Big Bend GMD 5 Model Peer Review

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Environmental & Water-Resource Consultants

February 2011

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Prepared for:

Kansas Department of Agriculture
Division of Water Resources

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Table of Contents

Page

List of Figures

List of Appendices

REPORT

Section 1
Introduction

The purpose of this report is to document my participation, along with staff of S. S. Papadopulos & Associates, Inc. (SSPA), as a peer reviewer and member of the Technical Advisory Committee (TAC) regarding the development of the hydrologic groundwater model for the Big Bend Groundwater Management District No. 5 (GMD 5) and my assessment of the resulting model. In addition, this report will document a 1-layer version of the model SSPA developed to assist in assessing the model performance and evaluating alternative parameter assumptions.

The model development work was performed by Balleau Groundwater, Inc. (BGI) and documented in a report dated June 2010. SSPA was retained by the Kansas Department of Agriculture, Division of Water Resources (DWR) to serve in a peer review capacity. BGI was retained by GMD 5 to develop the model.

The study area considered by BGI extended beyond the boundaries of GMD 5 to the west and included parts of GMD 1 and GMD 3 as well as the Pawnee River basin beyond the boundary of GMD 5. My work as a peer reviewer and TAC member on behalf of DWR focused on the portion of the study area and model domain within and near GMD 5. Consequently, the discussion and comments in the sections that follow are limited to the area within and near GMD 5.

My work also focused on the potential uses of the model in addressing water management questions and issues germane to the interests of DWR. It was understood that some of the interests of GMD 5 and BGI in developing the model went beyond those of DWR and that these additional interests affected the nature and scope of model development work conducted by BGI. As a result, some of the discussion and comments below must be considered with that perspective in mind.

Section 2
Background

Portions of the model domain that includes the area within and near GMD 5 have been studied previously and models have been developed. I served as a peer reviewer in much the same capacity as I am here for a modeling project conducted by the Kansas Geological Survey (KGS) on the Middle Arkansas River Subbasin. This study was completed in 2006 and was one source of information used by BGI in their model development work.

Prior to my formal retention as a peer reviewer and TAC member for the model development by BGI, SSPA had begun to evaluate the possibility of combining the Middle Arkansas model developed by KGS and some earlier modeling work on the Rattlesnake Creek Subbasin. After some discussion among the various parties involved and considering the more expansive goals of GMD 5 regarding model development, it was decided that BGI would be responsible for model development for a domain that would include the areas we had begun to evaluate as well as areas further to the west that were of interest to GMD 5 and BGI. From that point forward, my role has been that of a peer reviewer and TAC member. In that role, I have tried to provide comments and constructive advice to BGI in their effort of model development. I have also periodically tested and evaluated the model as BGI progressed through the model development process. It should be noted, however, that my efforts to test and evaluate the model have focused on the GMD 5 area and have not included evaluations of parts of the model domain located further to the west of GMD 5.

Section 3
General Observations

The BBGMD5 model represents an attempt to integrate a significant amount of information and data into a quantitative framework. The resulting model includes significant detail regarding hydrologic and hydrogeologic characteristics and conditions throughout the model domain. In some respects, and in particular from the perspective of overall water management within GMD 5, the model includes more detail than is necessary to provide a useful tool for overall water management. It is understood that the interests of GMD 5 and BGI in terms of model application are perhaps broader than those of DWR and this interest generally explains the desire for greater detail. Also, one can argue that the inclusion of greater detail is not problematic if the overall performance of the model is satisfactory. The principle drawback of the more detailed model is that the resulting tool is more cumbersome to use and the ability to test and calibrate the model is made more difficult.

Overall, the development of the BBGMD5 model was made using reasonable and appropriate methods to structure and parameterize the model. This would include selecting grid spacing and time steps, assigning boundary and initial conditions, constructing the stream network, and compiling calibration targets. In some of these selections, such as grid spacing, the detail was perhaps greater than was necessary to address certain issues (i.e. a 7-layer representation versus a 1-layer representation). As discussed previously, the extra detail does not compromise model results per se but does make the model more cumbersome to run and evaluate.

We collapsed the 7-layer representation in the BBGMD5 model into a 1-layer representation to demonstrate that, for many purposes, the 1-layer representation can be used to obtain the same results that were obtained with the 7-layer representation and to facilitate evaluation of model performance. The 1-layer representation was constructed by aggregating transmissivity for 7 layers into 1 layer and adjusting remaining input parameters to reflect the single layer rather than 7 layers. Global water budgets for the 7-layer model and the 1-layer model were then compared for the run of historical conditions. These comparisons are shown in appendices to this report and show that the two models give essentially the same results. Other comparisons of computed groundwater levels and stream flows were also made and confirmed that the 1-layer representation was giving essentially the same results as the 7-layer representation.

Model calibration is perhaps the most important step in the modeling process. Studies have shown that calibration to measured data is the most important indicator of model reliability and that a properly calibrated model can often overcome the lack of detailed information about the physical conditions that describe the groundwater system being modeled (Hill, et. al., 1998).

Overall, the calibration of the BBGMD5 model appears to be satisfactory. The BGI report provides a brief discussion of the model calibration process in their report and provides numerous charts in the report appendix illustrating the comparison between model results and measured data for groundwater levels and stream flows. The BGI report also provides a few summary charts and maps in the report (Figures 43, 44, 46 and 47) to illustrate some overall water level calibration results.

Figure 44 in the BGI report is a scatter plot showing the comparison between simulated or computed water levels and observed (measured) water levels. This comparison shows what appears to be excellent correlation between the computed and measured values. However, given the geographic scope of the model domain and the significant influence of generalized topography and specified stream elevations on computed water levels, good performance of this metric is not particularly surprising.

The graph on Figure 46 is a better indicator of model performance with respect to water levels. This graph shows that, overall, the model has a slight bias toward overestimating water levels. This tendency for overestimation is also evident when one compares the percentiles surrounding the median. For example, the 80th percentile is generally over 10 feet whereas the 20th percentile is around -5 feet. Similarly, the 90th percentile is generally above 15 feet whereas the 10th percentile is generally about 10 feet. Also, there is only a slight downward trend in the average or median residual over this time period suggesting that the model results are generally following the data time trends over this period. These graphics illustrate that, with respect to groundwater levels, the model has a tendency to overestimate groundwater level elevations but generally follows the changes in elevations over time.

The results depicted on Figure 46 of the BGI report cover the entire model domain. Since my review focused on the GMD 5 area, we conducted an independent review of the model calibration that focused on the GMD 5 area. This review of groundwater levels within the GMD 5 area showed a similar positive bias in computed groundwater elevations as was shown on Figure 46 of the BGI report. Potential causes and remedies for this bias is discussed in greater detail later in this report (see Section 4).

The BGI report also discusses comparisons of model results to measured stream flows. Data from 33 gaging stations and transect data from along Rattlesnake Creek and the Arkansas River in the Mid Ark area are referenced and are compared in graphic and tabular form in the report and in Appendix G to the BGI report (Appendix G – Hydrographs). These comparisons are important metrics of model performance in spite of the significant variability in measured stream flows. The graphics are helpful in comparing model results to measured data but the variability in stream flows limits the utility of the hydrographs for making visual comparisons. The flow-frequency plots are much better in this regard and provide some indication of long-term changes.

We have independently reviewed the model calibration with respect to stream flows. In our independent review we have used some statistical and graphical comparisons to try to better evaluate the changes in stream flows both spatially and temporally. These evaluations will be discussed in greater detail later in this report.

The biggest questions arising from the model development and calibration relate to determination of recharge, runoff and evapotranspiration. These questions will be discussed in greater detail in the following section.

Section 4
Methods to Estimate Recharge, Runoff, and Evapotranspiration

Recharge and runoff in the model were determined using relationships between precipitation and recharge or runoff. The BGI report devotes some significant discussion to reviewing different recharge mechanisms and various studies and experiments that attempt to quantify recharge or related quantities. In the end, BGI chose to determine model recharge from a set of curves relating monthly precipitation to monthly recharge. Different curves were applied to different zones within the model domain and the curves for some zones were different for periods before and after 1970 to reflect land-use changes. These results were adjusted to reflect transmission losses associated with runoff and the potential for ponding. The runoff (and apparently transmission loss) was also determined from a set of curves for different hydrologic response units or zones that related monthly precipitation to runoff. The various curves were developed based on model calibration and, in effect, translated monthly precipitation into runoff and recharge using a somewhat empirical relationship. It is unclear how the different mechanical steps that were used to derive the values may have influenced the final determinations and what specific parameters or assumptions were adjusted during the calibration process.

Groundwater evapotranspiration (ET) in the model was represented by specifying areas where groundwater ET could potentially occur (any location where the predevelopment water level was within 10 feet of ground surface) and a reference crop ET_0 rate using the Hargreaves method. According to the BGI report (page 60), the area of potential groundwater ET was adjusted to include an approximately 200-foot corridor along riverbeds where predevelopment depth to water was greater than 10 feet by scaling the maximum ET rate. This adjustment was made to allow for the potential rise in groundwater levels beneath the stream beds. This adjustment seems to be a minor factor in that the potential area of ET shown on Figure 26 of the BGI report appears to extend well beyond the locations of stream cells in most areas. The ET surface was initially based average 10-meter DEM elevations with some adjustments in certain soil areas and along streams. In addition, a regional adjustment of a few feet was made during model calibration. The details of these adjustments are not provided in the BGI report and were not discussed in TAC meetings.

There were, however, significant discussions as to the nature and amount of ET that was estimated by the model. These discussions focused on the potential for ET to occur in areas beyond the river corridor or within low lying areas of shallow groundwater such as the Quivira National Wildlife Refuge. The discussions also focused on the potential for bare soil evaporation from underlying groundwater in areas where depth to groundwater is several feet below ground surface but within the 10-foot depth where the model calculates ET. Balleau Groundwater subsequently provided the TAC with references to support the notion that significant groundwater ET can occur from bare soil. While these references discussed the nature and occurrence of ET, data supporting the occurrence of significant groundwater ET from bare soil when groundwater is more than about one meter below the ground surface was not particularly compelling. The impact of ET assumptions on model calibration and model operation will be discussed further in subsequent paragraphs in this section.

Recharge from incidental precipitation in the model occurs primarily in the months of May through August. Recharge in July is the highest, followed by May, June and August in that order. Over 70 percent of the model recharge is estimated to occur during these months. Only about 10 to 15 percent of the model recharge is estimated to occur in the months of February, March and April. While this seasonal pattern of annual recharge is somewhat counterintuitive, the seasonal distribution is probably not a significant factor in terms of larger-scale longer-term model performance.

The overall amount of recharge estimated in the BBGMD5 model is somewhat higher than the corresponding amount estimated in the modeling study of the Mid-Ark area conducted by KGS. The recharge in the BBGMD5 model over the equivalent Mid-Ark model area is estimated to be about 20 to 25 percent higher than that computed in the Mid-Ark model. However, since the amount of ET in the BBGMD5 model is higher than the corresponding ET in the Mid-Ark model, differences in net stream interaction are likely smaller.

A direct comparison of the net stream interaction is difficult because the BBGMD5 model includes runoff in its stream accounting whereas the Mid-Ark model only considers upstream surface inflow. The impact of pumping on stream flow within the Mid-Ark area was estimated by the Mid-Ark model to be about 29,000 acre-feet per year by comparing the water budget for the period from 1944 to 1973 with the period from 1990 to 2004 (see Table 6 of KGS report). In the BBGMD5 model over roughly the same area, the difference in groundwater losses from the streams between those same periods was about 20 cfs or about 15,000 acre-feet per year. The difference in these two results is likely related to the amount of ET computed in each model. In the Mid-Ark model, the difference in average ET for the two periods described above was about 9,000 acre-feet per year. The total stream and ET impact was then about 38,000 acre-feet per year. In the BBGMD5 model, the pumping impact on stream flow and ET is split about 45 percent stream flow, 55 percent ET. Using this ratio, the total impact in the BBGMD5 model would be about 33,000 acre-feet per year with ET accounting for about 18,000 acre-feet per year. These comparisons show that while the two models predict a similar or roughly similar amount of combined impact to streams and ET, the distribution of the impact between stream depletion and ET is quite different. This difference highlights a principal difference between the two models and the role that ET plays regarding the potential for pumping or pumping curtailment to impact stream flow.

The actual amount of ET from groundwater cannot be directly measured although estimates can be made based on various data such as solar radiation, temperature, and plant species. Indirect measurements can also be made using satellite imagery. The BGI report contains an example of such imagery on Figure 7 of their report. However, a direct comparison to model results is complicated by various factors, a major one being that the model is only calculating ET from groundwater whereas the imagery is depicting all ET, regardless of the origin of the water.

Furthermore, the change in ET associated with changing groundwater levels is assumed to be linear within the range where ET is active. That relationship is also uncertain. The calibration process provides some confidence in model results with regard to groundwater levels and/or stream flows. With respect to ET, the calibration to groundwater levels and stream flows provides only a limited metric. Since much of the ET from groundwater occurs along stream channels, it can be difficult to distinguish between groundwater ET and stream accretion as a groundwater discharge mechanism. Similarly, stream losses that are consumed by ET in the immediate vicinity of the stream channel can be equally difficult to quantify.

To illustrate this point, we used the 1-layer representation of the BBGMD5 model to run some alternative calibration simulations. As described previously, the 1-layer representation of the BBGMD5 model was first tested to be sure it produced essentially the same results as the 7-layer model. Using the 1-layer representation, we ran an alternative calibration in which the overall recharge rate was reduced by 20 percent and the maximum evapotranspiration rate was reduced by 40 percent. The 20 percent reduction was selected because it roughly produced an amount of recharge that was comparable to the Mid-Ark groundwater model for the equivalent area. The evapotranspiration rate was reduced to try to maintain the calibration to stream flows that was achieved by the BBGMD5 model.

The alternative model produced calibration statistics that were as good as, or in some cases, better than the original model, at least for the area of GMD 5. For example, water level residuals for the BBGMD5 model show a slight positive bias of about 4 feet (see BGI Report, Figure 46, for example). In the alternative calibration run, this residual is reduced to less than 1 foot. These results are illustrated on Figures 1 and 2 below. Note the generally positive bias after 1970 for the BBGMD5 model whereas for the alternative model, that bias is significantly diminished.

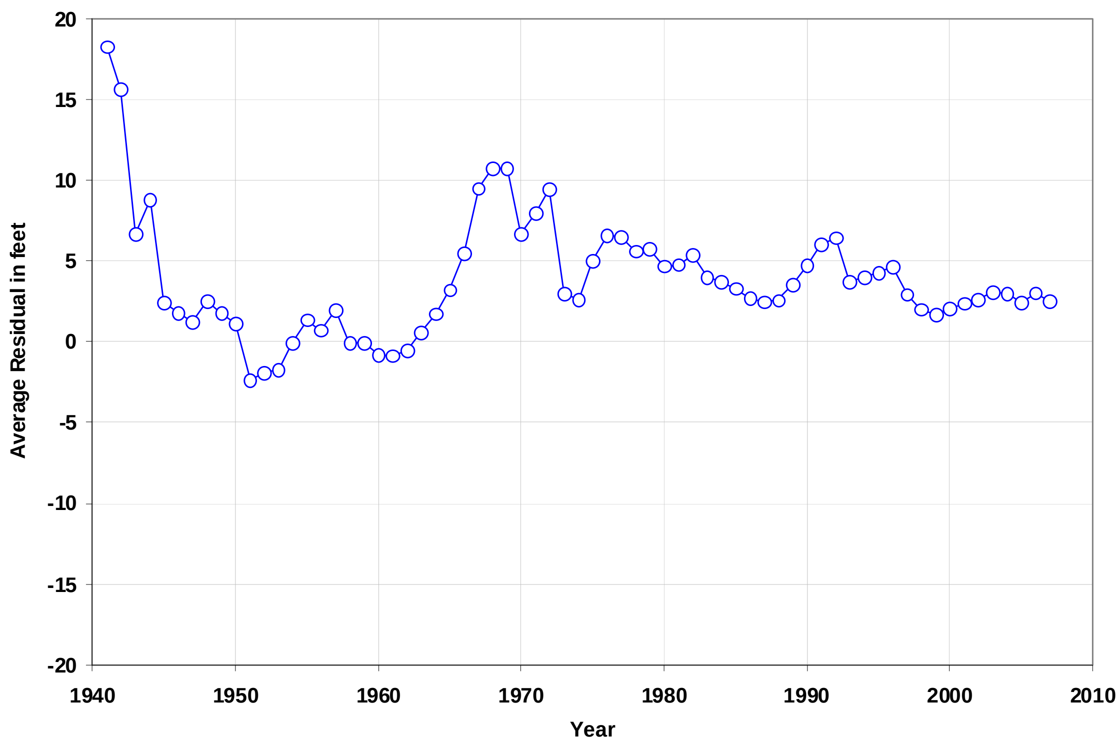


Figure 1 – Average residual for groundwater levels in GMD 5 area using 1-layer representation of BBGMD5 model.

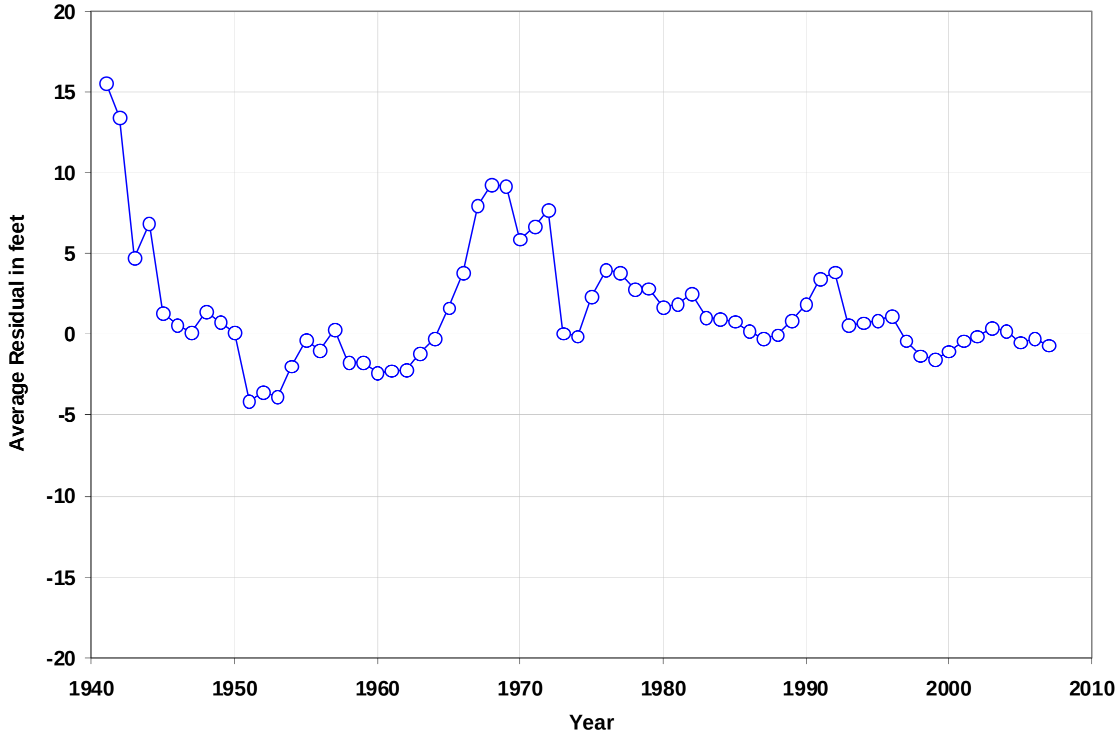


Figure 2 – Average residual for groundwater levels in GMD 5 area using alternative 1-layer representation of BBGMD5 model.

Calibration to stream flow is generally difficult because of the variability in stream flow conditions. Establishing appropriate stream flow metrics is also difficult because of the variability and because the best metric depends to some degree on the ultimate use of the model. One of the model uses for the GMD 5 area is likely to be estimating impacts of changes in pumping patterns and amounts on stream flows. An appropriate metric for evaluating model performance associated with this use is to examine gains and losses along the streams and the difference in those gains and losses over different time periods.

Comparisons such as these were made using results from the BBGMD5 model and the alternative 1-layer model. Again, the alternative calibration run showed some improvements in model results for stream reaches from Dodge City to Kinsley, Kinsley to Great Bend and for Rattlesnake Creek near Macksville (see report appendices for specific comparisons). For example, the computed and measured monthly stream flow gains between Dodge City and Kinsley are compared on the figures below.

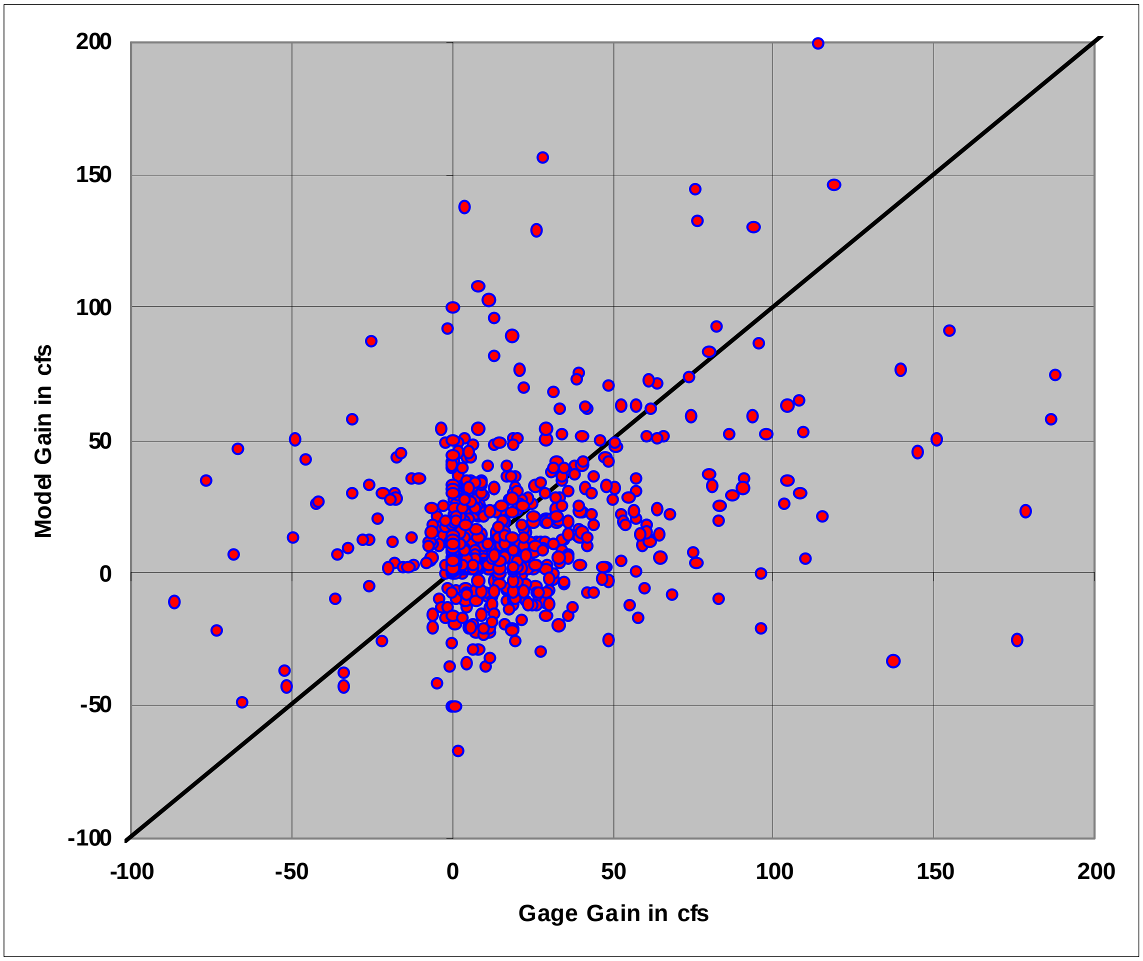


Figure 3 – Scatter diagram of computed and measured (gaged) gains between Dodge City and Kinsley using 1-layer representation of BBGMD5 model.

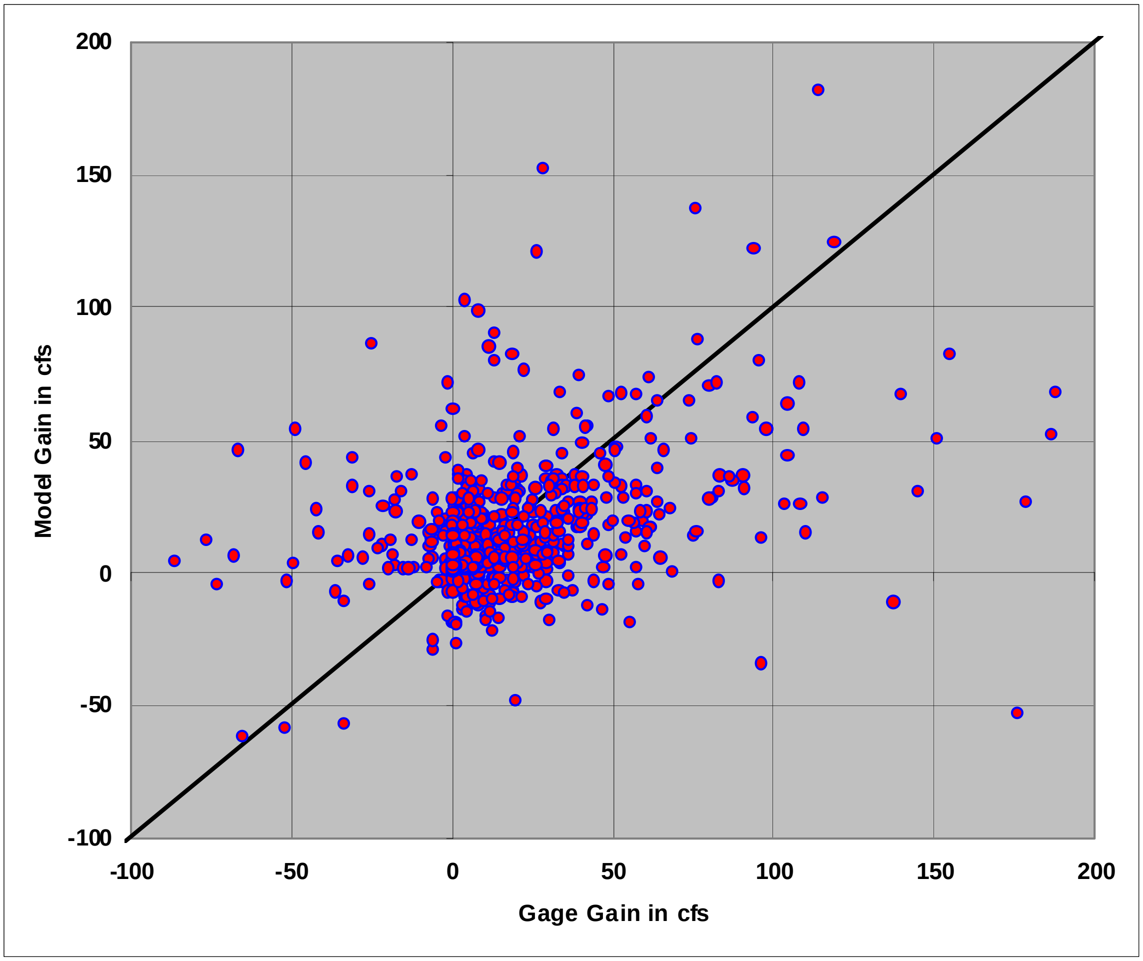


Figure 4 – Scatter diagram of computed and measured (gaged) gains between Dodge City and Kinsley using alternative 1-layer representation of BBGMD5 model.

As shown on Figures 3 and 4, both models exhibit a fair degree of scatter in this comparison of stream flow gains. However, the scatter using the alternative 1-layer model is more tightly clustered around the 45-degree line than the scatter using the 1-layer representation of the BBGMD5 model. Similar slight improvements were noted for other reaches when the alternative 1-layer model was used. While these improvements were not overwhelming, they do illustrate that the calibration process does not provide a lot of guidance on appropriate amounts of groundwater ET and, to some degree, precipitation recharge.

It should be noted that some calibration statistics that we examined (water level changes over specific time periods) did deteriorate in the alternative 1-layer model calibration run. However, it is likely that other adjustments could be made, particularly to recharge rates during anomalously wet years that would eliminate the deterioration in model results. A second alternative calibration was made to test that assertion by increasing the recharge used in the alternative run during selected wet years. Specifically, the recharge used in the alternative model run for the years 1992-1993 and 1995-1996 was increased by 20 percent from the values used in the BBGMD5 model run. This adjustment effectively removed the deleterious effect on the water level change statistics although it did reinstate some of the positive bias in computed water levels that was noted in the BBGMD5 model (see Appendix F for example comparisons).

The upshot of these alternative runs is to demonstrate the inability of the calibration process to establish a unique combination of recharge and groundwater ET. The inability to accurately establish ET has some particular consequences when the model is used to assess the impact of changes in pumping on stream flows. In the BGI report, a figure (Figure 65) is presented to illustrate the potential impact of reduced future pumping. This figure is reproduced below as Figure 5 and shows the potential impact of future pumping curtailment on stream flow, ET and groundwater storage. After some time has elapsed, the principal impact of pumping curtailment is estimated to be increased groundwater ET with a lesser fraction going to increased stream flow.

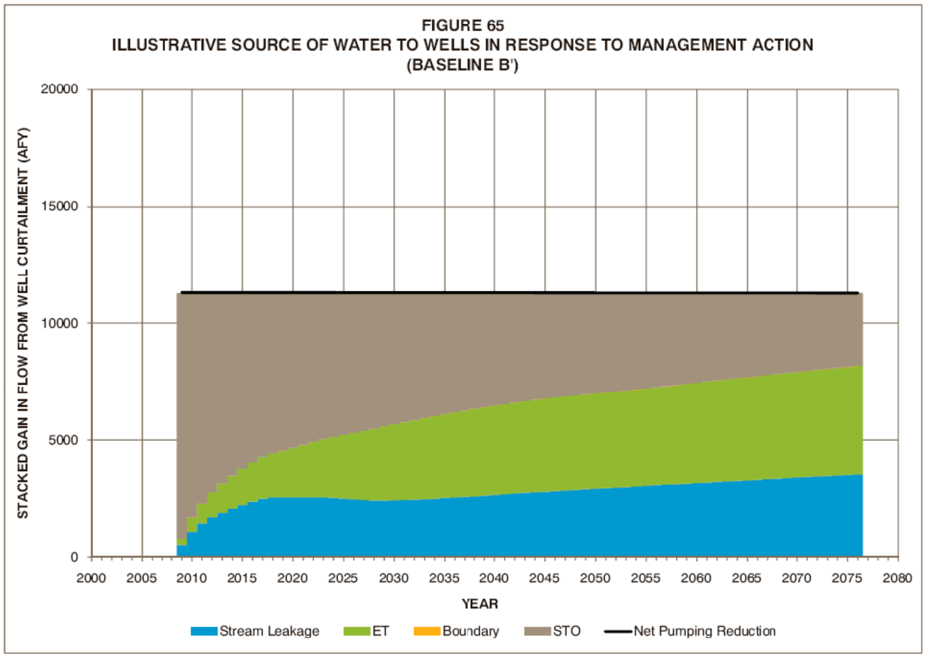


Figure 5 – Illustration of pumping impacts on stream flow/leakage and ET using the BBGMD5 model.

When the same simulation is made using the reduced ET conditions that were used in the alternative calibration run, the results are quite different as shown below on Figure 6. The principal impact of pumping curtailment (as between ET and stream flow) is now increased stream flow with a smaller fraction going to increased ET. These results demonstrate that the BBGMD5 model may not accurately estimate the relative impact of different pumping scenarios on ET and stream flow.

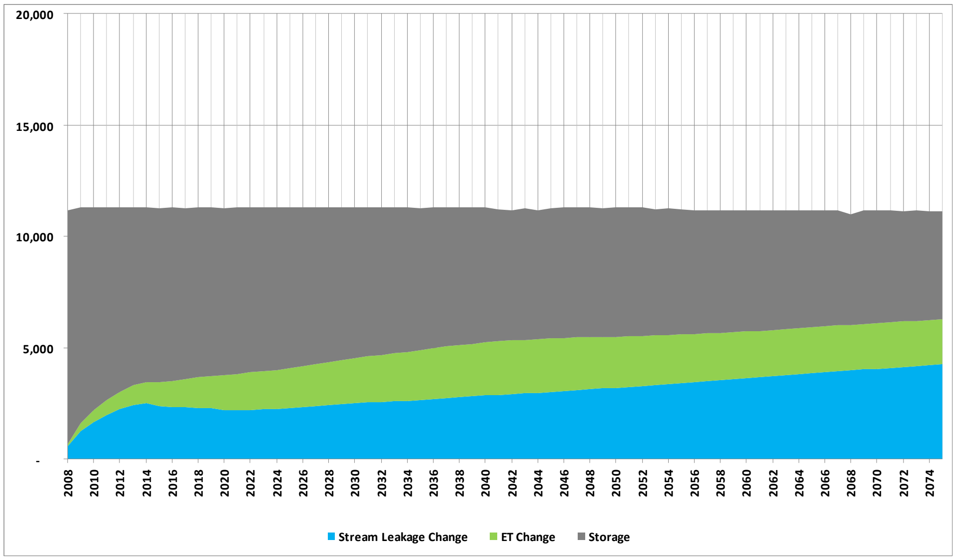


Figure 6 – Illustration of pumping impacts on stream flow/leakage and ET using the alternative 1-layer representation of the BBGMD5 model.

As mentioned previously, the BGI report does present a figure (Figure 7) that depicts LANDSAT imagery on July 19, 2004. The image has been processed to illustrate the strength of evaporative loss. While evaporative losses occurring on irrigated land or in areas such as the Quivira Wildlife Refuge are readily apparent, losses along the stream corridors such as the Arkansas River are much less apparent. Model results near this same time period seem to show greater groundwater ET along the river corridor, especially near Great Bend, than the amount of evaporative loss estimated from the LANDSAT imagery. A direct comparison of ET amounts, however, is complicated by the cell size in the model versus the actual width of the stream corridor and is limited by the fact that image only represents conditions on a single day. Further evaluation of groundwater ET, perhaps through more comparisons to LANDSAT imagery, is necessary before definitive conclusions can made. At this point, it is important to note that model results regarding the relative balance between groundwater ET and stream flow should be viewed with caution.

Section 5
Characterization of System Yield

The BGI report refers to "system yield" in discussing the model water budget (see for example, Table 8B). System yield is defined in the report as "the supply generated from surface and groundwater sources combined". This term should be viewed with caution as it represents the total amount of surface water and groundwater recharge input into the BBGMD5 model domain without consideration of location, accessibility, or uncertainty. The values quoted in the report are simply the sum of surface water inflow, computed runoff, and computed recharge for the entire BBGMD5 model domain. Of the 1.4 to 1.6 million acre-feet per year cited in Table 8B, about 500,000 afy is computed runoff. Surface water inflow at the western model boundary is estimated to range from 200,000 afy to 69,000 afy (pre-development steady state versus net long-term sustainable). Recharge from precipitation makes up the balance ranging from about 700,000 afy to 1,000,000 afy (pre-development steady state versus net long-term sustainable).

While these numbers do represent a total amount of computed water supply, somewhere between 400,000 and 600,000 afy is lost to groundwater evapotranspiration according to the model calculations. The ability to salvage significant amounts of this loss is questionable even though model calculations suggest that as much as 160,000 afy of groundwater ET can be salvaged by lowering groundwater levels by pumping. Also, the ability to divert or recharge significant amounts of runoff or stream flow is uncertain. As a result, the amount of realistically usable water supply is likely much smaller than the system yield. As an example, the future baseline scenario described in the BGI report shows results for future pumping averaging about 950,000 afy. About 300,000 afy of this pumping was supplied by groundwater storage depletion. This would suggest that only about 650,000 afy of pumping would be sustainable without continuing declines in groundwater levels. It should also be noted that these values represent conditions over the entire model domain which includes portions of GMD1 and GMD3 in addition to GMD 5.

Section 6
Suggestions for Future Work

The BBGMD5 groundwater model provides a comprehensive tool for evaluating water resources within GMD 5. The 1-layer representation of the model provides a more utilitarian version of the model that would likely be applicable to most water resource related assessments that required some level of groundwater modeling. For use in GMD 5, the model could likely be scoped down further by moving the western model boundary nearer to the western boundary of GMD 5. This would reduce the model domain size by almost a factor of two and reduce model run times accordingly.

Model performance in the northeastern portion of the GMD 5 area was evaluated to a much lesser degree than the remainder of GMD 5. This was in part due to data availability but also to constraints on time and budget. This is an area of generally shallower groundwater with greater amounts of groundwater ET. Some additional evaluation of model performance in this area is probably warranted, especially if the model is to be used to assess water resource questions that focus on this specific area.

The amount of groundwater ET and, more importantly, the change in groundwater ET associated with changes in groundwater levels are the most significant outstanding questions or issues related to the BBGMD5 model. To be fair, these questions/issues are not unique to the BBGMD5 model. The amount and changes to groundwater ET are largely untested in many groundwater models that are similar in scope and structure to the BBGMD5 model. It is possible that further evaluation and assessment of satellite imagery data could be beneficial. The satellite imagery provides information on a scale that is comparable to that of the model and the availability of the information in electronic form can facilitate compilations for comparison with the model. However, additional study and research may be necessary to reduce and/or focus the imagery information so as to be more comparable to the groundwater ET computed by the model.

Section 7
Model Uses and Limitations

As with any model of natural systems, improvements to the BBGMD5 model based on new data and information are always possible. In the meantime, the model and its 1-layer equivalent can be used to evaluate water resource and water use related issues within the GMD 5 area. In making such evaluations, it is important to be mindful of the model limitations such as the relationship between stream flow and groundwater ET that has been discussed in this report. These limitations are not totally debilitating in that carefully constructed sensitivity analyses can be used to illustrate and perhaps bracket model results that are being used for water management decisions. At the very least, such analyses can alert water managers and others to uncertainties in model results or the lack of significance for some model parameters. In either case, the additional information can be helpful and is available through use of the model.

APPENDICES

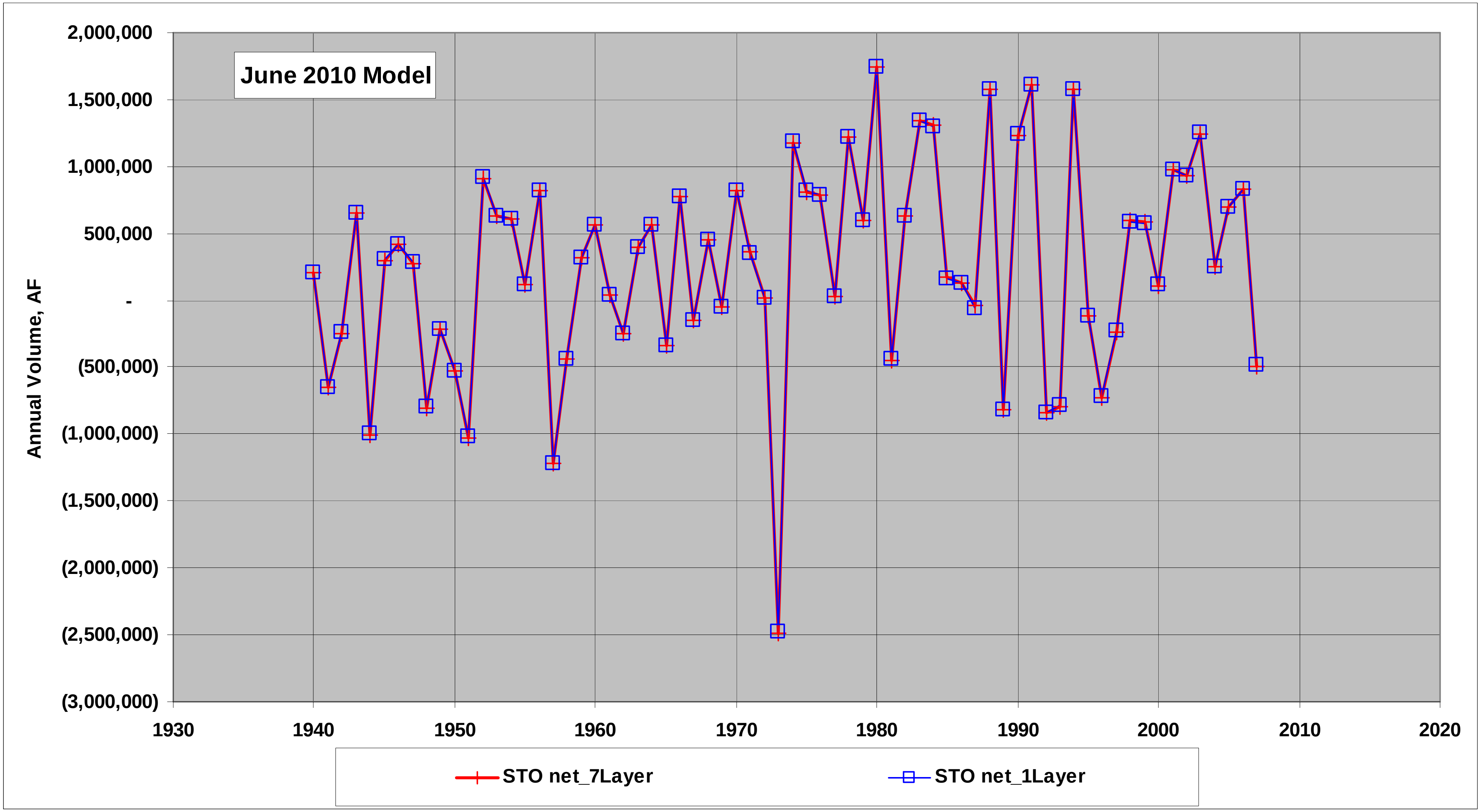
Appendix A

Water Budget Comparisons

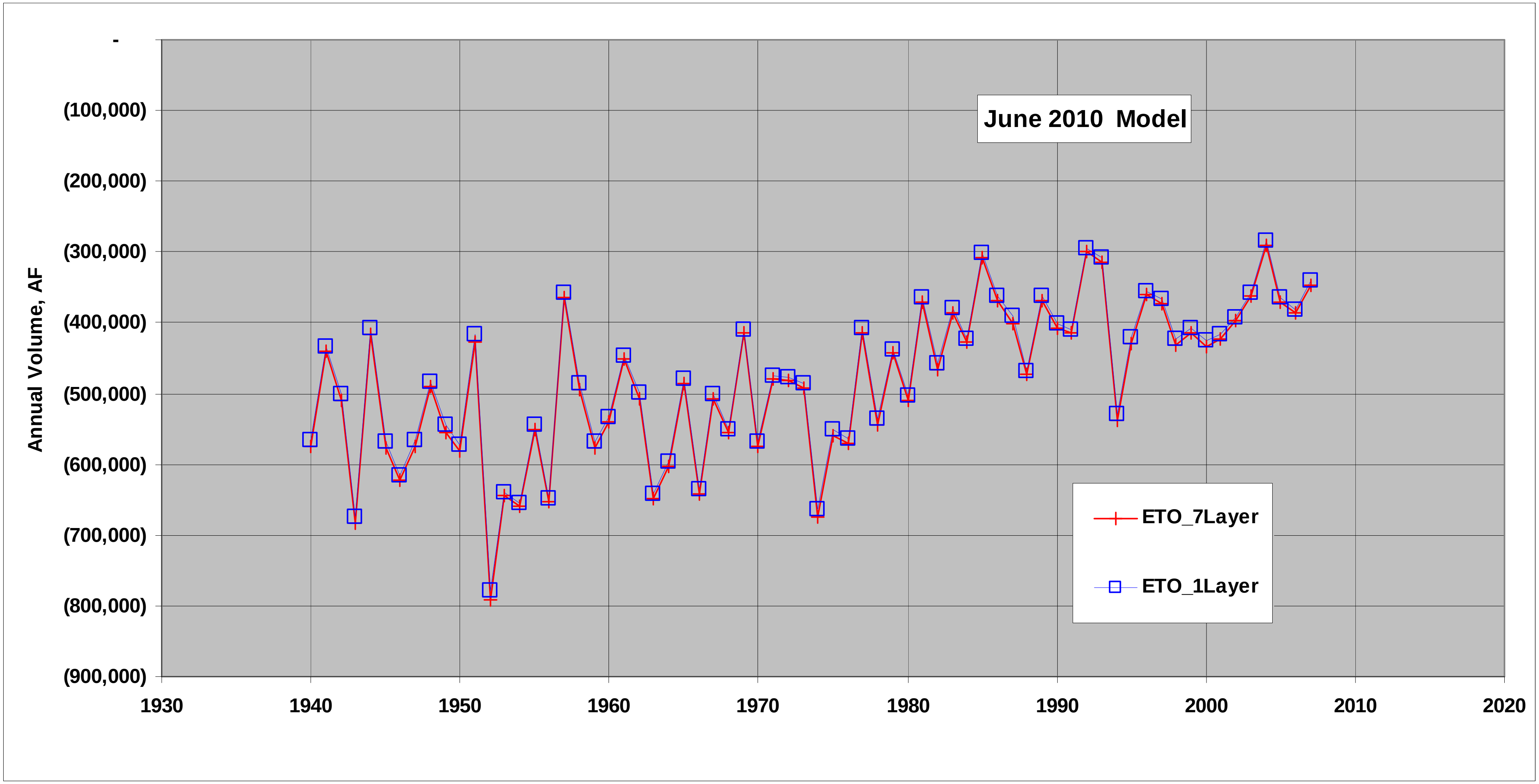
7-Layer Model
and
1-Layer Model

Note: Net annual pumping and recharge volumes for the two models were identical and are not included.

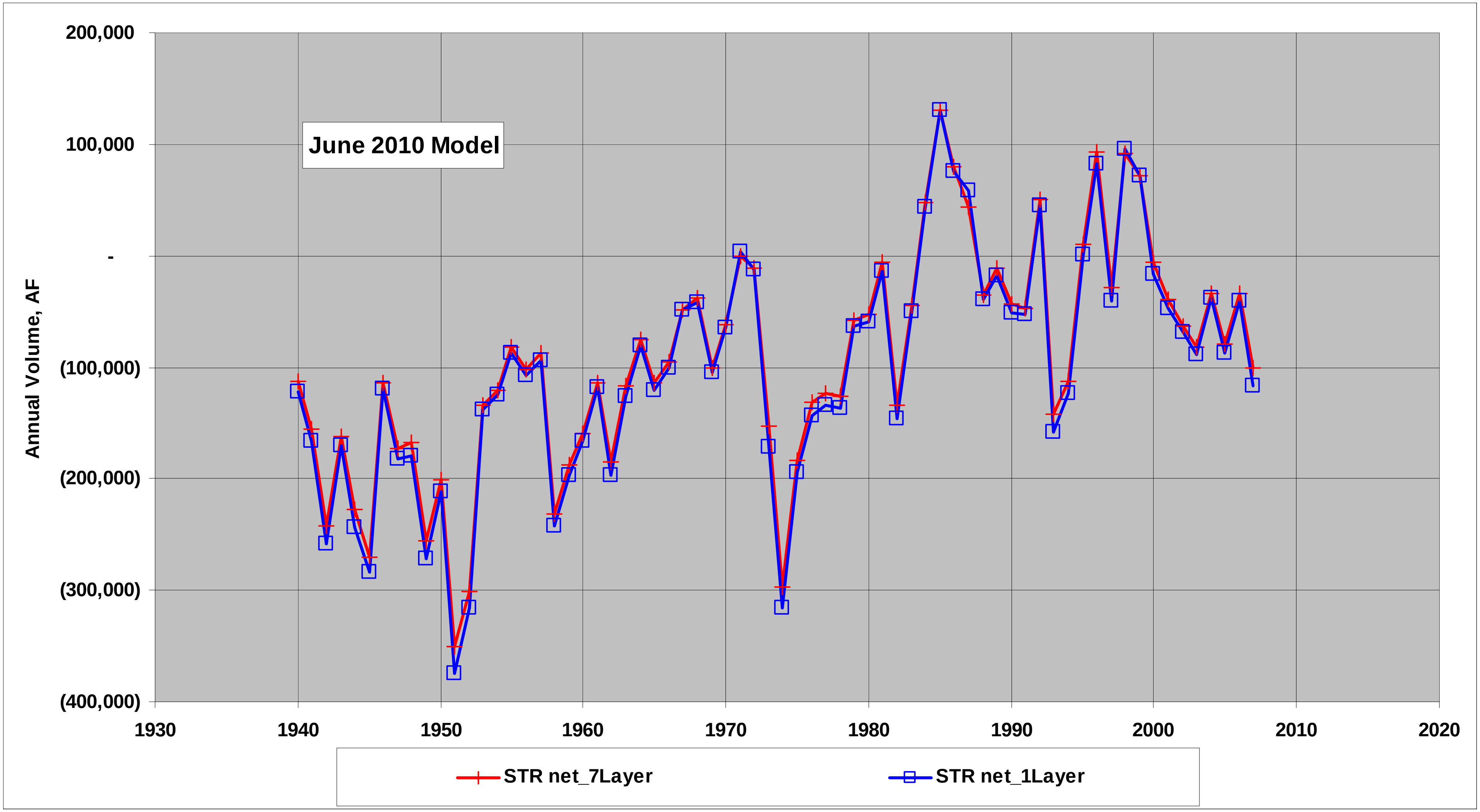
Net Annual Storage Volume



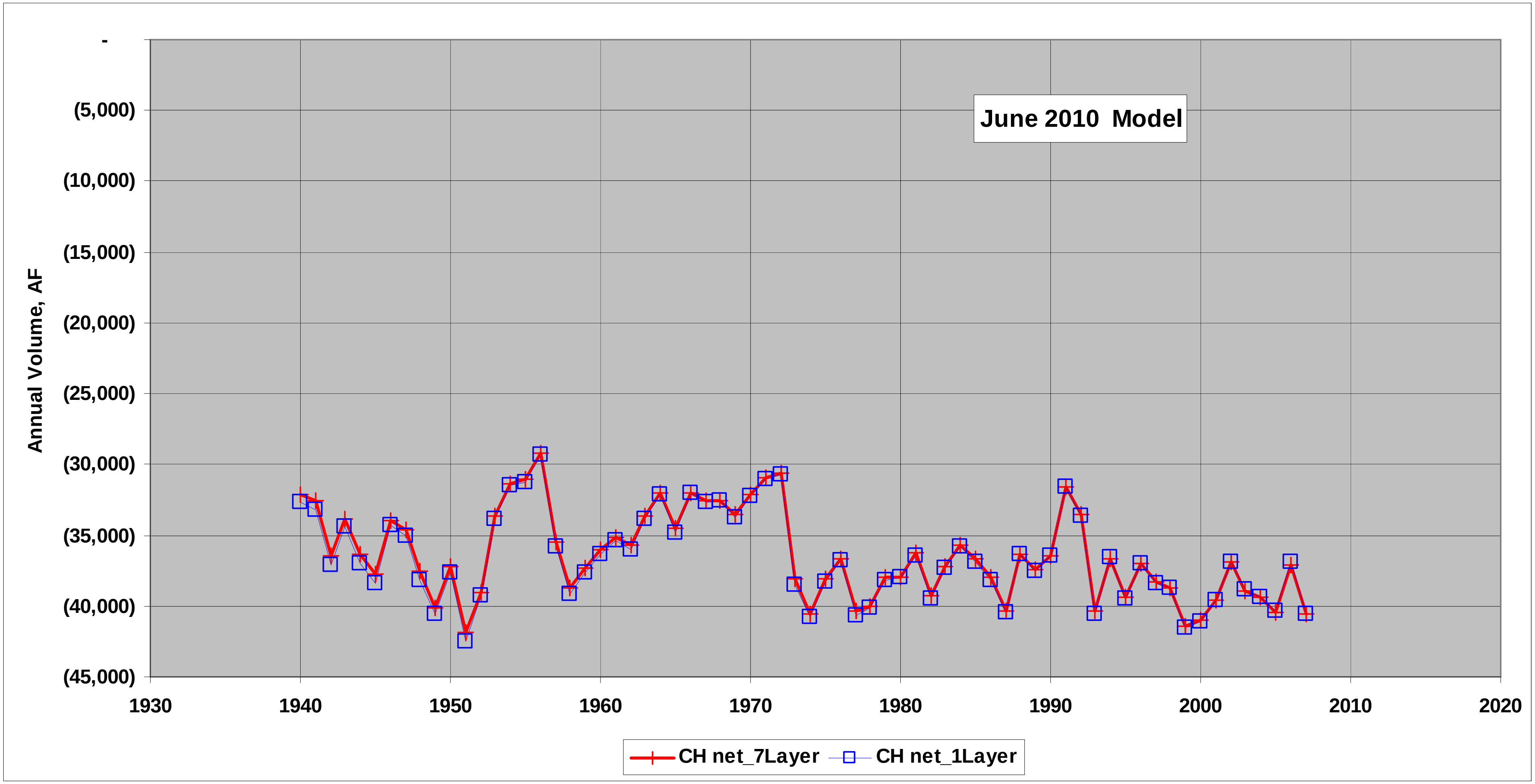
Groundwater Evapotranspiration Volume



Net Annual Stream-Groundwater Volume



Net Annual Constant Head Volume



Appendix B

Stream Flow Gain Comparisons

7-Layer Model - Balleau Groundwater
and
1-Layer Model - Revised

Gain Dodge City to Kinsley

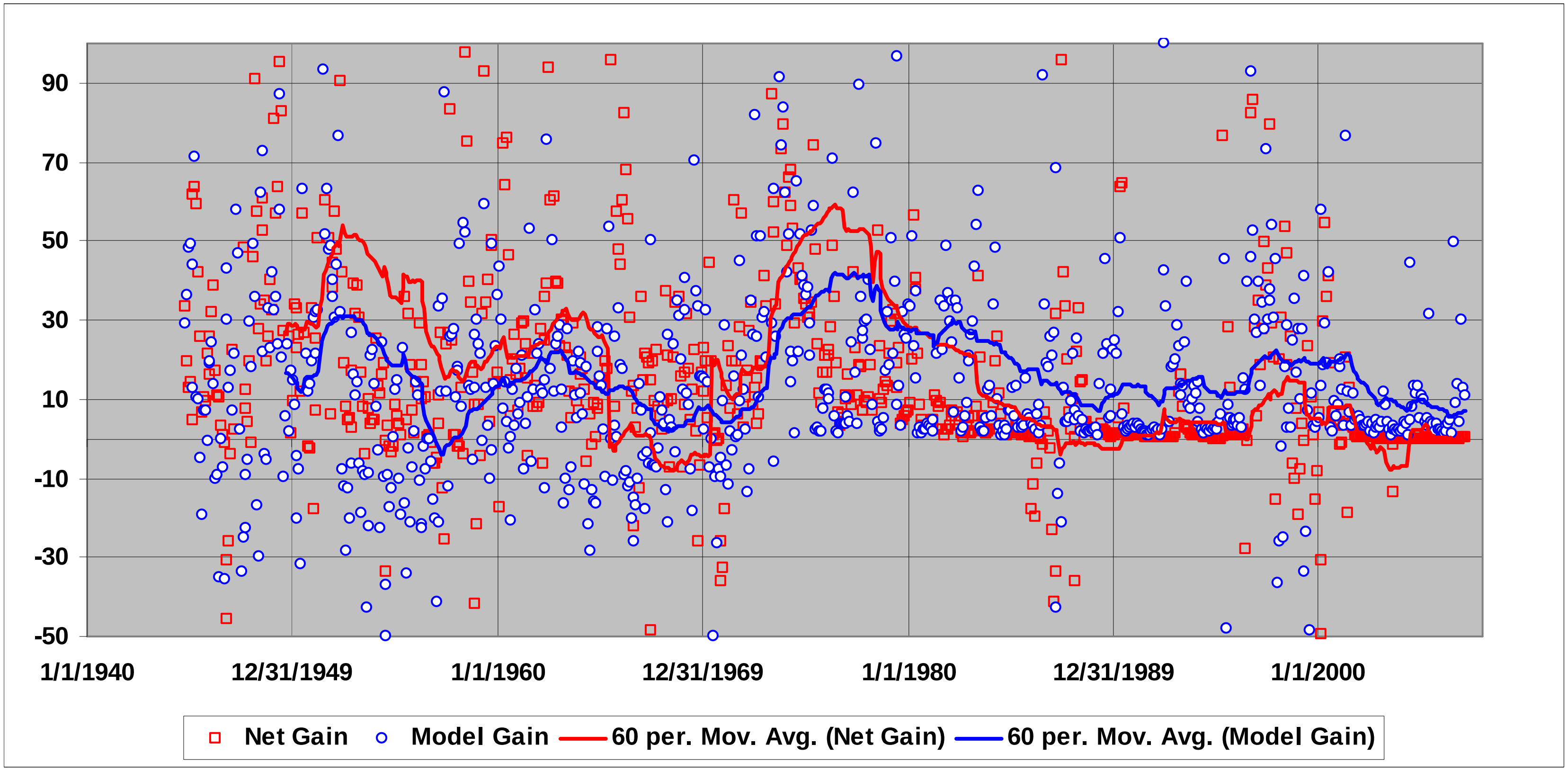
Balleau model

	Gage	Model	Difference
Average	16.6	16.4	-0.2
Median	7.8	9.1	1.3
Pre70			
	Gage	Model	
Average	21.8	13.7	-8.1
Median	16.8	11.4	-5.4
Post70			
	Gage	Model	
Average	13.1	18.2	5.1
Median	2.9	7.5	4.5

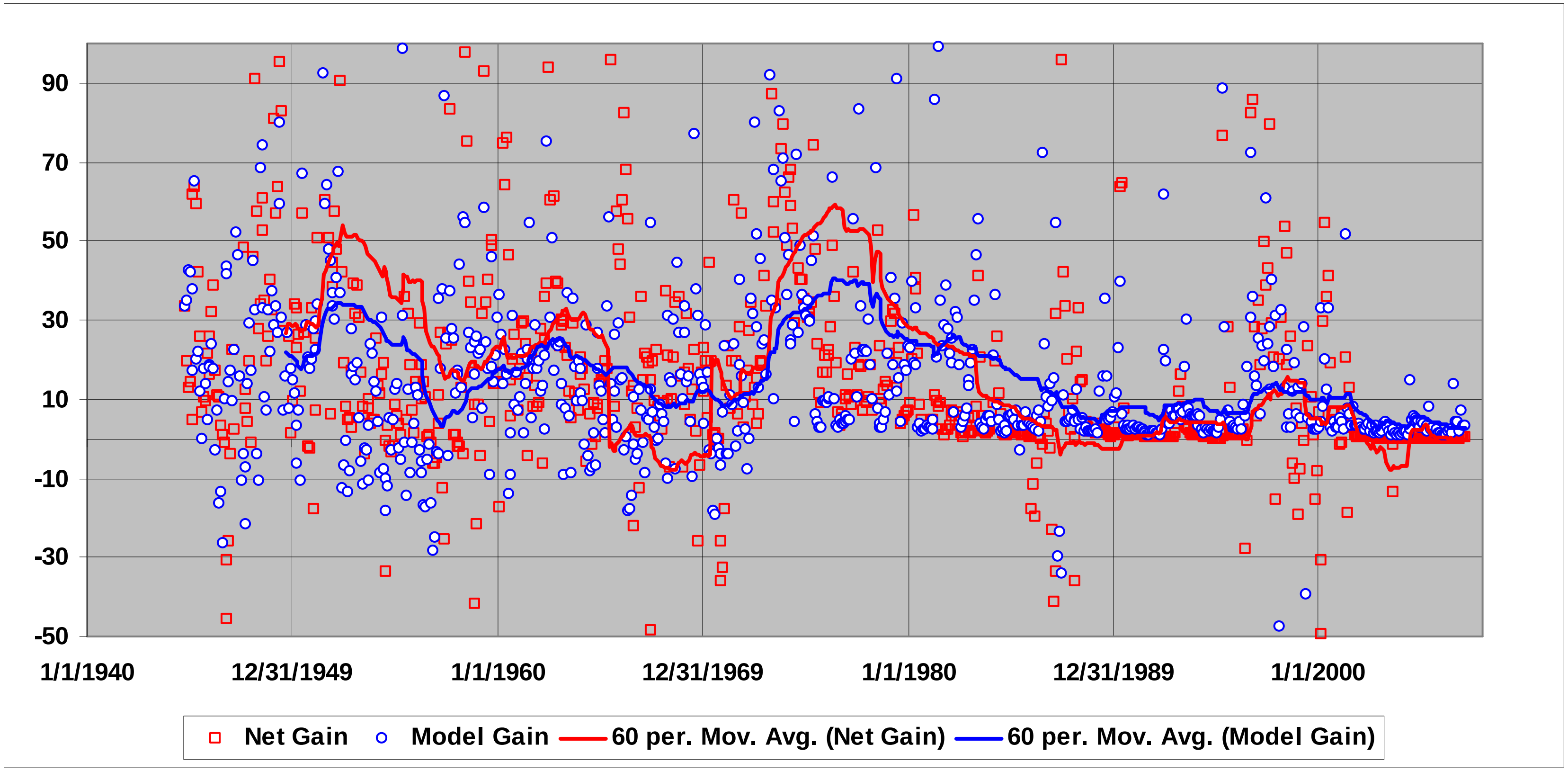
Revised model

	Gage	Model	Difference
Average	16.6	15.9	-0.7
Median	7.8	7.4	-0.4
Pre70			
	Gage	Model	
Average	21.8	18.4	-3.4
Median	16.8	14.8	-2.0
Post70			
	Gage	Model	
Average	13.1	14.2	1.1
Median	2.9	4.9	2.0

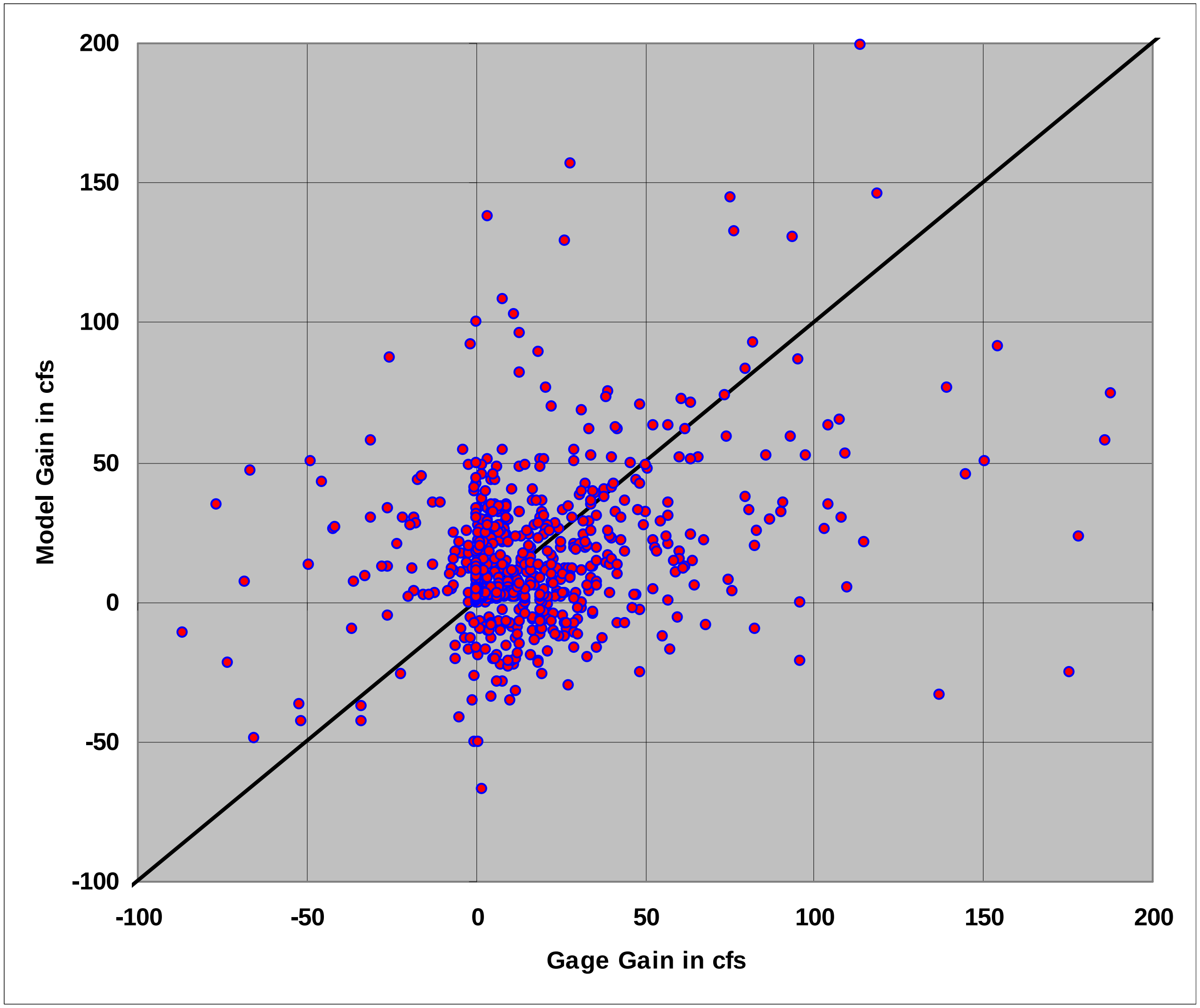
Gain Dodge City to Kinsley
Balleau model



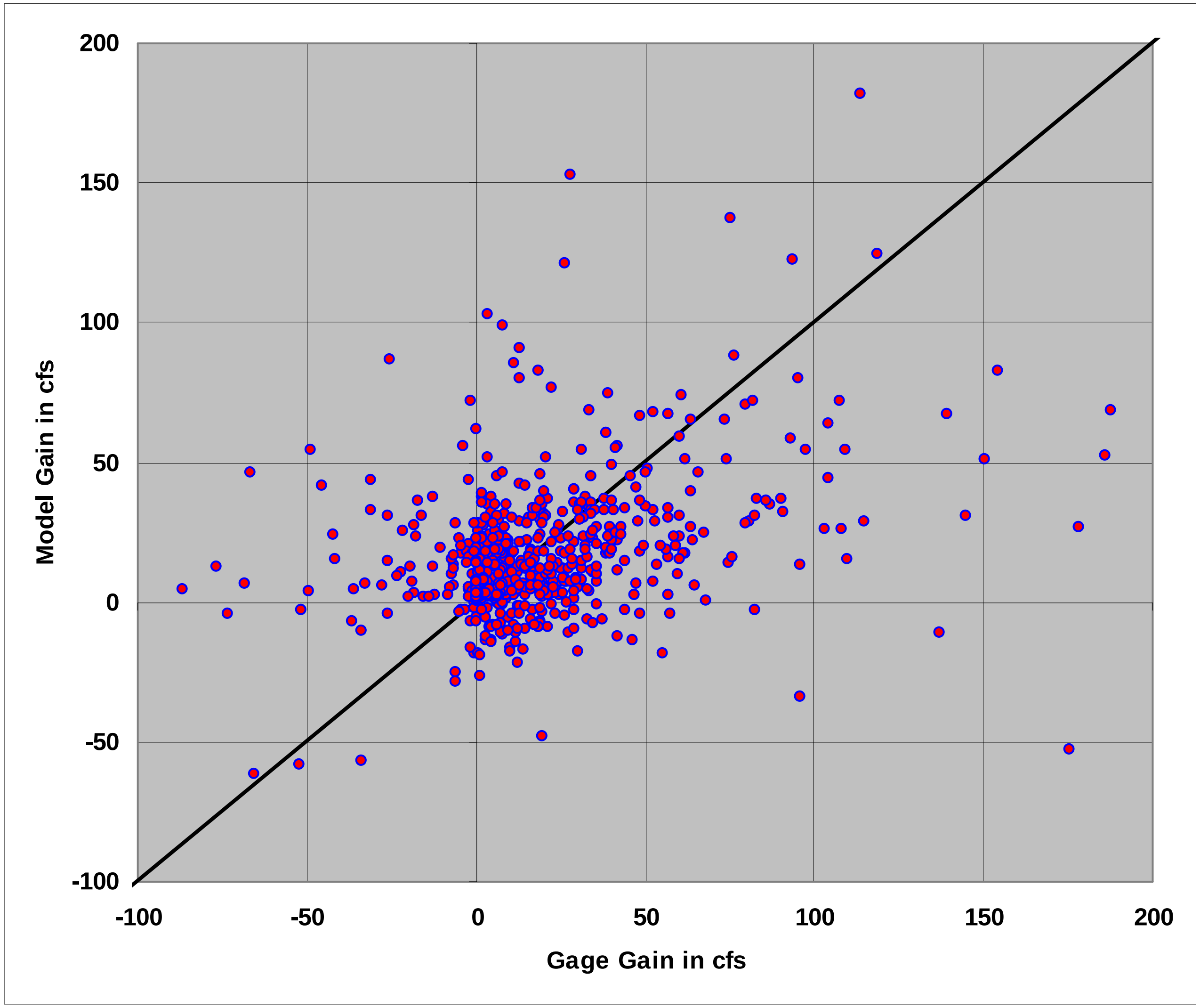
Gain Dodge City to Kinsley
Revised model



Gain Dodge City to Kinsley - Balleau



Gain Dodge City to Kinsley - Revised



Gain Kinsley to Great Bend

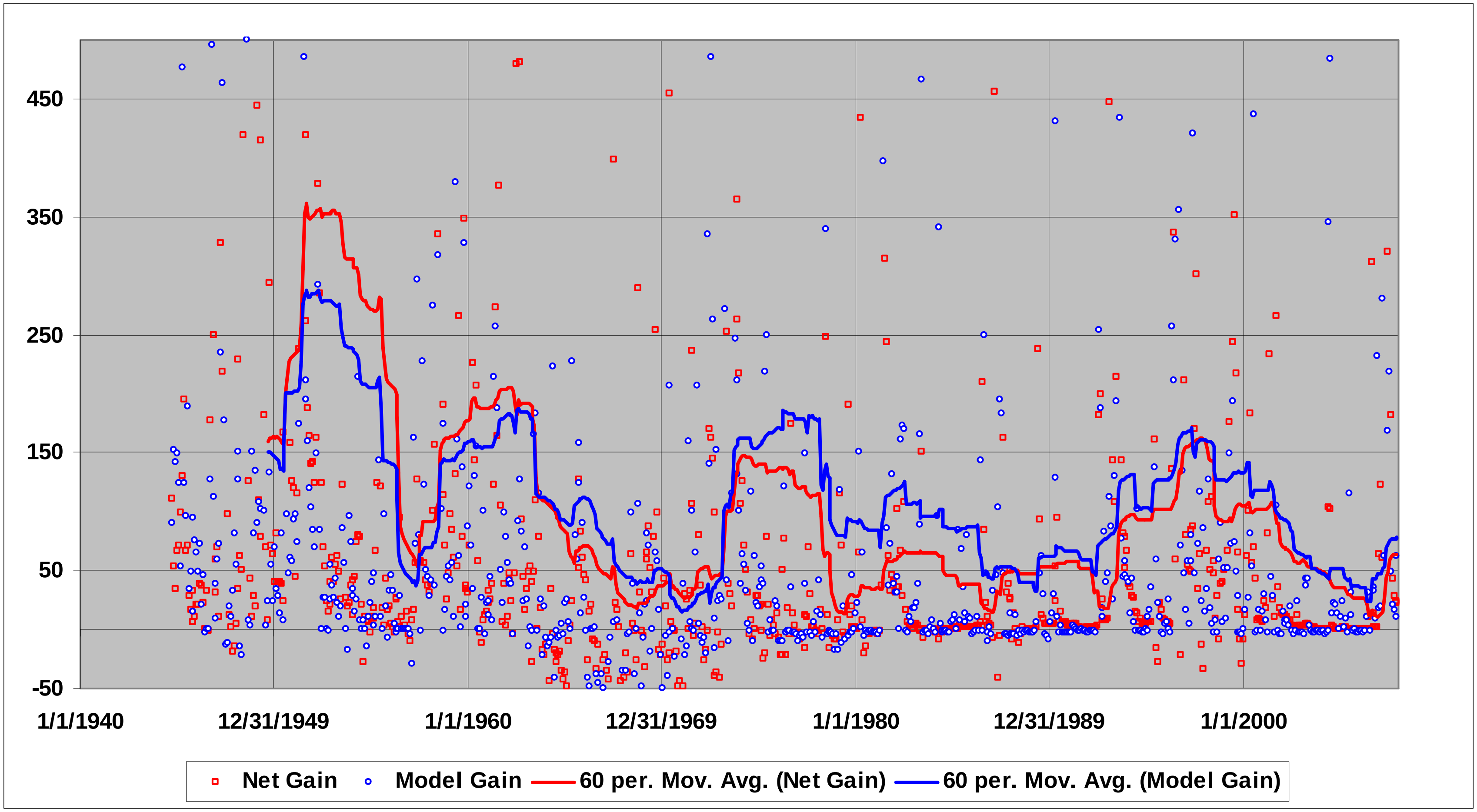
Balleau model

	Gage	Model	Difference	
Average	102.7	111.1	8.3	
Median	15.8	19.4	3.6	
Pre70				
	Gage	Model		
Average	146.1	130.9	-15.3	
Median	39.9	37.6	-2.3	
Post70				
	Gage	Model		
Average	75.3	97.9	22.7	
Median	6.1	9.2	3.0	

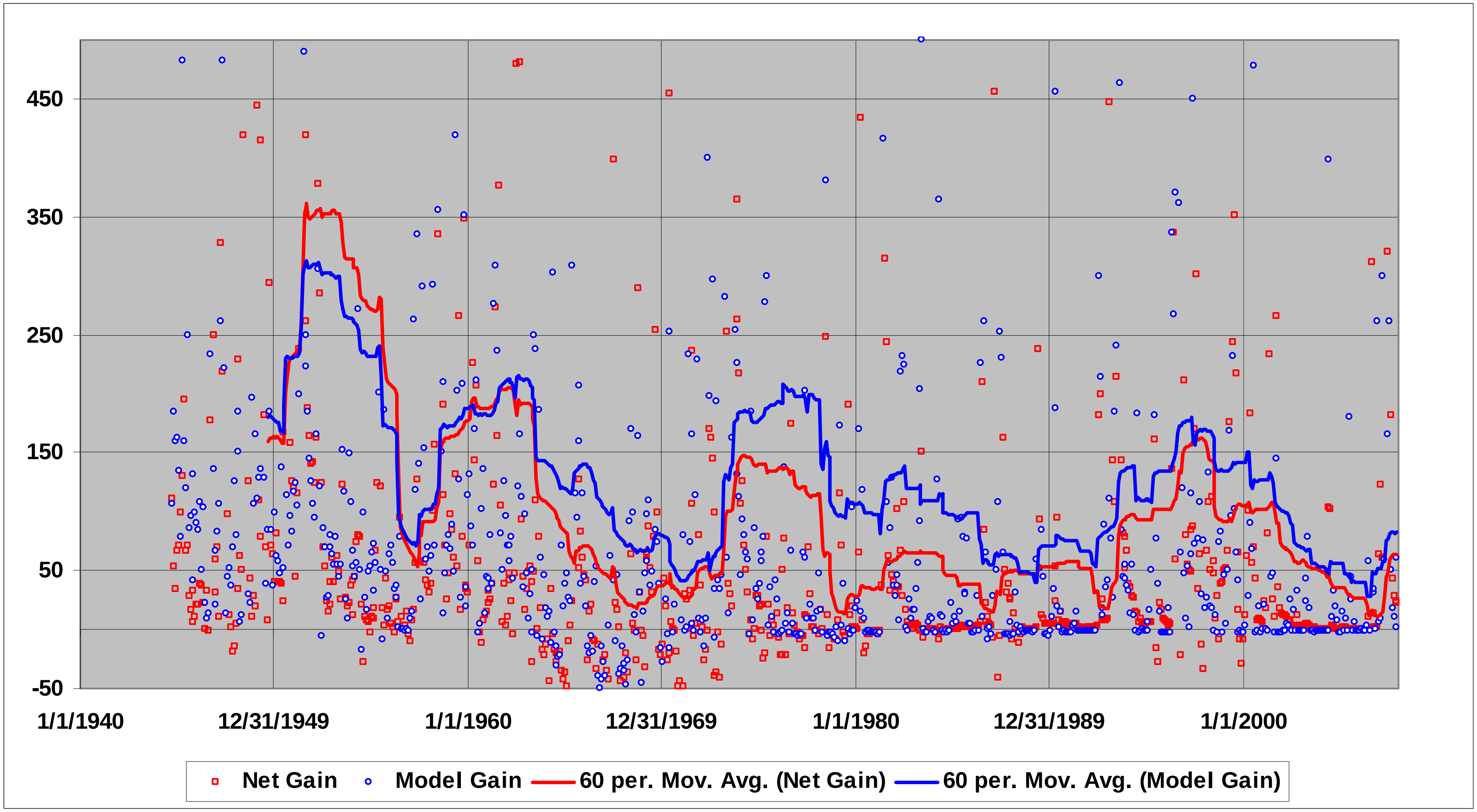
Revised model

	Gage	Model	Difference	
Average	102.7	128.8	26.1	
Median	15.8	38.1	22.3	
Pre70				
	Gage	Model		
Average	146.1	159.4	13.2	
Median	39.9	70.9	31.0	
Post70				
	Gage	Model		
Average	75.3	108.5	33.3	
Median	6.1	12.9	6.7	

Gain Kinsley to Great Bend
Balleau model



Gain Kinsley to Great Bend
Revised model



Gain Rattlesnake near Macksville

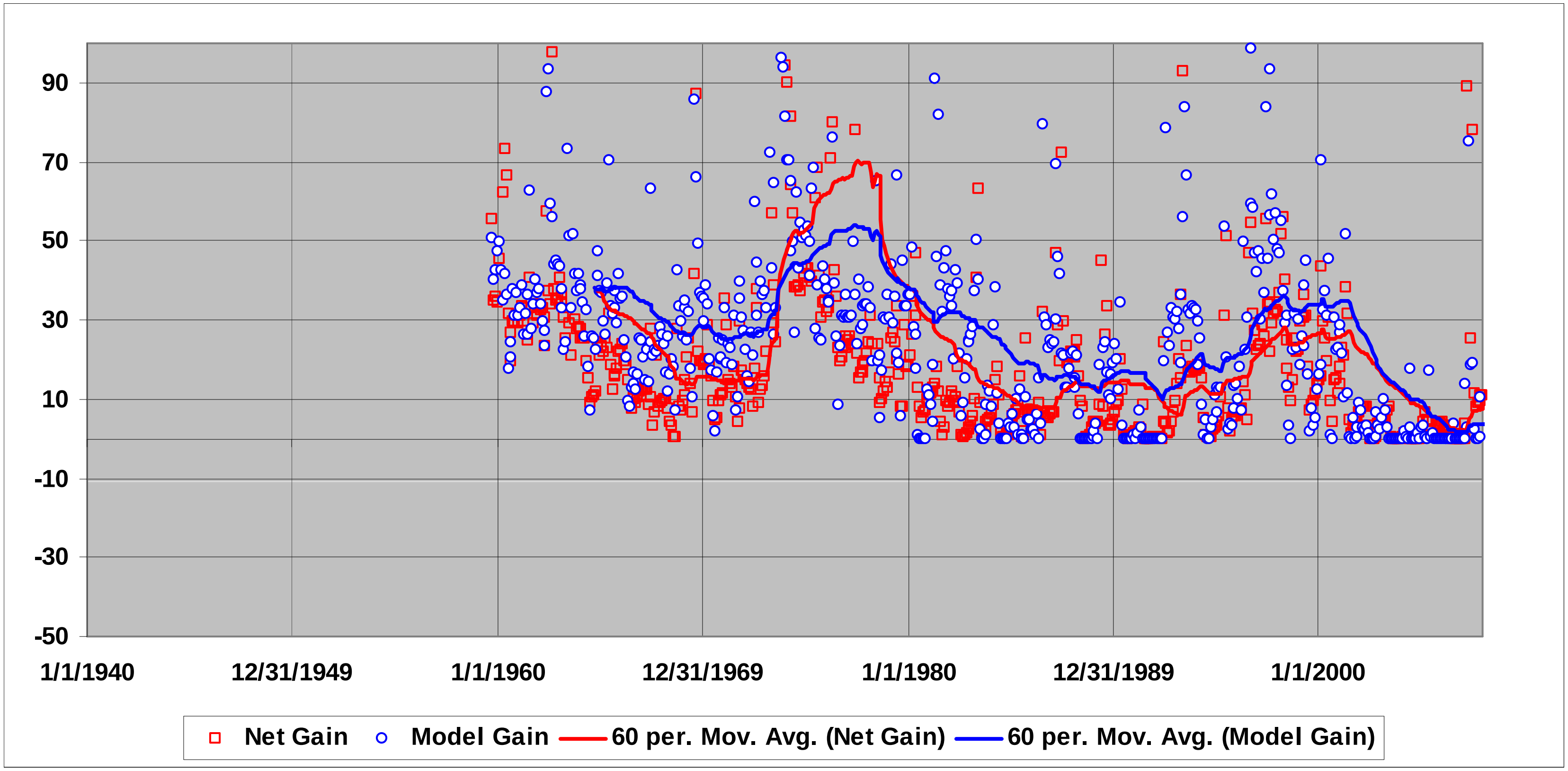
Balleau model

	Gage	Model	Difference	
Average	22.8	26.2	3.3	
Median	13.6	23.5	9.9	
Pre70				
	Gage	Model		
Average	26.9	33.3	6.5	
Median	23.5	32.7	9.2	
Post70				
	Gage	Model		
Average	21.8	24.2	2.4	
Median	10.8	19.3	8.5	

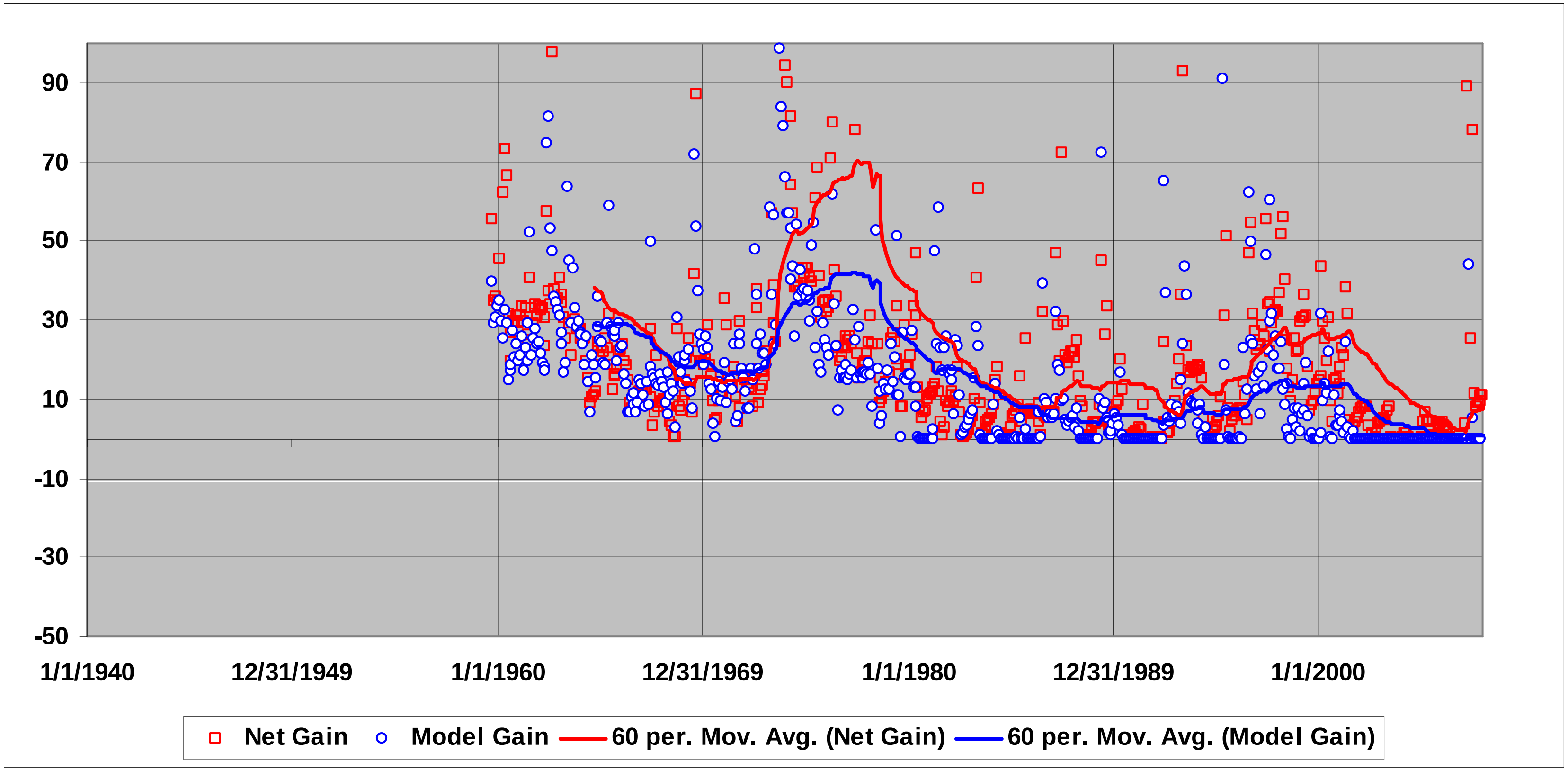
Revised model

	Gage	Model	Difference	
Average	22.8	15.3	-7.6	
Median	13.6	9.9	-3.7	
Pre70				
	Gage	Model		
Average	26.9	24.2	-2.6	
Median	23.5	21.6	-1.9	
Post70				
	Gage	Model		
Average	21.8	12.9	-9.0	
Median	10.8	5.3	-5.5	

Gain Rattlesnake near Macksville
Balleau model



Gain Rattlesnake near Macksville
Revised model



Gain Rattlesnake Macksville to Zenith

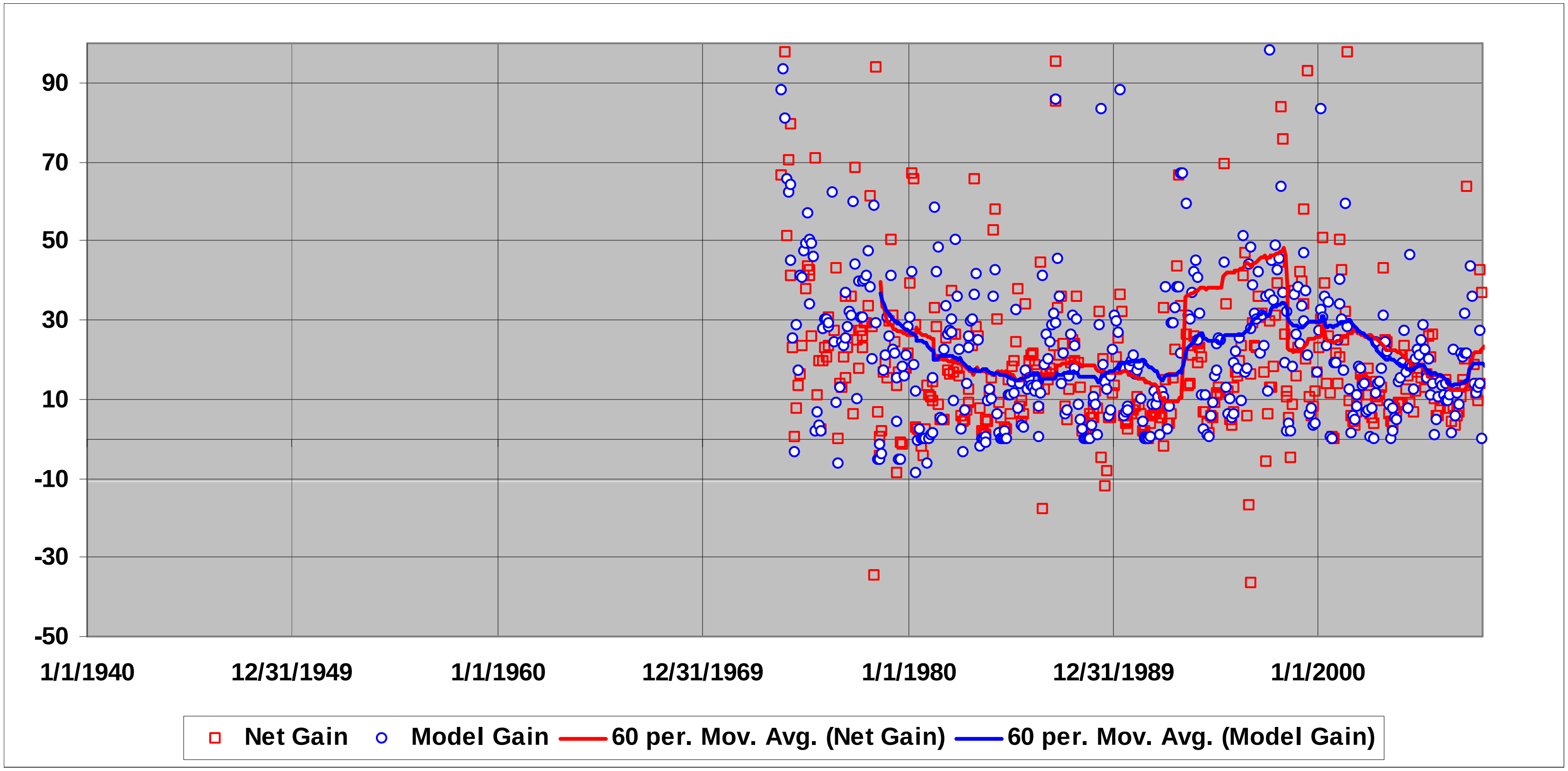
Balleau model

		Gage	Model	Difference	
	Average	27.0	22.0	-5.0	
	Median	15.6	17.8	2.2	
	Pre70				
		Gage	Model		
	Average				
	Median				
	Post70				
		Gage	Model		
	Average				
	Median				

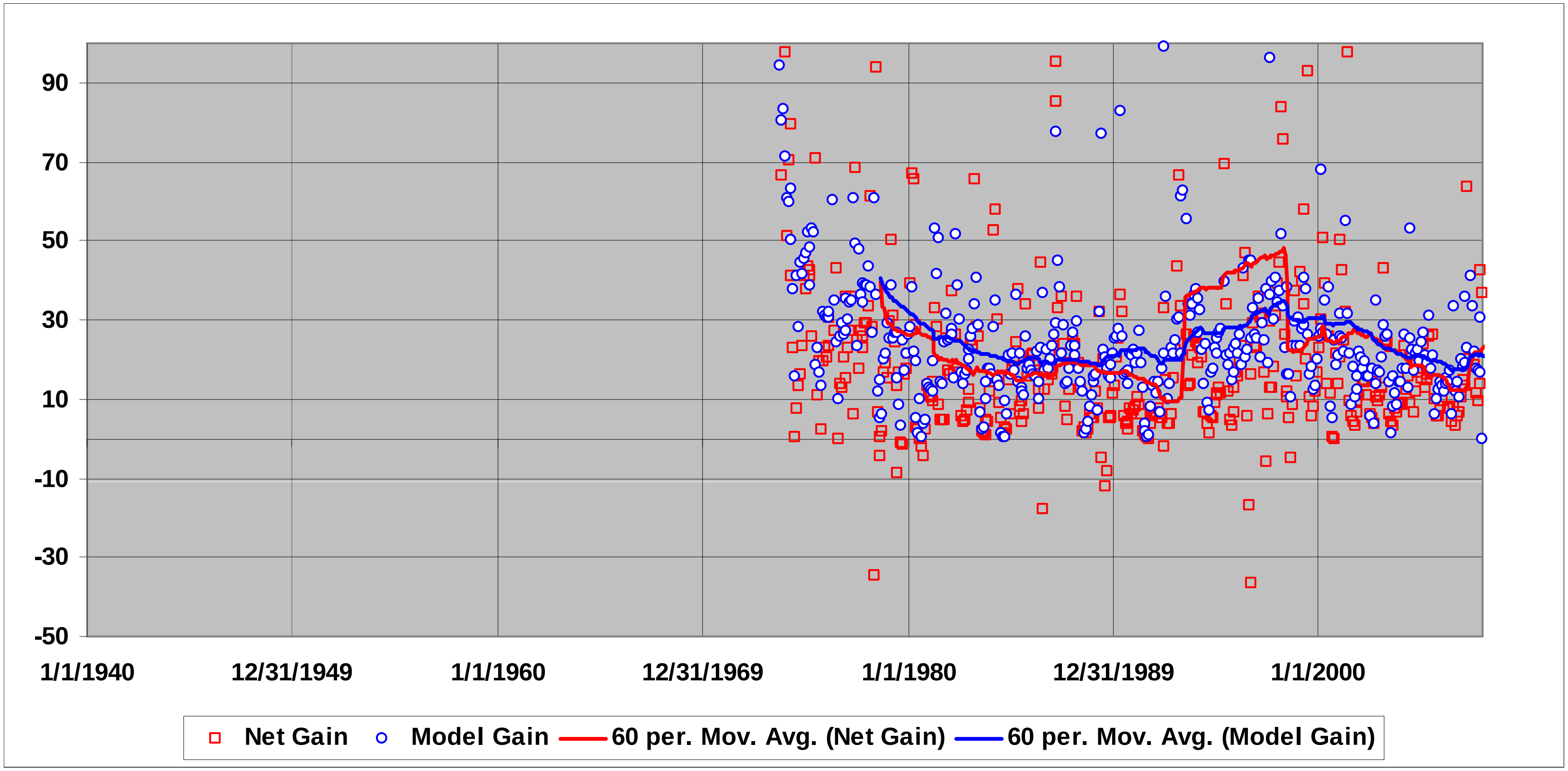
Revised model

		Gage	Model	Difference	
	Average	27.0	24.8	-2.3	
	Median	15.6	21.4	5.8	
	Pre70				
		Gage	Model		
	Average				
	Median				
	Post70				
		Gage	Model		
	Average				
	Median				

Gain Rattlesnake Macksville to Zenith Balleau model



Gain Rattlesnake Macksville to Zenith
Revised model



Gain Kinsley to Great Bend excluding Pawnee above gage

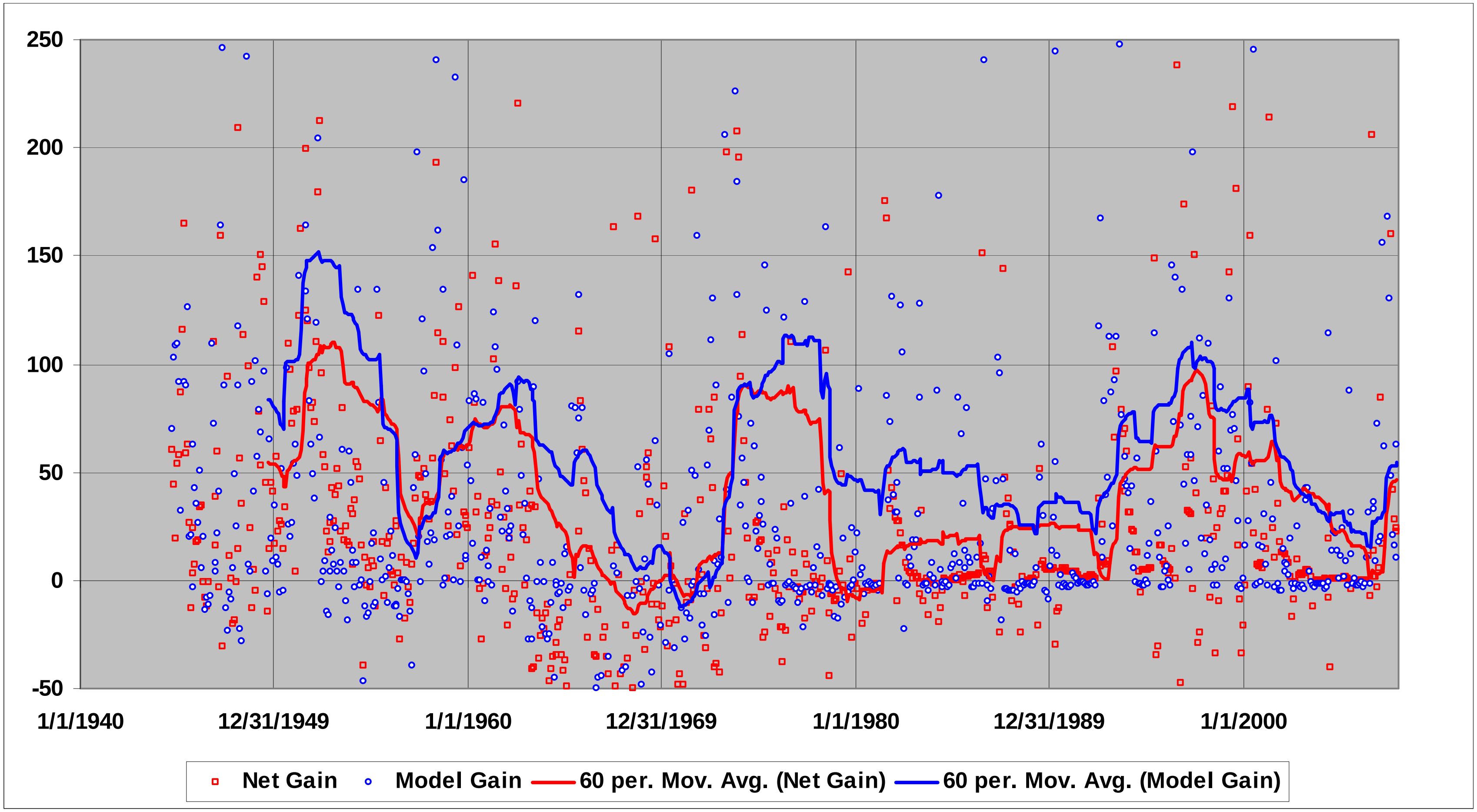
Balleau model

		Gage	Model	Difference	
	Average	41.8	60.3	18.4	
	Median	5.5	10.2	4.7	
	Pre70				
		Gage	Model		
	Average	44.2	63.4	19.2	
	Median	22.1	13.6	-8.5	
	Post70				
		Gage	Model		
	Average	42.0	58.2	16.2	
	Median	3.3	8.2	4.9	

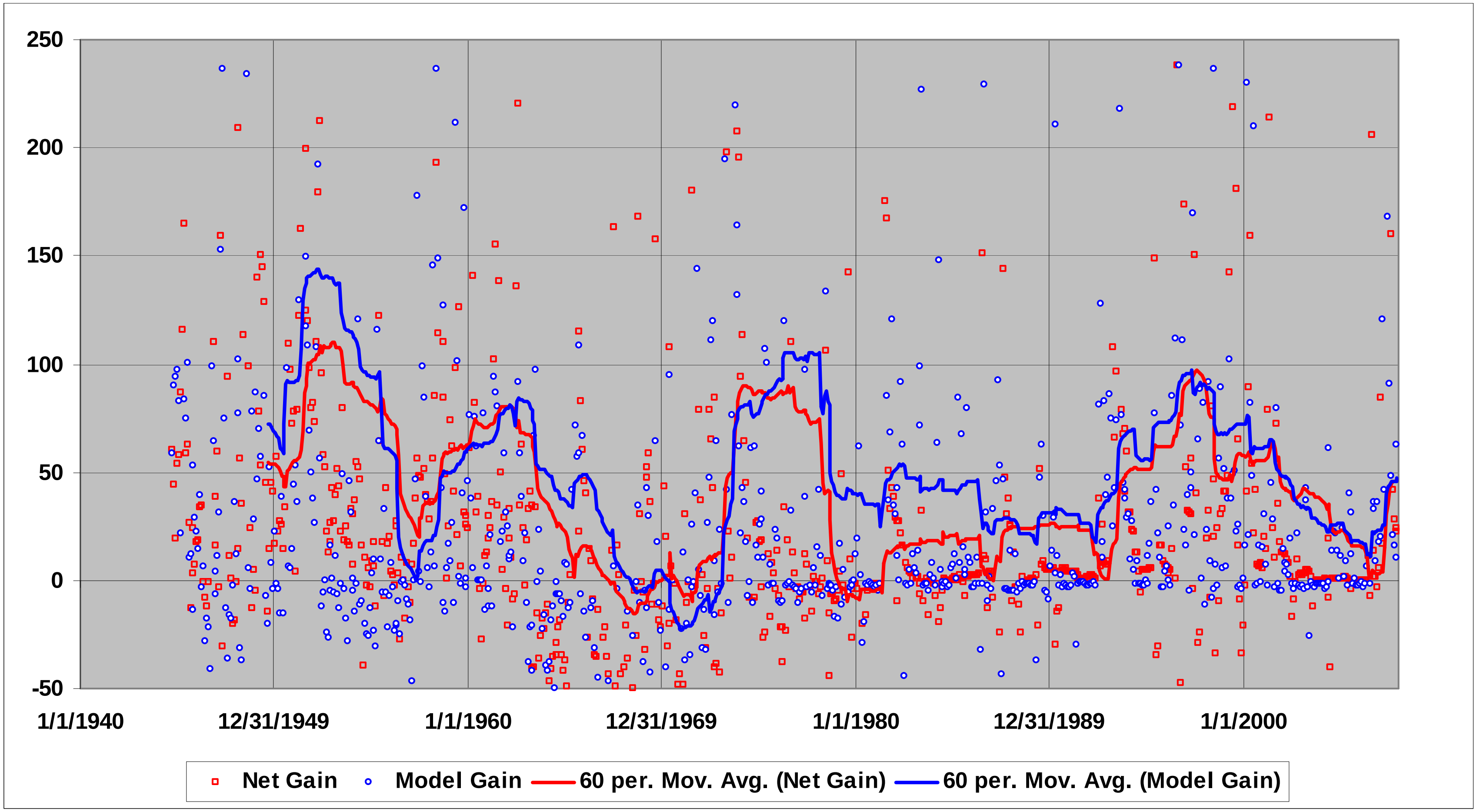
Revised model

		Gage	Model	Difference	
	Average	41.8	51.7	9.9	
	Median	5.5	5.3	-0.2	
	Pre70				
		Gage	Model		
	Average	44.2	53.4	9.2	
	Median	22.1	5.2	-16.9	
	Post70				
		Gage	Model		
	Average	42.0	50.7	8.6	
	Median	3.3	5.5	2.2	

Gain Kinsley to Great Bend excluding Pawnee above gage Balleau model



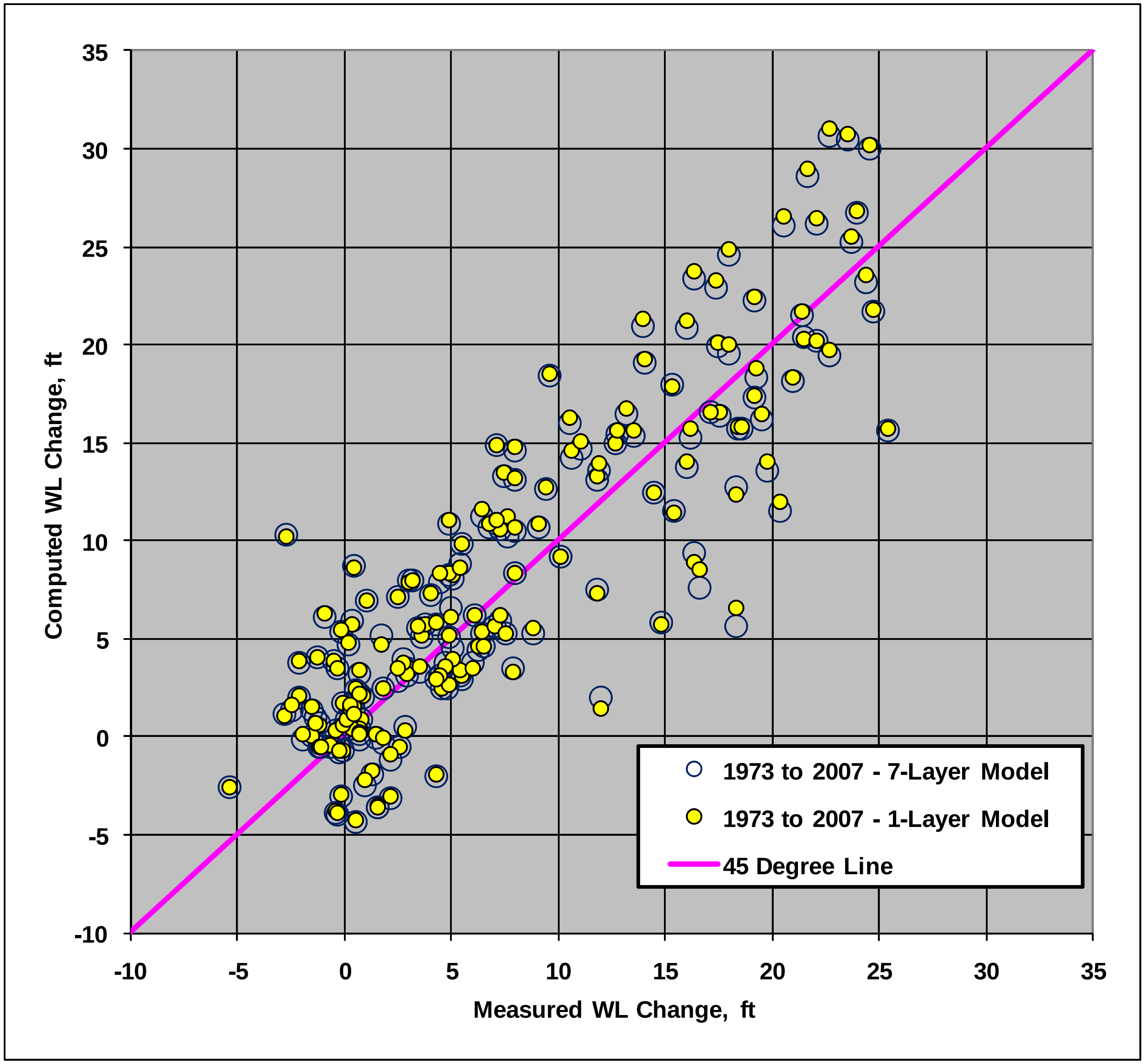
Gain Kinsley to Great Bend excluding Pawnee above gage Revised model



Appendix C

Water Level Decline Comparisons

7-Layer Model - Balleau Groundwater
and
1-Layer Model



35
30
25
20
15
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5
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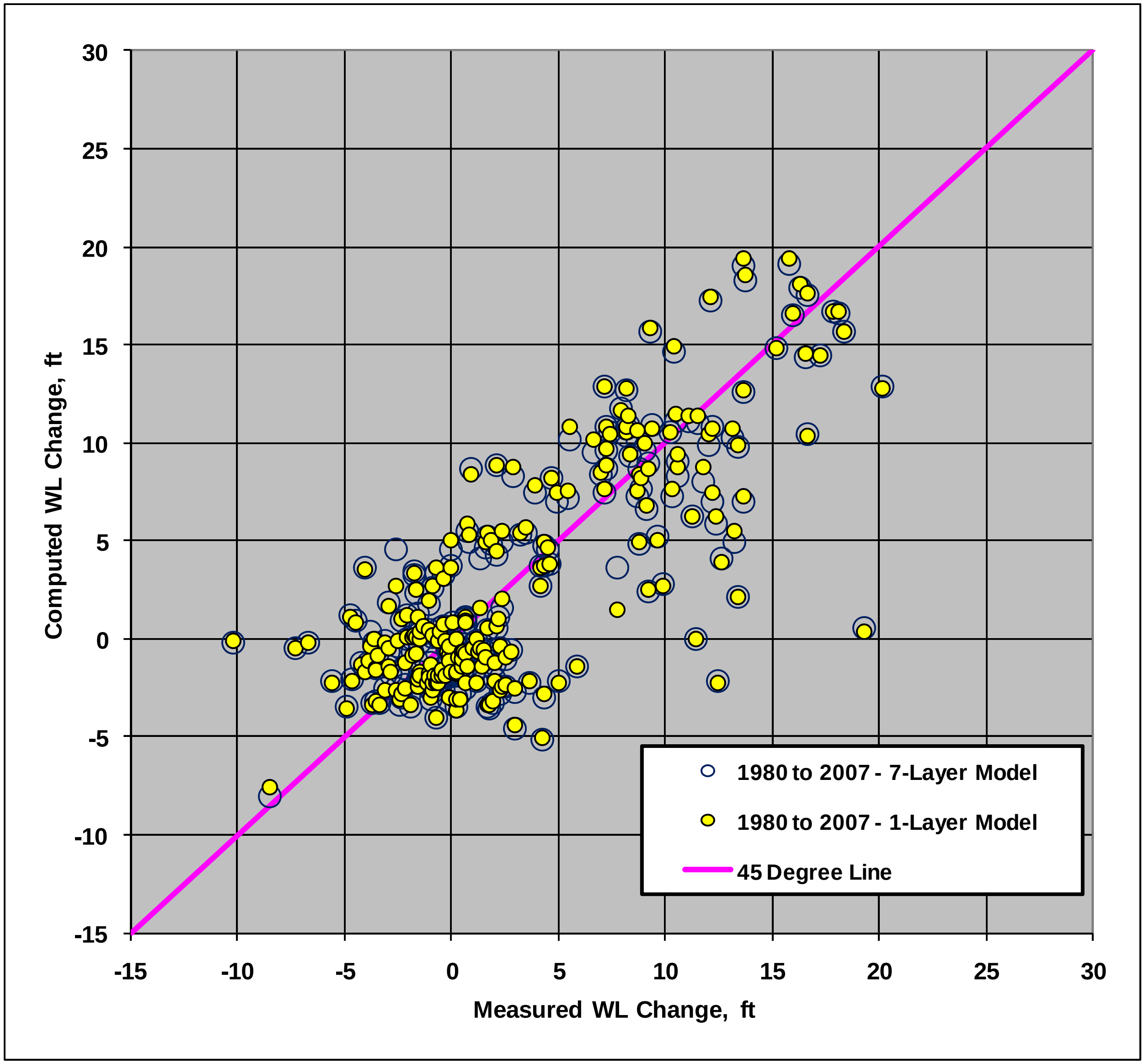
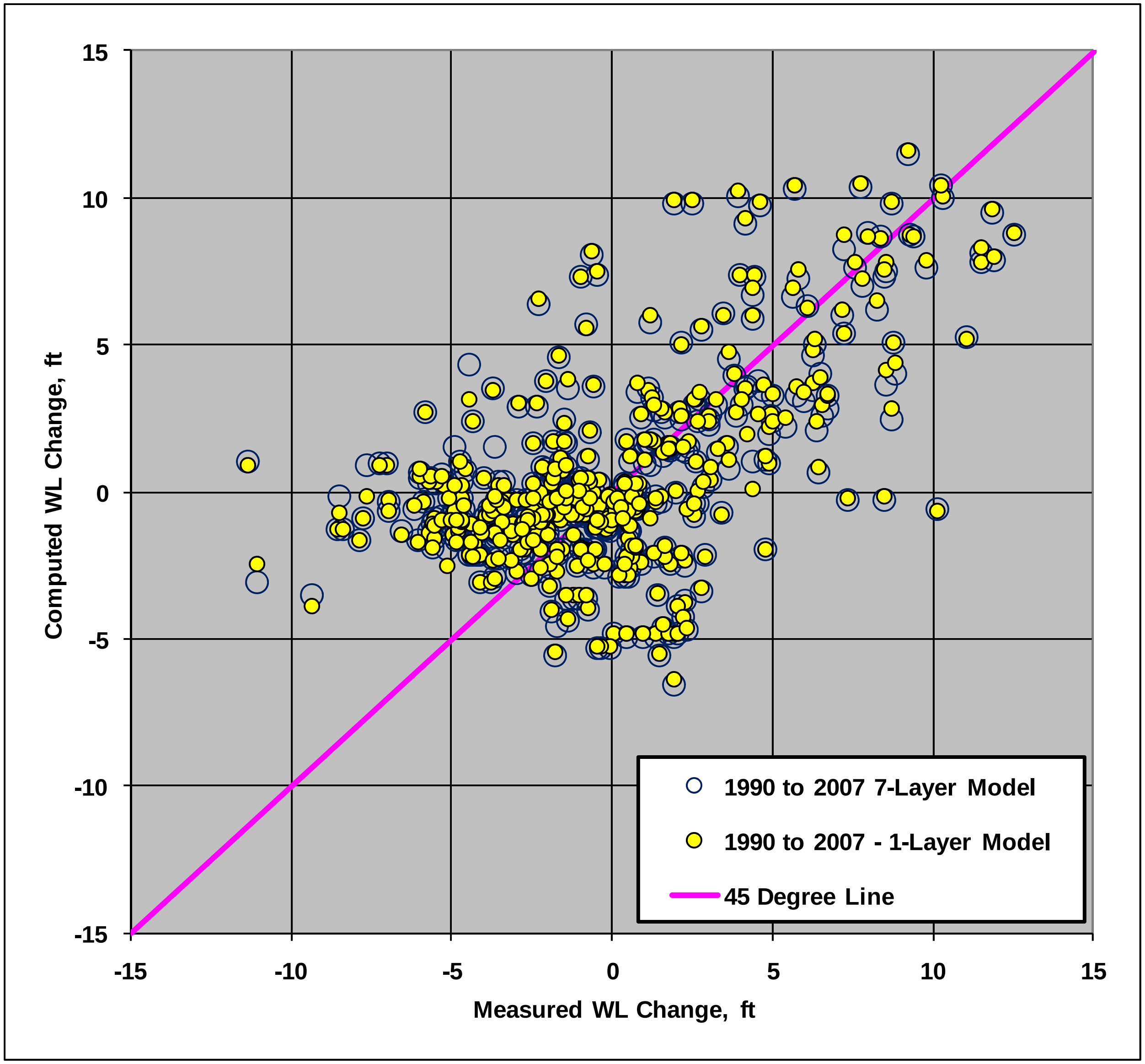
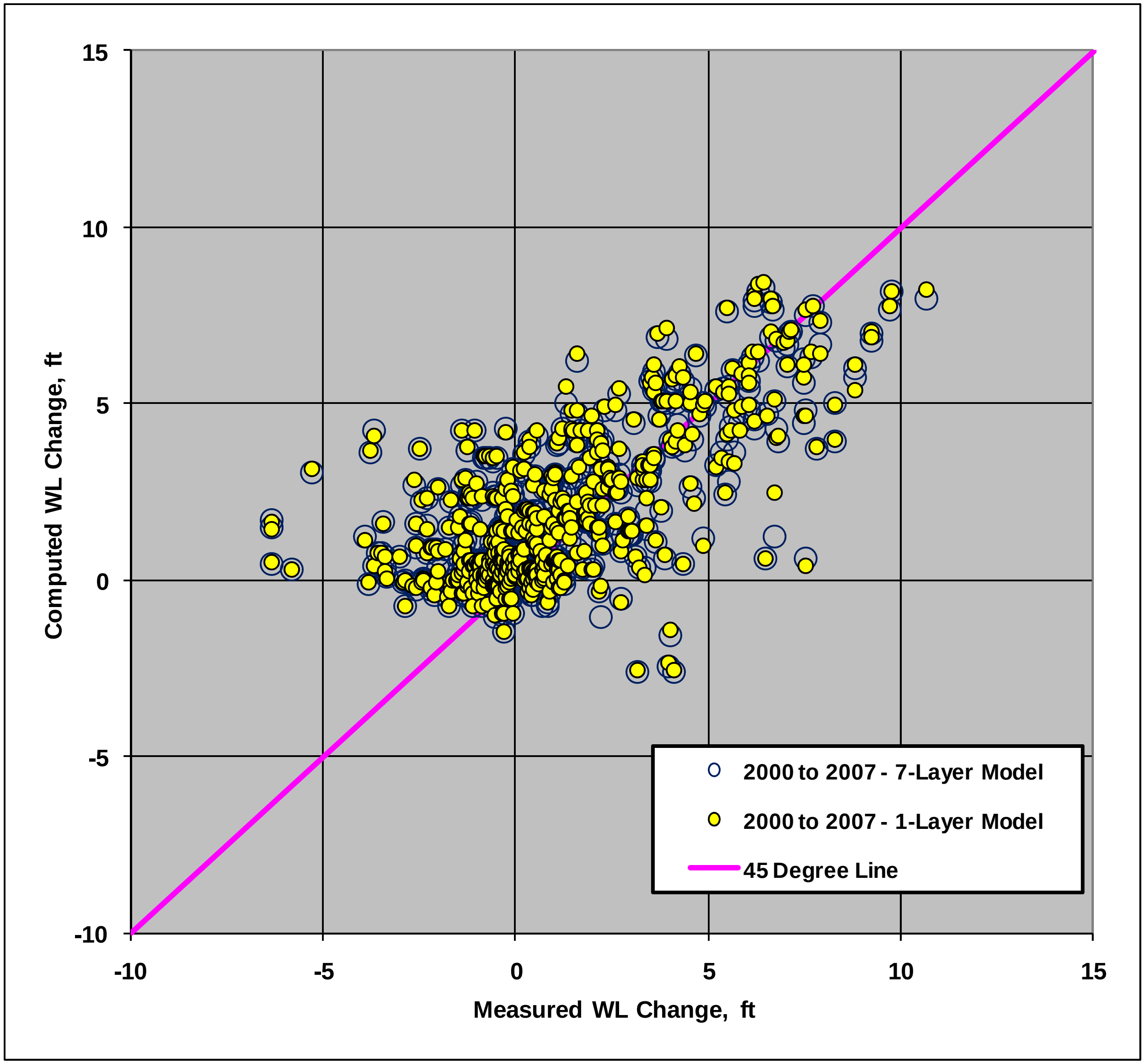
-5
-10
-10
-5
0
5
10
15
20
25
30
35
Computed WL Change, ft
Measured WL Change, ft
1973 to 2007 - 7-Layer Model
1973 to 2007 - 1-Layer Model
45 Degree Line



Computed WL Change, ft
Measured WL Change, ft
30
25
20
15
10
5
0
-5
-10
-15
-15
-10
-5
0
5
10
15
20
25
30
1980 to 2007 - 7-Layer Model
1980 to 2007 - 1-Layer Model
45 Degree Line



15
10
5
0
-5
-10
-15
Computed WL Change, ft
-15
-10
-5
0
5
10
15
Measured WL Change, ft
1990 to 2007 7-Layer Model
1990 to 2007 - 1-Layer Model
45 Degree Line



15
10
5
0
-5
-10
-10
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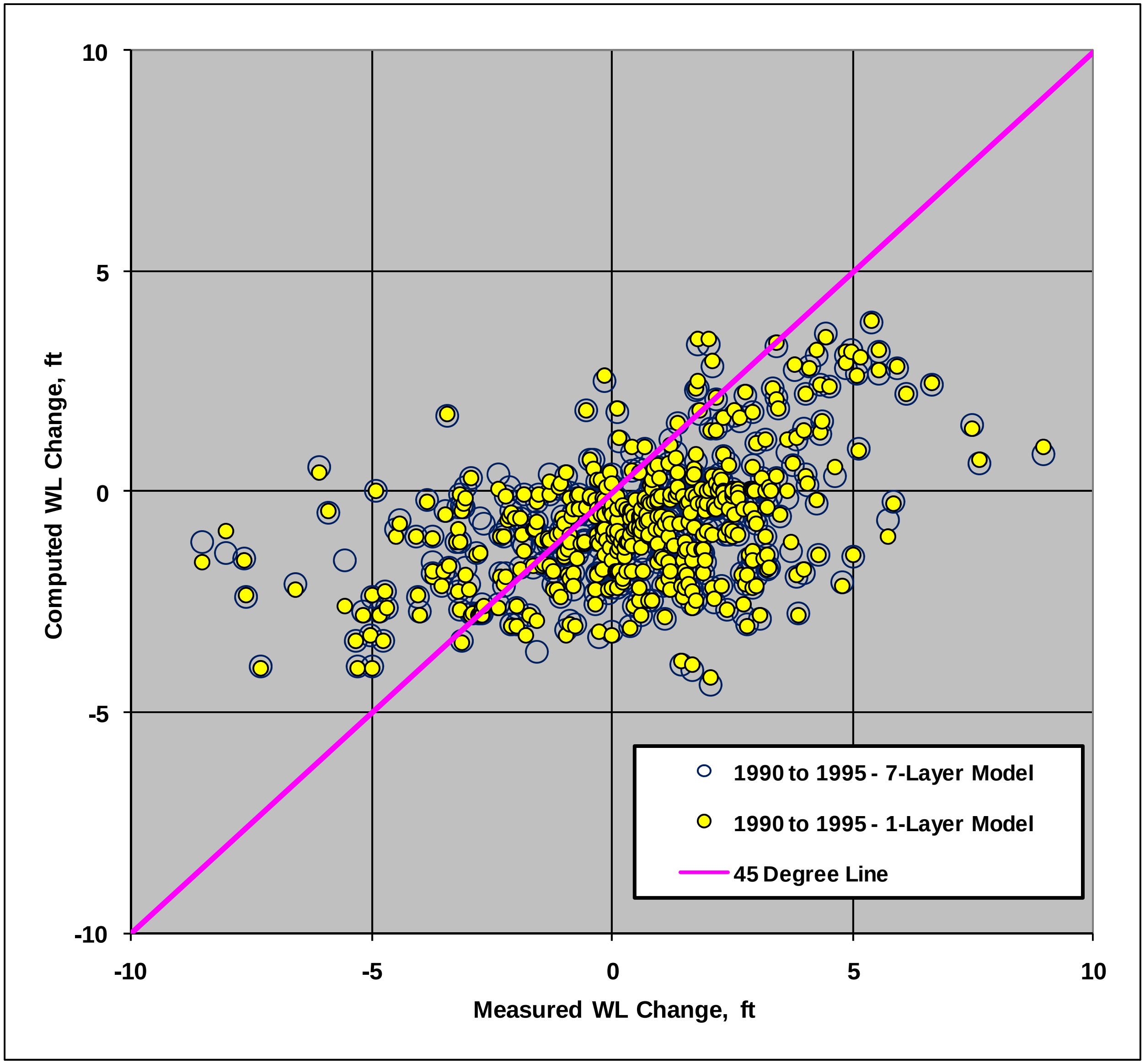
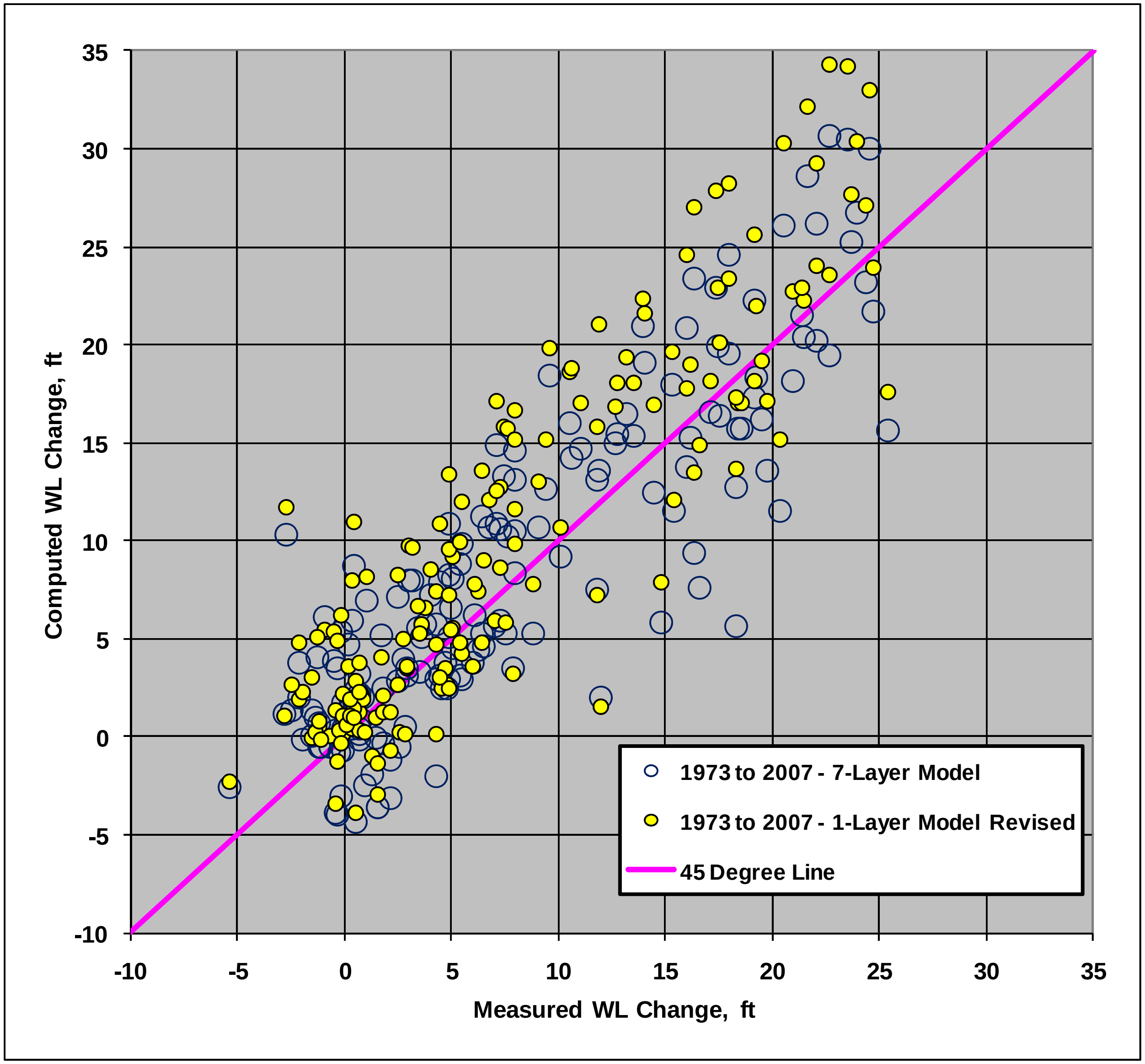
5
10
15
Computed WL Change, ft
Measured WL Change, ft
2000 to 2007 - 7-Layer Model
2000 to 2007 - 1-Layer Model
45 Degree Line


10
5
0
-5
-10
Computed WL Change, ft
-10
-5
0
5
10
Measured WL Change, ft
1990 to 1995 - 7-Layer Model
1990 to 1995 - 1-Layer Model
45 Degree Line

Appendix D

Water Level Decline Comparisons

7-Layer Model - Balleau Groundwater
and
1-Layer Model - Revised



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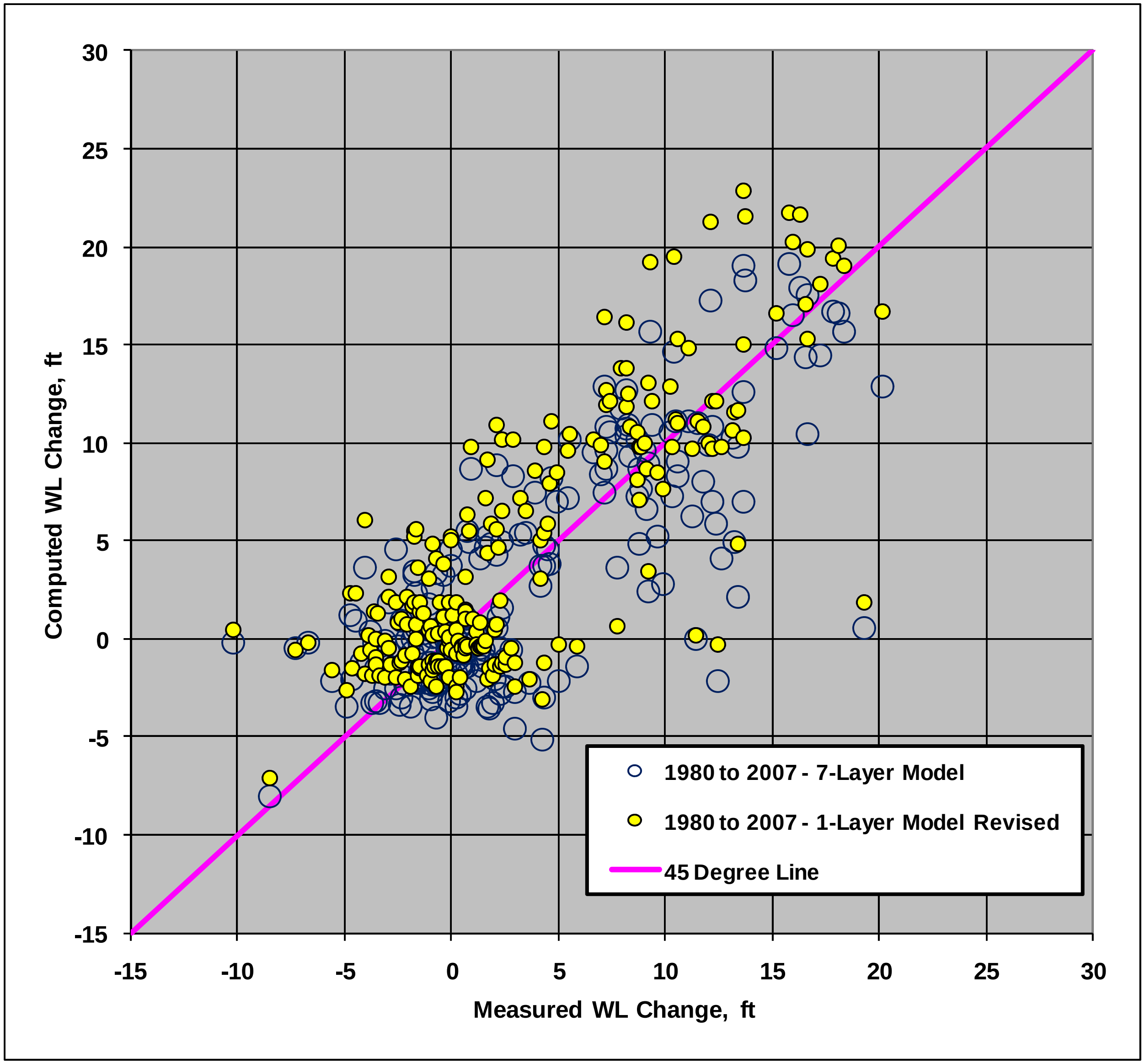
30
25
20
15
10
5
0
-5
-10
Computed WL Change, ft
-10
-5
0
5
10
15
20
25
30
35
Measured WL Change, ft
1973 to 2007 - 7-Layer Model
1973 to 2007 - 1-Layer Model Revised
45 Degree Line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25
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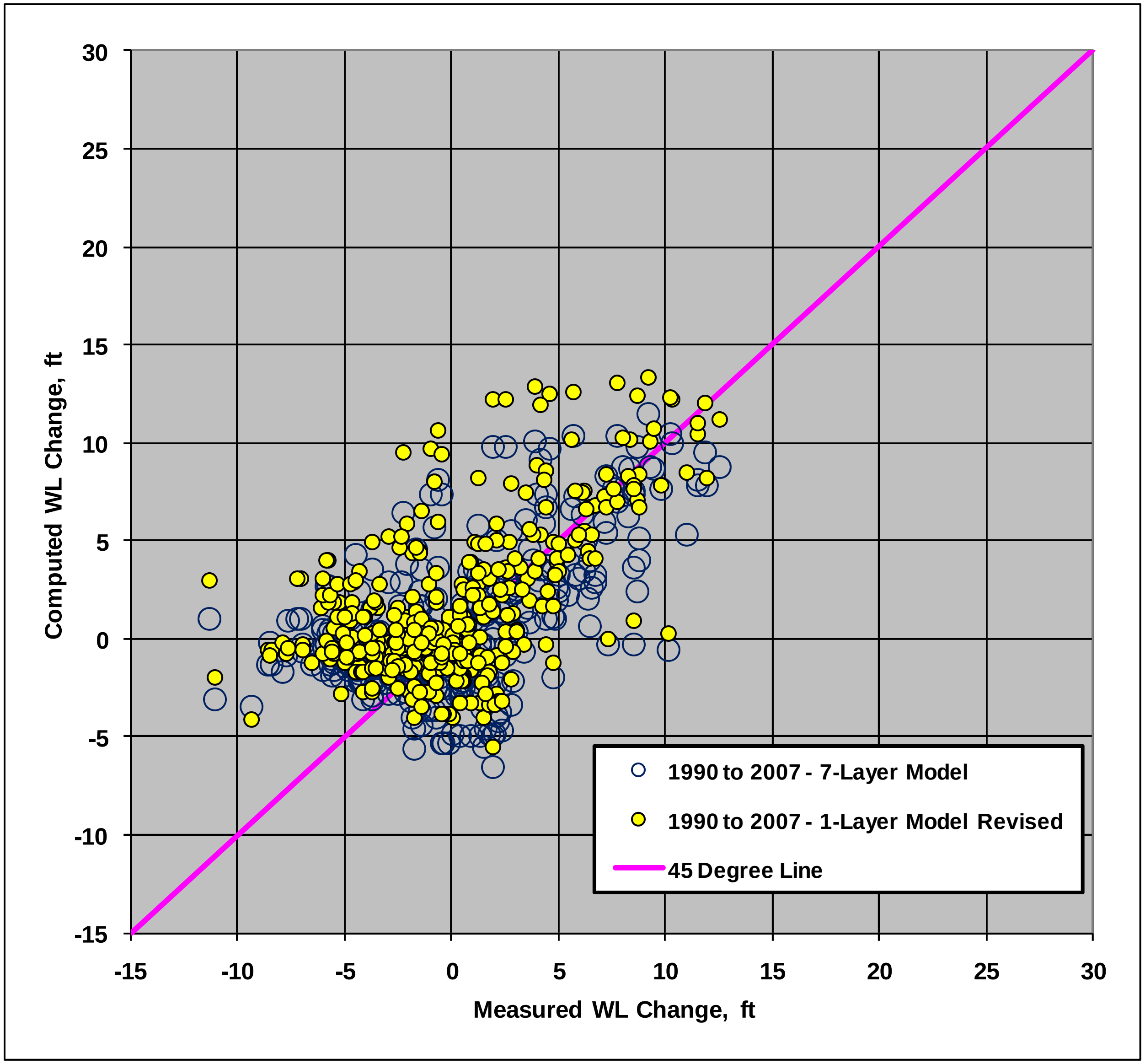
10
5
0
-5
-10
-15
Computed WL Change, ft
-15
-10
-5
0
5
10
15
20
25
30
Measured WL Change, ft
1980 to 2007 - 7-Layer Model
1980 to 2007 - 1-Layer Model Revised
45 Degree Line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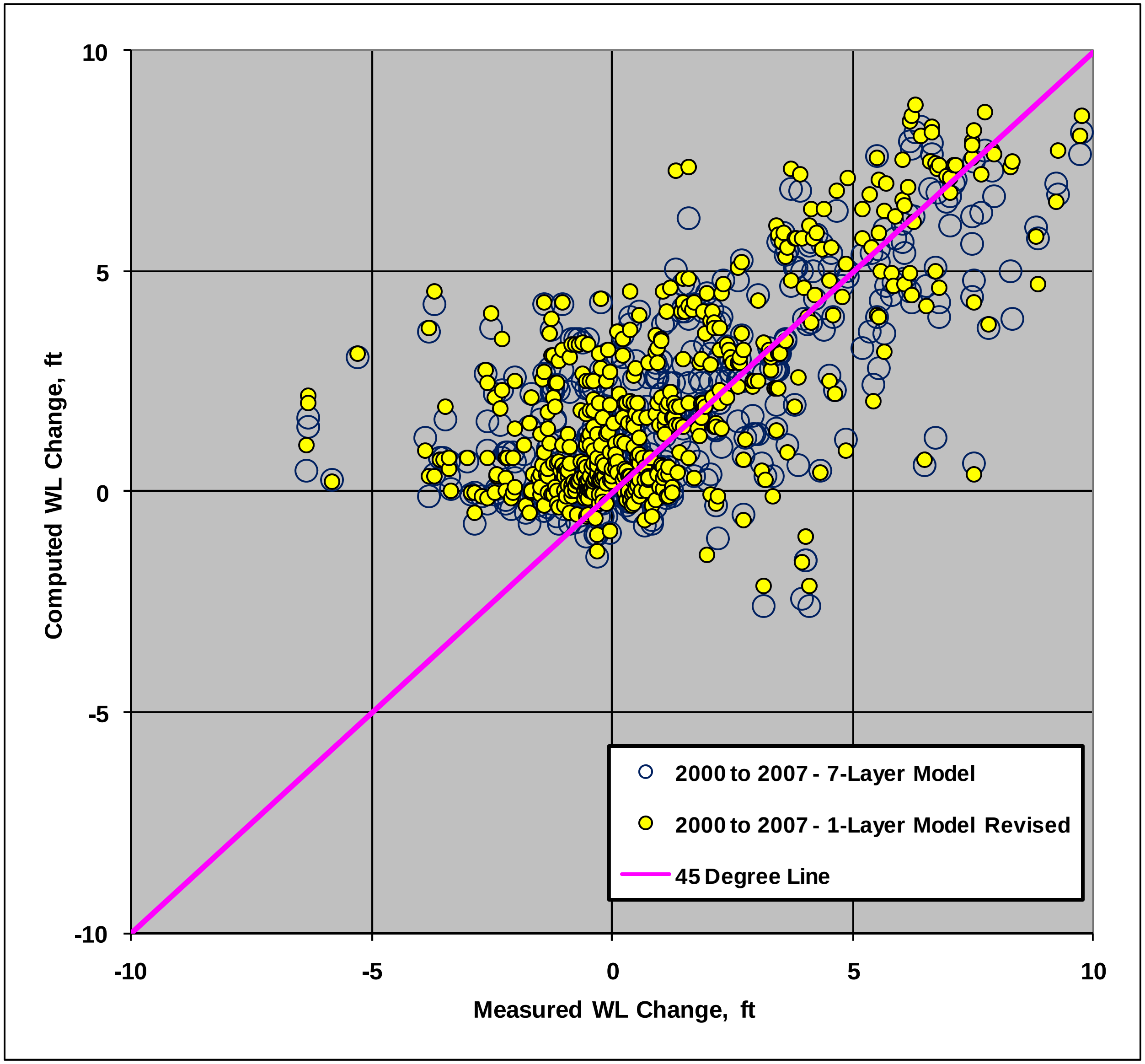
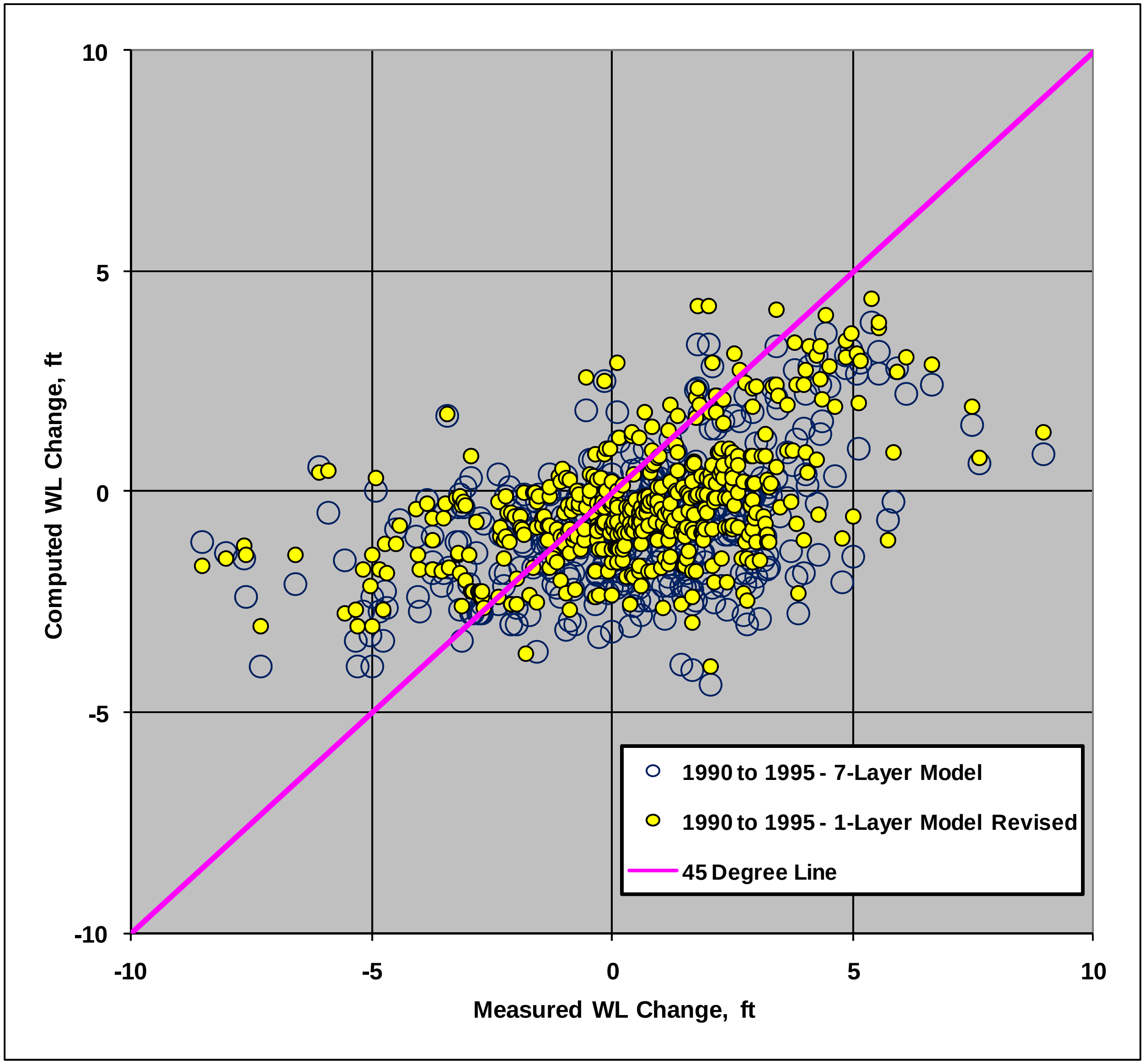
25
20
15
10
5
0
-5
-10
-15
Computed WL Change, ft
-15
-10
-5
0
5
10
15
20
25
30
Measured WL Change, ft
1990 to 2007 - 7-Layer Model
1990 to 2007 - 1-Layer Model Revised
45 Degree Line



10
5
0
-5
-10
-10
-5
0
5
10
Computed WL Change, ft
Measured WL Change, ft
2000 to 2007 - 7-Layer Model
2000 to 2007 - 1-Layer Model Revised
45 Degree Line


10
5
0
-5
-10
-10
-5
0
5
10
Computed WL Change, ft
Measured WL Change, ft
1990 to 1995 - 7-Layer Model
1990 to 1995 - 1-Layer Model Revised
45 Degree Line

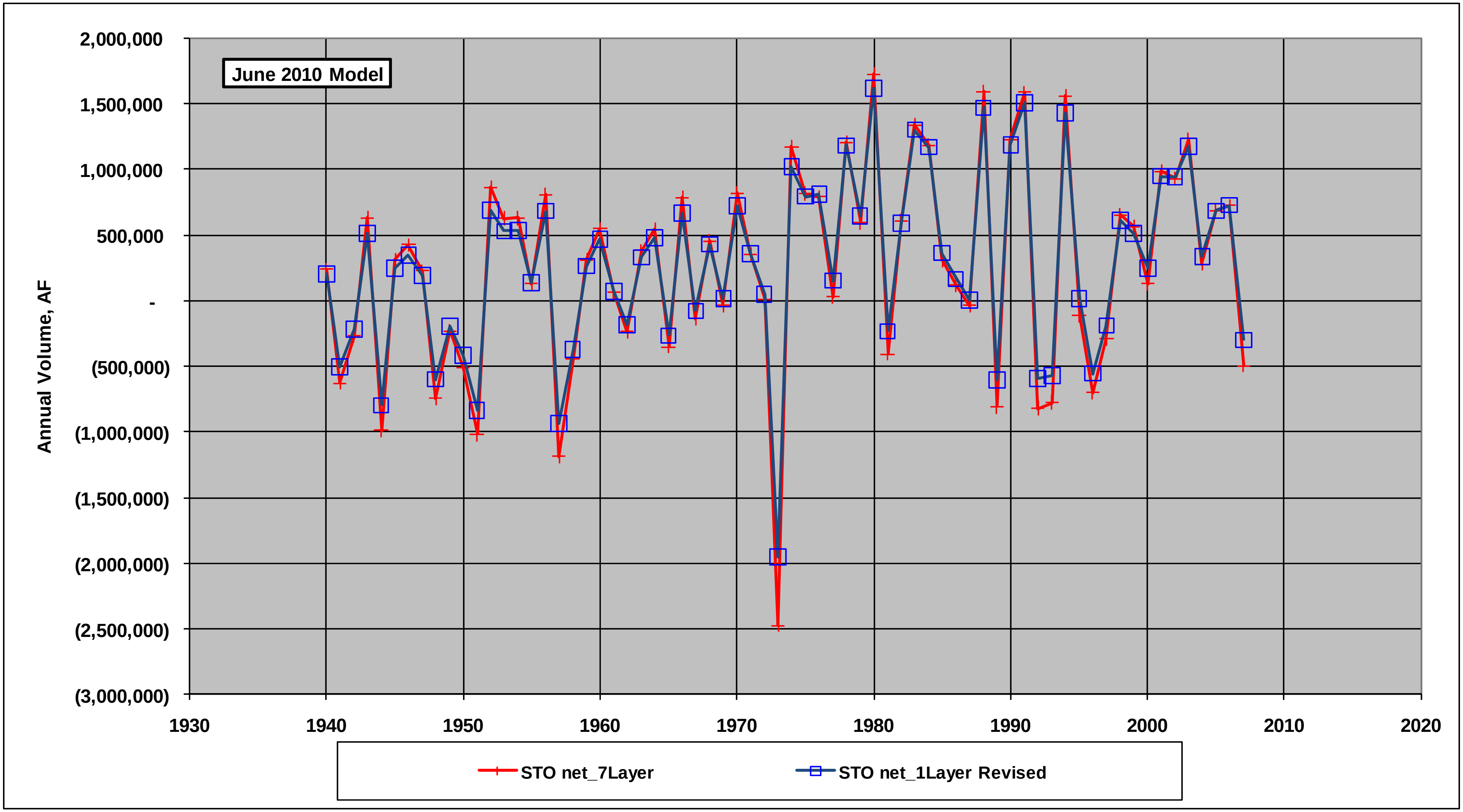
Appendix E

Water Budget Comparisons

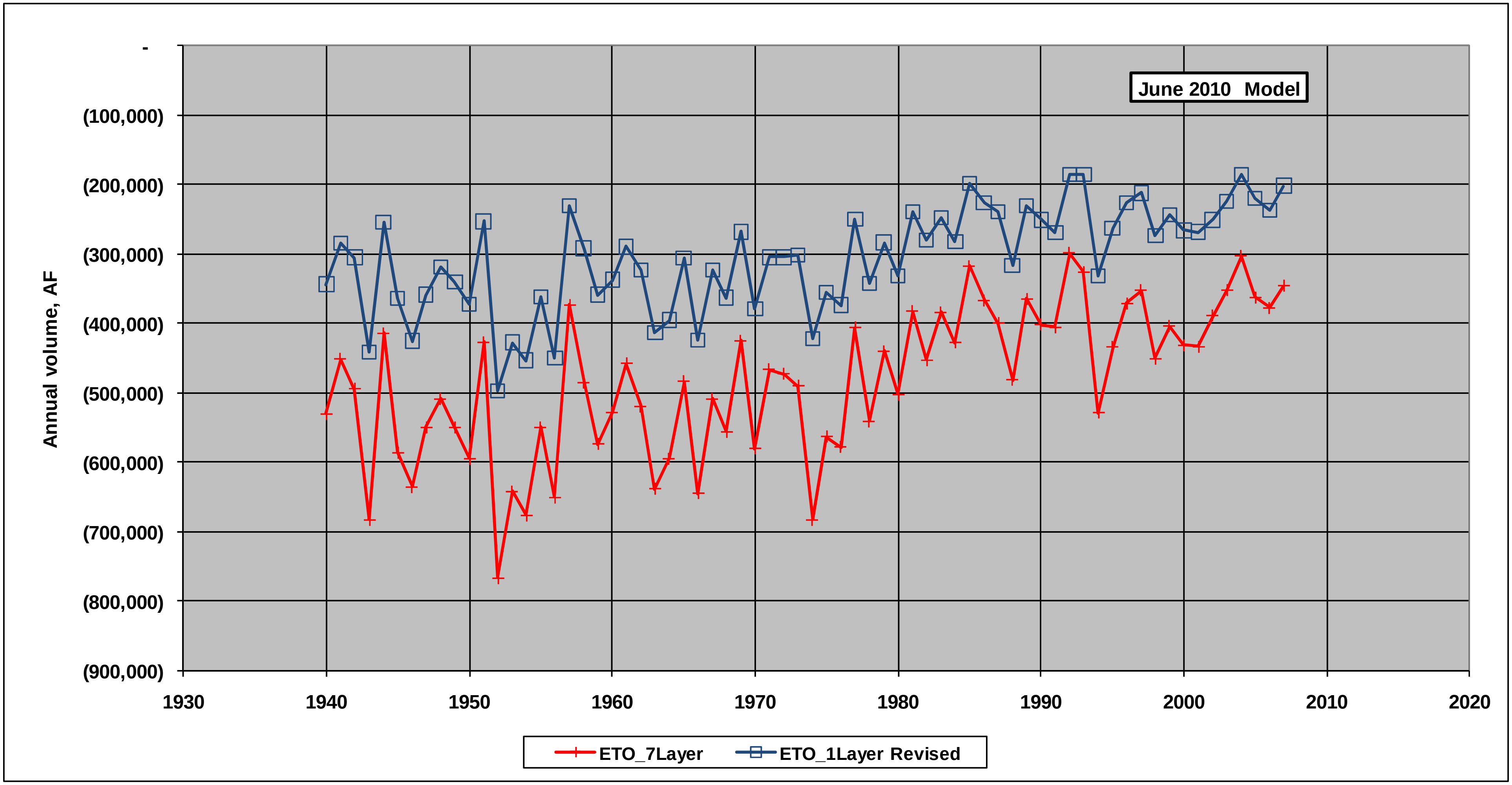
7-Layer Model
and
1-Layer Model Revised

Note: Net annual pumping volumes for the two models were identical and are not included.

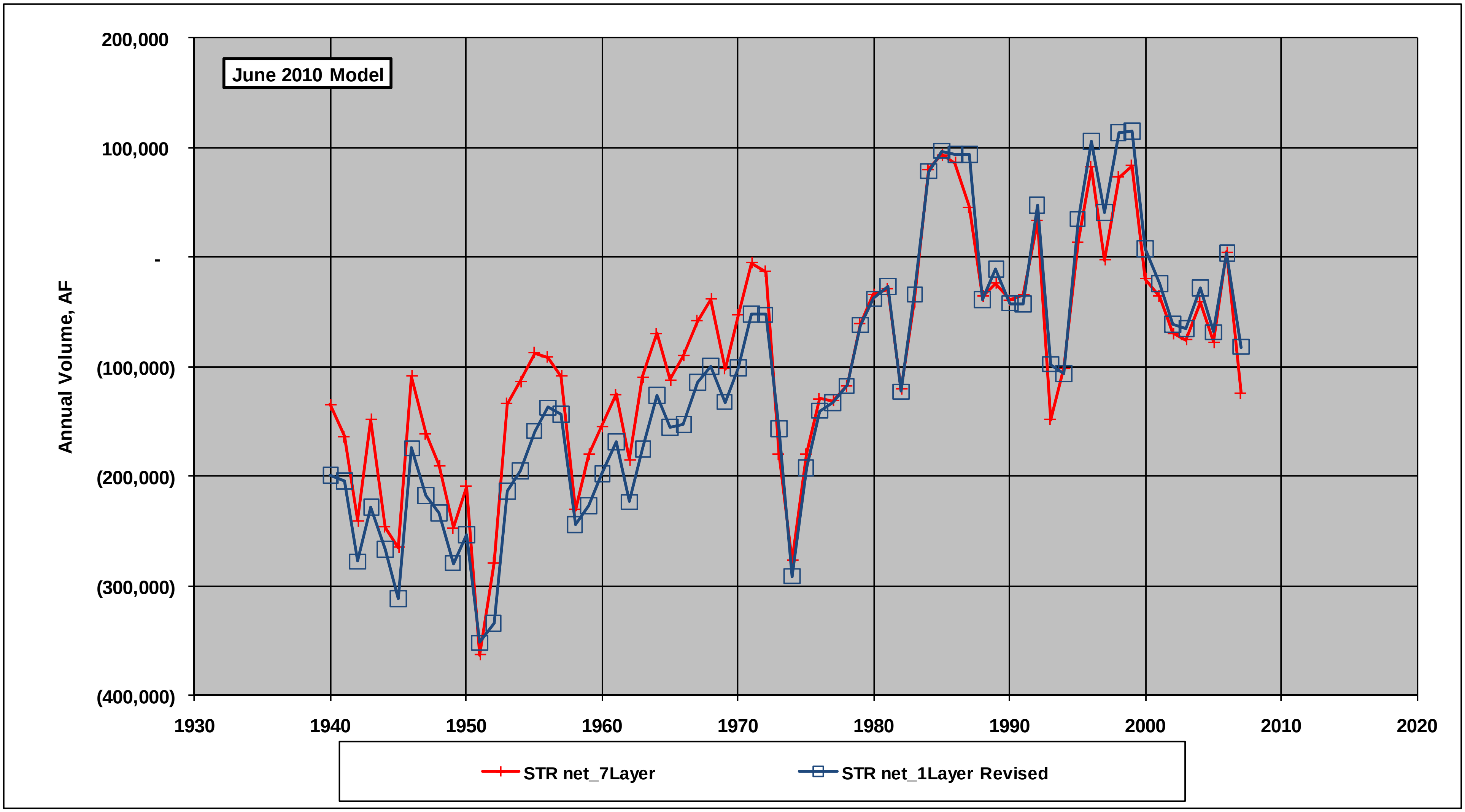
Net Annual Storage Volume



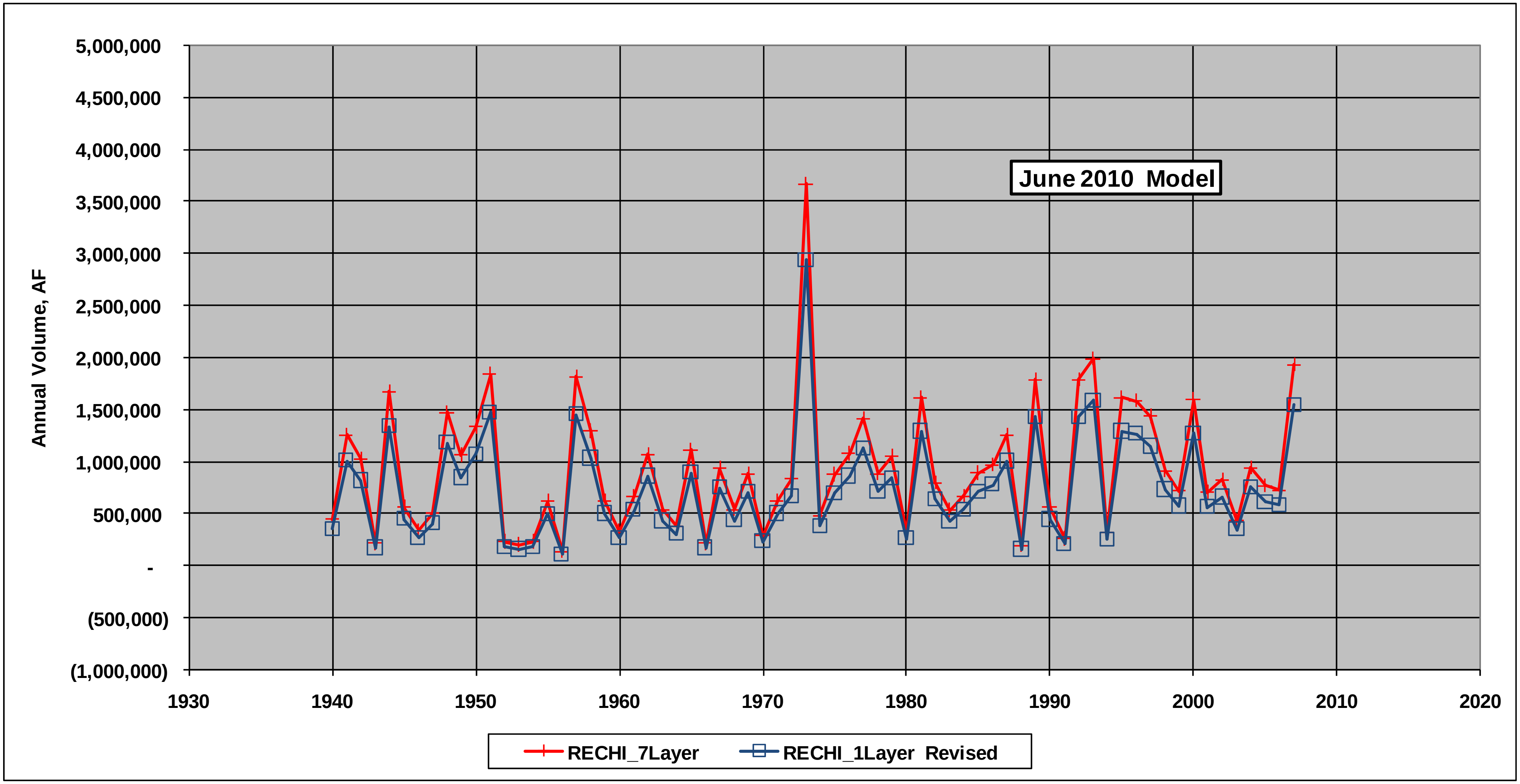
Groundwater Evapotranspiration Volume



Net Annual Stream-Groundwater Volume



Net Annual Recharge Volume



Pre 70 versus Post 70 Water Budget

7-Layer Model

RECHI_7Layer	STRI_7Layer	STOO_7Layer	CHO_7Layer	WELLO_7Layer	ETO_7Layer	RECHO_7	STRO_7Layer	-	IRR in_7Layer	IRR out_7Layer	STO net_7Layer	STR net_7Layer
768,326			(38,541)	(294,141)	(551,269)				72,952	(183,297)	64,209	(154,777)
1,053,618			(41,433)	(1,298,264)	(424,450)				201,992	(1,187,420)	417,507	(41,820)
285,291			(2,892)	(1,004,123)	126,819				129,041	(1,004,123)	353,297	112,957
					21%						60%	19%
									(589,791)	590,182		

1-Layer Model Revised

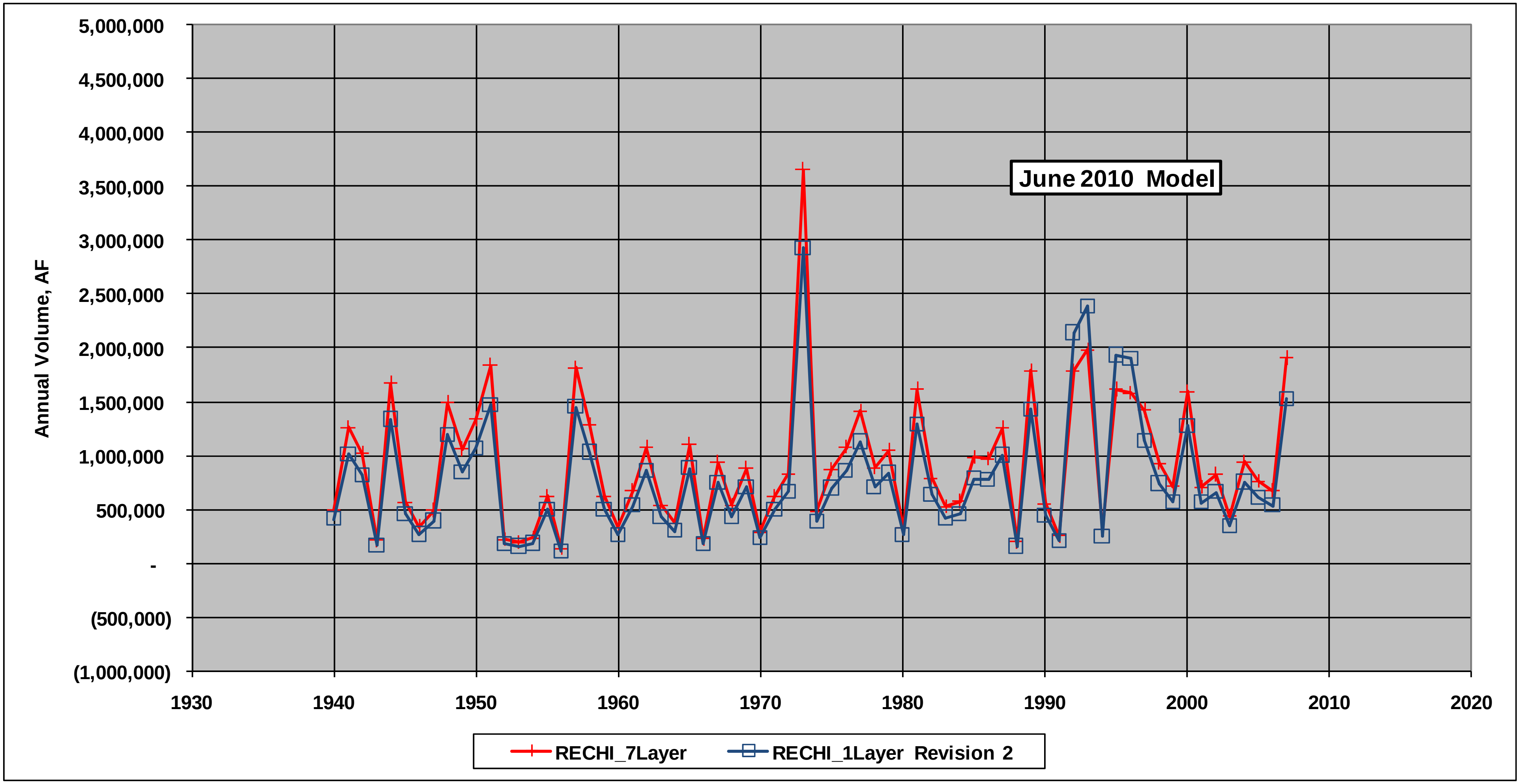
RECHI_1Layer	STRI_1Layer	STOO_1Layer	CHO_1Layer	WELLO_1Layer	ETO_1Layer	RECHO_1	STRO_1Layer	-	IRR in_1Layer	IRR out_1Layer	STO net_1Layer	STR net_1Layer
614,661			(37,814)	(294,141)	(353,900)				72,952	(183,297)	67,596	(203,128)
842,894			(38,986)	(1,298,264)	(266,034)				201,992	(1,187,420)	459,163	(33,844)
228,233			(1,172)	(1,004,123)	87,866				129,041	(1,004,123)	391,567	169,284
					14%						60%	26%
									(646,849)	647,545		

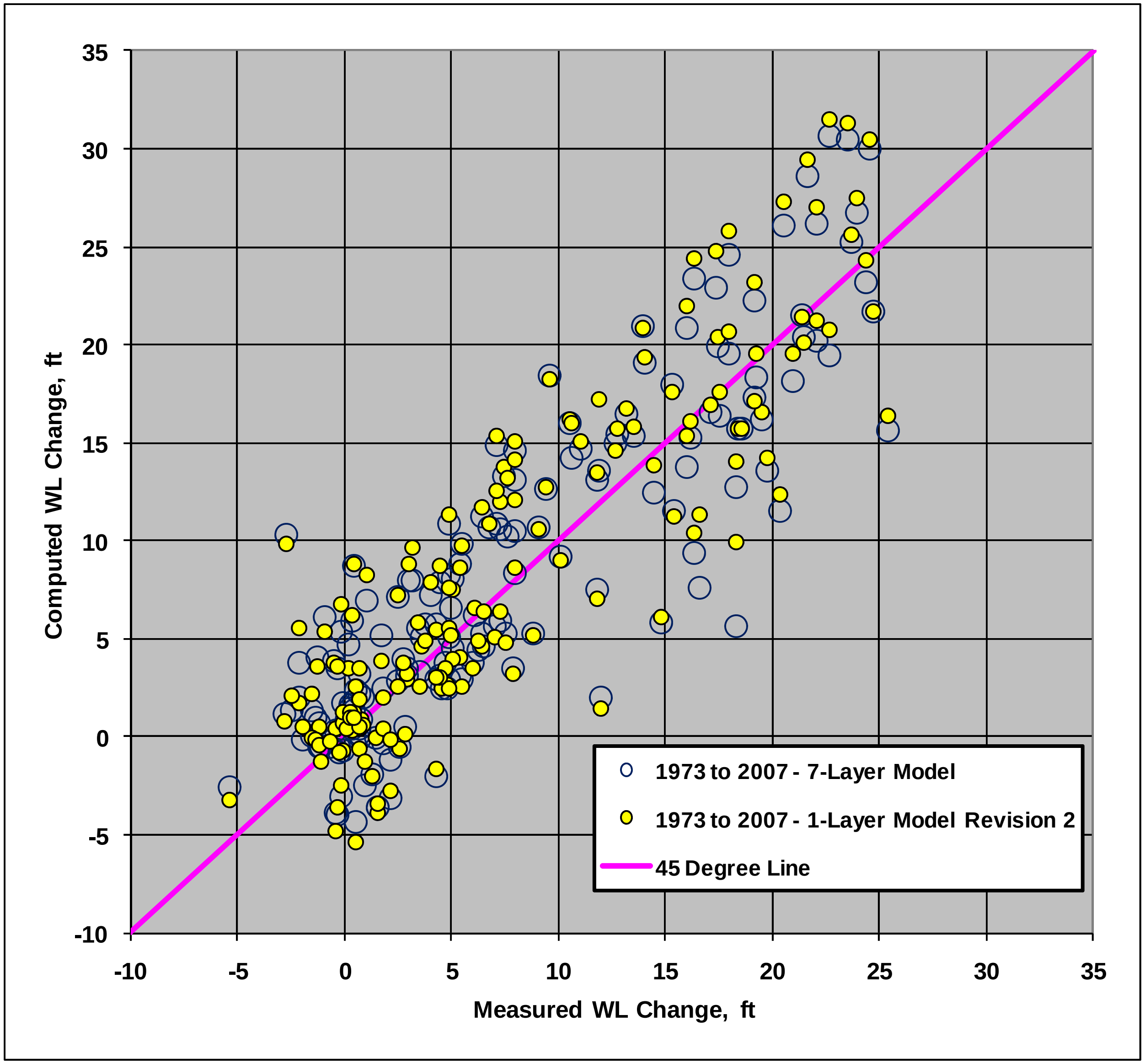
Appendix F

Water Level Decline Comparisons

7-Layer Model - Balleau Groundwater
and
1-Layer Model – Revision 2

Annual Recharge Volume – Revision 2




Computed WL Change, ft
Measured WL Change, ft
35
30
25
20
15
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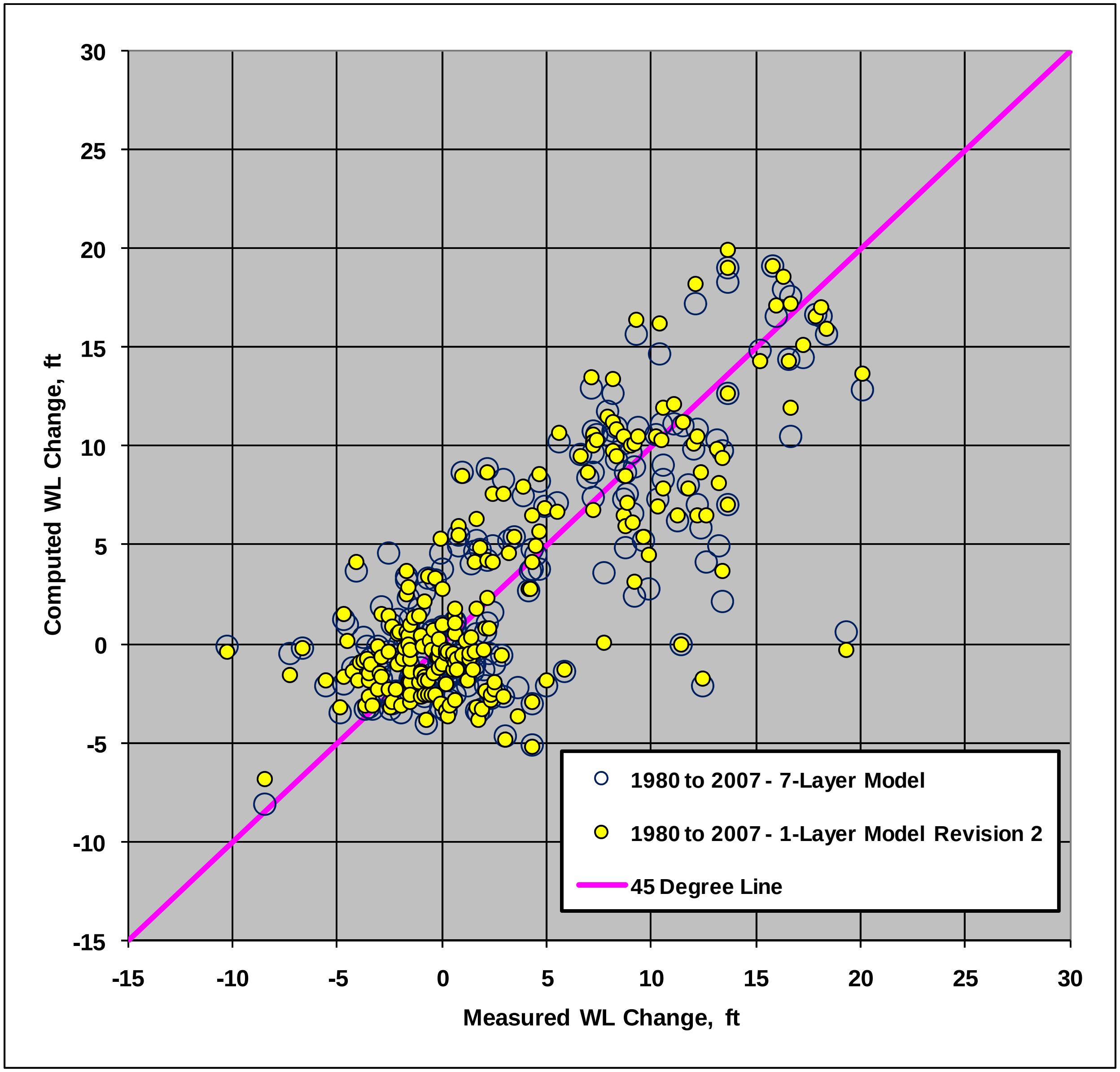
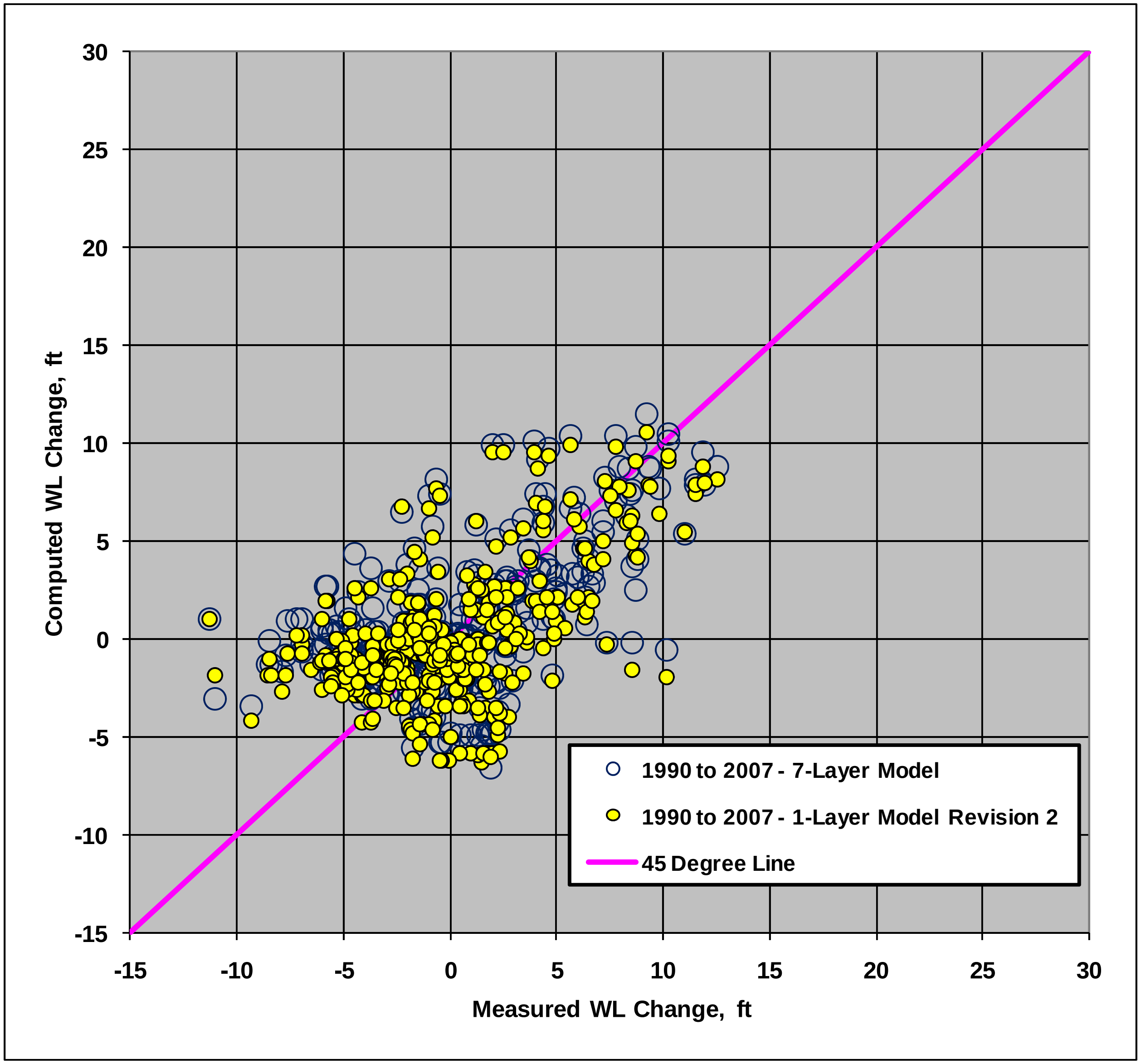
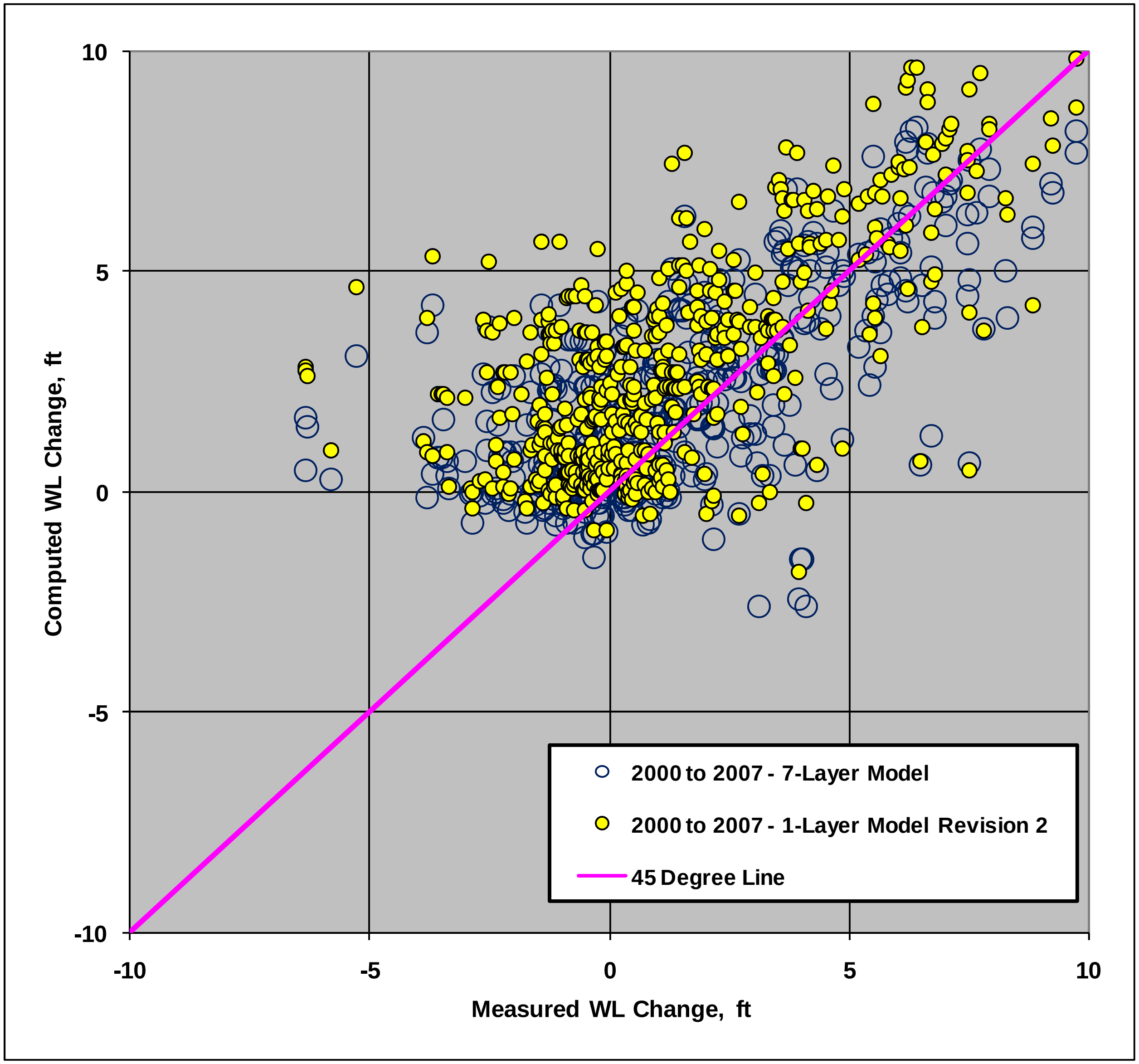
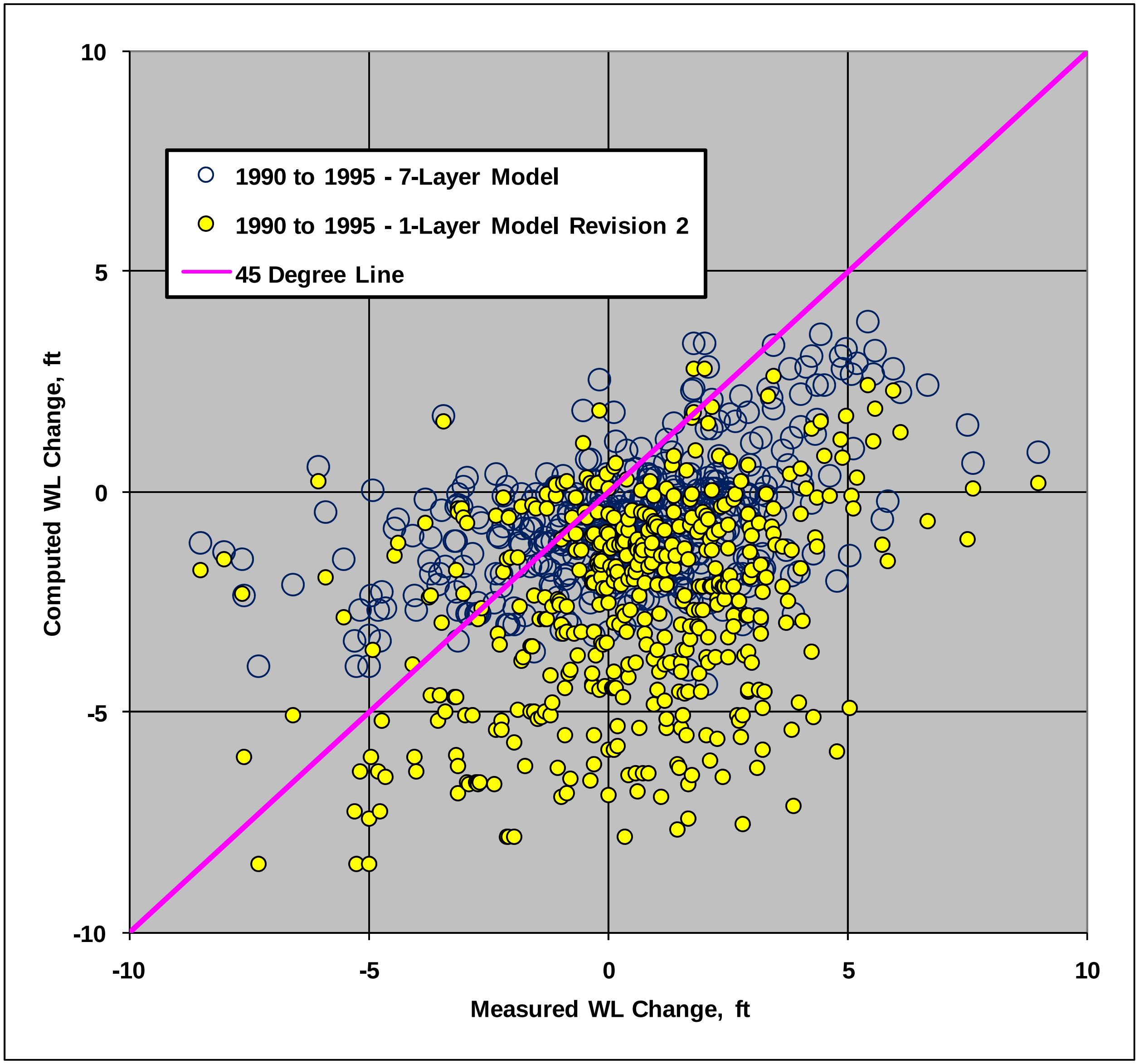
-10
-10
-5
0
5
10
15
20
25
30
35
1973 to 2007 - 7-Layer Model
1973 to 2007 - 1-Layer Model Revision 2
45 Degree Line


30
25
20
15
10
5
0
-5
-10
-15
Computed WL Change, ft
-15
-10
-5
0
5
10
15
20
25
30
Measured WL Change, ft
1980 to 2007 - 7-Layer Model
1980 to 2007 - 1-Layer Model Revision 2
45 Degree Line



Computed WL Change, ft
Measured WL Change, ft
30
25
20
15
10
5
0
-5
-10
-15
-15
-10
-5
0
5
10
15
20
25
30
1990 to 2007 - 7-Layer Model
1990 to 2007 - 1-Layer Model Revision 2
45 Degree Line


10
5
0
-5
-10
Computed WL Change, ft
-10
-5
0
5
10
Measured WL Change, ft
2000 to 2007 - 7-Layer Model
2000 to 2007 - 1-Layer Model Revision 2
45 Degree Line



1990 to 1995 - 7-Layer Model
1990 to 1995 - 1-Layer Model Revision 2
45 Degree Line
10
5
0
-5
-10
-10
-5
0
5
10
Computed WL Change, ft
Measured WL Change, ft