*	*196*	*480*	*200*	*345*	*246*	*409*
Rural Domestic																	
Total rural domestic	7,818	0	8,169	0	8,572	0	8,974	0	9,272	0	9,509	0	9,703	0	9,801	0	9,946
Subtotal in ac-ft per stress period	*970*	*0*	*1,013*	*0*	*1,063*	*0*	*1,113*	*0*	*1,150*	*0*	*1,179*	*0*	*1,204*	*0*	*1,216*	*0*	*1,234*
Industrial																	
DynoNobel	1,797	1,569	1,542	1,096	1,051	571	398	370	458	636	390	410	757	620	1,311	891	1,448
Subtotal in ac-ft per stress period	*223*	*270*	*191*	*189*	*130*	*98*	*49*	*64*	*57*	*109*	*48*	*71*	*94*	*106*	*163*	*153*	*180*
Irrigation																	
Total irrigation pumping	556,380	0	426,742	0	454,102	0	457,625	0	622,016	0	391,646	0	388,481	0	246,059	0	387,367
Subtotal in ac-ft per stress period	*69,013*	*0*	*52,933*	*0*	*56,326*	*0*	*56,763*	*0*	*77,154*	*0*	*48,579*	*0*	*48,187*	*0*	*30,521*	*0*	*48,049*
Total pumping per stress period, m3/d	596,457	10,737	455,149	12,267	482,138	6,631	488,990	5,836	656,074	7,576	428,696	4,846	431,977	9,932	289,391	10,728	431,220
Total pumping per stress period, ac-ft	73,984	1,845	56,456	2,118	59,804	1,140	60,654	1,003	81,379	1,302	53,175	837	53,582	1,707	35,896	1,844	53,488

Table 6.3 - Transient Calibration Statistics (Head Targets)	
Residual Mean (m)	3.28
Residual Standard Deviation (m)	10.15
Absolute Residual Mean (m)	6.25
Residual Sum of Squares (m^2)	6850000
RMS Error (m^2)	10.67
Minimum Residual (m)	-22.89
Maximum Residual (m)	33.55
Range of Observations (m)	449.39
Number of Observations	60147

Table 6.4 Transient Water Budget (ac-ft per water year)

	Water Year (October - September)																
Inflows	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Precipitation	57,000	99,800	83,000	91,000	76,300	88,900	55,000	73,300	47,400	73,500	65,000	77,100	64,500	73,200	78,200	91,600	87,200
Underflow	2,300	2,200	2,200	2,200	2,200	2,200	2,300	2,200	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,200	2,200
Stream losses																	
to Horse Creek	700	500	500	500	700	500	800	700	800	700	700	700	900	700	600	500	500
to all other streams	15,300	14,800	15,200	14,900	15,200	15,400	14,300	14,800	13,800	13,700	13,200	13,900	14,000	13,500	13,700	14,500	14,600
Change in storage	103,800	7,200	40,600	25,500	60,300	16,900	91,700	36,800	80,800	39,700	51,300	40,700	71,200	33,700	31,800	6,700	29,900
Total in	**179,000**	**124,500**	**141,500**	**134,000**	**154,600**	**123,800**	**164,200**	**127,800**	**145,100**	**129,800**	**132,400**	**134,600**	**152,900**	**123,500**	**126,600**	**115,600**	**134,500**
Outflows																	
Underflow																	
to Nebraska	8,800	8,800	8,800	8,800	8,700	8,700	8,600	8,500	8,400	8,400	8,400	8,400	8,300	8,300	8,300	8,400	8,400
to Horse Creek basin	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Stream gains																	
to Horse Creek	20,900	20,300	20,800	20,700	20,300	20,500	19,900	19,600	19,600	19,600	19,800	19,800	19,400	19,500	20,100	20,700	20,800
to all other streams	51,600	49,800	51,100	49,600	47,400	47,700	40,800	39,600	35,900	38,100	36,800	39,200	37,400	35,900	38,500	43,600	44,800
Surface runoff	4,700	4,500	4,400	4,400	4,300	4,200	4,100	4,000	3,900	3,900	3,900	3,900	3,800	3,800	3,800	3,800	3,800
Groundwater pumping	91,600	39,700	54,800	49,100	72,500	41,200	89,200	54,600	75,700	58,300	61,900	61,800	82,400	54,500	54,400	37,600	55,300
Total out	**179,100**	**124,600**	**141,500**	**134,000**	**154,600**	**123,900**	**164,200**	**127,800**	**145,100**	**129,800**	**132,300**	**134,600**	**152,900**	**123,500**	**126,600**	**115,500**	**134,500**

Table 6.5. Average Modeled Groundwater Consumptive Use

Average from Transient Model		Conceptual Equalities					
Modeled Use Category	Acre-Feet per Year(1), (2)	Annualized Rate (Gallons per Minute)	Acre-Feet per Acre	Water Column in Inches	Gallons per Acre	Gallons per Person per Day	Gallons per Household per Day(4)
Irrigation	54,450	33,650	0.93	11.16	303,041	n/a	n/a
Municipal(3)	4,430	2,740	n/a	n/a	n/a	59	238
Domestic/Stock/Miscellaneous	980	610	n/a	n/a	n/a	85	340
Small Water Supply	630	390	n/a	n/a	n/a	n/a	n/a
Industrial	360	220	n/a	n/a	n/a	n/a	n/a

Notes:

(1) Modeled acre-feet per year derived from a simple average over the 17-year calibration period

(2) For more detailed breakdown of consumptive use by stress period, see Table 6.2

(3) Assumed population of 66,552 obtained from the 2013 Cheyenne Water and Wastewater Master Plans, Final Draft- Volume 3, Water Supply and Delivery (9/20/13, prepared for City of Cheyenne BOPU by HDR Engineering, AMEC, and AVI Professional Corporation), and represents year 2003. Municipal use includes commercial and industrial entities on City water.

(4) Based on a four-person household

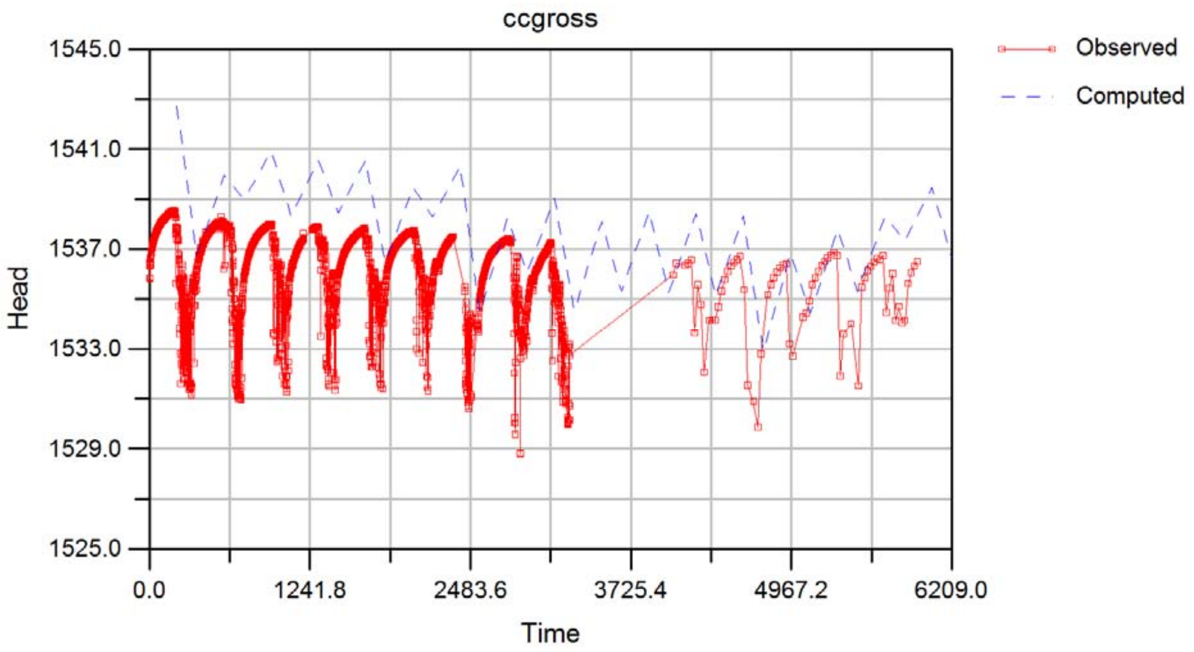
Table 7.1 Summary of Baseline Scenario Groundwater Demand Assumptions

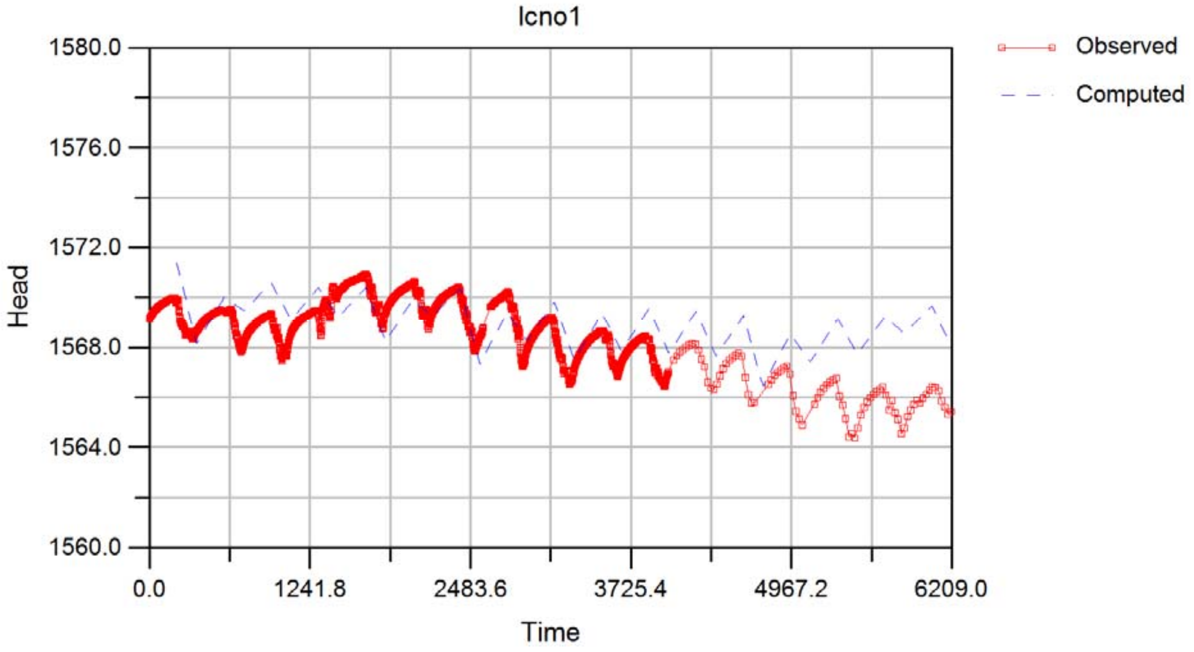
Cities and Towns	Demand Description
Cheyenne	5,000 af/yr of new withdrawals by 2033: 1,000 from the Bell well field, 2,000 from outside the model domain, and 2,000 from a new northern well field
Pine Bluffs	159 af/yr of new withdrawals by 2060 based on population projections
Burns	55 af/yr of new withdrawals by 2060 based on population projections
Albin	22 af/yr of new withdrawals by 2060 based on population projections
Small Community Water Supplies	
Winchester Hills	15 af/yr of new withdrawals by 2060 based on population projections
Orchard Valley	6 af/yr of new withdrawals by 2060 based on population projections
Carpenter W&S	1.6 af/yr of new withdrawals by 2060 based on population projections
Avalon Mobile Home Park	0 af/yr of new withdrawals
Hideaway Mobile Home Park	0 af/yr of new withdrawals
Rural Domestic	
Rural Density	174 af/yr of new withdrawals by 2060 based on population projections and County Land Use Plan
Rural Low Density	179 af/yr of new withdrawals by 2060 based on population projections and County Land Use Plan
Rural Very Low Density	61 af/yr of new withdrawals by 2060 based on population projections and County Land Use Plan
Irrigation	
All GW irrigation	117 af/yr of new permitted irrigation pumping, scales to 48.5 af/yr of consumptive use based on 1993-2010 permitted yield to consumptive use ratio
Industrial/Misc	
"Campstool Rd industrial area"	78.4 af/yr of new withdrawals
"Archer"	39.2 af/yr of new withdrawals
"Round Top"	29.4 af/yr of new withdrawals
"Hillsdale"	9.8 af/yr of new withdrawals
"Burns"	9.8 af/yr of new withdrawals
"Pine Bluffs"	9.8 af/yr of new withdrawals
"Hwy 85 / I-25"	9.8 af/yr of new withdrawals
"Hwy 85 / Terry Ranch"	9.8 af/yr of new withdrawals

Hydrogeologic Study
of the
Laramie County Control Area

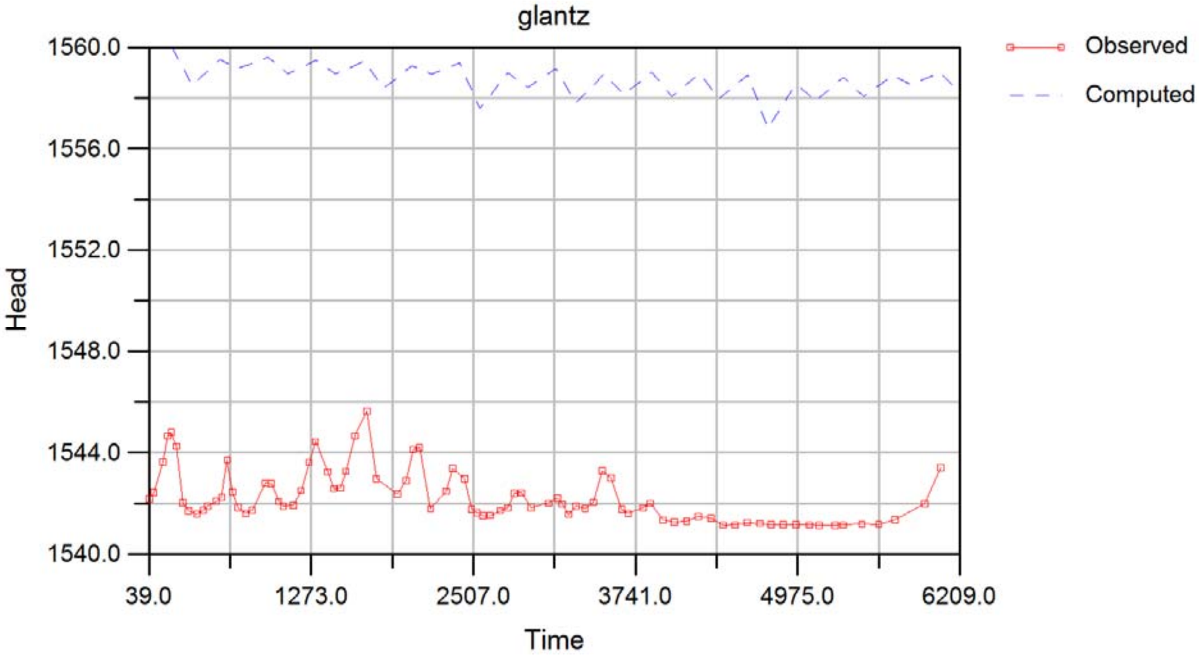
APPENDIX A

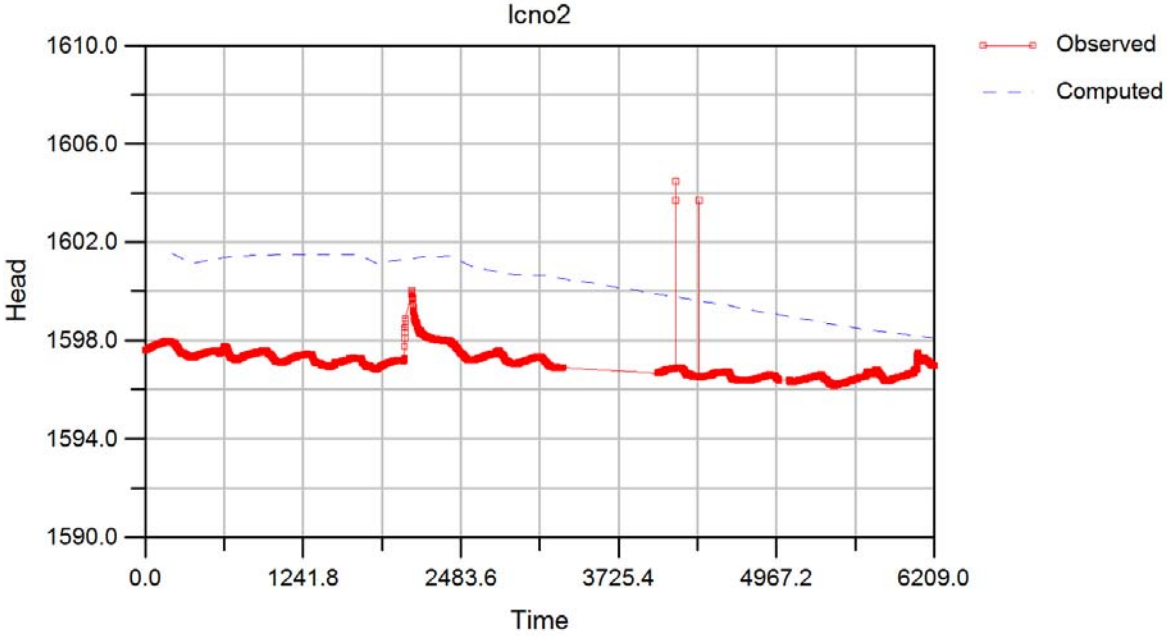
GROUNDWATER CONTROL AREA DISTRICT 1



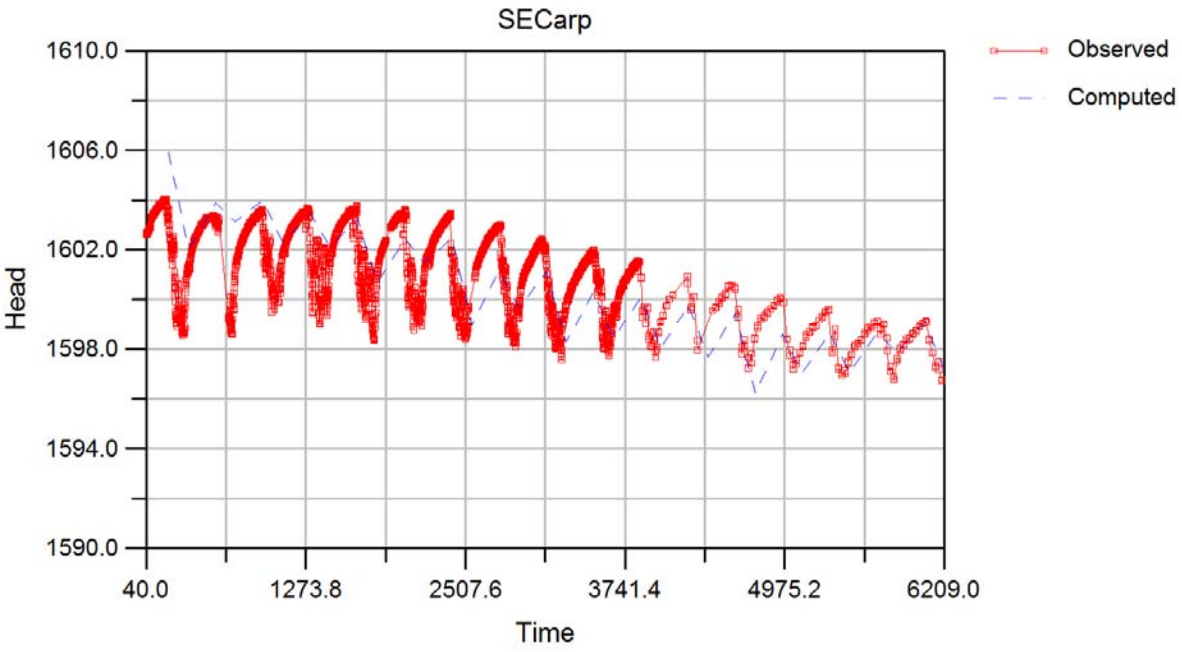


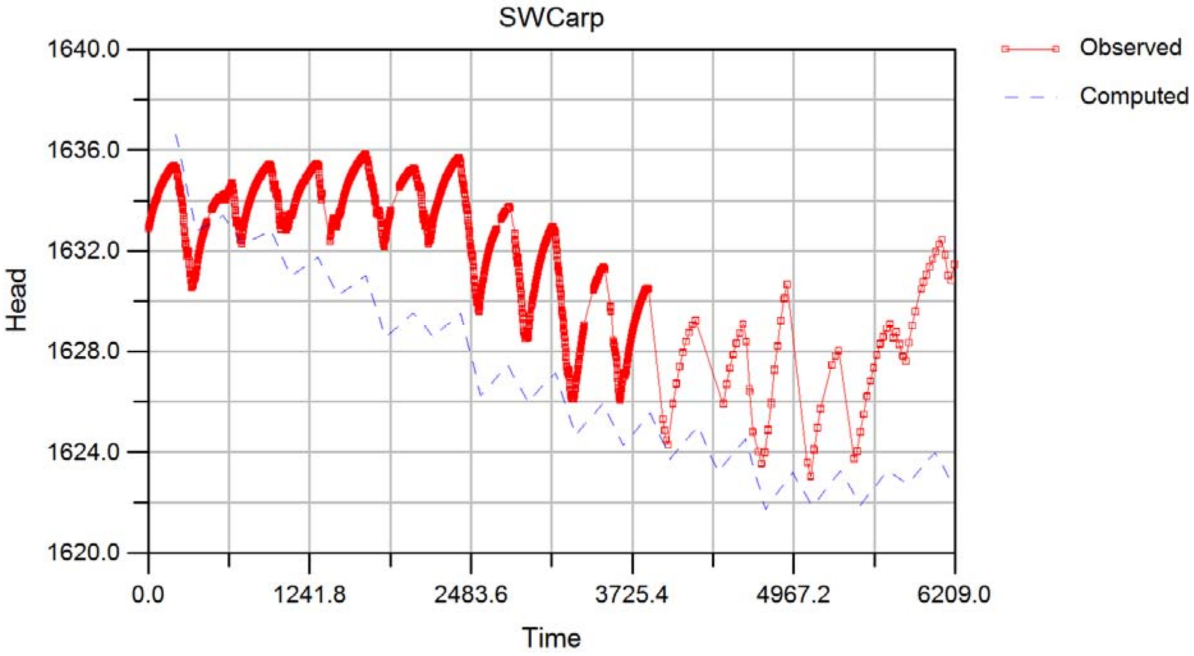
GROUNDWATER CONTROL AREA DISTRICT 1



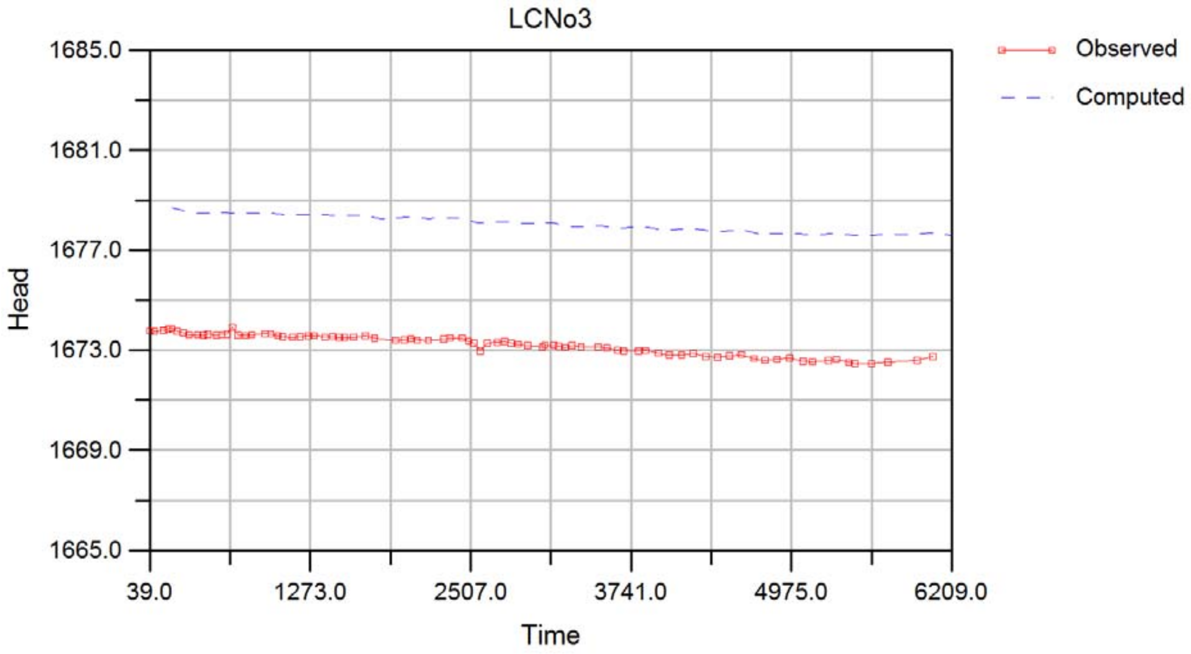


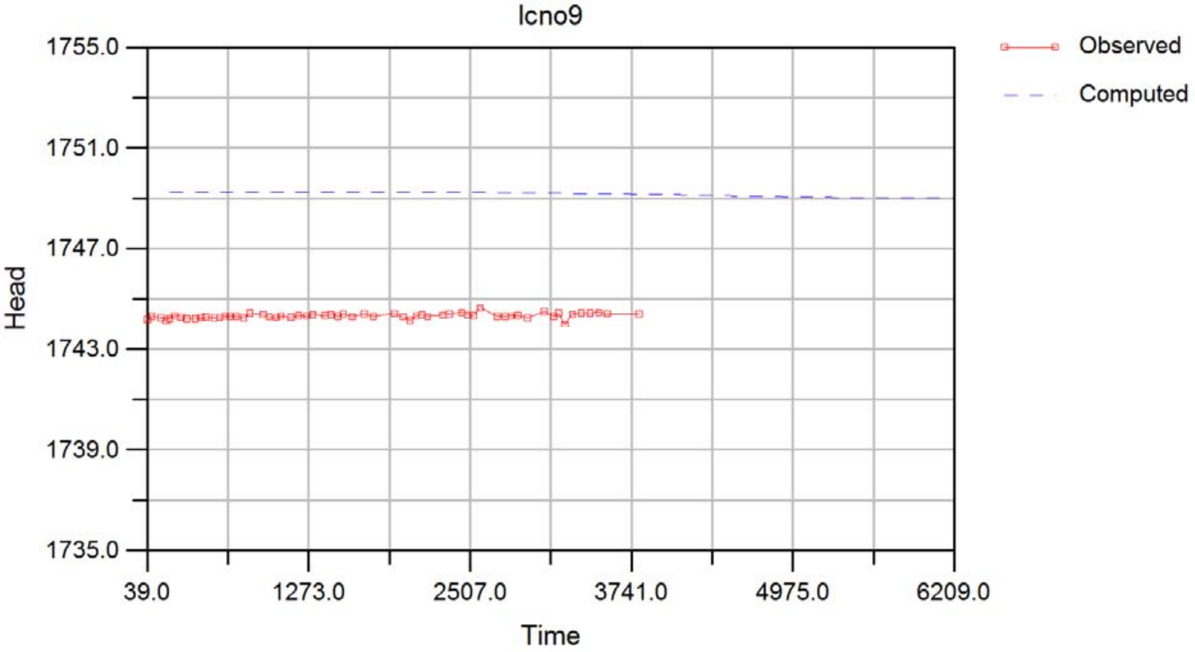
GROUNDWATER CONTROL AREA DISTRICT 2



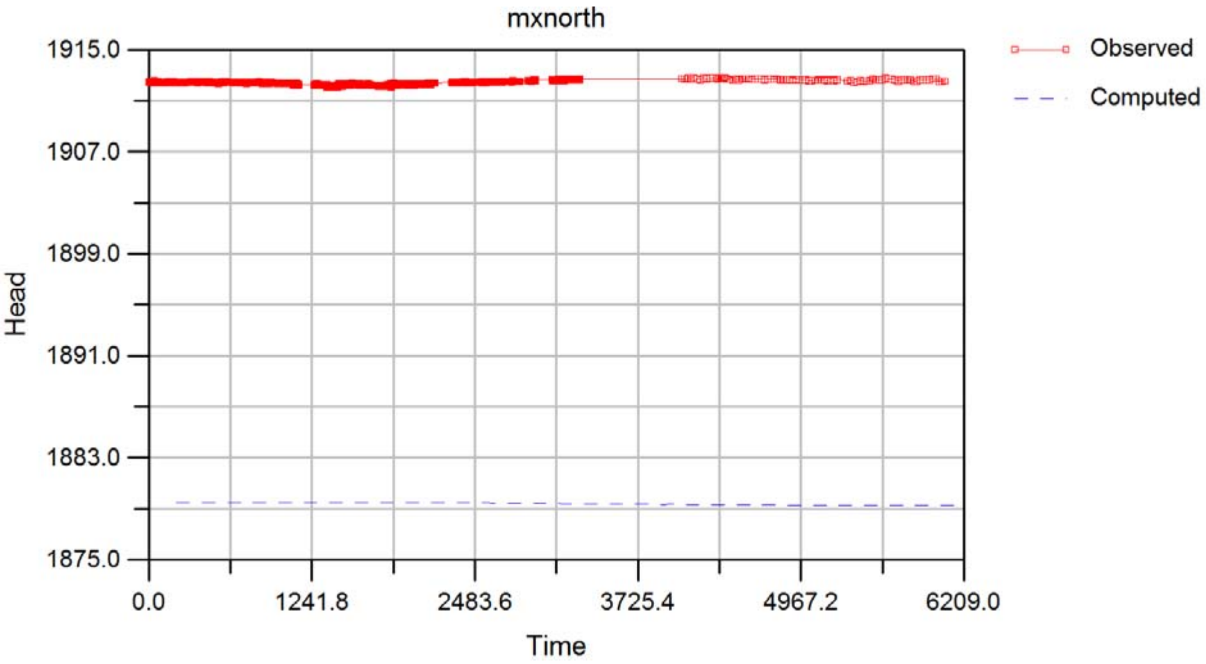


GROUNDWATER CONTROL AREA DISTRICT 3

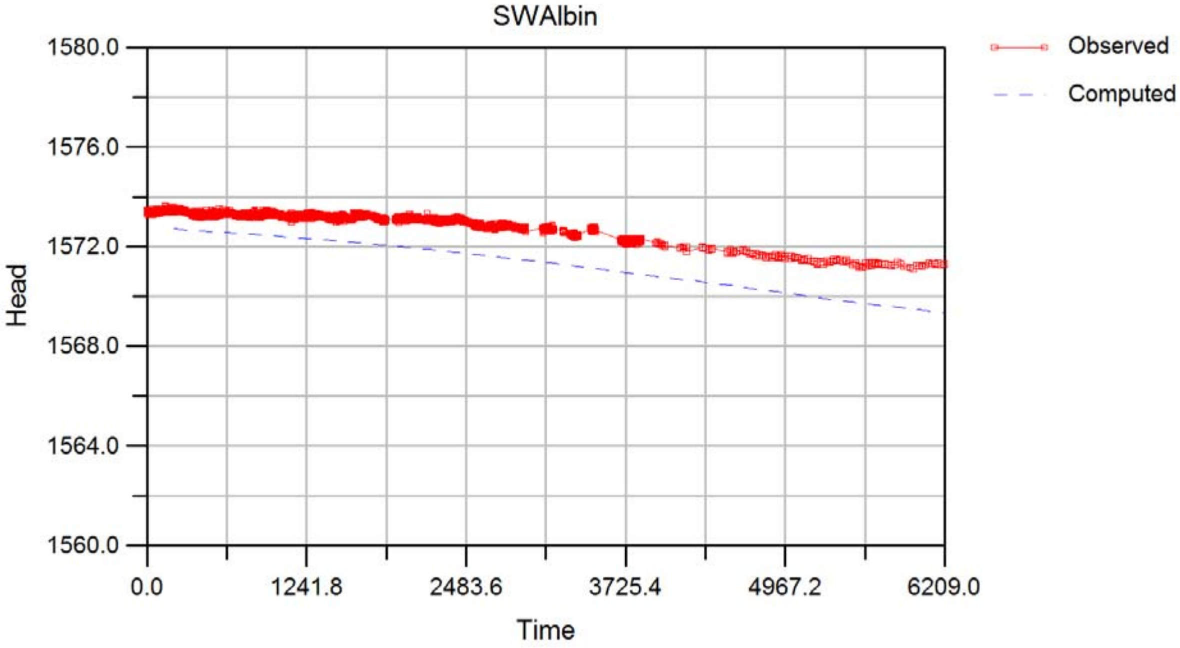


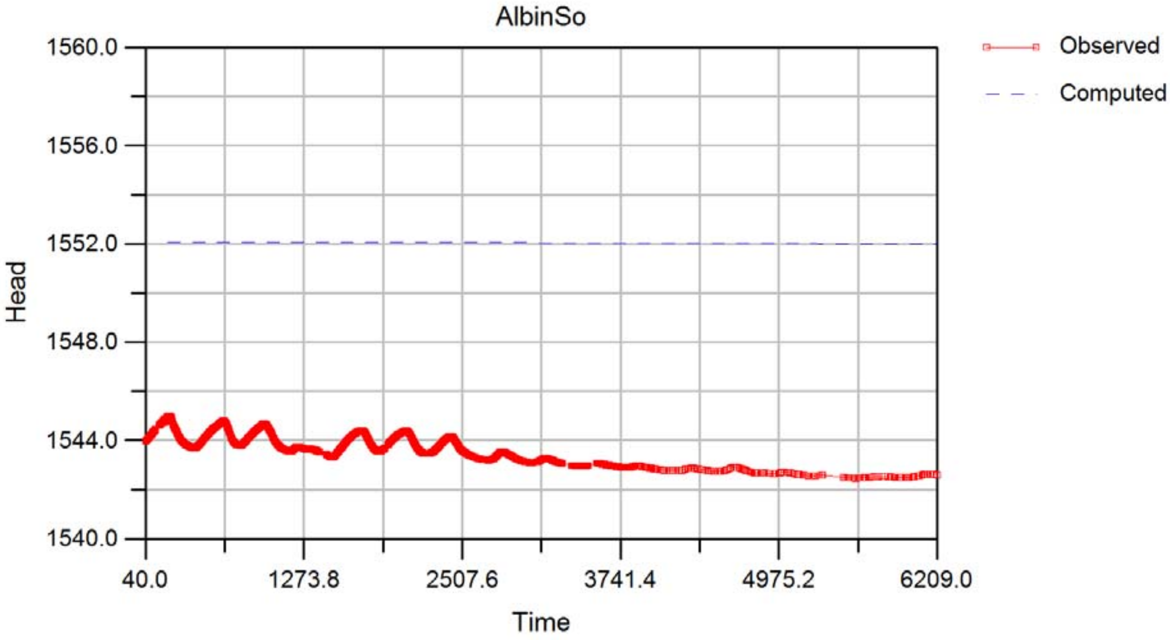


GROUNDWATER CONTROL AREA DISTRICT 4

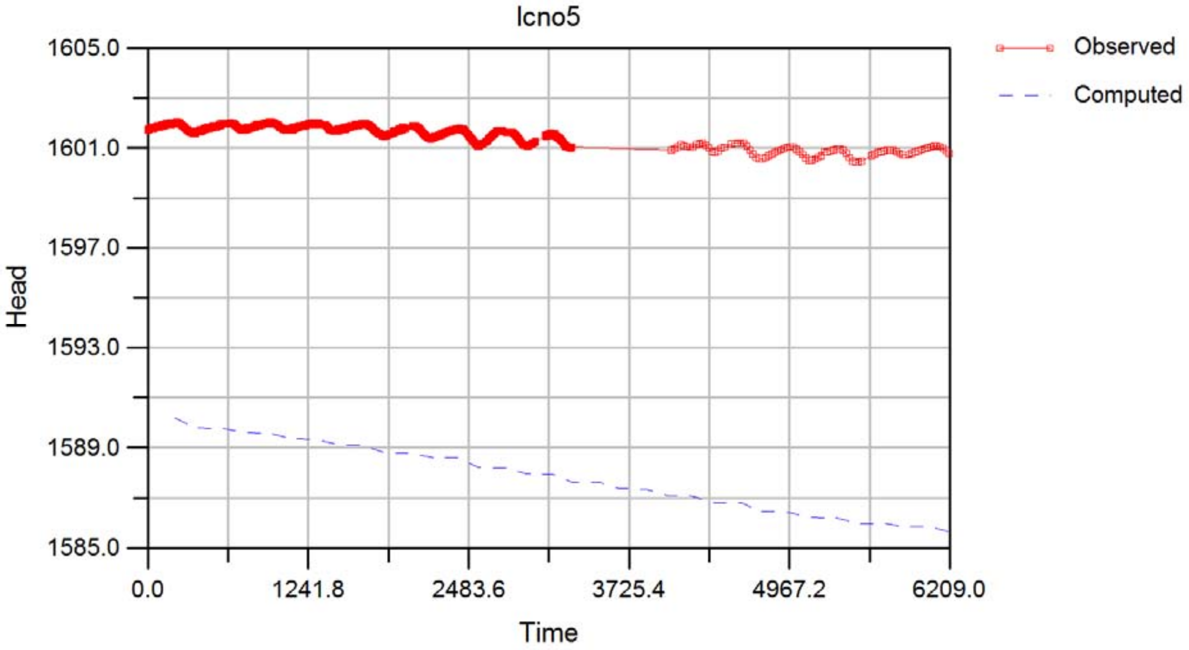


GROUNDWATER CONTROL AREA DISTRICT 5

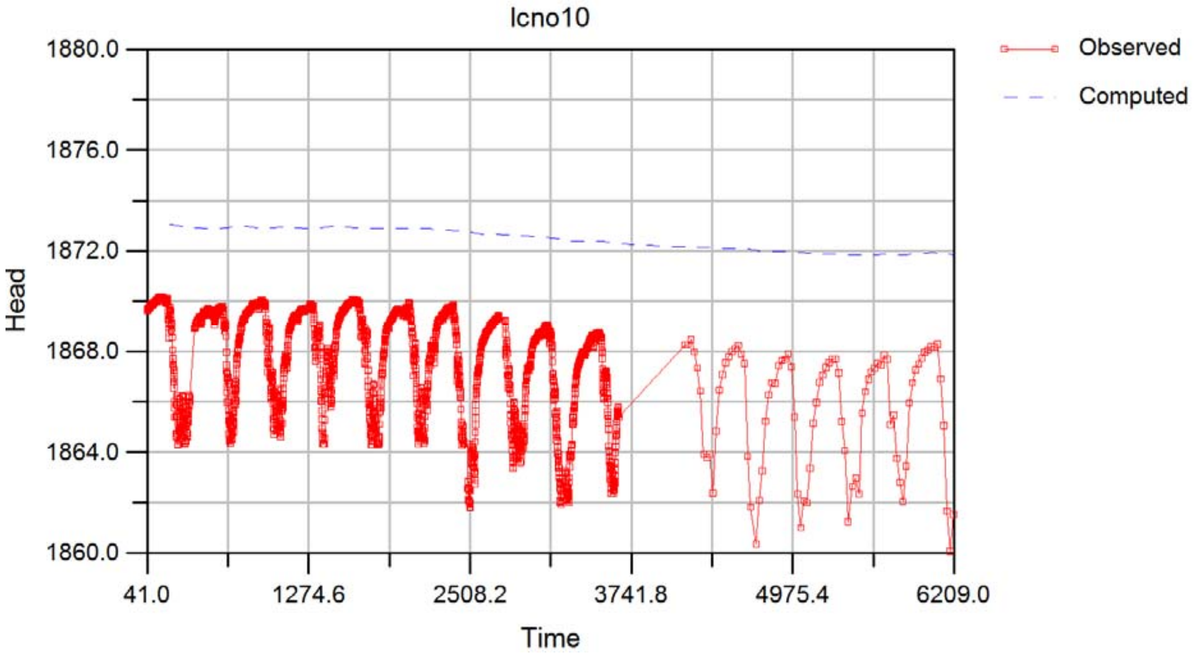


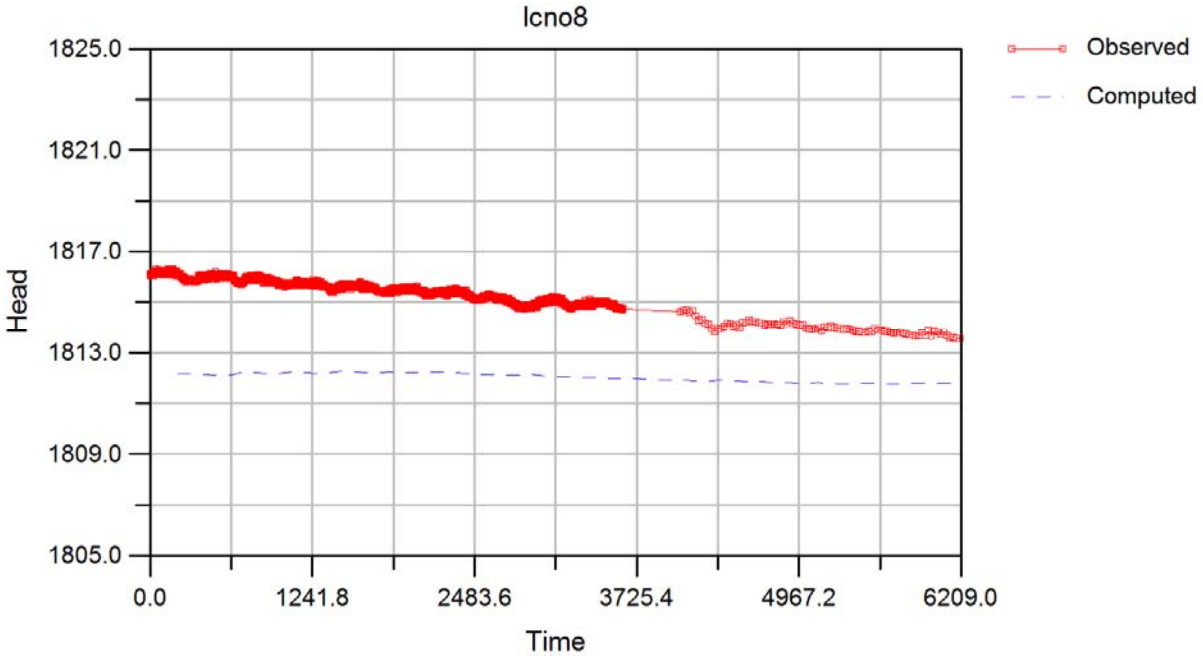


GROUNDWATER CONTROL AREA DISTRICT 5

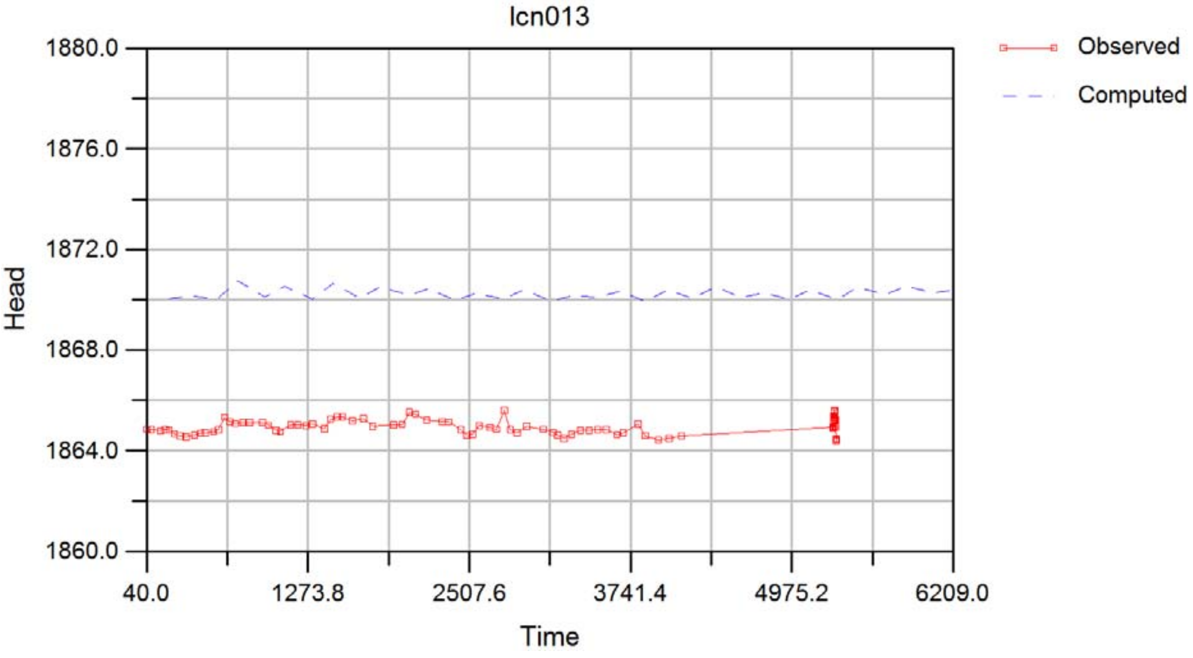


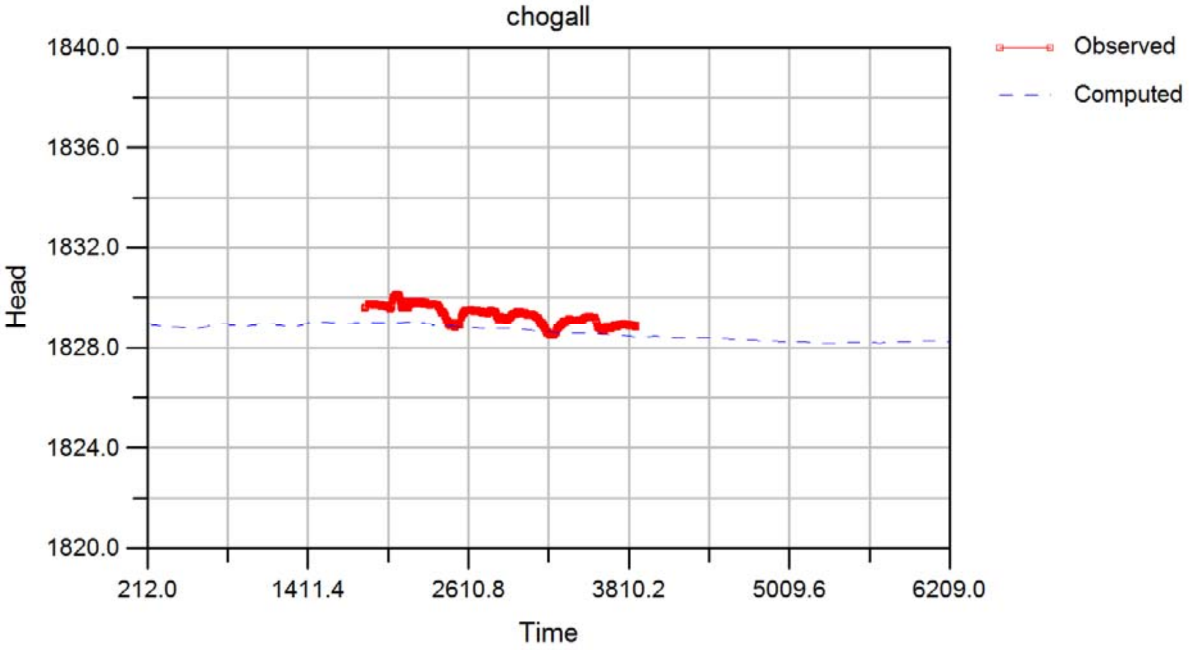
OUTSIDE GROUNDWATER CONTROL AREA





OUTSIDE GROUNDWATER CONTROL AREA





OUTSIDE GROUNDWATER CONTROL AREA