7. Groundwater Model

The purpose of the COHYST 2010 groundwater model is to simulate the response of the aquifer system to changes in pumping and recharge across the agriculture-dominated central Platte River basin. This section describes changes made to the initial model that was built by DNR and documented in the 2013 report. Sections 7.1 through 7.3 of this report describe changes made to the groundwater model to address specific issues, improve the simulation of the Platte River, improve the integration with the surface water model and watershed model, and solve logistical problems with operating the model. Sections 7.4 and 7.5 describe the methods used for optimizing the groundwater model and the optimization results. Section 7.6 describes the extension of the model through the 2006-2010 period and Section 7.7 describes a focused study of problems in Gosper and Phelps Counties.

7.1 2013 Adjustments to Address Specific Issues

Shortly after completing the 2013 model, the modeling team undertook seven tasks to address known concerns in that model. Three of these tasks were directly related to the groundwater model and were completed in 2013: adjust riparian ET, integrate Lake McConaughy seepage between the surface water model and groundwater model, and correct high groundwater levels near Sutherland Reservoir. A fourth task, to improve the ability to model dry river conditions that occur in times and places between Overton and Duncan was not completed until 2016; see discussion on baseflow comparisons in Section 7.5.

7.1.1 Evapotranspiration

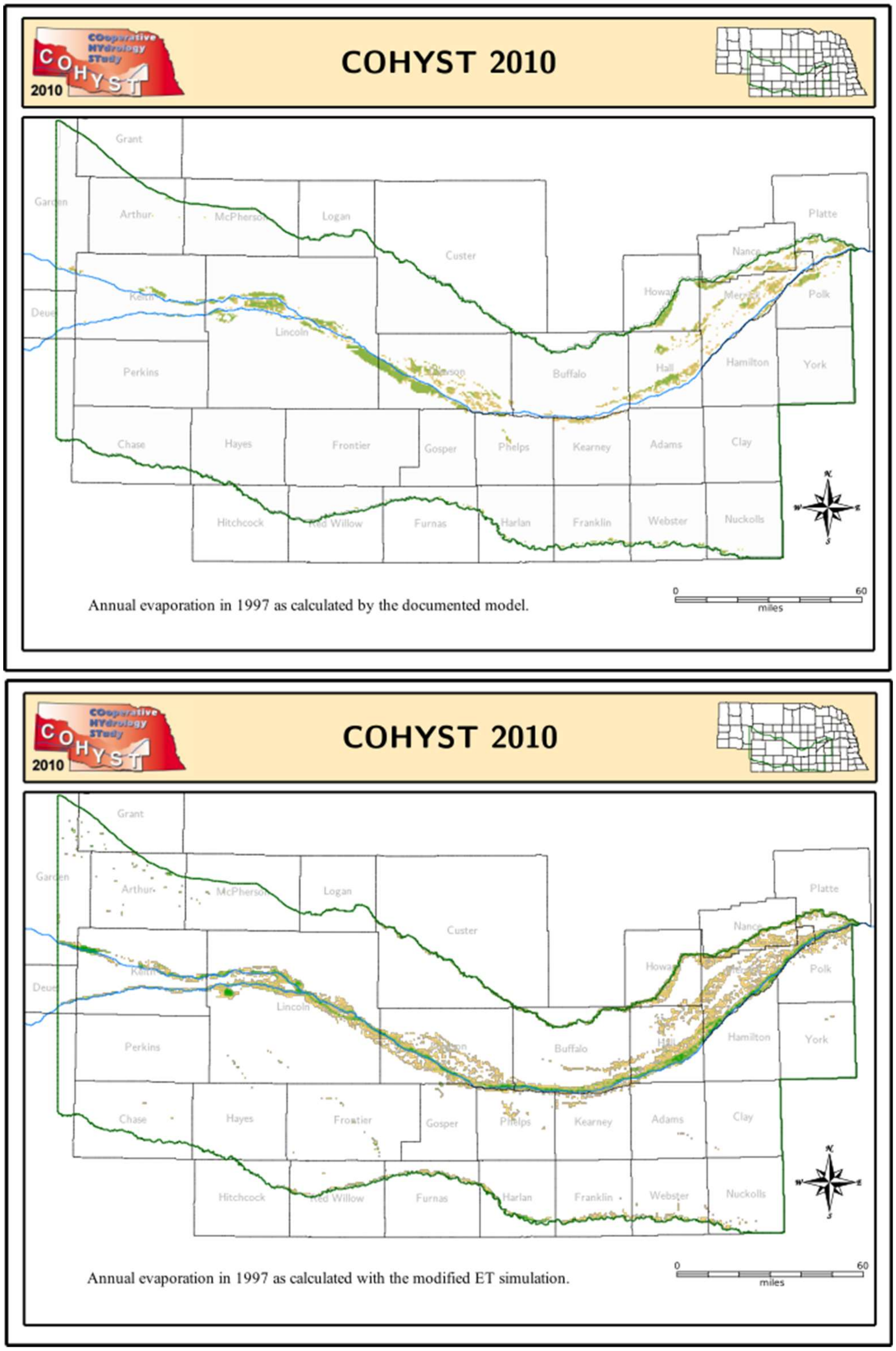
The 2013 groundwater model did not appropriately simulate stream flow losses at times and locations of observed loss on the Platte River. A survey of the groundwater model for causes of the stream flow problem found contributing factors in the simulation of riparian evapotranspiration (ET). One problem was that ET surface elevations were set at or near the highest elevations in a cell and ET extinction depths were above much of the land surface. Also, ET was not simulated in cells with stream boundaries, where much of the riparian wetlands are located. These problems were addressed by:

- setting the ET elevations to the average land surface elevations;
- setting the ET extinction depth to 8 feet;
- allowing groundwater ET to occur in cells that contained stream boundaries.

While addressing these problems, it was determined that the watershed model and the groundwater model both simulated evapotranspiration in the same areas and thus this component of the water balance was double counted. To reduce the overlap, ET from groundwater was limited to areas identified as wetland in the National Land Use Dataset (Homer, et al, 2012), and maximum groundwater ET rates were limited so that the groundwater model only simulated ET in excess of the rates already simulated by the watershed model. In addition, the original maximum ET rates that were based on historic climatic data were replaced with maximum ET rates that varied on a fixed annual cycle.

Figure 7.1-1 compares the total annual ET rate for 1997 (a wet year) as calculated by the 2013 COHYST groundwater model and the current COHYST groundwater model with the modified ET simulation. The modified model simulated ET over larger areas than the original package, with high rates along the Platte.

The changes to the ET module reduced the average annual evapotranspiration simulated by the groundwater model. The 2013 model lost 218,854 acre-feet per year through evapotranspiration. The modified model lost 187,416 acre-feet per year through evapotranspiration—a 14% reduction.



Annual evaporation in 1997 as calculated by the documented model.

Annual evaporation in 1997 as calculated with the modified ET simulation.

Figure 7.1-1. Rate and distribution of 1997 ET calculated by the documented model (top) and the modified model (bottom) 1997.

7.1.2 Seepage from Lake McConaughy

During model review it was noted that the surface water model and groundwater model used different methods and areas to calculate seepage from Lake McConaughy. The values used by the surface water model impacted the reservoir water budget but were not used by the groundwater model. The values used by the groundwater model impacted the aquifer water balance but had no relationship to the reservoir water budget. Going forward, model integration could be improved by using the seepage results from the groundwater model in the surface water model.

The groundwater model simulates Lake McConaughy with the general head boundaries and an historic monthly variation in lake stage. The lake area simulated by the groundwater model was smaller than the actual lake area, so nine new general head boundary cells were added to the lake simulation so that the groundwater model and surface water model simulated approximately the same lake area.

The groundwater model seepage rates were found to be unrealistically variable, which was a problem that needed to be solved before the results were used in the surface water model.

The high variability in the calculated seepage rate was caused by the storage coefficient used by the groundwater model in the area under the lake. The 2013 documented groundwater model used a specific yield value that simulated the lake as if the free surface were within the aquifer when actually the free surface was above the aquifer. To correct the problem, the storage coefficient under the lake was set to 0.002 which is the product of an approximate aquifer thickness of 200 feet and a specific storage value of 1x10-5 ft-1. This corrected the variability by moving much less water in and out of aquifer storage under the lake.

The adjustment had a large effect on the variability of the seepage, but a proportionately small change in the average seepage rate. Seepage rates from the 2013 calibrated model swung from a monthly high of 2400 AFY into the lake to a low of about 1500 AFY out of the lake. With the corrected storage coefficient, the seepage rates varied from 1112 AFY into the lake to 62 AFY out of the lake. In contrast, the average seepage rate changed by only 5%, from 24,300 AFY to27,300 AFY. The average seepage rate based on a water balance for the reservoir is 28,700 AFY.

7.1.3 Sutherland Water Levels

During the process of revising the groundwater model it was observed that groundwater levels beneath and around Sutherland Reservoir rose over time to elevations far above those observed. The problem was attributed to three causes:

- the 2013 groundwater model did not simulate drains below the dam that convey water to the Platte,
- a local, high permeability layer encountered during construction of the dam was not represented in the groundwater model,
- the spatial resolution provided by the groundwater model is too coarse for the model to simulate both the correct seepage rate and the correct gradient through the dam area.

The failure to account for inflow from Sutherland reservoir seepage in the surface water model was considered an important error. The interface between surface water model and the groundwater model was modified so that the groundwater model simulated only 10% of the seepage; the remaining 90% was sent directly to surface water. As a result, the much lower water levels now calculated by the groundwater model are considered acceptable.

7.2 Model Changes Made During Recalibration

A fundamental change from the 2013 to the 2016 model is that the latter uses MODFLOW2005 (Harbaugh, 2005) and the SFR module (Niswonger and Prudic, 2005), which replace MODFLWO 2000 and the STR module. The stream flow routing module (SFR) provides all the capabilities needed by the COHYST2010 groundwater model with far less input than is required by the 2013 simulation. The input file needed for the Platte simulation was reduced from 2.7 million lines to 54 thousand lines. That translated into lower cost of operation through improved ease of use, easier interface to the surface water model and watershed model and more effective quality control.

This change also facilitated the ability to make other model changes, such as providing the ability for diversions to “sweep the river”. The conversion also eliminated the need to directly address errors, incorrect assumptions, and incorrect model interfaces found in the SFR files. These problems adversely affected the integration of the groundwater model, watershed model and surface water model and had their greatest effect near the river.

It could be very difficult for a new user to deduce how hydrologic features are represented in the SFR module simulation of the Platte River and its tributaries. Eight tables in **Appendix 7-A** provide information necessary to interpret the SFR module construction and results.

Figure 7.2-1 maps the current configuration of the groundwater model boundary with the Platte River and its tributaries. The model domain is the same as 2013 model: 160 acre cells, which are unchanged as to which are active, identical lateral boundaries with two dimensions and a single layer having the same top and bottom aquifer elevations as previously, and monthly stress periods. Both the 2013 and current models simulate conditions in the unconsolidated sediments comprising the Ogallala and younger aquifers which underlie the Platte River valley and adjoining watersheds to the north and south.

A brief list of the revisions (some of which are discussed in more detail elsewhere in this Section) follows.

A. <u>Channel elevations</u>. The specified elevations of the channel bottom were below the aquifer bottom in several cells in the western part of the model. The error was reported by Groundwater Vistas (ESI, 2011), but did not have a noticeable effect on model results. The errors were eliminated by placing the channel bottom elevation at the model bottom plus 0.1 feet.
B. <u>Runoff values</u>. Runoff calculated by the watershed model was reported in units of cubic feet per month. In the 2013 model, those values were input to the Platte River simulation without the required conversion to cubic feet per day. As a result the runoff values simulated in the groundwater model were approximately 30 times the correct values. In the 2017 model, the problem was corrected by converting the inputs from cubic feet per month to cubic feet per day.

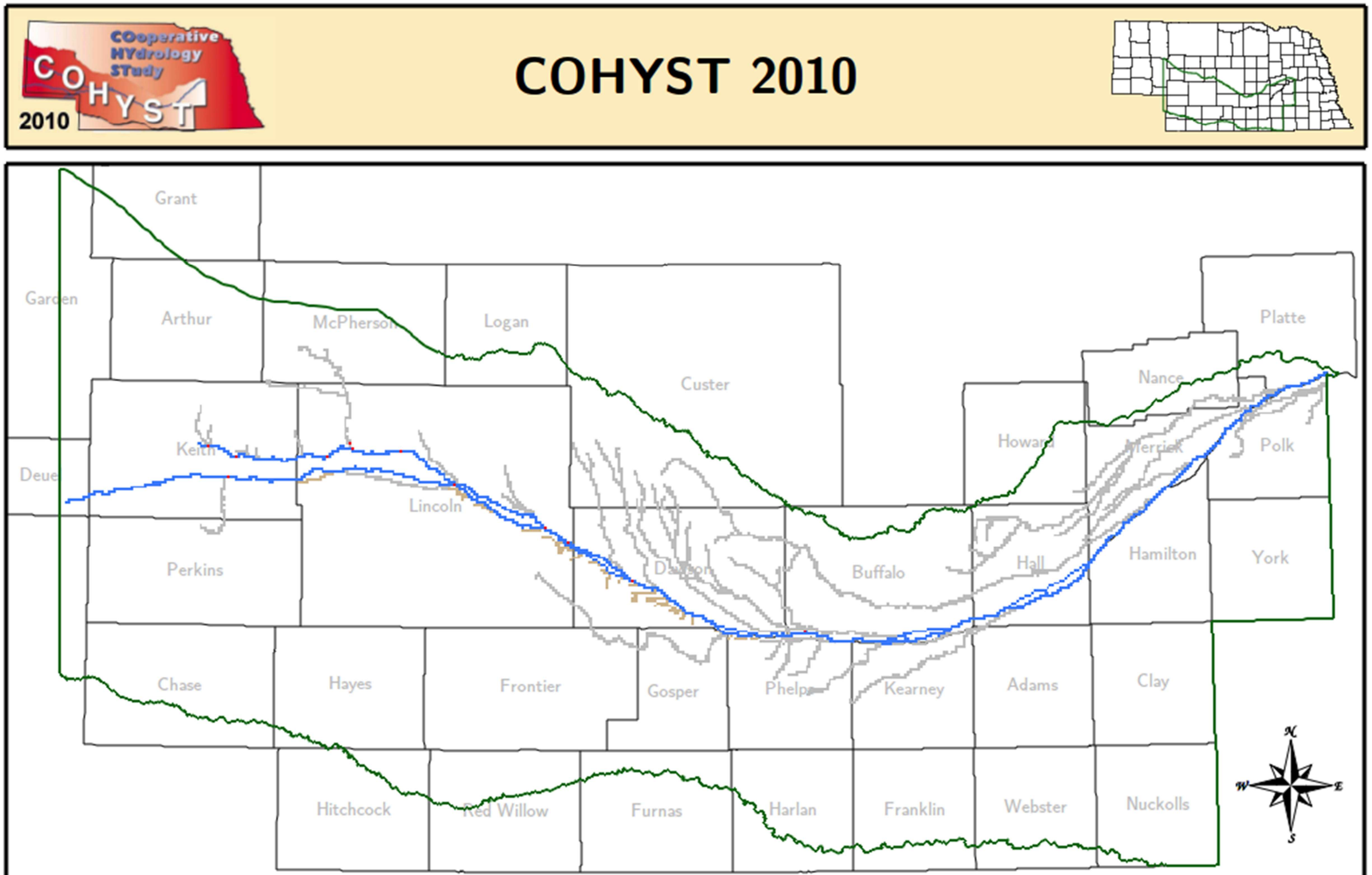


Figure 7.2-1. The SFR boundary with the Platte River and its tributaries. Tributary streams are shown in gray and drains are shown in tan. Cells with diversions are shown in red.

0 60
miles

C. Keystone diversion. The North Platte River inflow provided by the surface water model was for the river below Keystone Dam, but the groundwater model treated it as the total release from Lake McConaughy and diverted water for the Keystone Canal. That left too little water in the channel to supply downstream diversions. The problem was solved by removing the Keystone diversion from the groundwater model

D. Channel from Tri-County diversion to near Brady. The Platte from the Tri-County Canal diversion to the Gothenburg Canal diversion flows in the north channel, but in the 2013 model was simulated in the abandoned south channel. The abandoned channel in some areas is more than two miles away from the river. For the 2017 model, the input files were modified to include parameters necessary to simulate the north channel and flow from the dam was routed to the north channel. The south channel remains in the model and receives baseflow and runoff contributions.

E. Diversion locations. Diversions simulated in the 2013 model were located as if the model diverted water at the top of the stream segment that included the diversion. The STR module diverts water at the bottom of the stream segment that includes the diversion. All diversions were thus mis-located by the length of one segment, which could be from one-half mile to several miles. In the current model all diversions have been moved to their correct locations. In some cases revisions were made to the segment definitions to place diversions near their actual positions or to have tributary flows to enter the river above the diversions.

F. Orchard-Alfalfa return. The 2013 model returned flow from the Orchard Alfalfa canal immediately below the diversion. The return flow was moved downstream to be near its actual location.

G. Tributary channel widths. The 2013 model represented some tributary channels with unrealistically large channel widths. The channel widths were adjusted during the conversion from the STR module in MODFLOW2000 to the SFR module in MODFLOW2005 and will be discussed in a following section.

H. Add agricultural returns. The surface water model calculated return flows for the Gothenburg, Cozad and Dawson County Canals that were not used in the documented groundwater model. The simulation was modified to include those returns.

I. Simulate channel islands. The 2013 model was built so that the Platte River flowed in a single channel. It did not simulate the separation of the channel around channel islands. The simulation was changed in an effort to dry the river at Grand Island by simulating the channel islands below Grand Island. Flow to the added channel segments was set at a fixed proportion of the total flow or to zero, depending on the channel behavior and management. Changes were made to the channel upstream from Grand Island. The channel downstream from Grand Island was not changed.

J. Add drains. The 2013 model did not simulate agricultural drains along the Platte, with the exception of a single drain below Sutherland Reservoir that was described as an "Executive Tributary." That tributary corresponds closely to the location of the Applegate Drain. Other drains along the south side of the Platte and South Platte were added based on maps provided by CNPPID. Drain elevations were set six feet below land surface, channel widths were set to six feet and channel conductance was set to high values.

K. Sutherland seepage to Applegate Drain. As a result of Task 4 of the mid-term adjustments (described previously) 90% of the seepage from Sutherland Reservoir was directed to surface water. Later revisions to the interface between the surface water model and the groundwater model required that the groundwater model complete that process. Those flows were introduced as specified inflows to the segment that represents the Applegate Drain.

L. Drain boundaries. Some drain elevations were below the elevation of the model bottom, which was flagged as an error by Groundwater Vistas and would potentially contribute to model instability. The drain elevations were set to the minimum of the original drain elevation or the model bottom plus 0.1 feet. Also expanding Lake McConaughy upstream (see Section 7.1) created two general head boundary cells that overlapped with pre-existing drain boundaries. The overlapping drain boundaries were removed. A small number of duplicate drain boundaries were removed.

M. General head boundaries. The groundwater model uses general head boundaries to simulate flow across the east and west model boundaries and to simulate time-varying stages in Lake McConaughy, Hugh Butler Reservoir and Harry Strunk Reservoir. One stage value specified for Hugh Butler reservoir was below the bottom elevation of the model. The stage data for the date were missing and the value used for the date was from Harry Strunk reservoir. In the 2017 model, a value for the Hugh Butler stage was substituted that was interpolated between previous and following stages in a manner consistent with the stage variation at Harry Strunk. Also the input file for the general head boundaries contained several distinctly different data and combining them in a single file made it relatively difficult to find and modify the values. The input file was reformatted so that the input for the east and west model boundaries and each of the reservoirs were read from different files.

Model output, pre- and post-processing for the SFR module. The 2013 model had a relatively simple interface to the watershed model. Seepage between the STR boundary and the aquifer was recorded with the HYDMOD module in MODFLOW2000 and summed over reaches to provide the net aquifer interaction. That interface was adequate but did not provide information necessary to check and or/debug the groundwater model's complex surface water boundary.

Use of HYDMOD was abandoned in the MODFLOW2005 conversion and replaced with the output from the SFR module. The output of the SFR module was processed through a custom program constructed by LWA to provide both a detailed analysis of stream flows and interactions and a simplified table of aquifer interactions for use in the surface water model. Future use of the COHYST2010 groundwater model does not require the LWA program; tables in Appendix 7-A provide the necessary information.

The COHYST2010 surface water model and watershed model provide input to the groundwater model as simple spreadsheets. The spreadsheets are imported to tables in a database management system, then input to the SFR module is constructed by a script that uses SQL commands to extract data from the database manager and a FORTRAN program to insert the new values into an existing copy of the SFR input file.

7.3 Conversion to MODFLOW 2005

The 2013 model was constructed to use MODFLOW2000, but two problems required changes to the original MODFLOW2000 FORTRAN code: the STR module had to be modified to allow diversions to sweep the river, and an option had to be added to allow the model to continue after a minor failure to converge. With these changes, the model could only be run with the modified version of the code, which the project would have to provide to future users. This is unnecessary as the capabilities that were added to the MODFLOW2000 code are inherent in MODFLOW2005 using the SFR stream boundary module.

The COHYST2010 groundwater model was converted to MODFLOW2005 in three steps. The first conversion was from MODFLOW2000 to MODFLOW2005 without changing the way the Platte River and its tributaries were simulated. Second, the Platte River simulation from the current stream (STR) module was converted to the stream flow routing (SFR) module. Finally, the input to the SFR module was modified to change some unusual tributary channel widths.

7.3.1 Code Conversion

There are very few inherent differences between MODFLOW2000 and MODFLOW2005 input files. The MF2KtoMF05UC conversion program (Harbaugh, 2007) provided by the USGS completed the basic model conversion in seconds and without problems.

The 2013 model was calibrated with optimization routines inherent in MODFLOW2000. MODFLOW2005 does not contain a similar capability. UCODE 2005 was used to replace the optimization capability in MODFLOW2000. The MF2KtoMF05UC conversion software constructed the input files that were needed to use UCODE 2005 for optimization.

Conversion of the COHYST2010 groundwater model to MODFLOW2005 created no significant change in the model results. The unweighted RMS error for drawdown in the 2013 model was

5.5546 feet. The corresponding value from the version using MODFLOW2005 is 5.5555 feet. The head convergence criterion is 0.01 feet, so the difference in the RMS error of 0.0009 feet is well within the range of mathematical precision. **Figure 7.3-1** compares the cumulative water budget at the end of the 2013 model and the MODFLOW2005 simulation using 2013 inputs. The overall budget did not change significantly.

7.3.2 Stream Boundary Conversion

The stream flow routing module (SFR) provides all the capabilities needed by the COHYST2010 groundwater model with far less input than is required by the 2013 simulation. That translated into lower cost of operation through improved ease of use, easier interface to the surface water model and watershed model and more effective QA/QC.

The SFR module offers several options that aren't available in the STR module, some of which would be useful for COHYST2010 but have not been instituted—such as the ability to distribute runoff along a stream segment rather than concentrating runoff at a single inflow point.

The SFR module used most of the same model cells and stream segments used by the STR module. Segments used in the STR module only to specify runoff were not needed in the SFR module, so the SFR module had 50 fewer stream segments and the remaining segments were renumbered.

The primary features of the conversion are:

- The channel widths in the SFR input vary evenly from the top to bottom of each stream segment rather than being specified at each cell. If width variations were specified within a stream segment then those variations were lost.
- The channel conductance in the SFR module is calculated from the channel hydraulic conductivity and channel geometry rather than being specified at each cell. The hydraulic conductivity value and channel length specified for the stream flow routing module were calculated to closely approximate the constant specified in the current model and are not meaningful values for hydraulic conductivity or channel length.

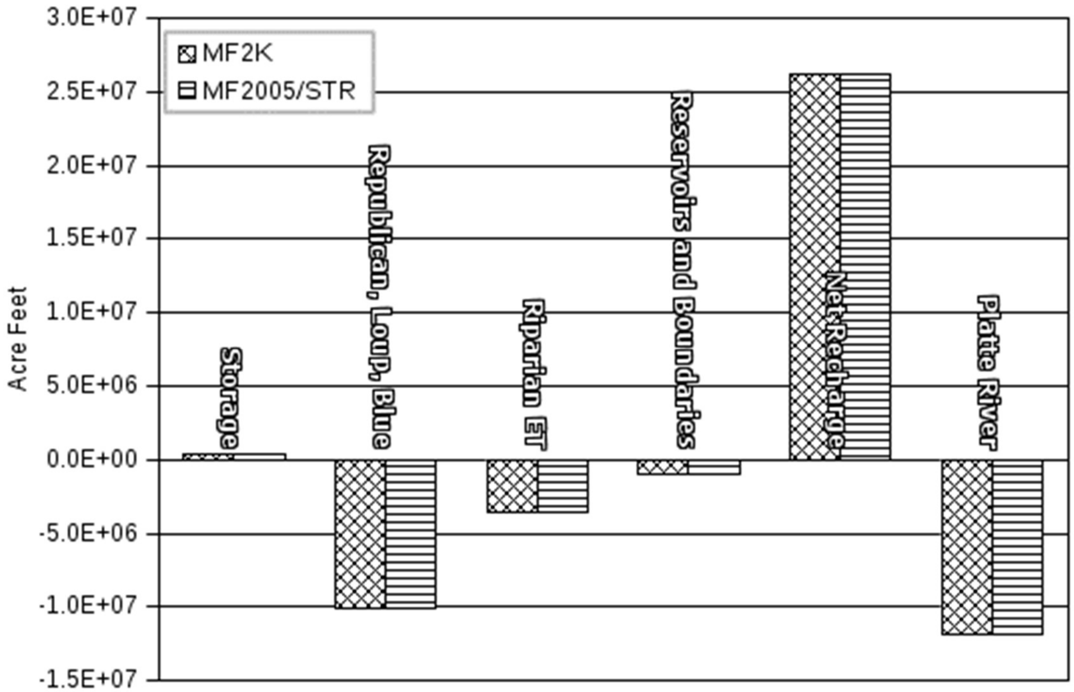


Figure 7.3-1. Net groundwater balance, comparing results from the conversion to MODFLOW 2005.

Conversion to the stream flow routing module produced only small changes in the model results. The unweighted RMS error in drawdown using the SFR module is 5.5547 feet, compared to 5.5555 feet using MODFLOW2005 and the STR module, and 5.5546 feet in the 2013 model. **Figure 7.3-2** compares the cumulative water budgets at the end of the simulation, using the 2013 model, MODFLOW2005 with the stream module and MODFLOW2005 using the stream flow routing module.

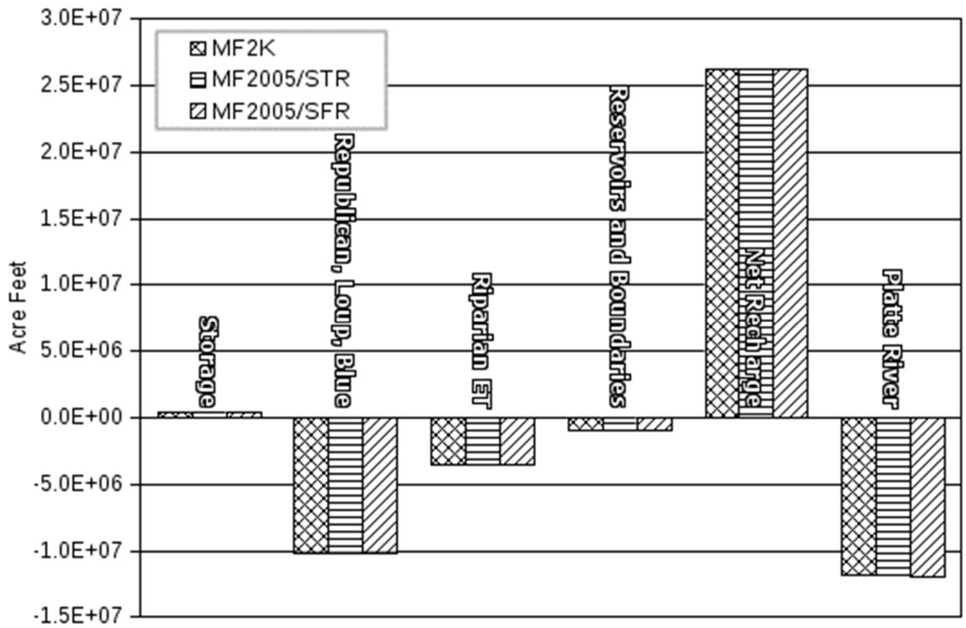


Figure 7.3-2. Net groundwater balance, comparing results from the conversion to MODFLOW 2005 with the SFR module.

7.3.3 Channel Width Adjustments

There were several unusual features among the widths specified in the 2013 model. Some tributaries were given the same channel width as the parallel section of the Platte. For instance, Wood River near Grand Island was assigned a width of 600 feet. The model also had large and unrealistic variations in channel width; for example the width of Plum Creek varied from five feet to 250 feet between adjacent model cells. The problem did not affect all of the tributaries; some tributaries were assigned realistic channel widths. We considered the widths given to the Platte to be acceptable.

Actual channel widths vary with flow as well as with distance along a stream. The COHYST2010 groundwater model was never built to capture the actual variations. With that in mind, we elected to use a simple generalization for the tributary channel widths. The widths were recalculated so that the water depth would be 1½ feet under median flow conditions. If the original calculation resulted in channel depths that were more than a fourth of the channel width then the channel width was recalculated so that the width:depth ratio under median flow conditions would be 4:1. The widths of dry channels were set to 1 foot. The channel width of the North Platte, South Platte and Platte Rivers were left unchanged.

The procedure resulted in generally reasonable widths. Changes in the calculated stage were expected and resulted in changes in simulated water levels in the aquifer. The unweighted RMS for drawdown from a simulation using the adjusted channel widths was 5.5606 feet, slightly higher than in the 2013 model. **Figure 7.3-3** illustrates the cumulative water balance from the simulation with adjusted channel widths, along with the results from previous tests.

Figures 7.3-4 through 7.3-6 show the effect of the channel width adjustment on simulated stage and discharge at three representative locations.

Prairie Creek near Silver Creek was originally simulated with a channel width of 600 feet. The width was recalculated to 14.3 feet. The simulated discharge shown in figure 7.3-4a changed very little. The stage simulated in the 2013 model varied by tenths of a foot over the range of

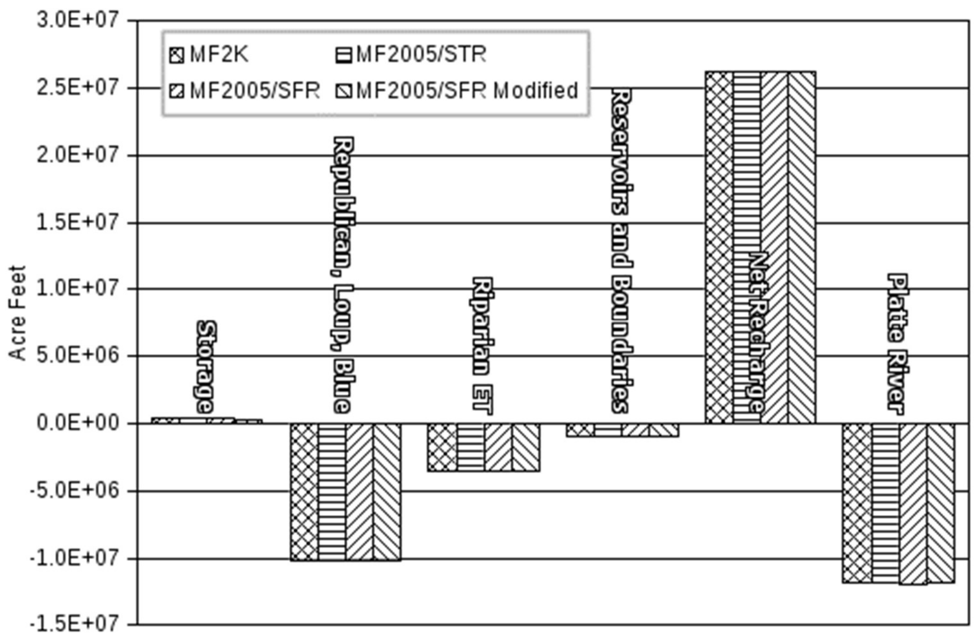


Figure 7.3-3. Net groundwater balance, comparing results from the conversion to MODFLOW 2005 with modified tributary widths.

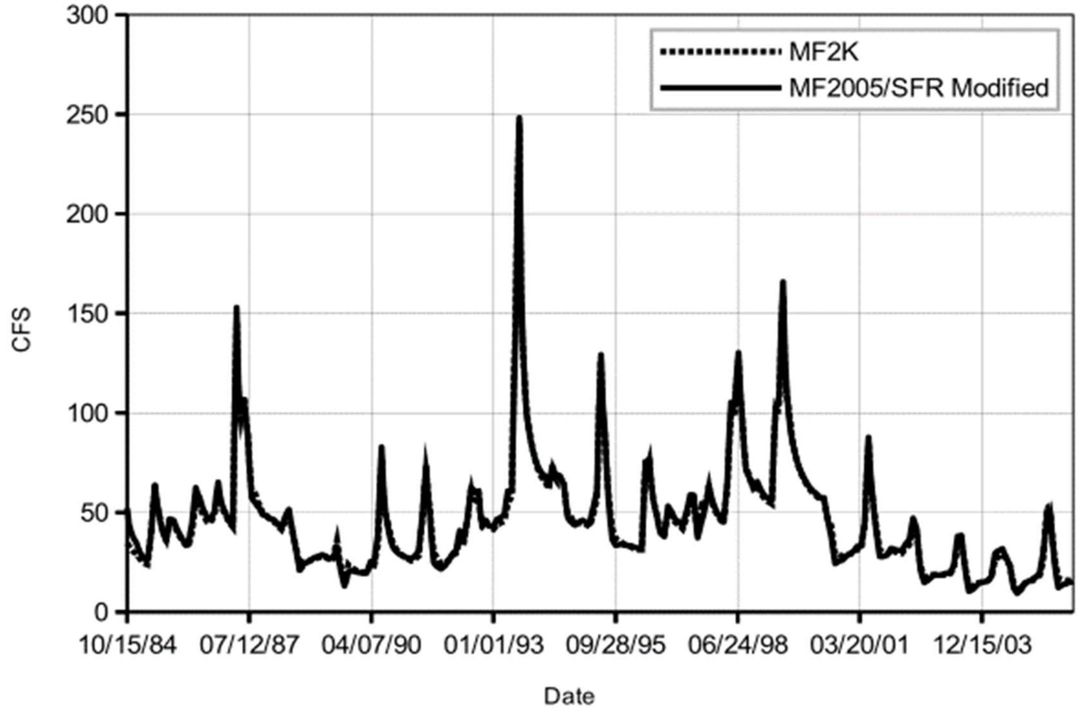


Figure 7.3-4a. Simulated discharge of Prairie Creek near Silver Creek.

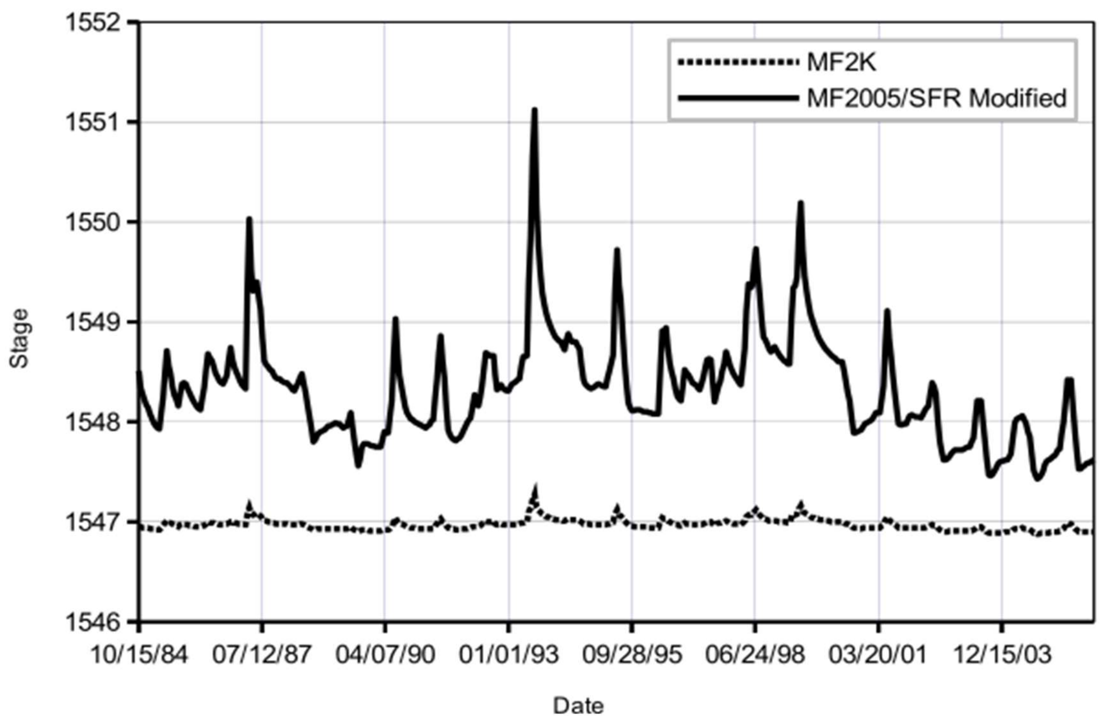


Figure 7.3-4b. Simulated stage of Prairie Creek near Silver Creek.

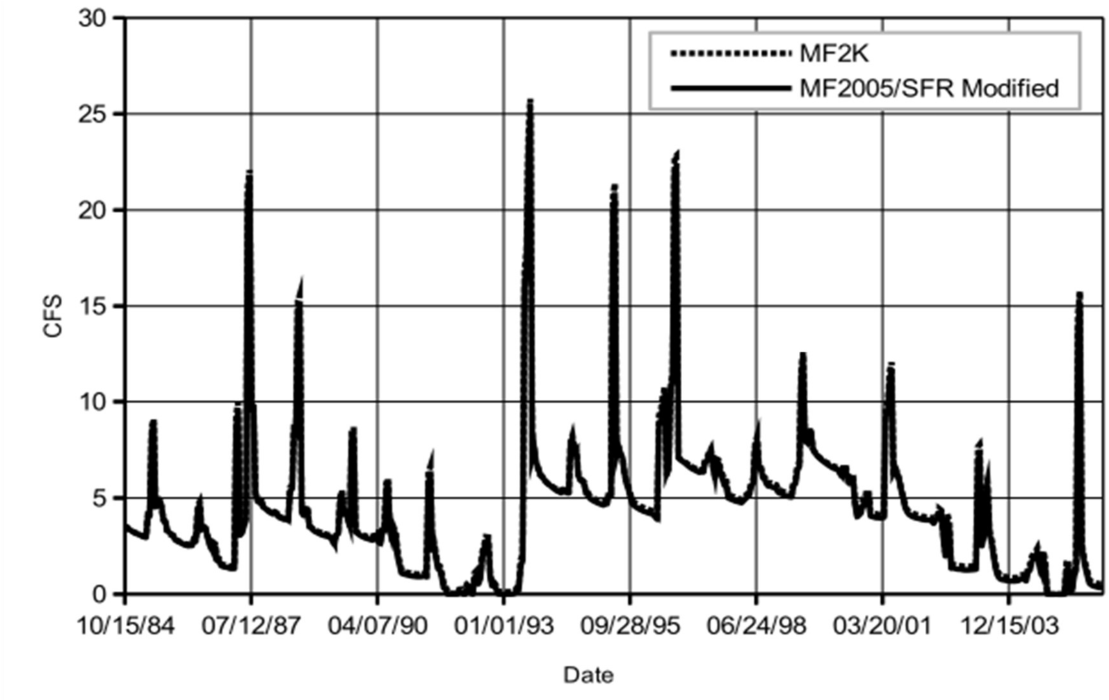


Figure 7.3-5a. Simulated discharge of Buffalo Creek near Overton.

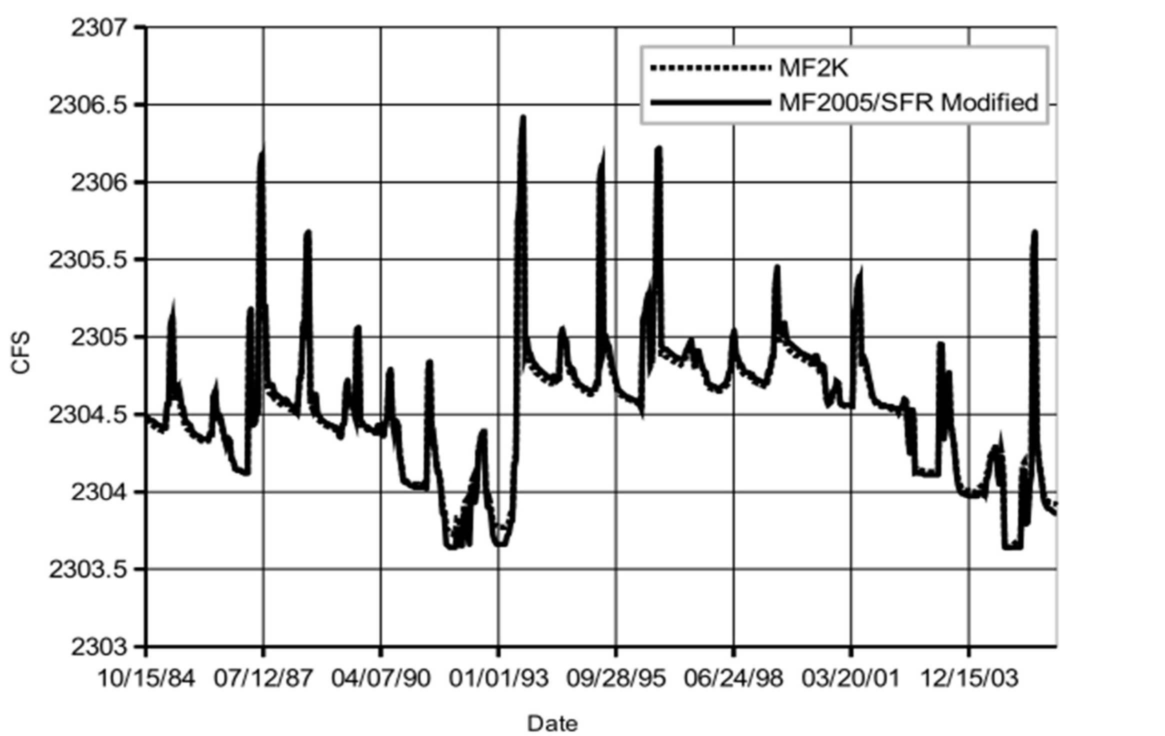


Figure 7.3-5b. Simulated stage of Buffalo Creek near Overton.

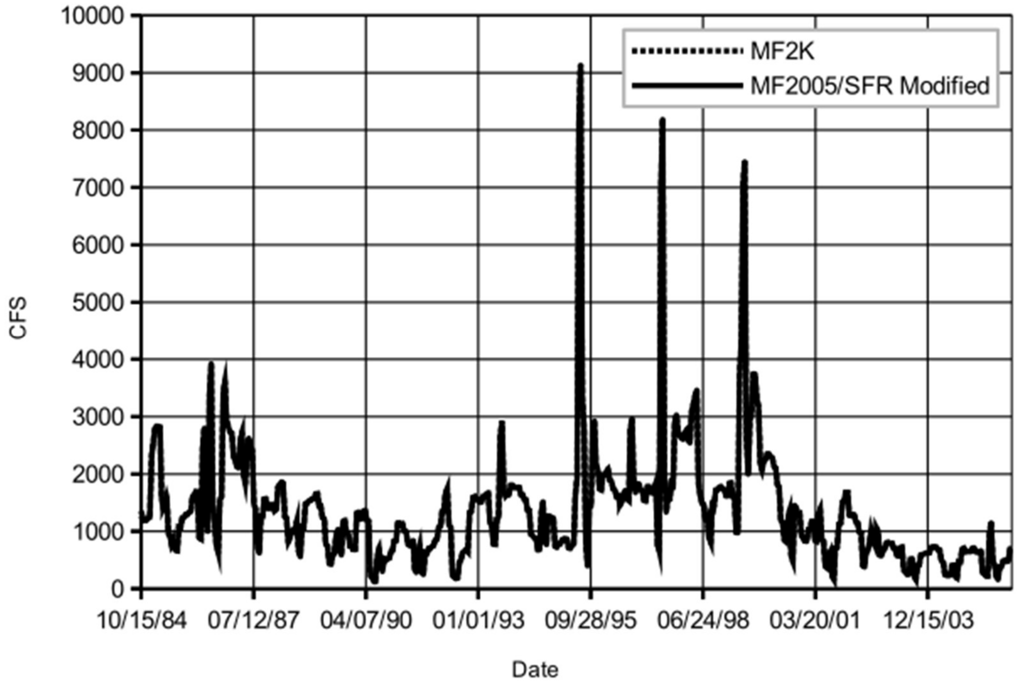


Figure 7.3-6a. Simulated discharge of the Platte River at Odessa.

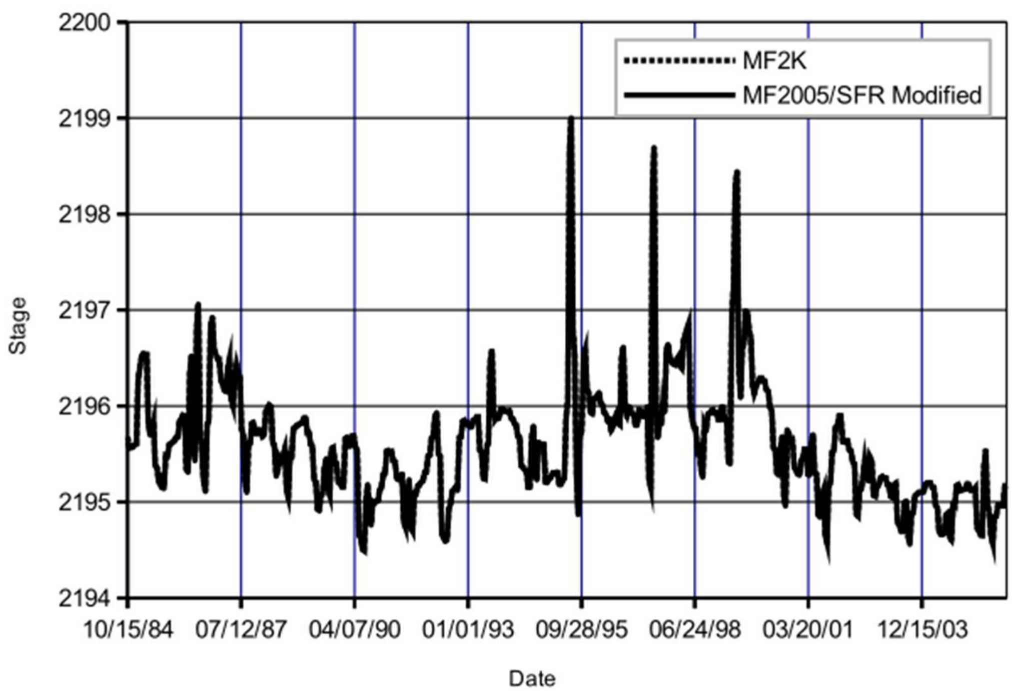


Figure 7.3-6b. Simulated stage of the Platte River at Odessa.

simulated flows. With the channel width adjustment the stage rose about 1.5 feet. Similar elevation changes elsewhere probably created the increase in the model RMS error and could be offset by lowering the channel elevations by 1.5 feet. The stage variations increased to about 3.5 feet over the range of simulated flows.

Buffalo Creek near Overton was originally simulated with a channel width of 5 feet. The original width was probably reasonable and the recalculated width of 4.7 feet was very similar. Figure 7.3-5a and 7.3-5b compare the original calculated discharge and stage. There is little change due to the adjustment, which shows that the simple method preserves reasonable input values.

The width of the Platte River channel was not changed. Figure 7.3-6a and 7.3-6b show the effect of changing the tributary channel widths on the stage and discharge of the Platte at Odessa. There is no distinguishable difference between the new simulation and the 2013 model. However, the simulated stage variation is normally within a foot, and only 3.5 feet over the entire range of calculated flows. The stage variation is probably unrealistically low and might be improved by applying a width adjustment to the Platte channel similar to that used on the tributaries.

7.4 Calibration method

The 2013 groundwater model was originally calibrated in two efforts in 2012 and 2013. The final effort was terminated with results that were acceptable to some parties, but were significantly inconsistent with prior data on the distribution of aquifer parameters. The documented version of the 2013 groundwater model excluded a reduction in recharge in the southwest part of the model area that was part of the calibrated model. As a result, the documented version gave water level changes that were significantly different from the calibrated model.

The original calibration was completed using the parameter optimization capability in MODFLOW2000. The effort was affected by instability in the initial optimization runs. Once the process was stabilized, insensitivity of the model error to parameter changes became a problem.

For the 2016 calibration the groundwater model was converted to use MODFLOW2005, with UCODE2005 as the parameter optimizer. The optimizer was subsequently updated to use UCODE2014 (Poeter, et al, 2014). As with the original calibration, the calibration period was from 1990-2005, inclusive.

Calibration data set. A new drawdown data set was constructed for the 2016 calibration. The data locations and values are listed in **Appendix 7-B**. The full set of data is included in model input, and is illustrated in **Appendix 7-C**. The goals in constructing the new data set were to:

- concentrate locations in areas of concern to the COHYST2010 sponsors;
- achieve an even distribution of data locations within two model subareas;
- enforce a minimum number of data points per location;
- use spring data with no more than one datum per year at each location;
- eliminate locations with unrepresentative data.

Figure 7.4-1 maps the selected locations with drawdown data used for calibration.

LWA retrieved a water level data set from the US Geological Survey that consisted of 136,642 measurements from 1984 through 2012 at 2,777 different sites within the COHYST2010 area.

Water level data were initially screened to exclude locations with water level measurements with fewer than 13 spring seasons (March-May) from 1990 through 2005. As a second screening criteria, the trend and correlation were calculated for the data at each location; if the slope exceeded 1 foot/year then selection required a minimum correlation coefficient of 0.5. That criteria was used to eliminate sites where the slope was due to a small number of presumed spurious data.

The screened locations with the distance between points below a given threshold were mapped and reviewed. Data locations were removed to produce an even spacing and in most cases the data were reviewed to make sure that the selected points had representative hydrographs. The process was repeated at higher threshold distances, separately for the area near the Platte (i.e. the area encompassing canals off the Platte or in the lowland area east of Kearney) and the areas distant from the Platte. The highest threshold was set to produce a little fewer than 400 data

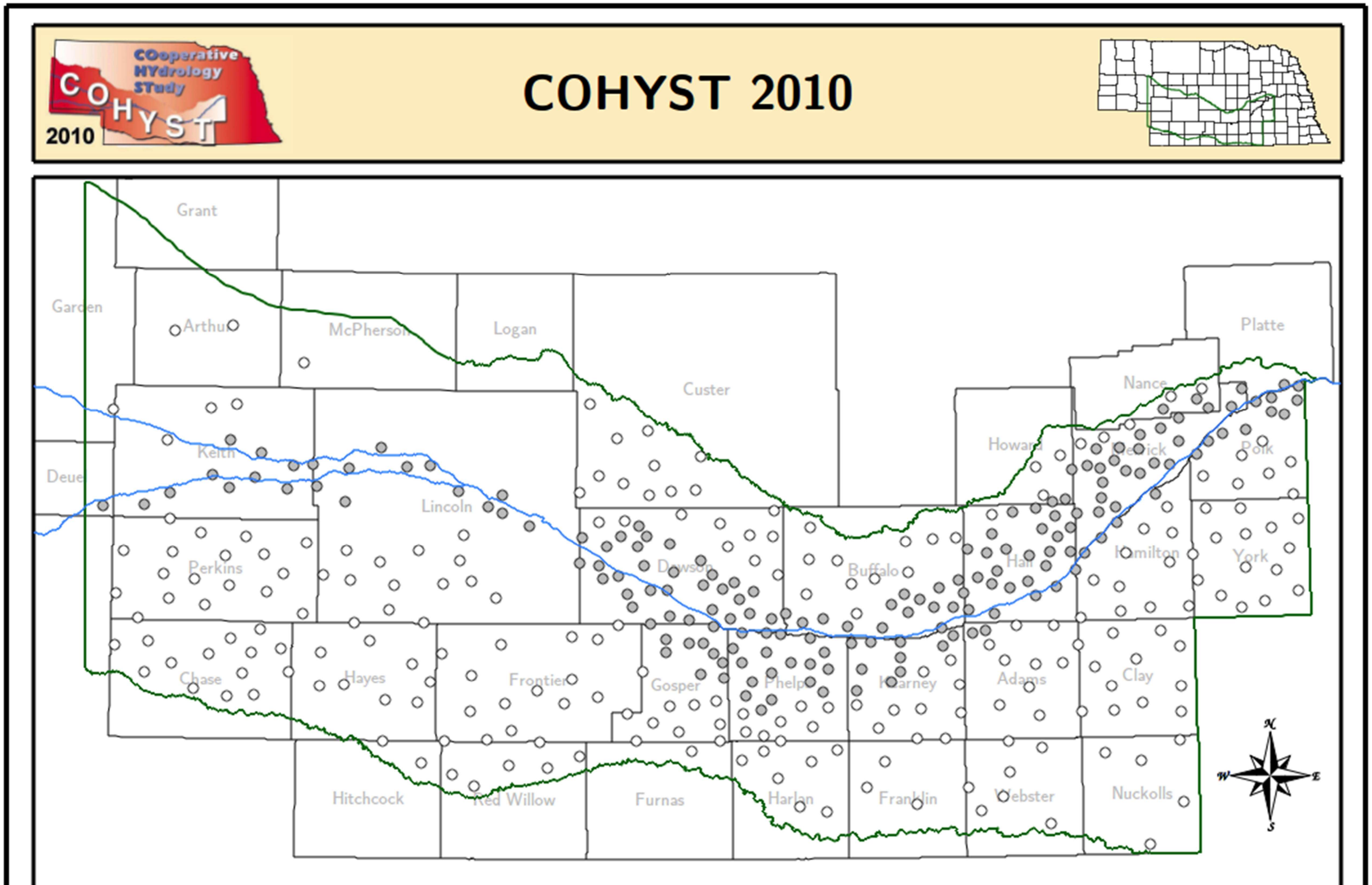


Figure 7.4-1. Locations of water level and drawdown data used for calibration of the COHYST2010 groundwater model. Locations inside the high-concentration area are shown with gray shading.

locations. The final density of data near the Platte was three times the density of data distant from the Platte.

The process resulted in a few areas with sparse data, so as a final step the criteria for the minimum number of data per location was lowered to ten, and if locations were available in those areas then they were included in the data set.

The final data set included measurements from 403 locations; 173 of those locations were in the area near the Platte (3,878 square miles) and 230 locations were outside that area (15,447 square miles). There were 22.4 square miles per location near the Platte and 67.2 square miles per location outside that area. One location in the southeast part of the model was subsequently removed because the model cell that contained the location was dry.

Baseflow values for tributaries in the Blue and Republican River basins were used for the original calibration were initially retained for the new effort. Those data were subsequently removed because the provenance of the data was unclear and because the calibration results were insensitive to the baseflow values. Baseflow data for the Platte were not used for calibration because the COHYST2010 technical committee expressed concerns over the usefulness of the values.

<u>Recharge file format</u>. Recharge input to the COHYST2010 model comes from the surface water model as canal and reservoir seepage, and from the watershed model as seepage from ephemeral streams and deep percolation at the bottom of the root zone. Runoff on intermittent and ephemeral tributaries—also from the watershed model—contributes recharge through the stream flow boundary.

The recharge input file for the current model differs from earlier versions. In the 2013 model the seepage values from the surface water model were combined with the deep percolation rates from the watershed model and provided to LWA as a MODFLOW input file. In order to investigate possible problems with the groundwater model is was often necessary to separate the two sources from the input file. The combination also meant that multipliers—for sensitivity testing, for instance—could not be applied to one source of recharge without affecting the other.

The problems were solved by parameterizing the recharge input file so that deep percolation and canal seepage were separate inputs. This also simplified the model integration because the surface water seepage went directly to the groundwater model rather than being filtered first through the watershed model.

Parameterization resulted in a small change in the recharge rates. Seepage rates were negative—the simulated feature gained from groundwater—on a portion of the canal between the J1 and J2 power plants and at the B1 reservoir. Those negative values were removed when the seepage rates were filtered through the watershed model, but retained in the parameterized input.

Recharge lag. An important issue in model construction is how to deal with the fact that recharge rates have changed over time as irrigation has increased, but the effects of this change on the water table is delayed in areas of a thick vadose zone. Correctly simulating the delay is important in order to correctly calibrate the model.

The COHYST2010 integrated model in 2013 assumes that deep percolation calculated at the bottom of the root zone by the watershed model reaches the water table without a delay. That is a realistic assumption only in those areas where the water table is very shallow. The water table is within a few feet of the surface in part of the COHYST study area near the Platte and Republican Rivers. In much of the rest of the study area the water table is at depths commonly near and above 100 feet. The COHYST2010 integrated model assumes that deep percolation calculated at the bottom of the root zone by the watershed model reaches the water table without a delay. That is a realistic assumption only in those areas where the water table is very shallow.

Several studies (e.g. McMahon, et al, 2006, Steele, et al, 2014) in and near the COHYST area have shown that water recharging at the water table in some areas predates atmospheric testing of thermonuclear weapons, which spanned the years 1952-1963. Simple methods described in McMahon et al, 2006 indicate that water now reaching the water table may predate the modern era of irrigated farming over much of the COHYST area.

During the initial calibration of the groundwater model in 2013, the automated calibration method was unable to resolve systematic trend errors in the southwest part of the study area. As a result, LWA allowed the model to estimate the rate of recharge in order to match the historic head trends. The model reduced the recharge rate by 29%, which appeared to bring the average rate down to a level typical of rangeland. That adjustment was consistent with the long recharge lag expected in the area.

The model was subsequently documented and used without the adjusted recharge rate, which resulted in a noticeable, systematic error. The current effort to calibrate the groundwater model includes the adjustment used in the 2013 calibration. As noted subsequently, while the result is appropriate for model calibration, it may affect use of the model in predictions.

Given the watershed model recharge rates, it is possible to estimate the average velocity of recent recharge water above the water table by adopting a representative value of the volumetric water content. Volumetric water content is the portion (as a percent) of the soil volume occupied by water. Water moves only in that fraction of the soil.

The formula is simply:

$$v=q/\omega$$

where:

v is the infiltration velocity (feet/year)

q is the recharge rate (feet/year)

ω is the moisture content (unit less)

In this formula, lower moisture content results in a higher infiltration velocity.

The recharge rate was averaged over the 1985-2005 period from the watershed model version 27 results for each cell in the COHYST2010 model and converted to feet/year.

A value for the volumetric water content of 20% was adopted for these calculations; that value is similar to what McMahon et al. found in their study near Imperial, and scattered other data suggests that 20% is probably representative in the Ogallala formation. Fine loess deposits and tills in the eastern part of the model probably would have a higher moisture content and lower infiltration velocity. The sand hill soils have a considerably lower moisture content—values less than 10% may be representative—and higher infiltration velocities (Rossman et al, 2014).

Typical deep percolation rates from the watershed model are in the range of two to four inches per year. With a 20% moisture content the infiltration velocity is in the range of one or two feet per year.

The time required for recharge to reach the water table is the distance from the bottom of the root zone (at a depth of six feet, for these calculations) to the water table, divided by the velocity. We used the average land surface elevation in each cell of the COHYST2010 model and the published water levels for spring, 1979 (ftp://ftp.dnr.ne.gov/Pub/cohystftp/2010Report/) to calculate the distance that water needs to travel. The resulting value was set to zero where the water table was at a depth of less than six feet.

The calculation is for steady flow conditions and neglects the effects from recharge rates increasing at the beginning of irrigation and the effects of low-permeability beds, both of which would tend to increase the lag time. As a result, the lag times calculated here may be systematically lower than what might actually be expected. The calculation also does not account for locally high recharge rates (under a leaky pond, for instance) or for dispersion, either of which could cause part of the water to reach the water table before the calculated lag time.

In **Figure 7.4-2** the calculated lag times are divided into three zones; less than one year, one to 50 years and more than 50 years. The area with a lag of more than 50 years is visually estimated to be over half of the COHYST area. In most of that area, the water that reaches the water table during the simulated period would have originated at the base of the root zone prior to the modern era of irrigation.

In the area with recharge lags of 1 to 50 years, recharge reaching the water table may have transitioned from natural rates to modern rates within the period of the simulation. For areas where the lag is less than one year, recharge would be expected to occur at the modern rate.

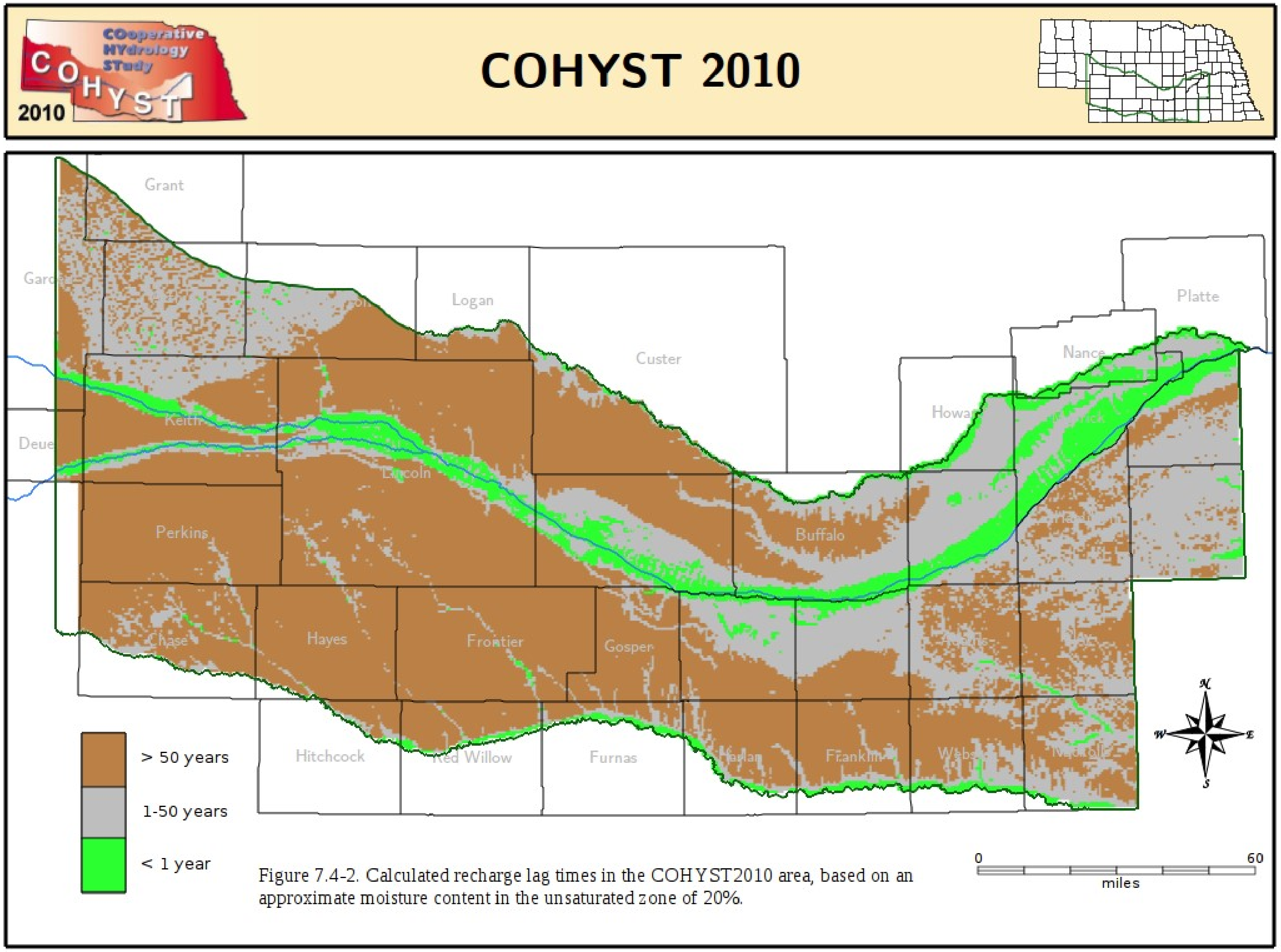


Figure 7.4-2. Calculated recharge lag times in the COHYST2010 area, based on an approximate moisture content in the unsaturated zone of 20%.

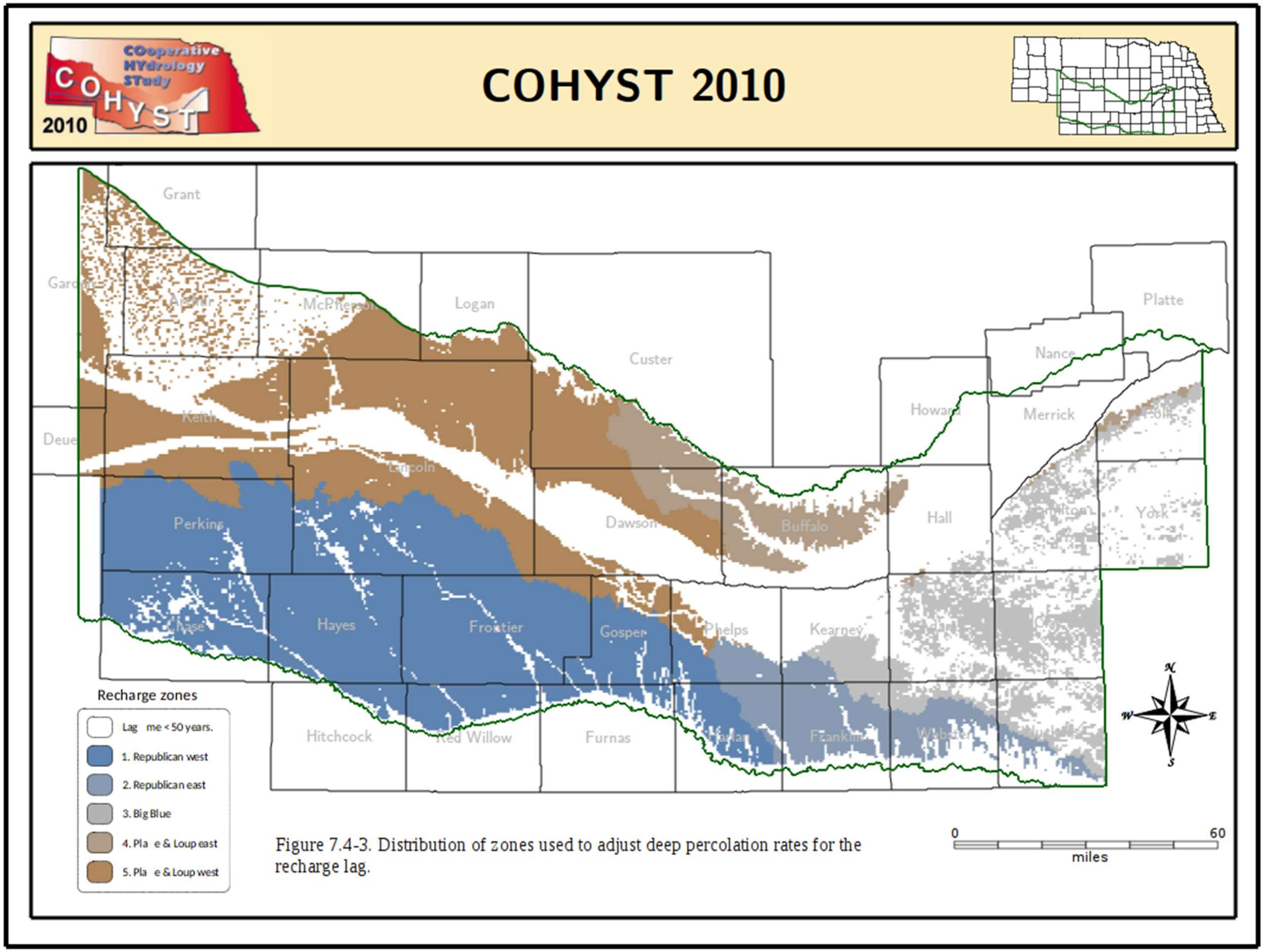


Figure 7.4-3. Distribution of zones used to adjust deep percolation rates for the recharge lag.

For the current calibration, multipliers were applied to the watershed model deep percolation rates to optimize recharge rates in areas where the lag times exceeded 50 years. The COHYST area was divided into five zones shown in **Figure 7.4-3** to provide for five different multipliers.

The process of using multipliers in some areas to approximate recharge rates from deep percolation rates is not an ideal solution. It does preserve spatial variations in recharge rates that result from variations in soil type, but it cannot predict future changes in recharge and may require alternative model approaches in predicting future conditions.

MODFLOW 2005 and later versions of MODFLOW include the ability to calculate flow through the unsaturated zone (Niswonger, et al, 2006). The unsaturated flow capability was added to MODFLOW to link a watershed management model to a groundwater model. For future COHYST efforts, that ability may provide a more appropriate solution for the recharge lag condition.

Evapotranspiration rates. Extensive changes were made to the groundwater model's simulation of riparian evapotranspiration since 2013, and those changes were described earlier in this section. For calibration, the evapotranspiration rates and the monthly distribution of ET used to calculate the maximum ET rates in the groundwater model were changed to match the rates and distribution of ET used in the watershed model.

Adjustments to the calibration process. Early results from the optimizer were not useful. The optimizer typically iterated no more than a few times and made only minor changes to starting parameters, even if the starting parameters were substantially changed. Two changes were made to the model to increase its sensitivity.

First, the comparison data set was edited to use only the last measured drawdown at each location. Two locations were removed from the calibration set because the last datum fell significantly above or below the trend of the hydrograph. The simplification reduced the number of calibration data from 6,116 points at 402 locations, to 400 points at 400 locations. The full set of 6,116 points at 402 locations was retained for illustrating model results.

Second, the hydraulic conductivity zones initially used by the model were the same used for the prior calibration. Those zones were created by contouring hydraulic conductivity values estimated from specific capacity data, and they include small isolated zones, narrow zones generated by contouring between two areas with highly contrasting conductivity, and irregular zone boundaries. The hydraulic conductivity zones were manually edited to reduce complexity. **Figure 7.4-4** contrasts the original zone distribution with the edited zone distribution.

With these modifications the optimizer responded to parameter changes as expected and produced optimized results, although it is still possible that the optimization is only local to the starting parameters.

7.5 Calibration Results

Match to optimization criteria. **Figure 7.5-1** illustrates the distribution of errors in calculated drawdown for the last available datum from the calibration period. Other measures of model performance can be used, but this figure represents the actual optimization criterion.

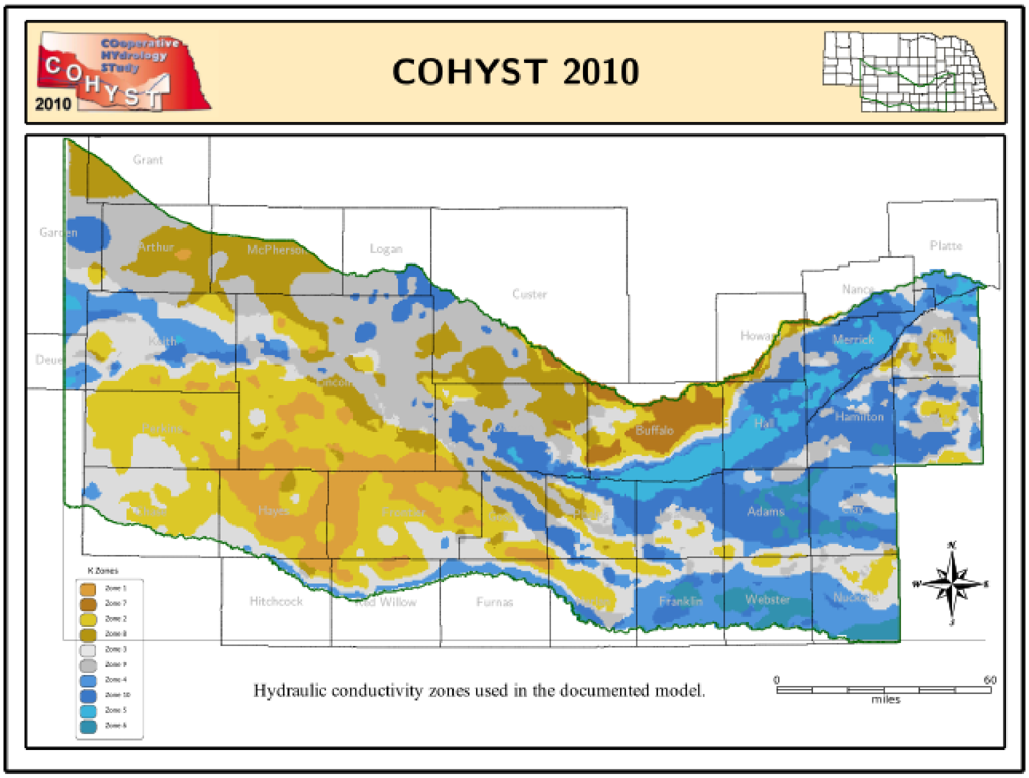
Ideally, all the points mapped in Figure 7.5-1 would be white circles. Any points that are not white should be equally distributed between blue (positive) and red (negative), and there should be no spatial concentration of either positive or negative errors.

In practice the optimization is generally good, but with a consistent error in Gosper and Phelps Counties. Five percent of the total error comes from a single site in southern Gosper County, where the initial water level used in the simulation may be incorrect.

Approximately half (192 out of 400) values were within +/- 2.75 feet. Overall, the average difference is 0.345 feet—slightly biased to positive errors—and the standard deviation of the errors is 5.49 feet. Errors in areas near the Platte are smaller than errors distant from the Platte. The average error for data points near the Platte was almost unbiased at 0.055 feet with a standard deviation of 4.43 feet. The average error for data not near the Platte was 0.565 feet with a standard deviation of 6.18 feet.

Appendix 7-C provides comparison hydrographs at each of the 402 observation locations. Where data exist, the hydrographs in the appendix extend beyond the calibration period.

Figures 7.5-2, 7.5-3 and 7.5-4 illustrate example hydrographs. Hydrographs typically show a good agreement between calculated and observed values. Many hydrographs near the Platte



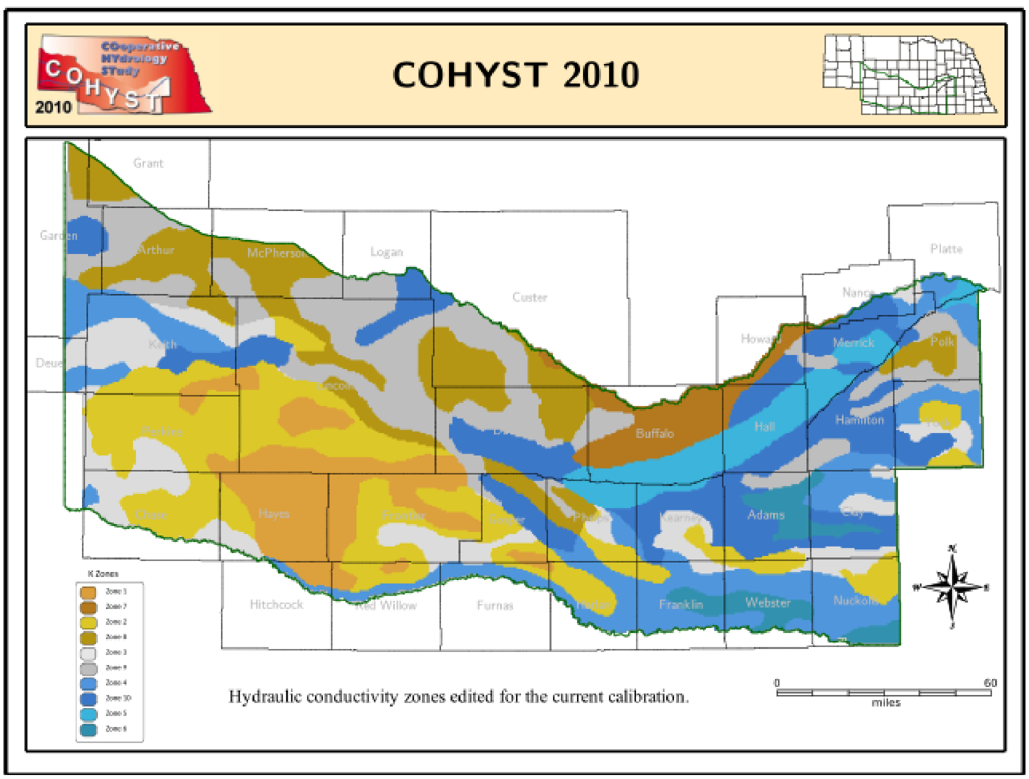


Figure 7.4-4. Hydraulic conductivity zones used in the documented model compared to the simplified zones in the current calibration.

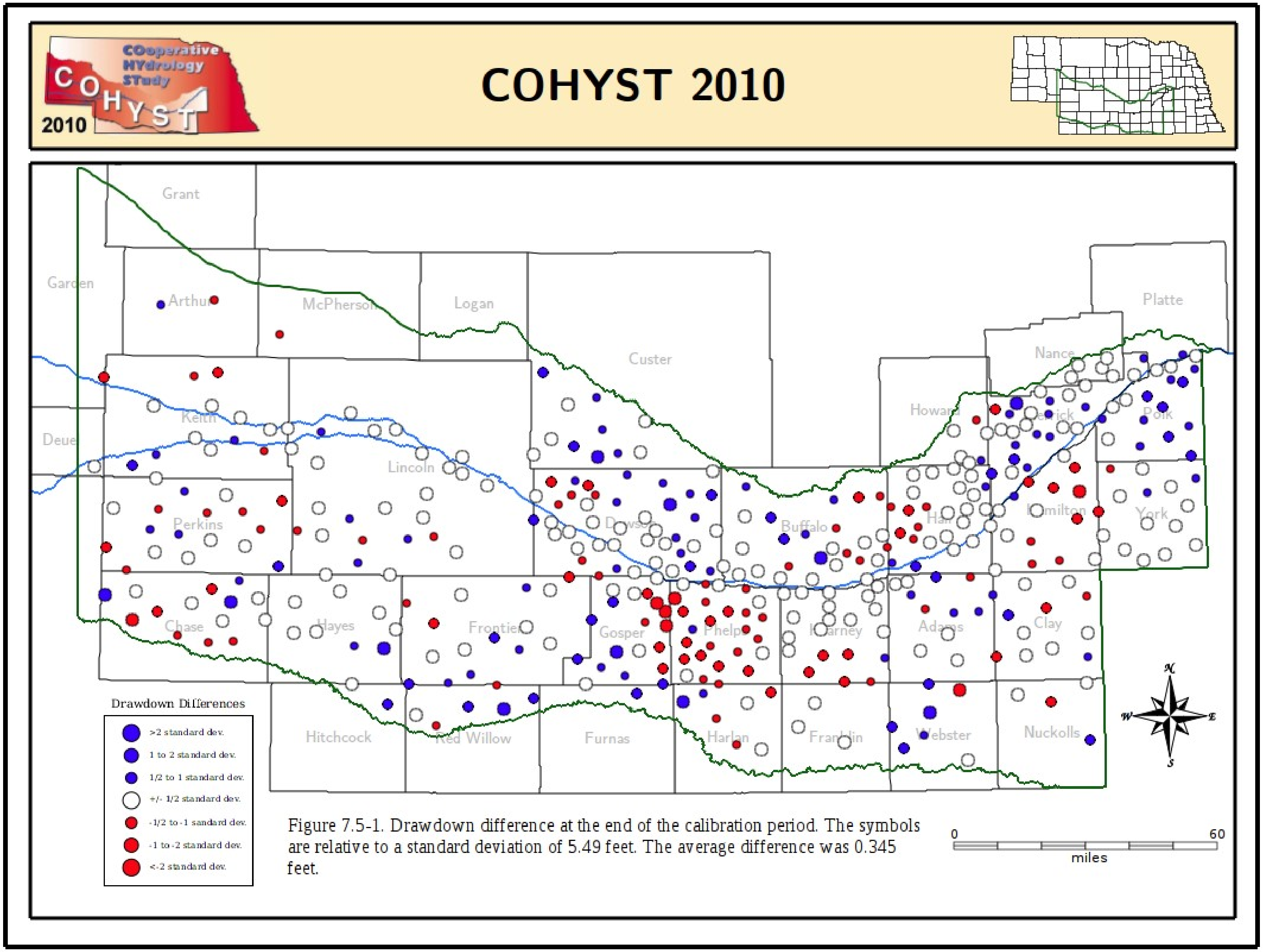


Figure 7.5-1. Drawdown difference at the end of the calibration period. The symbols are relative to a standard deviation of 5.49 feet. The average difference was 0.345 feet.

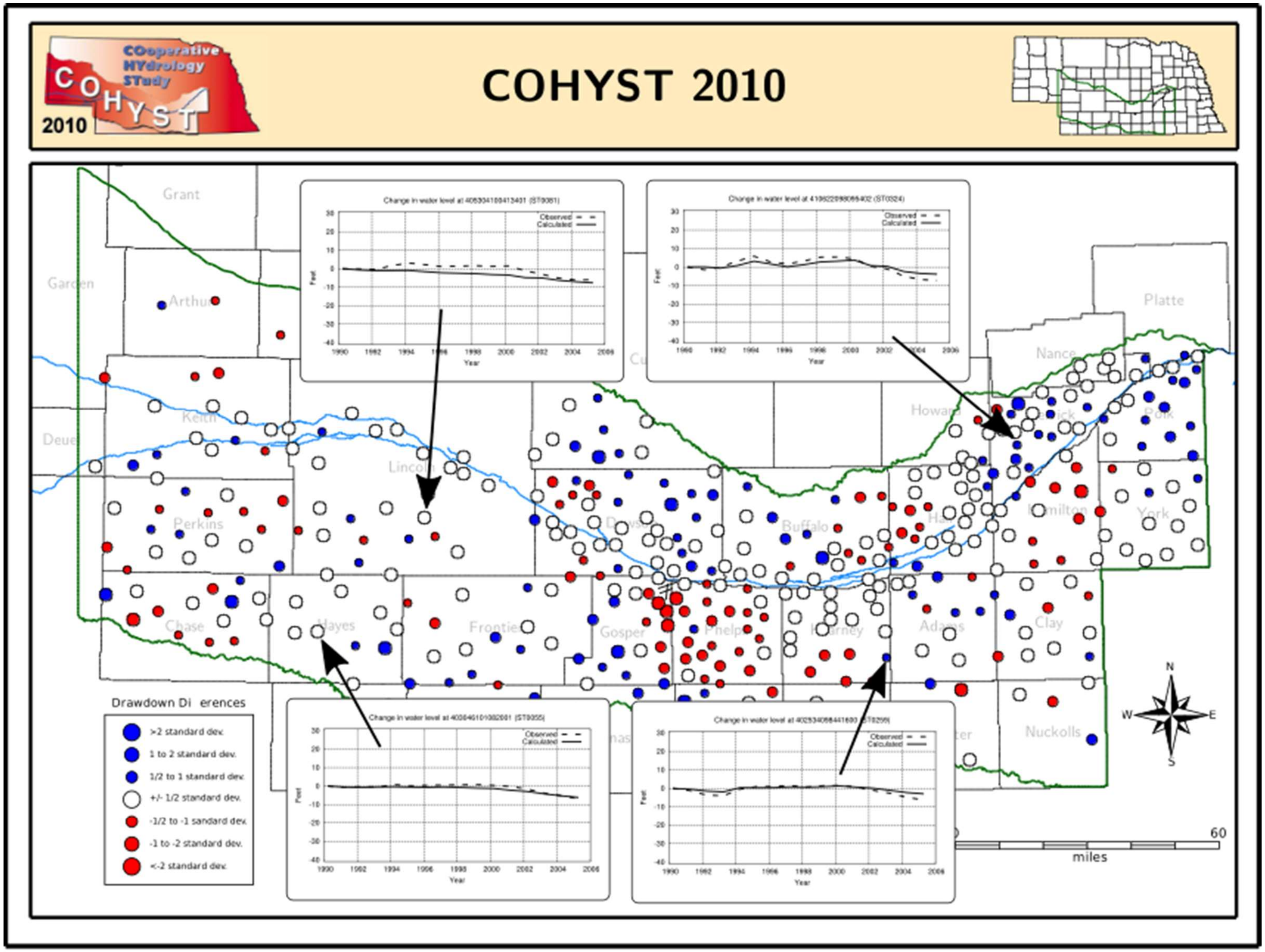


Figure 7.5-2. Examples of typical hydrograph comparisons.

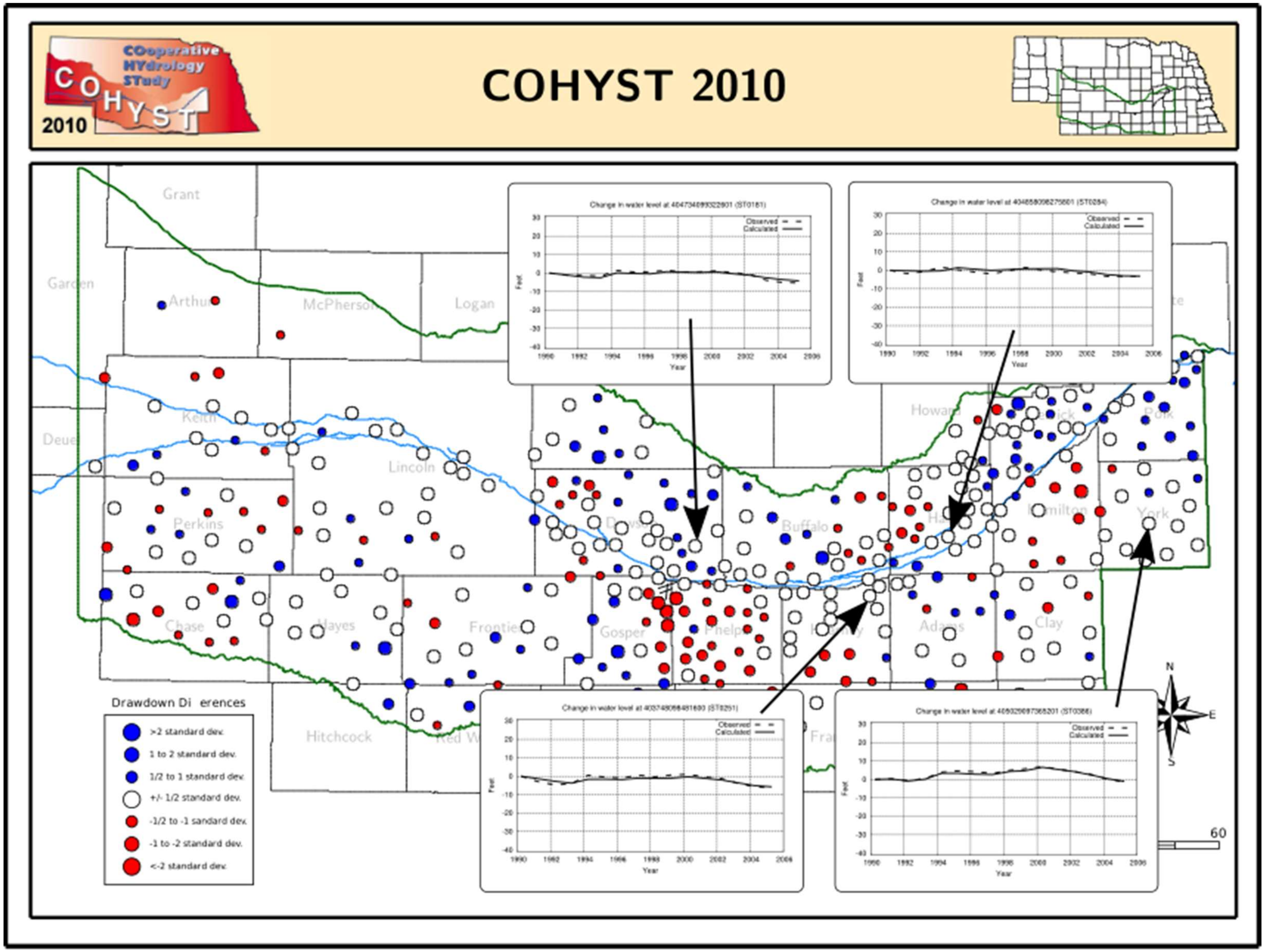


Figure 7.5-3. Examples of excellent hydrograph matches.

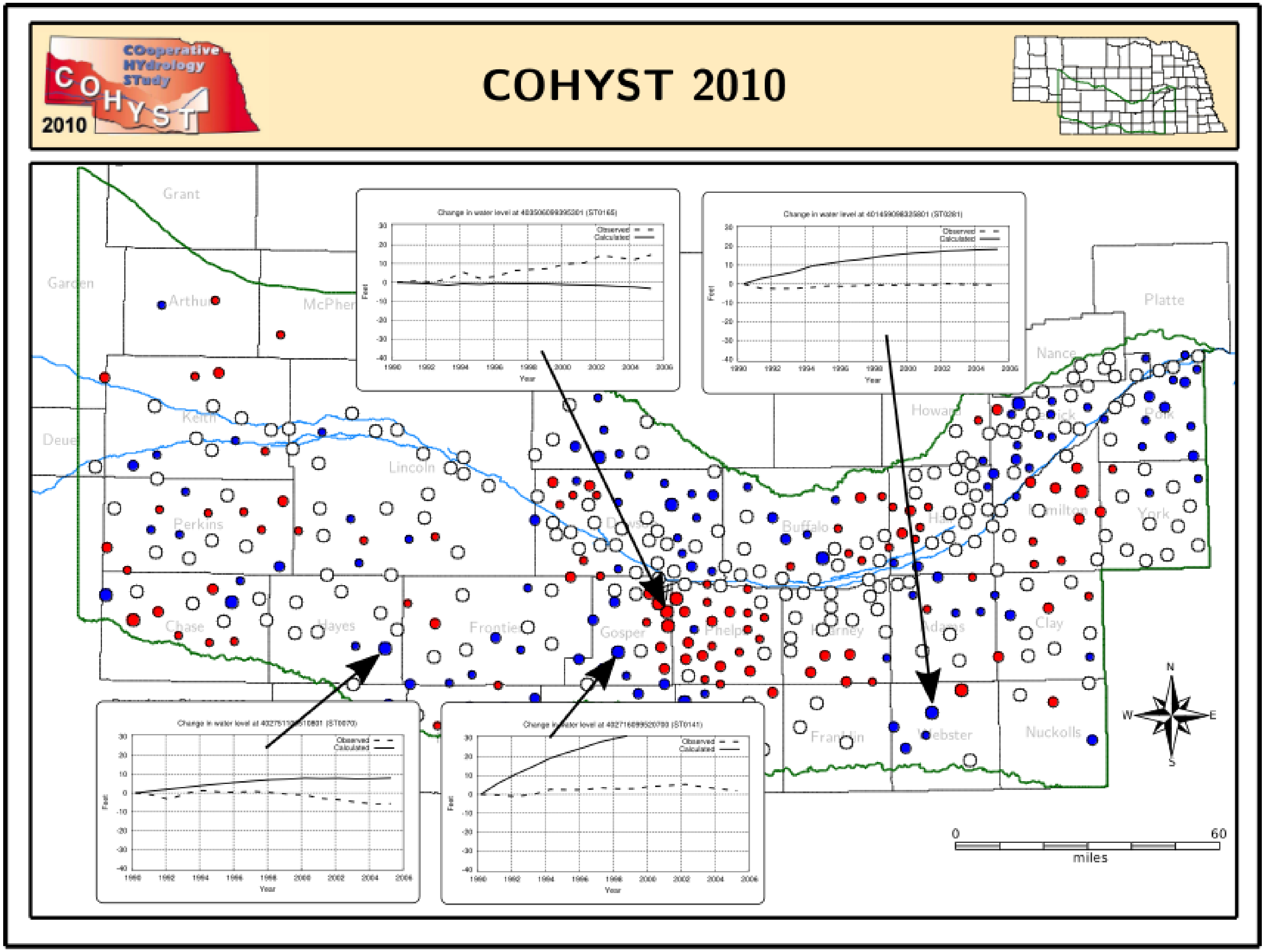


Figure 7.5-4. Examples of bad hydrograph comparisons.

are in excellent agreement with observations and the larger errors tend to be distant from the Platte. Optimization can produce good-looking results with unrealistic aquifer parameter values—getting the right answer for the wrong reasons—so it's important that the final parameters fall within a reasonable range of expectations, or that large differences have an explanation.

Hydraulic conductivity. Hydraulic conductivity was the principal parameter that was varied to optimize the model. **Figure 7.5-5** maps the hydraulic conductivity values from the final optimization, which are also provided in **Table 7.5-1**.

Table 7.5-1 Calibrated hydraulic conductivity

Zone	Value ft/day)
1	21.8
2	28.8
3	37.6
4	79.7
5	150
6	150
7	36.3
8	20
9	27.7
10	79.9

In Figure 7.5-5, the values for the derived zones (eight, nine and ten) are grouped with the values from zones one through four so that their results can be readily compared. Zones eight through ten were distinguished from zones two through four because wells in the area penetrate less than 60% of the aquifer. Zone seven was derived from the original zone one because the results from optimizations done in 2012 and 2013 indicated that behavior of water levels in areas of zone one north of the Platte River were different from the behavior of water levels in other areas. The calibration supports that conclusion.

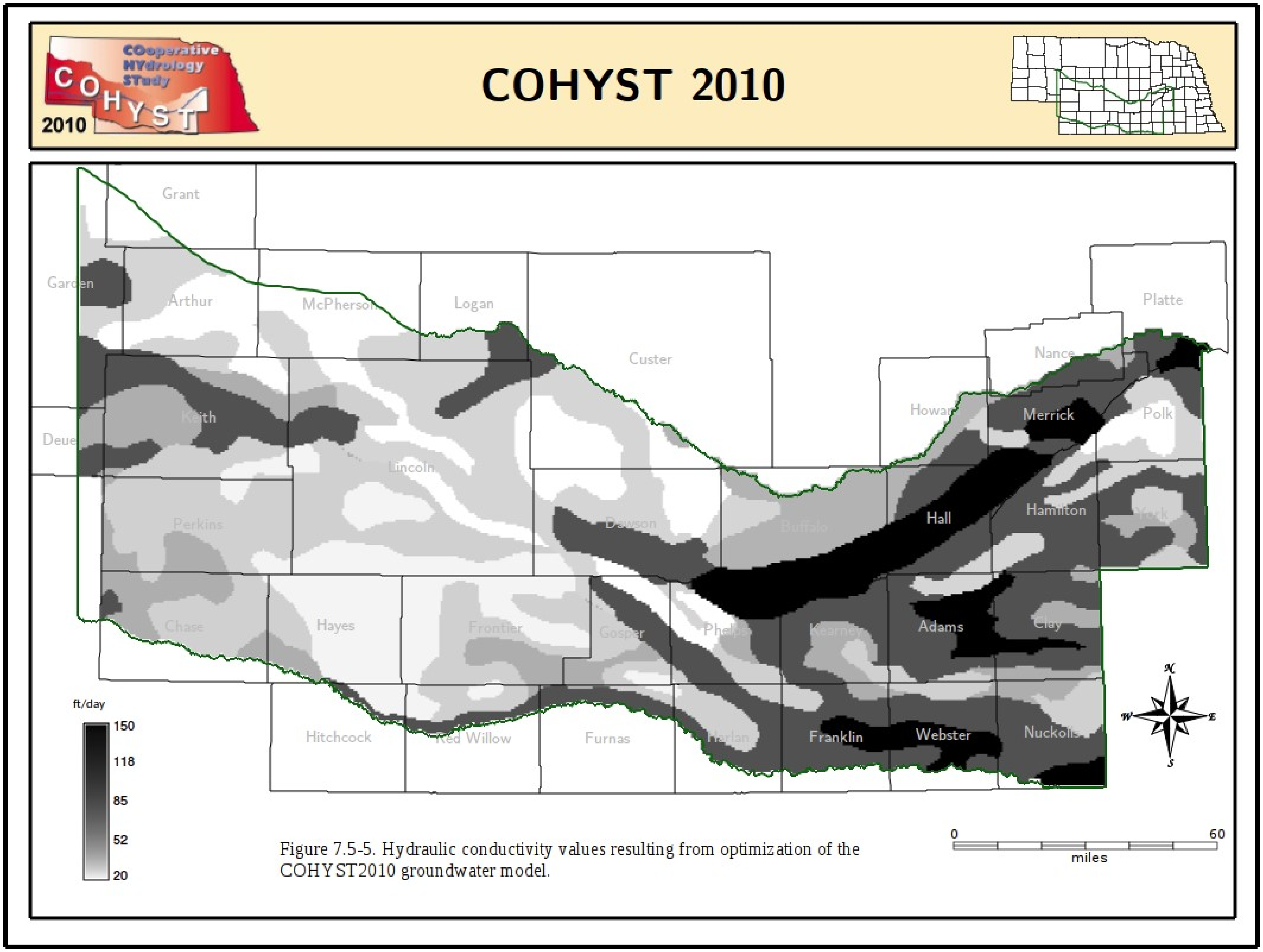


Figure 7.5-5. Hydraulic conductivity values resulting from optimization of the COHYST2010 groundwater model.

The hydraulic conductivity values in zones five and six were held constant during optimization. The values from initial optimizations tended to drift up to unreasonable results, so the hydraulic conductivity for zones five and six were set at the initial estimates.

The hydraulic conductivity values were initially estimated from specific capacity values for wells in Nebraska's database of registered wells (ftp://ftp.dnr.ne.gov/Pub/cohystftp/2010Report/), using the method of Driscoll (1986) for unconfined aquifers. **Figure 7.5-6** compares the optimized values to the initial estimates. The agreement between the initial estimates and the optimized values is excellent in all cases except but zones one and seven, where the optimized values are higher than expected.

We have two other sources of hydraulic conductivity values estimates that can be used for comparison. Borehole lithology was used to estimate hydraulic conductivity for the original COHYST models. **Figure 7.5-7** compares those estimates to the optimized values. The comparisons are generally acceptable, but show large differences in the highest conductivity zones, where the original estimates are low compared to the calibrated values.

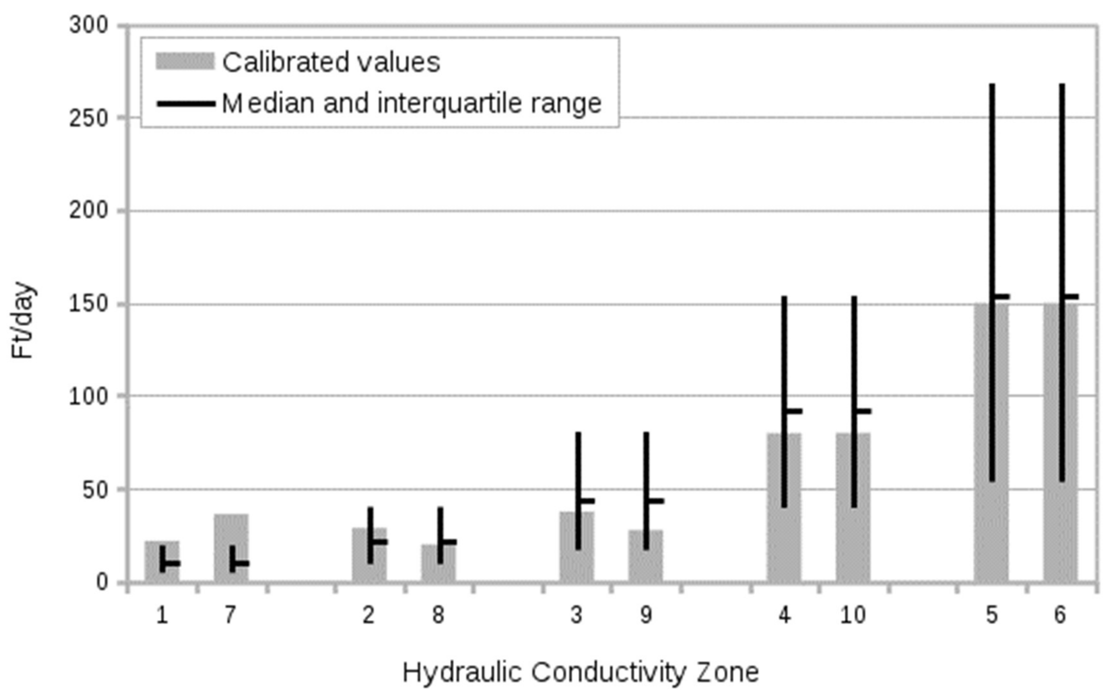


Figure 7.5-6. Calibrated hydraulic conductivity compared to prior expectations from specific capacity data.

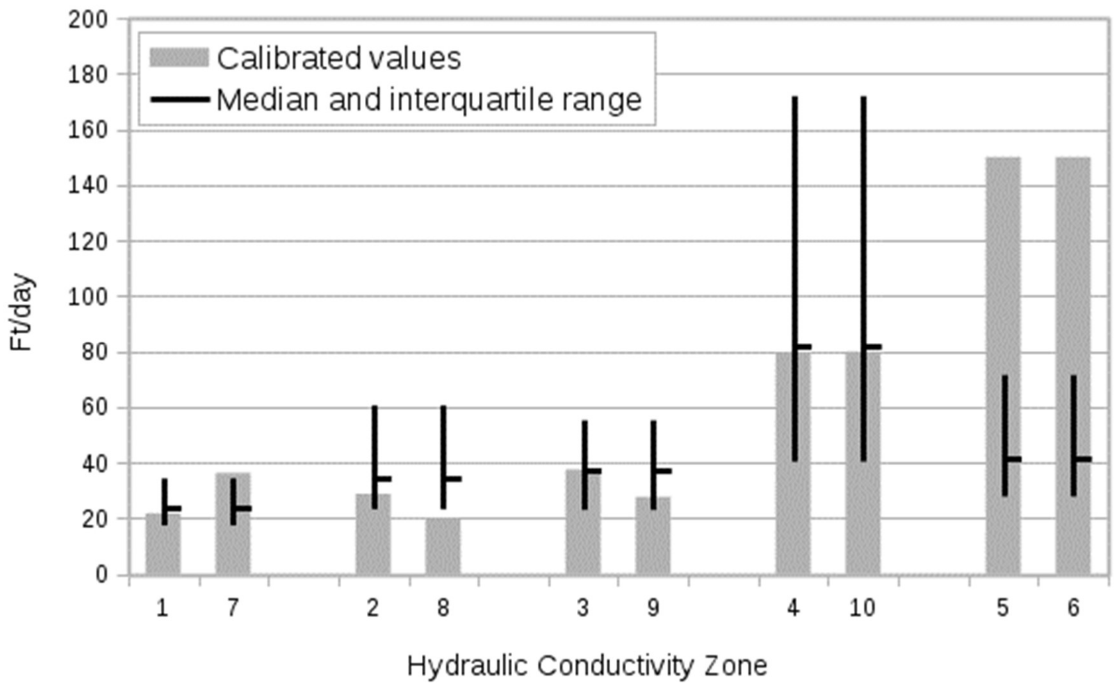


Figure 7.5-7. Calibrated hydraulic conductivity compared to prior expectations from lithology-based estimates done for COHYST.

Figure 7.5-8 compares the optimized values to the values resulting from aquifer tests in CPNRD provided by Duane Woodward (email communication). The aquifer tests were commonly from partially-penetrating wells, and in those cases results were combined with results from nearby wells or estimates for untested units to arrive at values for the entire aquifer. The agreement between the optimized values and the test values is generally good. The calibrated results for zone five are in good agreement with aquifer test results, so it appears that the lithology-based estimates (Figure 7.5-7) for zones five and six were unrepresentative.

Specific yield. For the 2013 calibration, the COHYST model area was divided into three zones to describe specific yield: zone one represented areas where the water table was in gravelly sections of the Quaternary, zone two represented areas where the water table was in sandy sections above the Ogallala aquifer, and zone three represented areas where the water table was in the Ogallala. Specific yield was not calibrated in that model, it was specified at 23% in zone one, 18% in zone two and 16% in zone three.

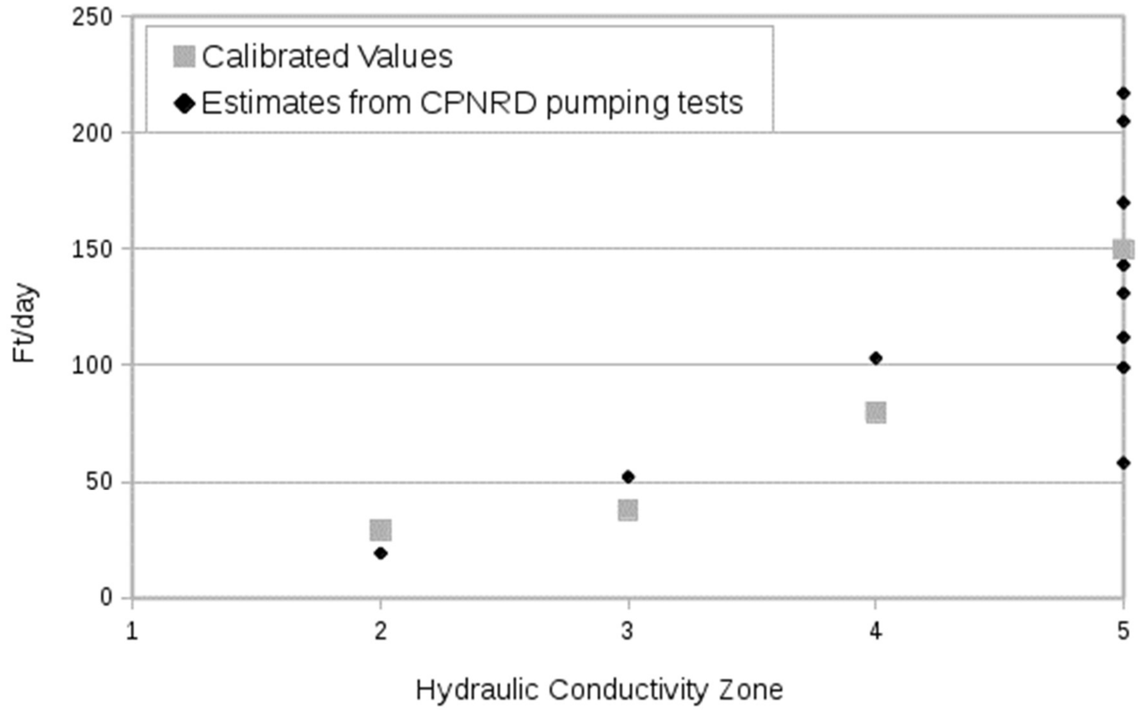


Figure 7.5-8. Calibrated hydraulic conductivity compared to prior expectations from CPNRD aquifer tests.

The current calibration maintains the same three zones but adds zone four under Lake McConaughy. **Figure 7.5-9** maps the specific yield zones. The specific yield in zones one and four were fixed at 20% and 0.002, respectively. The specific yield for zones two and three—which represent most of the model area—were equated in the optimizer and optimized at 15%.

There are limited prior data to compare to the estimated values. The results from aquifer tests within CPNRD were provided by Duane Woodward (email communication). Those tests provided ten values that average 13% and range from a low of 2% to a high of 25%. The optimized value of 15% falls well within a reasonable range.

<u>Recharge lag adjustments</u>. The zones used for the recharge lag adjustments were shown previously in Figure 7.4.3. Optimization worked well in recharge zone one—in the southwest part of the model—where optimization produced a value of 0.59. The 2013 calibration produced a value of 0.68 in part of the same area.

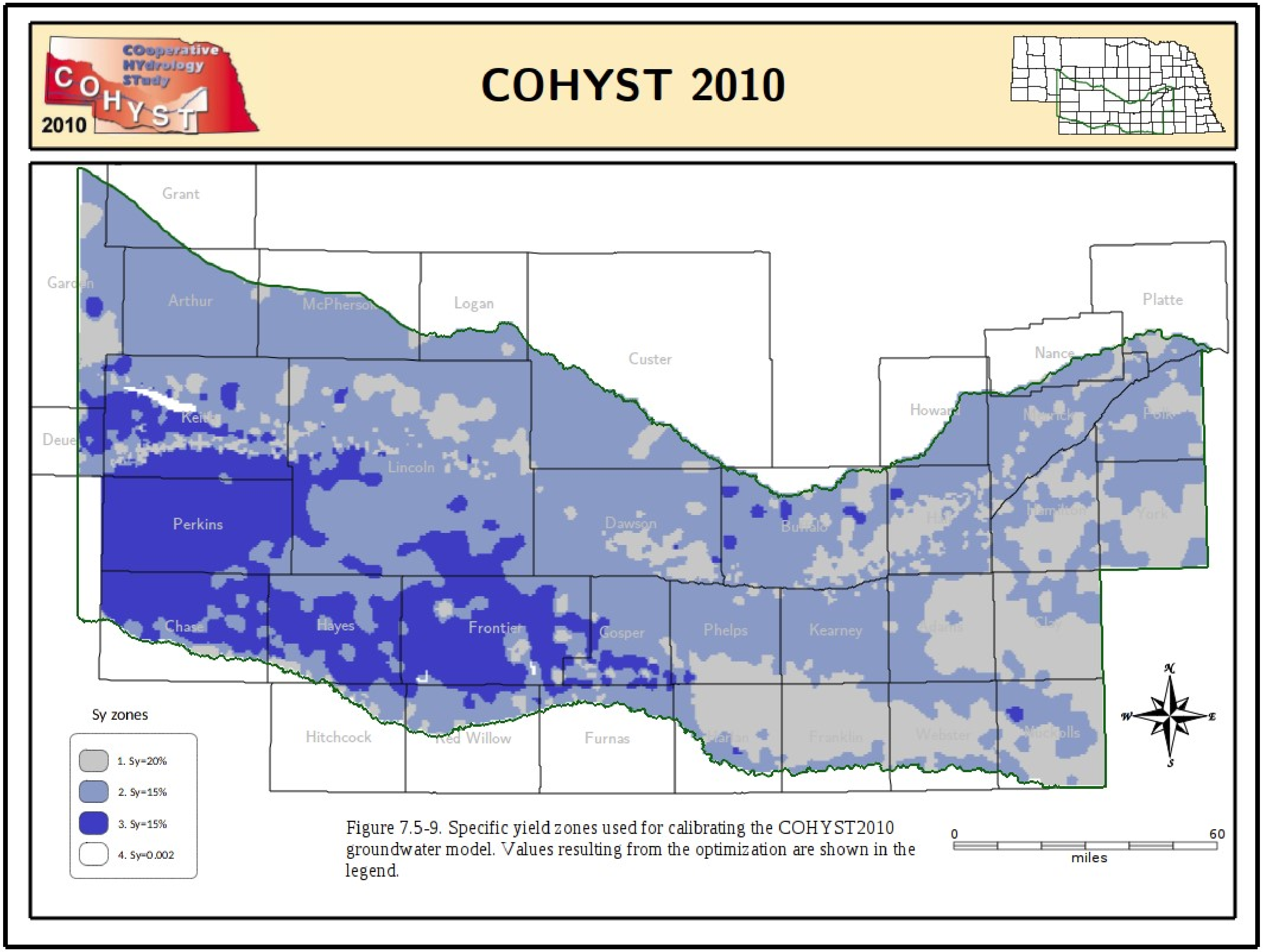


Figure 7.5-9. Specific yield zones used for calibrating the COHYST2010 groundwater model. Values resulting from the optimization are shown in the legend.

Optimization of the recharge lag was acceptable in zones three and four, which represent the eastern part of the model. The optimizer was allowed to adjust the recharge in only a small proportion of the area, and it resulted in a value near 1.0 for both zones. Subsequently, the lag adjustments was held at 1.0, which implies that historical recharge in the area wasn't significantly different from the deep percolation rates provided by the groundwater model.

Zones two and five represented the east end of the Republican River drainage and the northwest part of the model, respectively. In both areas the optimizer produced values of two or more for the recharge adjustment, which are considered physically unrealistic.

Recharge zones two and five include areas in Gosper and Phelps Counties where the model also underestimates the historical rise in water levels. It is possible that the problem with simulated drawdown in the area influenced the optimized recharge adjustment. As a result, the recharge adjustment in zones two and five was fixed at 1.0.

The recharge adjustment in zone one introduces a change to the water balance of the integrated model as well as to recharge rates in the groundwater model. Within zone one, all the deep percolation specified by the watershed model during the model period remains in unsaturated storage at the end of the simulation. The recharge rate at the water table is 59% of the deep percolation rate, so the net effect is an increase in unsaturated storage over the period of the simulation equal to 41% of deep percolation.

Modelers who apply the model to predict future conditions should determine if the conditions in the calibration period are representation of the period being simulated. If not, there is no standard adjustment to be made; rather each modeler should use her or his professional judgment to address this issue.

<u>Baseflow comparisons</u>. The comparison of calculated and estimated baseflows were criteria in the 2013 calibration, but not in the current calibration. Baseflow was removed as a calibration criteria because the optimization was largely insensitive to baseflow errors and because the provenance of some data used for the 2013 calibration was unclear. The baseflow values were retained to provide a qualitative measure of model performance.

Figure 7.5-10 illustrates two cases in which the current calibration improved the baseflow comparisons. The improvement on the reach from Odessa to Grand Island contributed to the model's ability to simulate dry conditions in the Platte at Grand Island; see Section 8.2.

Figure 7.5-11 illustrates two cases in which the current calibration did not improve the baseflow comparison. As was true with the 2013 calibration, baseflow to the Platte River

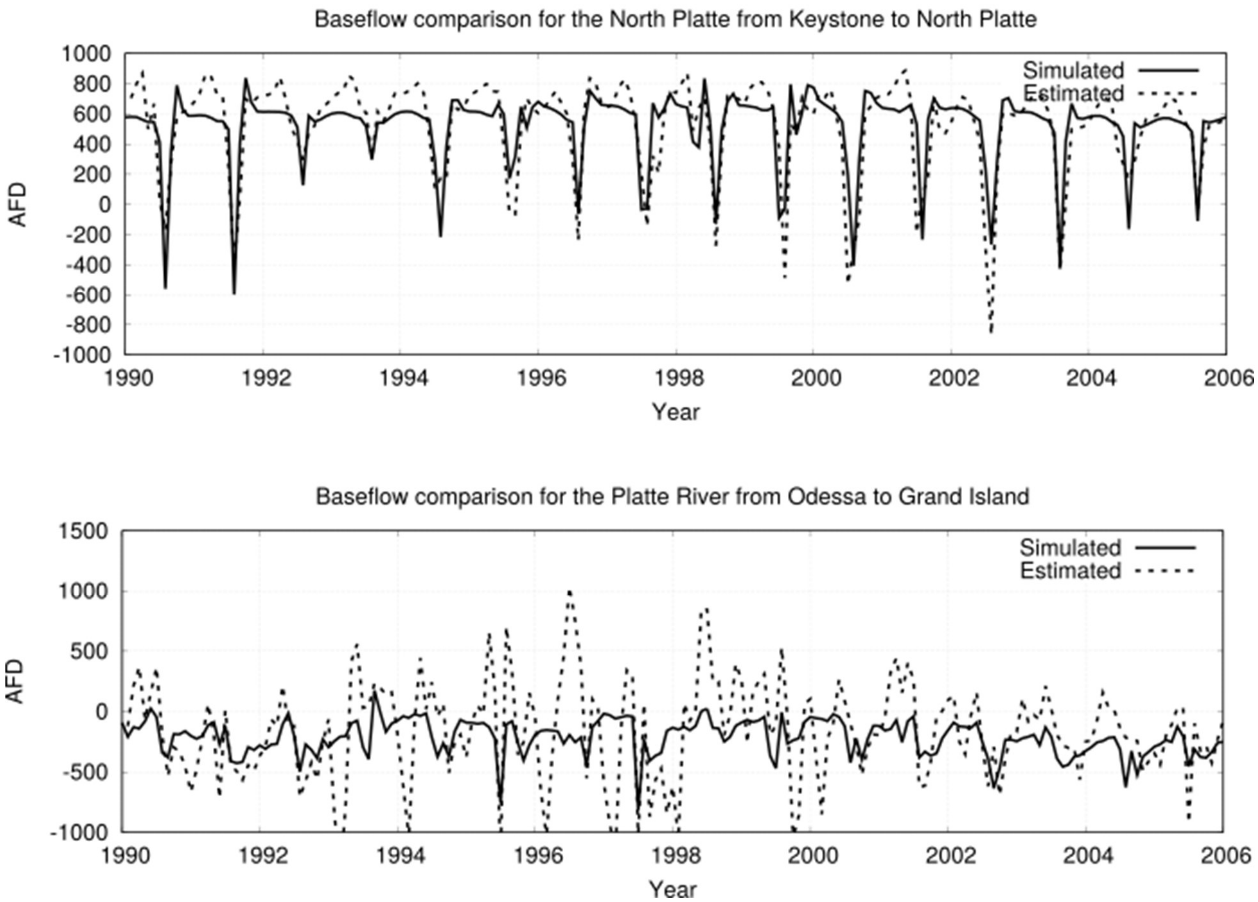
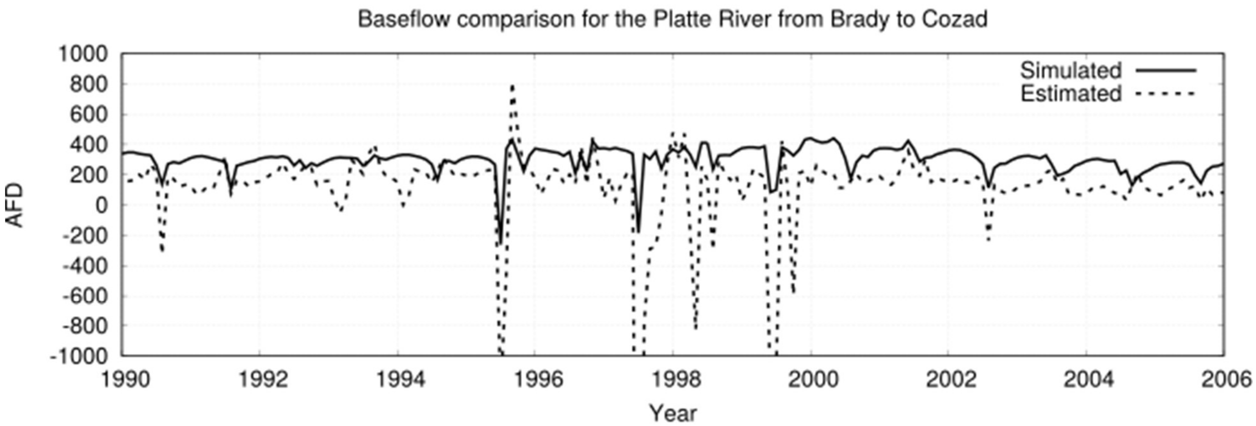


Figure 7.5-10. Two cases in which the optimization improved the baseflow match.



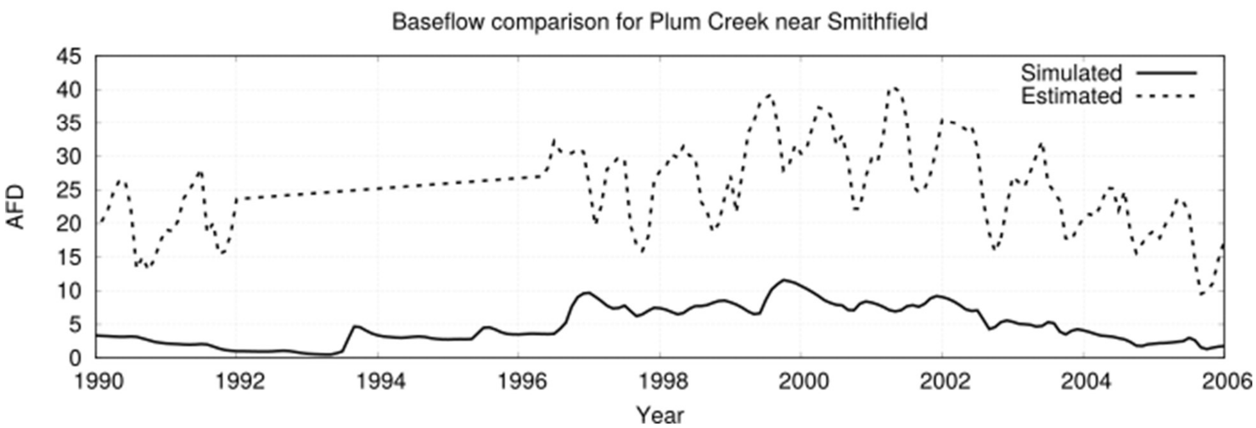


Figure 7.5-11. Two cases in which the optimization did not improved the baseflow match.

between Brady and Cozad tends to be high by about 200 AFD (100 CFS) throughout the calibration period. Baseflow in Plum Creek at Smithfield is low in the current calibration; it was high in the prior calibration. Plum Creek drains part of the area in Gosper and Phelps Counties where the model underestimates the historic rise in water levels. The baseflow error may be related to the error in simulated drawdown.

7.6 Extension to 2010

The COHYST2010 integrated model was extended through 2010 and the extended results were used to verify the model. Extended recharge and pumping rates are provided by the watershed model and the surface water model. The only non-trivial changes otherwise necessary to extend the groundwater model were the end-of-month reservoir levels at Lake McConaughy, Hugh Butler Reservoir, and Harry Strunk Reservoir, and the extended water level comparison data set.

For the purpose of this study, the groundwater model could be considered verified if the result at the end of the five-year extension did not reveal any previously unknown errors or produce substantially worsened results. Hydrographs in Appendix 7-C illustrate the water level and drawdown results through the verification period.

Figure 7.6-1 maps the differences between calculated and observed drawdown at the end of 2005—and the end of 2010. Overall the results are very similar. Results improved in Merrick and Phelps Counties. Results worsened in Gosper and Adams Counties, but the problems do not prevent the conclusion that the extended model results are consistent with the calibration.

The comparison is summarized in **Figure 7.6-2**. Although it’s not evident on the histogram, there is a shift in the extended results to more negative errors. The mean error improved from 0.345 feet over the calibration period to -0.27 feet at the end of the verification period.

There are no results from the extended model that are significantly different from results of the calibrated model. As a result, the groundwater model can be considered verified.

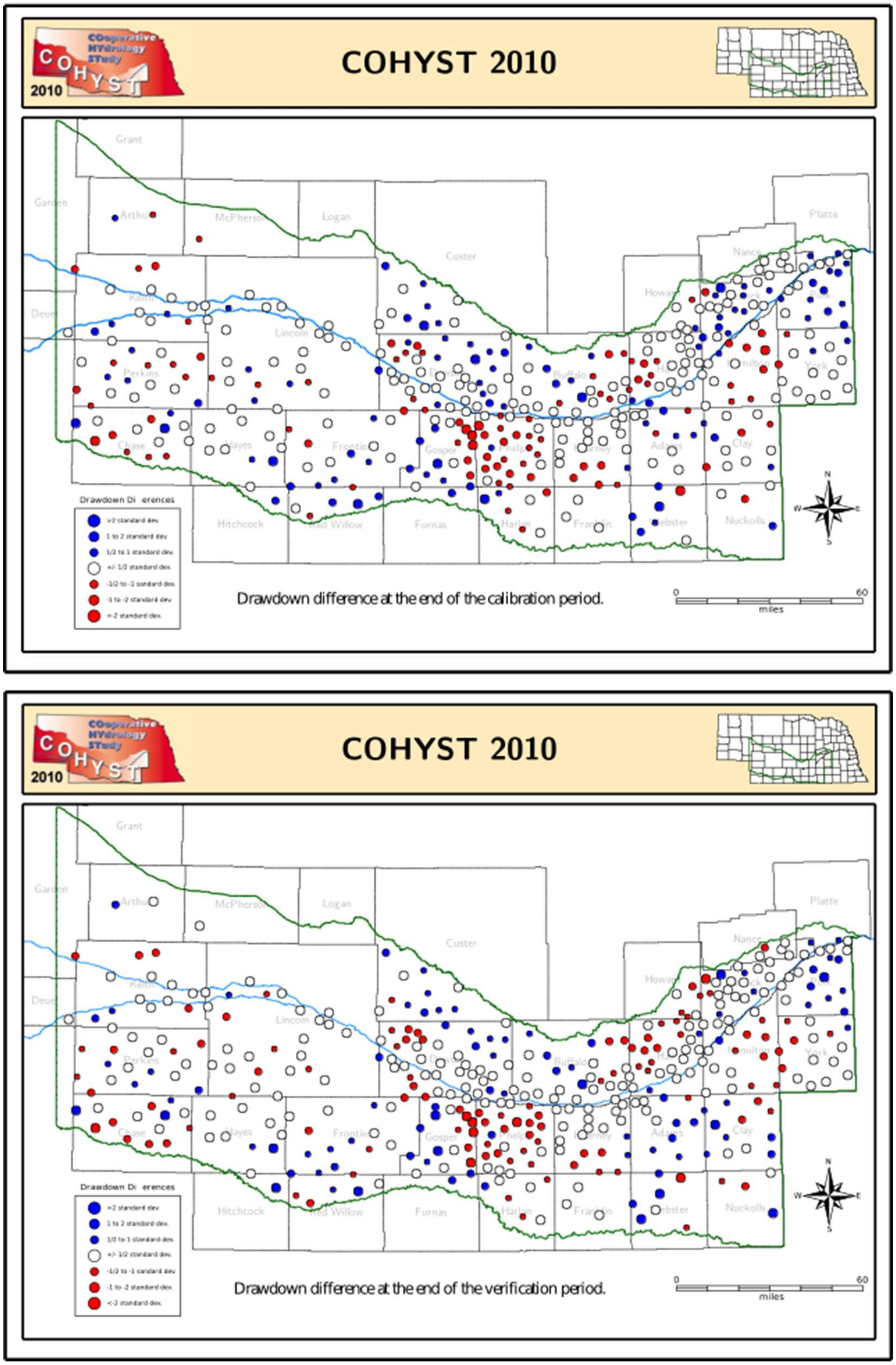


Figure 7.6-1. Drawdown differences at the end of the calibration period and verification period.

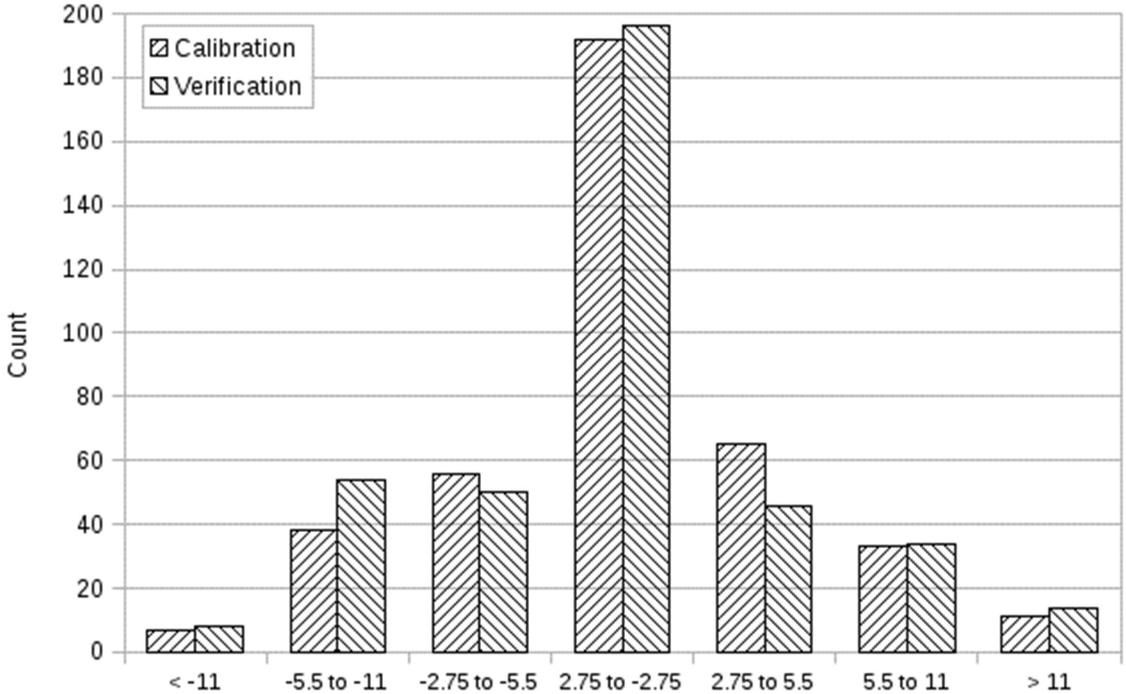


Figure 7.6-2. Drawdown difference (calculated-observed) at the end of the calibration and verification periods.

7.7 Gosper-Phelps Focused Study

The most prominent outstanding problem in the groundwater model is its failure to accurately reproduce the historic rise in water levels in Gosper and Phelps Counties. The problem is clearly illustrated in Figure 7.5-1 by the concentration of orange symbols in the area. The problem was absent in run 27b_14_27, which was the starting point for the current calibration.

Several checks were made to be sure that the problem was not due to errors introduced in pre-processing data from the watershed model and surface water model. Those tests produced no evidence for data transfer problems.

The area of the problem partly coincides with CNPPID's irrigation canal system. A series of test were run with seepage from the canals increased by factors of 1.2, 1.5, 2.0 and 3.0. It was possible to largely eliminate the problem by doubling the seepage rate from the canals, but such a large increase was unrealistic.

An alternate groundwater model was constructed, and that model was optimized to see if the problem could be reduced or eliminated.

- Hydraulic conductivity zones were redrawn to shrink the area of high conductivity near the Platte. The effort resulted in a more complex distribution of conductivity that made the parameter estimation less sensitive. The adjusted zones are shown in **Figure 7.7-1**.
- The zone used for the recharge lag adjustment was redefined so that it did not extend into eastern Gosper County.
- The drawdown observations in the area of Gosper and Phelps Counties were given higher weights so they would have a disproportionate influence on the optimization results.

The initial estimates for hydraulic conductivity were lowered. In zone eight the initial estimate was dropped from 20 ft/day to 15 ft/day, in zone nine the initial estimate was dropped from 27.7 ft/day to 20 ft/day, and in zone 10 the initial estimate was dropped from 79.9 ft/day to 50 ft/day. During optimization, the hydraulic conductivity in those zones rose to 15.08 ft/day in zone eight, to 21.1 ft/day in zone nine and to 52.08 ft/day in zone ten -all significantly lower than in the final calibration.

Figure 7.7-2 maps the distribution of errors after re-optimizing the model. The changes reduced the error in the Gosper Phelps area but did not eliminate the error. Errors increased outside of Gosper and Phelps Counties. **Table 7.7-1** gives the errors in the final integrated model run and in the Gosper Phelps study, broken down by groundwater basin.

Table 7.7-1. Model errors end 2005 in the final integrated run and in the Gosper-Phelps study.

Run	**Integrated run**		**Gosper-Phelps study**		
	Mean	RMSE	Mean	RMSE	Observations
Republican Basin	0.36	7.13	0.57	7.11	82
Blue River Basin	-0.39	4.57	-0.5	4.87	125
Loup Basin	2.6	5.69	2.77	6.01	38
Platte Basin	0.29	3.63	0.6	3.74	157
Overall	0.35	5.49	0.66	5.65	402

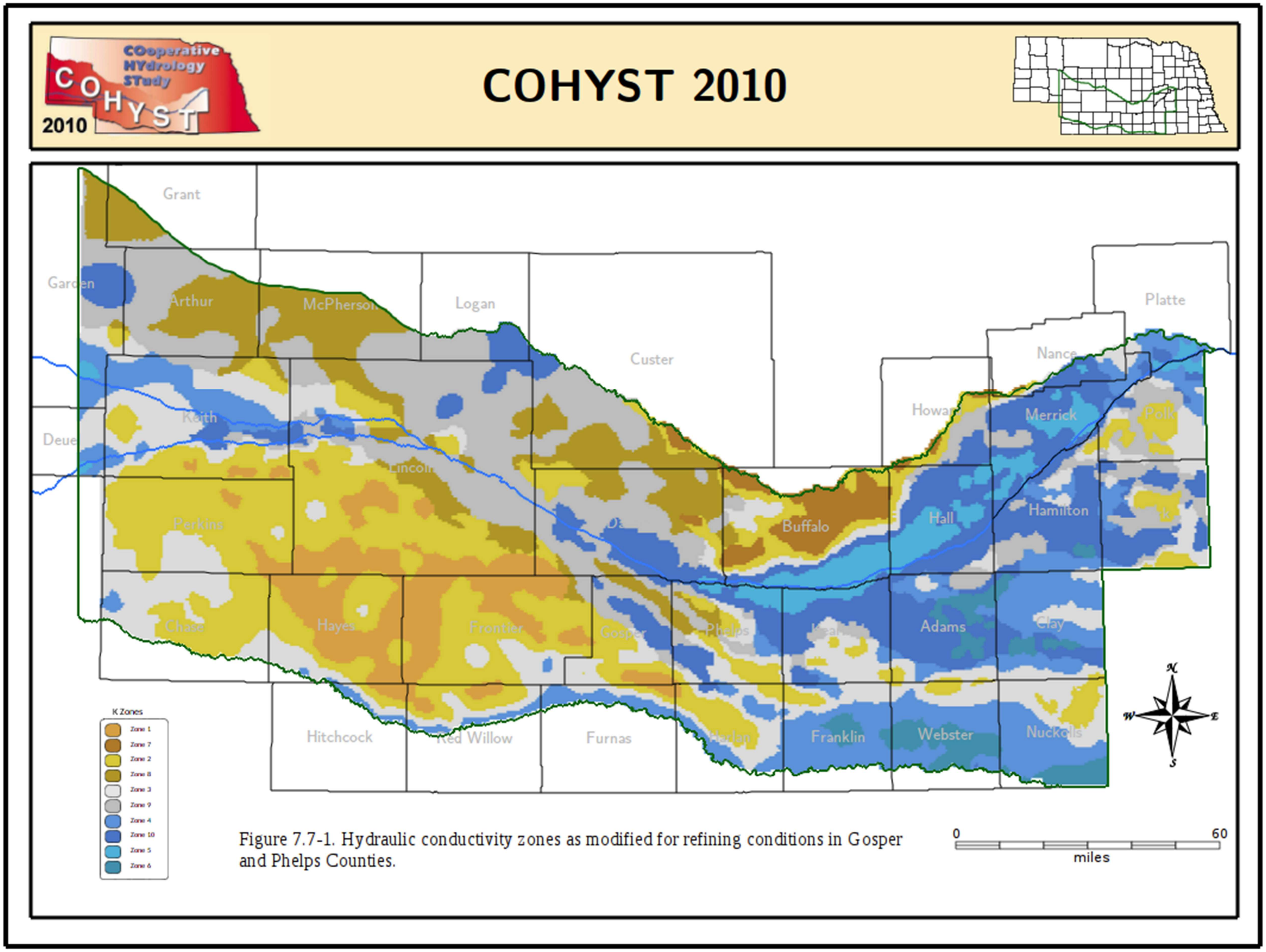


Figure 7.7-1. Hydraulic conductivity zones as modified for refining conditions in Gosper and Phelps Counties.

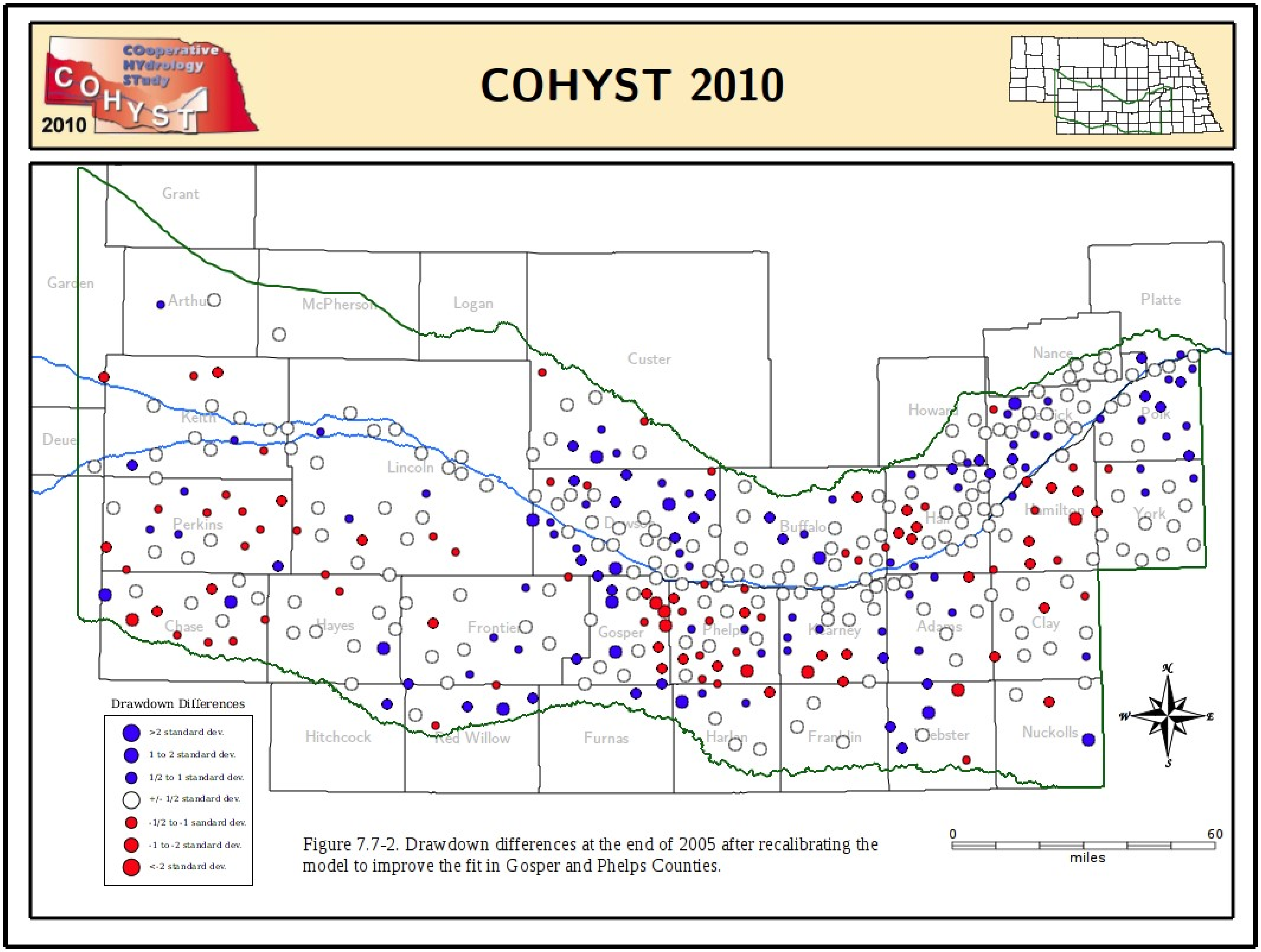


Figure 7.7-2. Drawdown differences at the end of 2005 after recalibrating the model to improve the fit in Gosper and Phelps Counties.

Water level changes in Gosper and Phelps Counties are better simulated with hydraulic conductivity values and zones from the earlier calibration, but those same zones and values produce poorer results outside of Gosper and Phelps Counties.

A more accurate simulation of water level changes in Gosper and Phelps Counties may require hydraulic conductivity values that are unique to that area. The conductivity zones that appear to work well outside the area do not provide a good representation of conditions within the area.