Appendix 3-A

Phase I Water Budget for Central and Eastern Model Areas

Appendix 3-A

Water Budget and Flow Charts
Developed for the
Central and Eastern Model Area
(COHYST 2010 area)

Prepared for the COHYST Sponsors

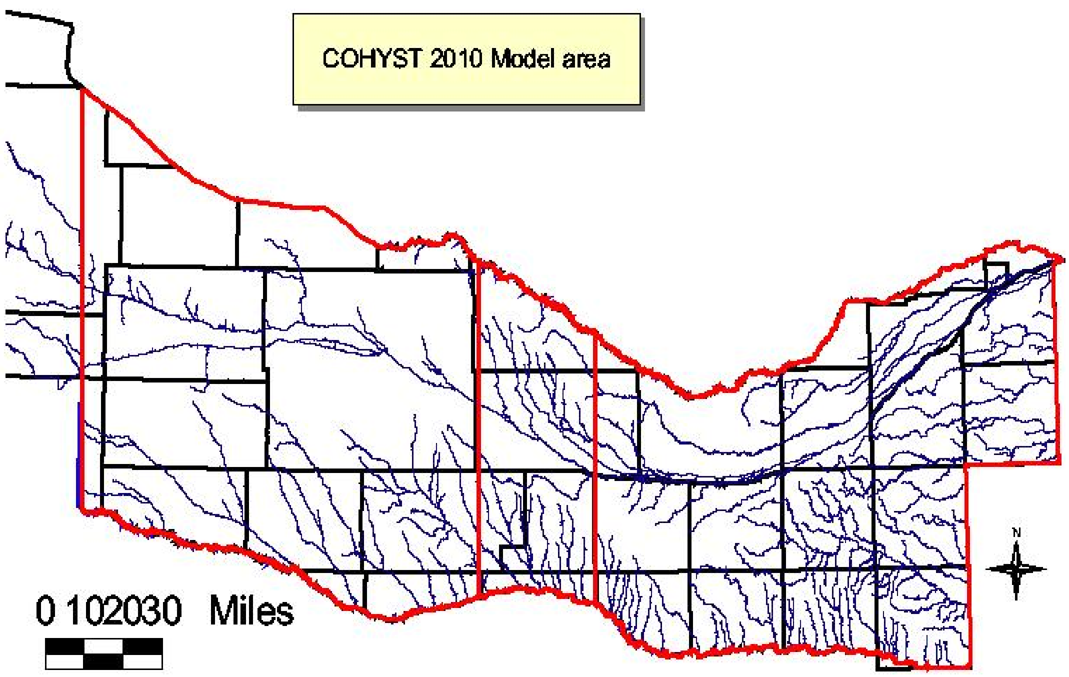
This work is referred to as the **Phase I Water Budget**

June 2010
Updated in 2012
Update 2013

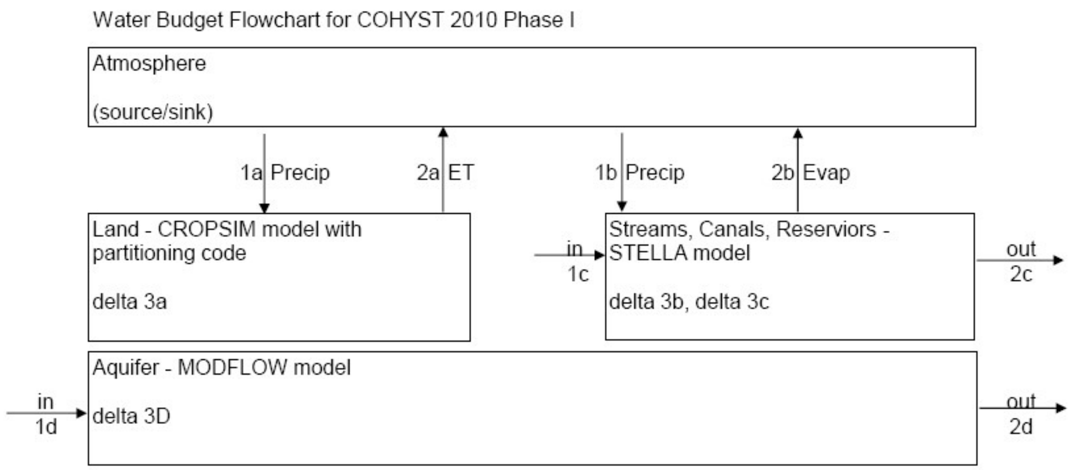
NDNR
CPNRD
HDR Engineering
The Flatwater Group

Water Budget Development

The COHYST Sponsors have provided guidance regarding the first steps to addressing goals and objectives developed for the newly developed (2009) Operating plan and incorporating common goals and objectives shared by the Conjunctive Water Management Sponsors. Phase one of this approach includes development of a complete water budget in the region encompassed by the combined COHYST eastern and central model units (COHYST 2010 model area). This paper describes the development of this water budget as updated for the period from January 1, 1985 to December 31, 2005, reported annually by calendar year. This water budget is entirely derived from measured data readily available. It provides general guidance and understanding of the model area water availability and use. It also provides water budget constraints for the modeling efforts that were develop in Phase II of the COHYST and Conjunctive Water Management studies.



First, a generalized flowchart was prepared.



The water budget contains the following inflow:

- 1a Precipitation (onto land surface and water surfaces)
- 1c Stream flow in (surface water from North Platte and South Platte Rivers)
- 1d Groundwater inflow

The following outflow:

- 2a & 2b Evapotranspiration (from land surface and water surfaces)
- 2c Stream flow out the Platte River and other basins
- 2d Groundwater flow

It reflects changes in storage relating to:

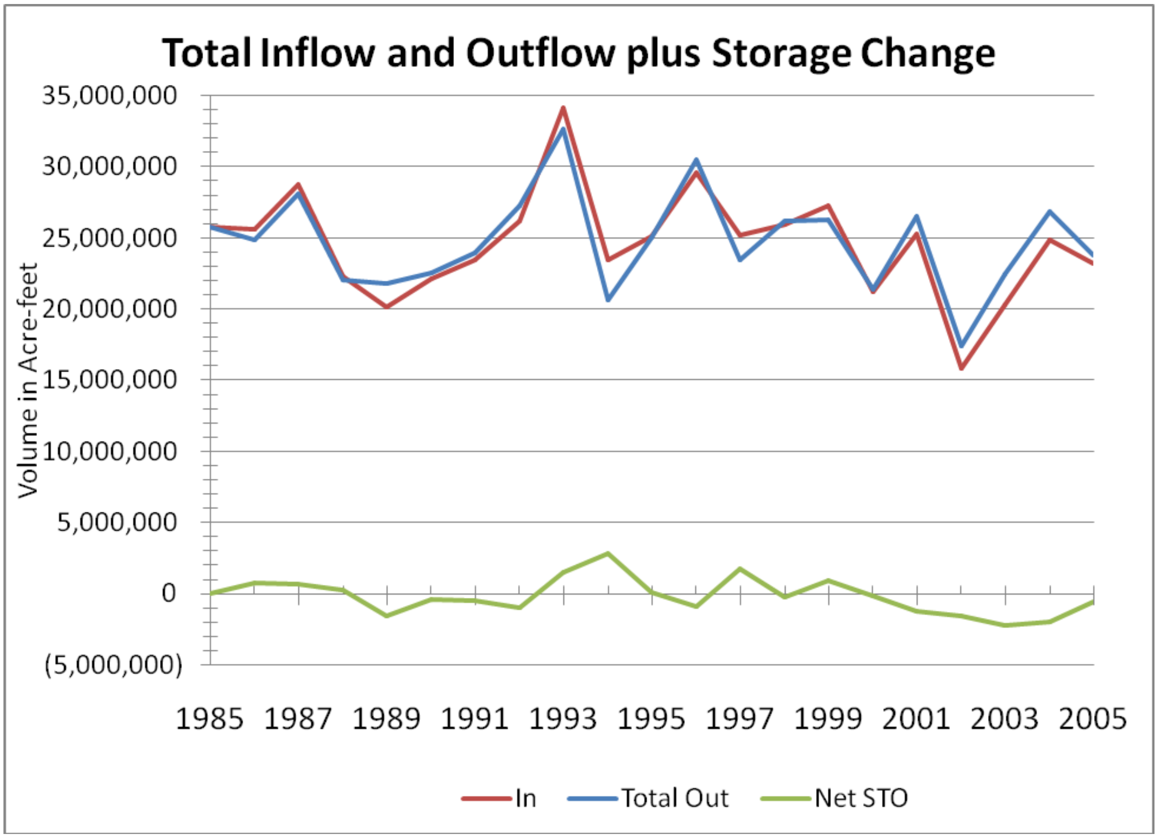
- 3c Reservoirs
- 3d The Aquifer
- 3a Soil moisture (not utilized for this analysis)
- 3b Bank storage (not utilized in this analysis)

This table shows the overall Phase I water budget derived for the model area in thousands of acre-feet.

	In			Out			
Time	Precip	Streams	GW	ET***	Streams	GW	STO Change
1985	24,094	1,614	66	23,387	2,349	78	(40)
1986	23,122	2,456	66	21,842	2,969	78	755
1987	26,974	1,722	66	25,486	2,563	78	635
1988	20,958	1,295	66	20,293	1,692	78	256
1989	19,243	860	66	20,515	1,173	78	(1,597)
1990	21,145	939	66	21,249	1,210	78	(388)
1991	22,471	961	66	22,893	1,020	78	(493)
1992	25,120	1,043	66	26,059	1,108	78	(1,016)
1993	32,881	1,206	66	29,505	3,053	78	1,517
1994	22,464	951	66	19,006	1,565	78	2,832
1995	22,720	2,351	66	22,284	2,710	78	66
1996	28,054	1,452	66	28,135	2,308	78	(949)
1997	22,766	2,364	66	20,630	2,770	78	1,718
1998	24,069	1,776	66	23,287	2,810	78	(264)
1999	24,649	2,533	66	23,283	2,942	78	945
2000	20,038	1,127	66	19,724	1,623	78	(194)
2001	24,201	1,045	66	25,008	1,476	78	(1,250)
2002	15,260	542	66	16,737	618	78	(1,565)
2003	19,721	500	66	21,925	497	78	(2,213)
2004	24,321	485	66	26,357	405	78	(1,968)
2005	22,454	665	66	23,075	637	78	(606)
Total	486,726	27,885	1,378	480,679	37,497	1,632	(3,819)
Max	32,881	2,533	66	29,505	3,053	78	2,832
Min	15,260	485	66	16,737	405	78	(2,213)
Mean	23,177	1,328	66	22,889	1,786	78	(182)

*** ET is calculated as residual.

A time series of the total water budget summary is shown in the figure below.

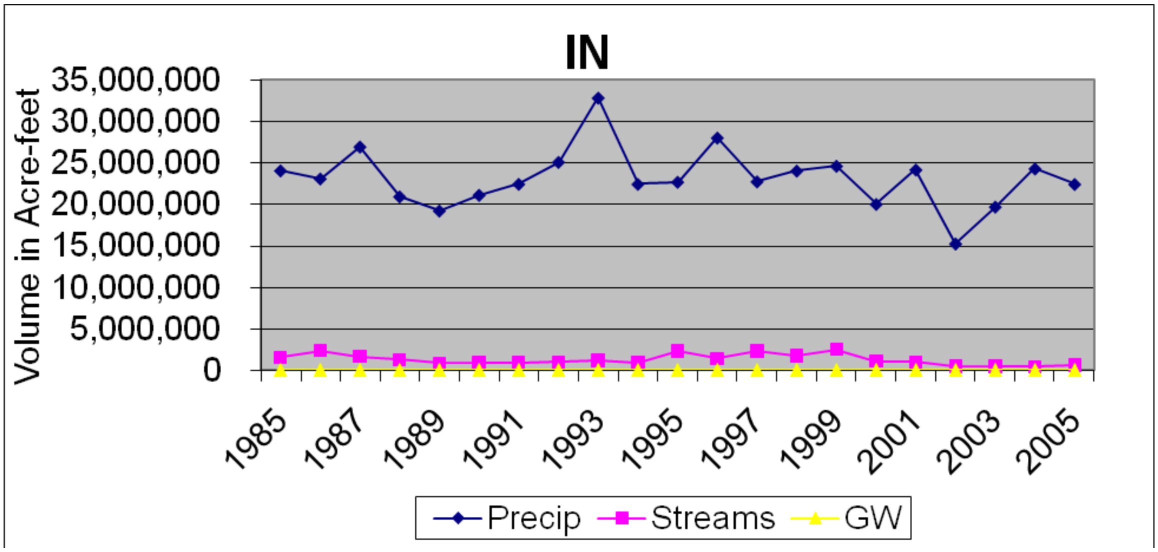


Inflow

Inflow to the model area consists of precipitation, streamflow, and groundwater inflow from up-gradient sources. It was derived from various data sources and processed to provide annual data for 1985 to 2005. A summary of model inflows are included in Table 1 and displayed as a time series in the figure below.

Table 1: Summary of COHYST 2010 model area inflows in thousands of acre-feet.

	In		
Time	Precip	Streams	GW
1985	24,213	1,614	95
1986	23,230	2,456	95
1987	27,120	1,722	95
1988	21,075	1,295	95
1989	19,333	860	95
1990	21,246	939	95
1991	22,585	961	95
1992	25,246	1,043	95
1993	33,033	1,206	95
1994	22,572	951	95
1995	22,839	2,351	95
1996	28,200	1,452	95
1997	22,880	2,364	95
1998	24,194	1,776	95
1999	24,794	2,533	95
2000	20,142	1,127	95
2001	24,324	1,045	95
2002	15,344	542	95
2003	19,818	500	95
2004	24,453	485	95
2005	22,565	472	95
Total	489,205	27,693	1,995
Max	33,033	2,533	95
Min	15,344	472	95
Mean	23,295	1,319	95



Inflow: <u>Precipitation</u>

Historical records from 41 National Weather Service (NWS) stations were used to develop the precipitation input information for this study. Daily precipitation values from January 1, 1985 through December 31, 2005 were downloaded from the High Plains Regional Climate Center (HPRCC). Annual calendar year total precipitation values were calculated for each station. These annual point values were distributed to the COHYST model grid using the standard inverse distance weighting function found within ArcGIS such that each cell was assigned an average precipitation depth for a given water year. The annual depths (which were in inches) were converted to a volume (acre-feet) per cell. The volumes for each cell across the study area were summed together to arrive at the water year volume totals presented in Table 2. Figure 1 presents a graphical view of the 1985-2005 average calendar year precipitation depth per cell (expressed in inches) across the study area.

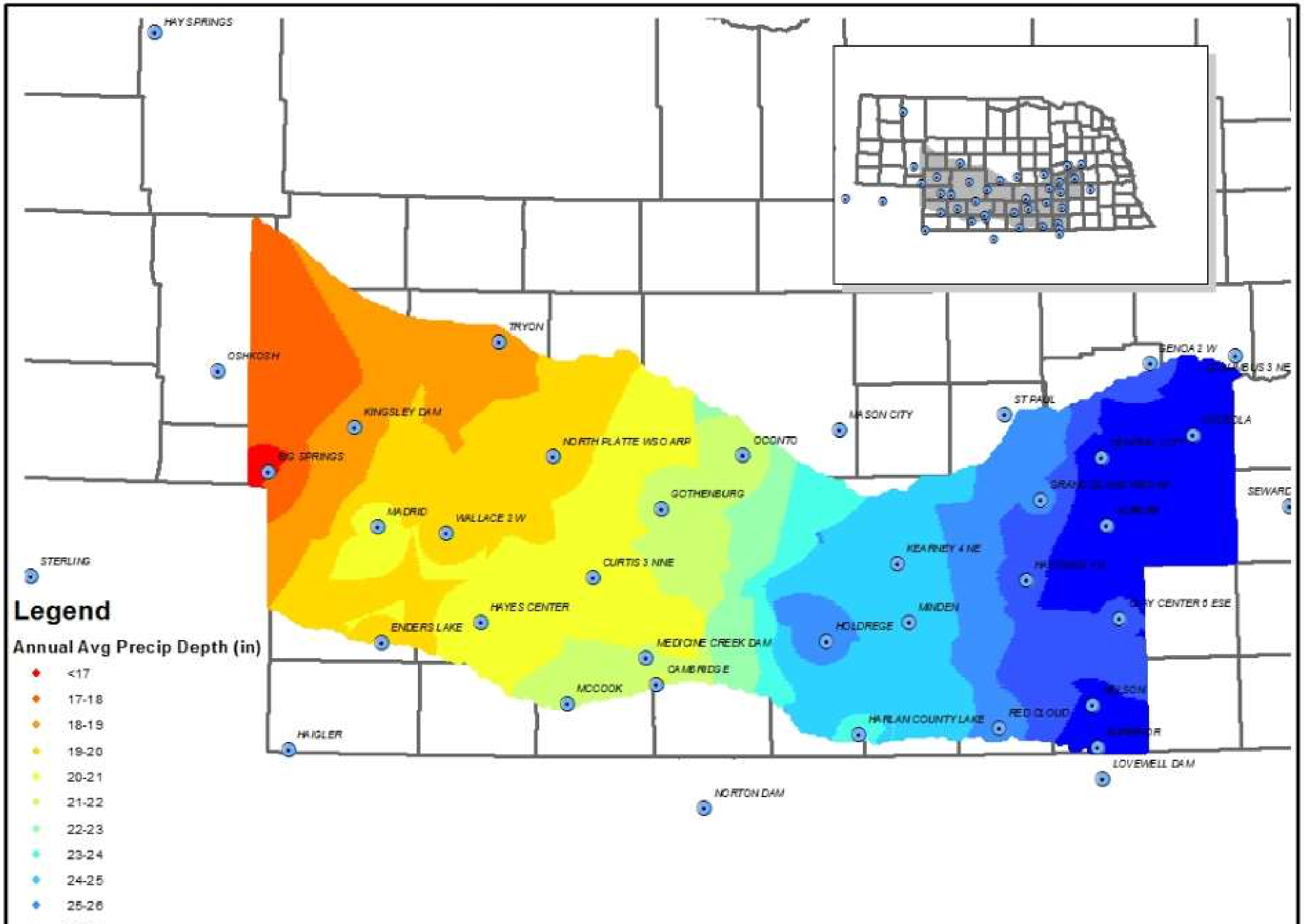


FIGURE 1 - ANNUAL AVERAGE PRECIPITATION (CALENDAR YEARS 1985-2005)

Table 2: COHYST 2010 model area Calendar year annual precipitation volume in acre-feet.

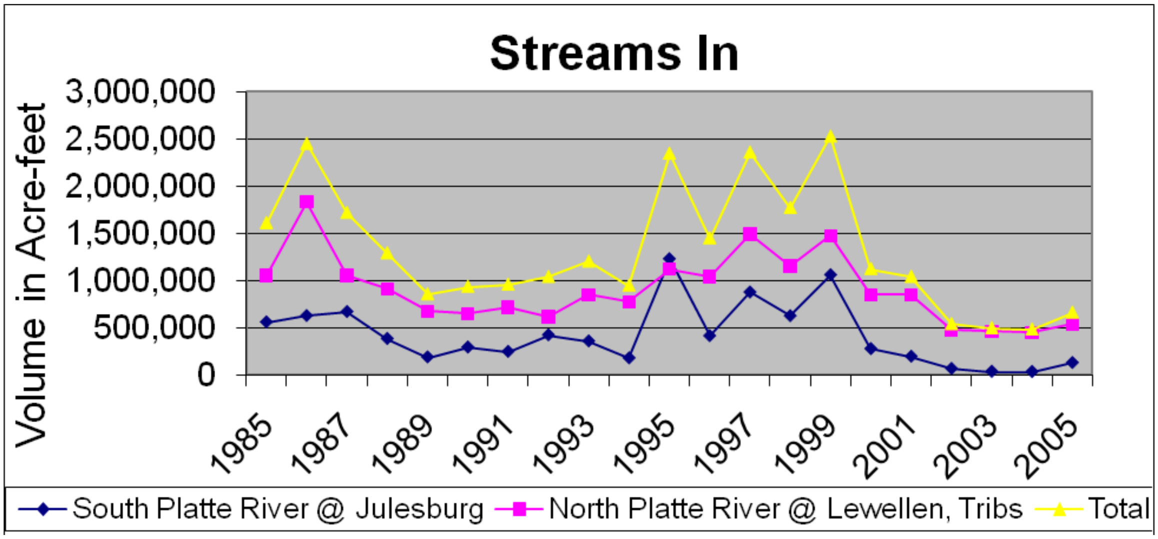
Year	Model Area Precipitation Volume (AF)
1985	24,094,290
1986	23,122,120
1987	26,973,658
1988	20,958,306
1989	19,242,638
1990	21,144,840
1991	22,471,442
1992	25,120,402
1993	32,880,580
1994	22,463,820
1995	22,720,136
1996	28,053,616
1997	22,766,244
1998	24,068,822
1999	24,648,966
2000	20,038,186
2001	24,201,436
2002	15,260,102
2003	19,720,798
2004	24,321,392
2005	22,453,836
Average	23,177,411
Total	486,725,630

Inflow: <u>Stream flow</u>

Streamflow into the COHYST 2010 area is limited to those recorded by gauges on the South Platte River at Julesburg and the North Platte River at Lewellen plus Lake McConaughy tributaries. Mean daily gaged flows were tabulated and converted to annual volumes for this exercise. Results are reported in Table 3.

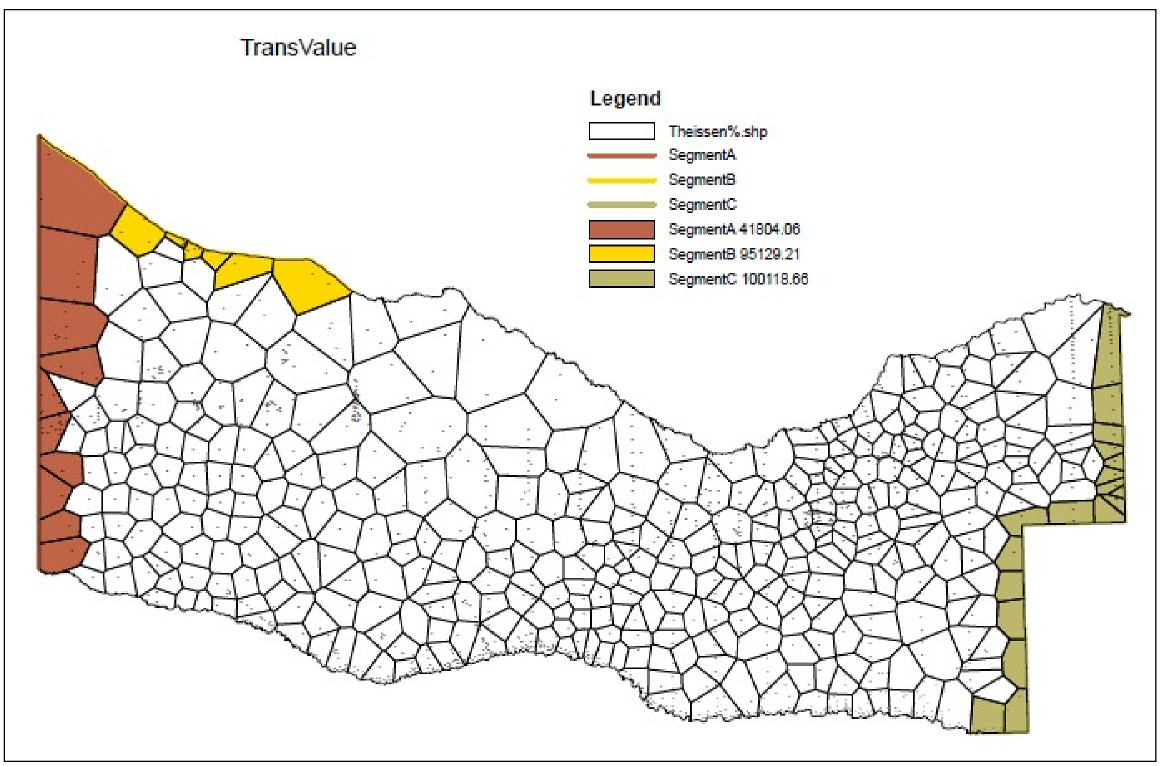
Table 3: COHYST 2010 model area stream inflow in thousands of acre-feet.

Time	South Platte River @ Julesburg	North Platte River @ Lewellen, Tribs	Total
1985	561	1,054	1,614
1986	628	1,827	2,456
1987	670	1,052	1,722
1988	385	910	1,295
1989	189	671	860
1990	293	645	939
1991	247	713	961
1992	424	619	1,043
1993	359	847	1,206
1994	179	773	951
1995	1,232	1,120	2,351
1996	414	1,038	1,452
1997	878	1,486	2,364
1998	627	1,150	1,776
1999	1,062	1,471	2,533
2000	277	850	1,127
2001	196	849	1,045
2002	67	475	542
2003	36	464	500
2004	33	451	485
2005	129	535	665
TOTAL	8,886	19,000	27,885
Max	1,232	1,827	2,533
Min	33	451	485
Mean	423	905	1,328



Inflow: <u>Groundwater</u>

Groundwater inflow will occur along the west (Segment A) and northwest (Segment B) model boundaries where other hydrologic boundaries (streams) do not occur as illustrated in the figure below. Where the model area is bounded by streams, flow is assumed to be accounted for as groundwater discharge to the streams, with no flow beneath the streams to aquifers beyond this study area. This assumption is consistent with previous studies in this area.



Inflow was estimated from the flow equation Q=-KA**dh/dl,* where Q is the calculated groundwater inflow, *dh/dl* represents the gradient, K is the hydraulic conductivity, and A is the area across which groundwater is flowing. For the purposes of groundwater flow calculation here, KA = Td; where T is transmissivity and d is the length of the boundary across which groundwater flows.

The gradient (dh/dl) was defined by identifying the locations where the topographic contours cross streams or are otherwise a reflection of the regional gradient at the model boundary. The 50-foot contour interval was divided by the distance between the points where the contours cross the steams to get the gradient between contours. These calculations were repeated for the interval corresponding to the COHYST 2010 boundary, and for two contour intervals inside the model boundary, as well as two contour intervals outside the model boundary on the North Platte River, the South Platte River, and Frenchman Creek. Not all contour interval data was usable because of lack of data, or other significant features (Lake McConaughy). Table 4 shows the contour interval information used to compute a mean for the segment. The regional gradient was estimated in the sand hill boundary (Segment B) by using contours present in the inter-dune lowlands, which are often a reasonable reflection of the water table surface. All calculations were then averaged to provide a generalized regional gradient representing the model boundary by the segments defined in the figure above. The gradient for segment B was arbitrarily divided by 5 to account for a relatively low angle between the direction of the regional gradient and the model boundary in the region.

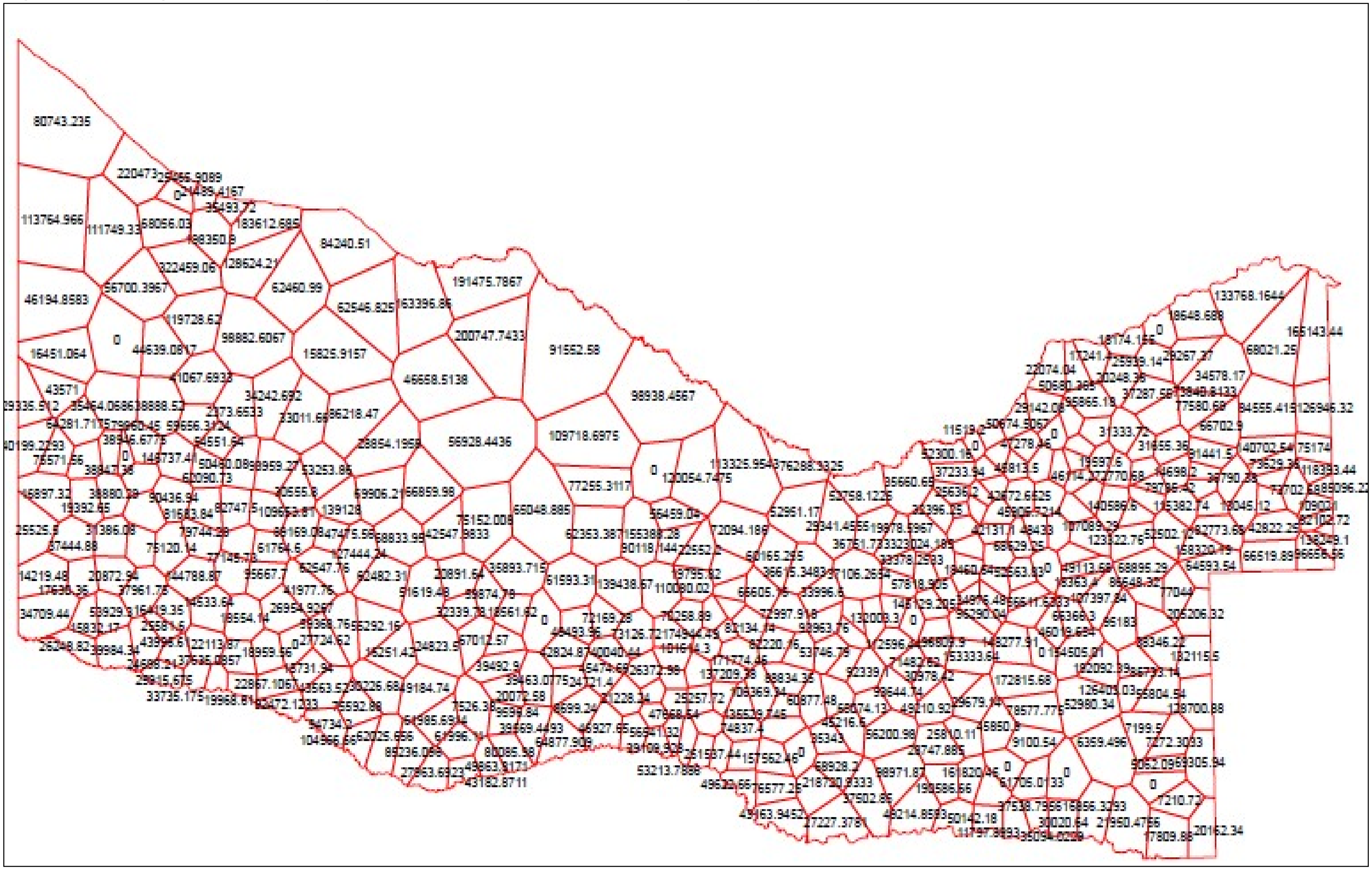
Table 4: Gradient calculation for groundwater inflow segments in the model area.

Calculated gradients along and near to COHYST 2010 area western boundary							
Segment B		Along Model Bound		@ bound	Along Model Bound		Mean
	Sandhills	0.003125	0.003846	0.004167	0.003846	0.003125	0.000724

		In 2	In 1	@ bound	Out 1	Out 2	Mean
Segment A	NP River gradient			0.001087	0.001087	0.001639	0.002447
	SP River gradient	0.002222	0.001389	0.002222			
	Frenchman Cr gradient	0.004545	0.003704				

The hydraulic conductivity (K) and area (A) terms were combined for the calculations such that KA = T*d*, where T is transmissivity from the CSD point database of test holes within the COHYST 2010 area, and *d* is the distance between the endpoints of segments A and B. Transmissivity was computed by segment as the approximate average of the polygon values along each boundary as shown in the figure below. The polygon values represent the average value of all CSD test holes within each polygon displayed in the figure above. The resulting transmissivity estimates are 95,000 gal /day /foot for the sand hills boundary (Segment B) and a value of 42,000 gal /day /foot for the western boundary (Segment A). Completing the calculation resulted in a total groundwater inflow for both boundaries of 65,619 acre-feet / year. This value was assumed to be the same for every year.

Figure of average Transmissivity values from CDS testhole data in gal /day/ foot



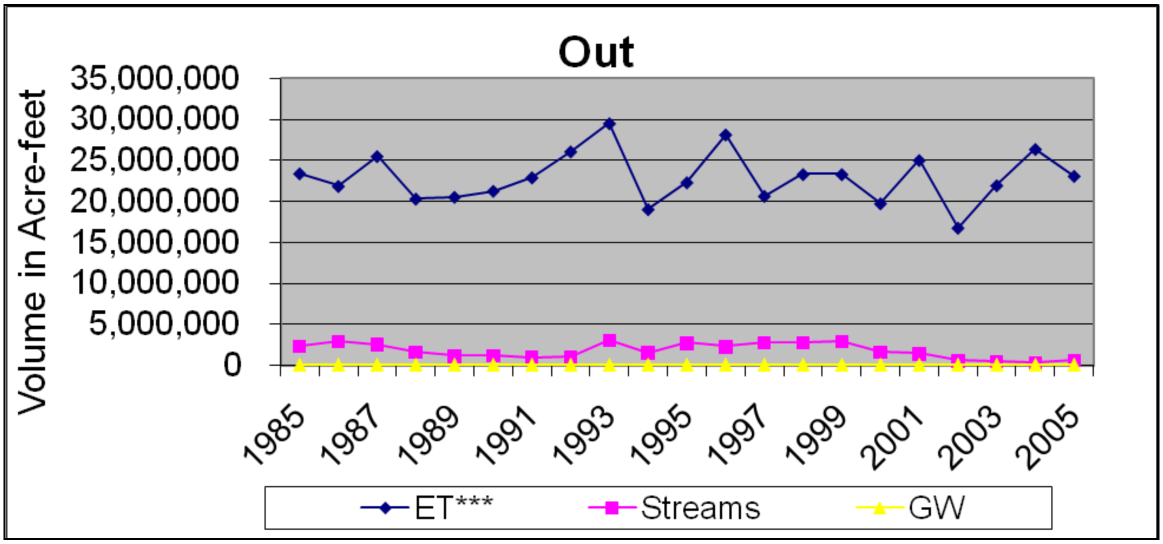
Outflow

Outflow to the model area consists of evapotranspiration, streamflow, and groundwater outflow to down-gradient sources. It was derived from various data sources and processed to provide annual calendar year data for 1985 to 2005. A summary of outflows is provided here as Table 5;

Table 5: Summary of COHYST 2010 model area outflow in thousands of acre-feet.

	Out		
Time	ET***	Streams	GW
1985	23,387	2,349	78
1986	21,842	2,969	78
1987	25,486	2,563	78
1988	20,293	1,692	78
1989	20,515	1,173	78
1990	21,249	1,210	78
1991	22,893	1,020	78
1992	26,059	1,108	78
1993	29,505	3,053	78
1994	19,006	1,565	78
1995	22,284	2,710	78
1996	28,135	2,308	78
1997	20,630	2,770	78
1998	23,287	2,810	78
1999	23,283	2,942	78
2000	19,724	1,623	78
2001	25,008	1,476	78
2002	16,737	618	78
2003	21,925	497	78
2004	26,357	405	78
2005	23,075	637	78
Total	480,679	37,497	1,632
Max	29,505	3,053	78
Min	16,737	405	78
Mean	22,889	1,786	78

*** ET is the computed balance of the inflow-outflow+Change in STO



Outflow: <u>Evapotranspiration</u>
Evapotranspiration was a calculated term in this water budget, which represents the residual of all the measurement-based terms. This is necessary since current measured data is not regionally extensive enough to provide a quality estimate of such a large budget term.

Outflow: <u>Streamflow</u>
Streamflow out of the COHYST 2010 model area consists of two main components: flows out of the model area along the mainstem of the Platte River, and flows out of other basins. The Platte River outflow is represented from the gage data recorded for the Platte River at Duncan. Flows out through other basins were calculated independently and added to the gauged flows for the Platte River at Duncan to determine the total outflow shown in table 6. Separate calculations were conducted for the Republican River, Blue River, and Loup River basins according to the following calculations:

Republican River Basin (out) = Republican River @ Hardy + Courtland Canal - Prairie Dog Creek @ Harlan - Sappa Creek @ Stamford - Driftwood Creek @ McCook - Republican River @ Stratton

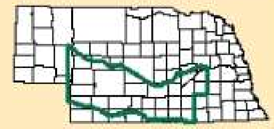
Blue River Basin (out) = Big Blue R @ Surprise + Lincoln Creek @ Seward + West Fork Big Blue R @ Dorchester + Turkey Creek @ Wilbur + Big Sandy Creek @ Alexandria + Little Blue River @ DeWeese

Loup River Basin (out) = Loup R @ Genoa + Loup R Power @ Genoa - Beaver Cr @ Genoa - North Loup @Saint Paul - Cedar R @ Fullerton - Mud Creek @ Sweetwater - Middle Loup @ Saint Paul + South Loup @ Saint Michael

The gaging locations are shown in the figure below.

COHYST 2010

Surface Water streamgage stations used in outflow estimates



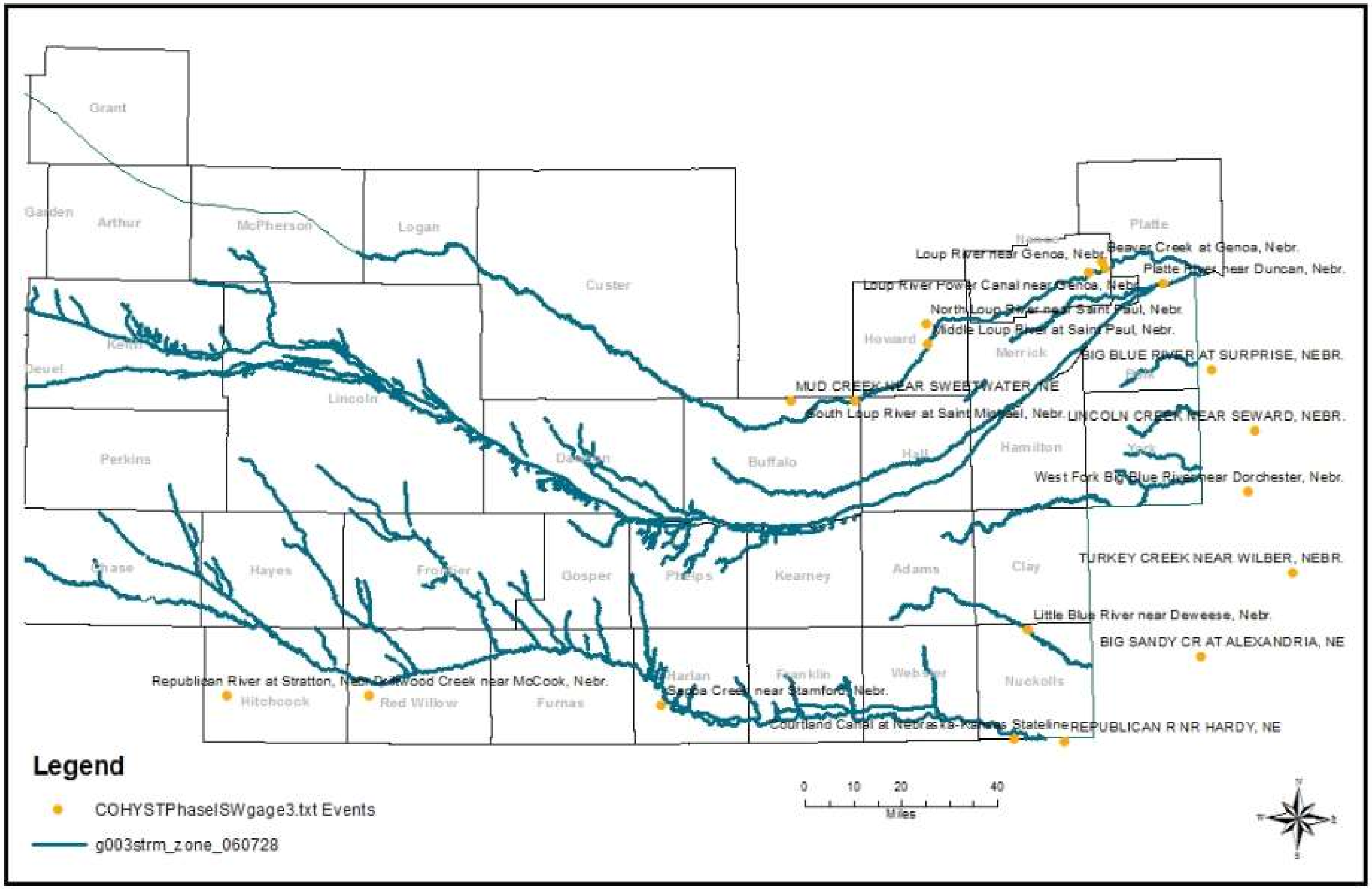
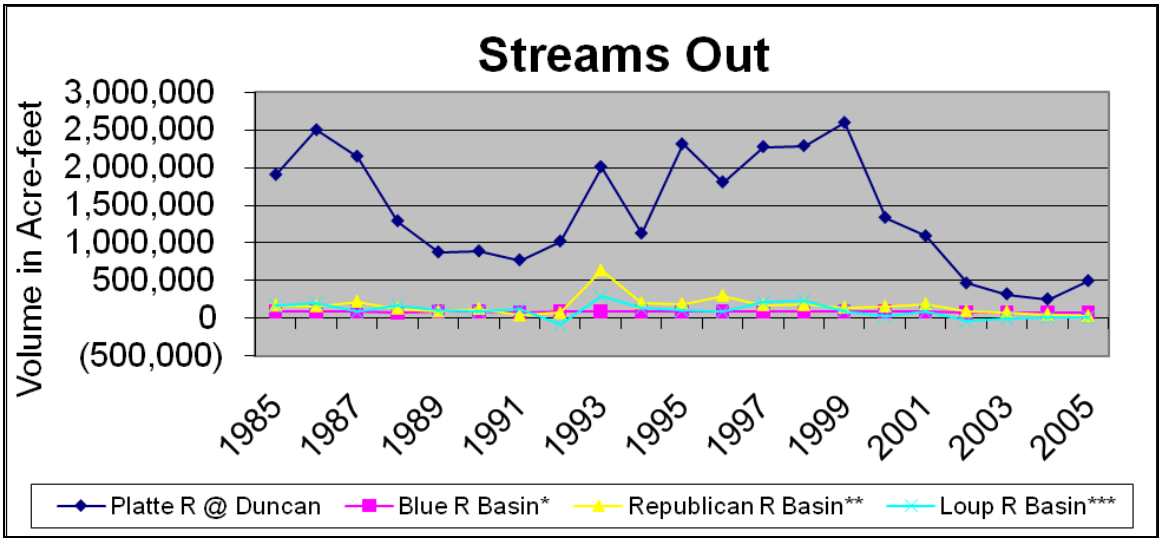


Table 6: COHYST 2010 model area stream outflow in thousands of acre-feet.

Time	Platte R @ Duncan	Blue R Basin*	Republican R Basin**	Loup R Basin***	Total
1985	1,908	95	175	171	2,349
1986	2,502	95	168	204	2,969
1987	2,151	95	229	88	2,563
1988	1,294	83	137	178	1,692
1989	880	90	95	107	1,173
1990	894	92	132	92	1,210
1991	776	80	43	121	1,020
1992	1,025	88	75	-80	1,108
1993	2,012	94	648	299	3,053
1994	1,130	95	205	135	1,565
1995	2,314	92	199	104	2,710
1996	1,810	94	309	95	2,308
1997	2,278	93	182	218	2,770
1998	2,290	96	185	239	2,810
1999	2,599	94	148	101	2,942
2000	1,340	93	163	28	1,623
2001	1,095	93	194	95	1,476
2002	468	85	98	-34	618
2003	324	83	88	2	497
2004	257	81	56	11	405
2005	500	83	35	19	637
TOTAL	29,848	1,892	3,563	2,193	37,497
Max	2,599	96	648	299	3,053
Min	257	80	35	-80	405
Mean	1,421	90	170	104	1,786



Outflow: <u>Groundwater</u>
Groundwater outflow will occur along the east (Segment C) model boundary (see map). Outflow was estimated from the flow equation Q=-KA**dh/dl,* where Q is the calculated groundwater outflow, *dh/dl* represents the gradient, K is the hydraulic conductivity, and A is the area across which groundwater is flowing in the same way as it was determined above under Inflow: Groundwater. The gradient values for five 50 contour intervals are shown in table 7. One was at the boundary, two were from inside the model In1 and In2, and two were outside the model area Out1 and Out2.

Table 7: Gradient calculation for groundwater outflow area of the model area.

	In 2	In 1	@ bound	Out 1	Out 2	Mean
Platte River	0.00151515	0.000847	0.001786	0.002083	0.000529	0.001548
Little Blue (Rising City)			0.002	0.002632	0.001136	
Big Blue River	0.00125	0.000833	0.001099	0.002174	0.000775	
W Fork Big Blue (East Bound)	0.00119048	0.0025	0.000885	0.000826	0.001282	
W Fork Big Blue (South Bound)	0.00151515	0.001111	0.001429	0.00119	0.0025	
Little Blue River	0.00507614	0.000935	0.001724	0.001471	0.001333	
Republican River	0.00147059	0.001351				

The resulting transmissivity when completing an identical calculation to that describe above in the inflow calculation was 100,000 gal/ day/ foot. Completing the calculation by the same method used to calculate inflow resulted in a total groundwater outflow for the east boundary of 77,712 acre-feet / year. This value was also assumed to be the same for every year.

Storage Change

Storage changes were estimated for the surface water system (reservoirs) and the groundwater system.

Reservoir storage data was collected for Lake McConaughy, Sutherland Reservoir, Lake Maloney, Jeffrey Reservoir, Elwood Reservoir and Johnson Lake. Differences were calculated by subtracting the end of year (December 31) storage from the subsequent year's end of year storage, resulting in the net change during that water year. A summary of the resulting values are included as Table 8.

Table 8: Surface water storage changes in acre-feet.

	Lake McConaughy	Sutherland Reservoir	Lake Maloney	Jeffrey Reservoir	Elwood Reservoir	Johnson Lake	Annual Total
1985	-42,000	4,431	165	1,015	-3,152	0	(39,541)
1986	19,600	5,455	-325	750	-2,130	2,115	25,465
1987	-96,800	-10,812	-160	-600	-360	-2,820	(111,552)
1988	-59,100	6,032	810	785	1,270	1,410	(48,793)
1989	-174,100	-3,805	-165	110	-2,936	-235	(181,131)
1990	-216,300	-6,660	-320	-385	-846	1,410	(223,101)
1991	4,300	7,816	320	110	-1,801	-235	10,510
1992	52,500	5,192	0	-1,300	-2,537	-470	53,385
1993	334,700	-7,535	165	1,350	6,036	-235	334,481
1994	-42,100	-1,731	0	0	-11,141	2,410	(52,562)
1995	79,700	1,649	-325	440	-181	-2,880	78,403
1996	-42,900	0	-320	-440	1,752	-470	(42,378)
1997	103,700	-6,066	-160	695	-387	235	98,017
1998	-219,500	4,901	320	-275	-381	0	(214,935)
1999	206,100	8,491	-160	110	2,652	2,630	219,823
2000	-477,500	-5,205	645	110	-2,455	-2,410	(486,815)
2001	17,400	-2,887	-485	-440	574	-235	13,927
2002	-354,800	-532	-640	330	-1,258	-3,290	(360,190)
2003	-144,700	7,221	-1,575	275	1,066	1,410	(136,303)
2004	-67,000	-585	780	-440	-5,923	-235	(73,403)
2005	88,067	-3,549	-5,730	205	-140	-470	78,383
							(1,058,310)

Groundwater storage change was calculated from annual water table monitoring data compiled by UNL-CSD. The data was queried to obtain spring water table elevation data for each year. It was determined that there were more than 900 data points available which were measured in the spring of every year from 1985 to 2005. Fall readings, which would be potentially a better approximation of changes during each water year, were not possible because there were less than 50 data points with readings in every year and the distribution of those points would result in an extremely coarse estimate of storage changes. The monitoring locations were more densely spaced in some areas, and some points did not have specific yield values associated with them, so 453 points containing both values were used to construct areas (Theissen polygons, see Figure below) over which storage changes were calculated. The water level change was multiplied by the specific yield and the polygon area to get a volumetric storage change for each polygon. All the changes were then summed to obtain a total for the entire model area. A summary of storage changes is included in Table 9.

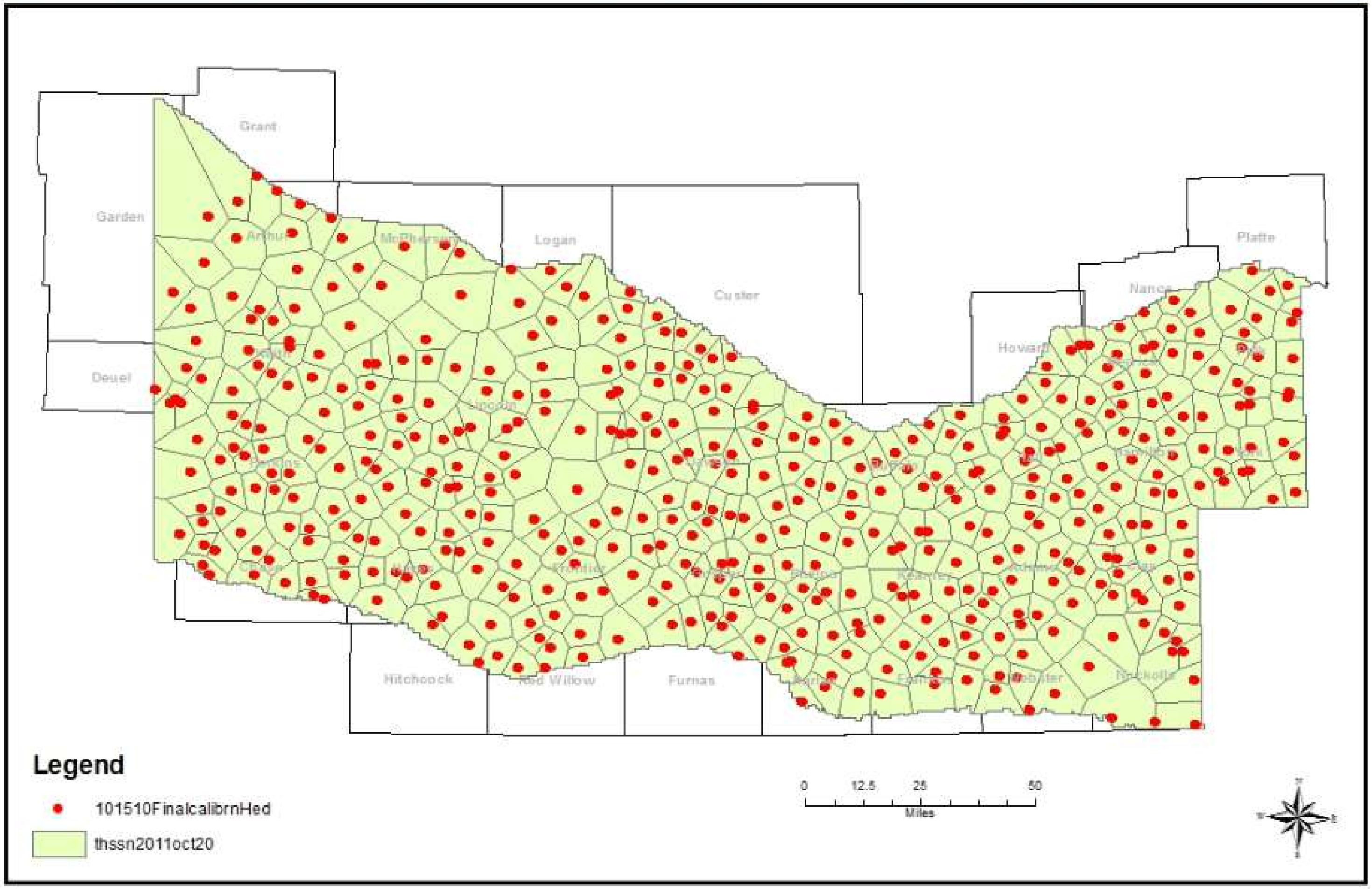
Table 9: Summary of storage changes relating to reservoirs and groundwater in acre-feet. Negative changes in storage are contained in parentheses.

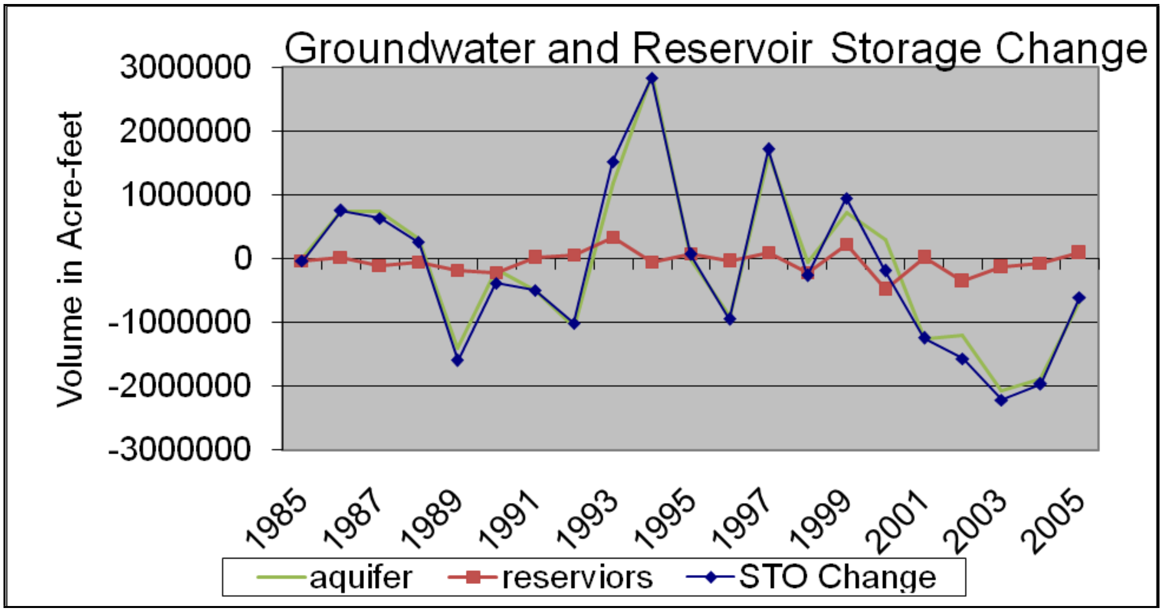
Year	Groundwater	Reservoirs	Total Storage Change
1985	0	(39,541)	(39,541)
1986	724,083	25,465	749,548
1987	744,704	(111,552)	633,152
1988	307,542	(48,793)	258,749
1989	(1,416,984)	(181,131)	(1,598,115)
1990	(168,513)	(223,101)	(391,614)
1991	(508,866)	10,510	(498,356)
1992	(1,073,935)	53,385	(1,020,550)
1993	1,186,133	334,481	1,520,614
1994	2,890,437	(52,562)	2,837,875
1995	(24,603)	78,403	53,800
1996	(910,026)	(42,378)	(952,404)
1997	1,621,078	98,017	1,719,095
1998	(52,923)	(214,935)	(267,858)
1999	725,960	219,823	945,783
2000	294,665	(486,815)	(192,150)
2001	(1,279,387)	13,927	(1,265,460)
2002	(1,213,327)	(360,190)	(1,573,517)
2003	(2,087,379)	(136,303)	(2,223,682)
2004	(1,907,930)	(73,403)	(1,981,333)
2005	(702,186)	78,383	(623,803)
Total	(2,851,458)	(1,058,310)	(3,909,768)

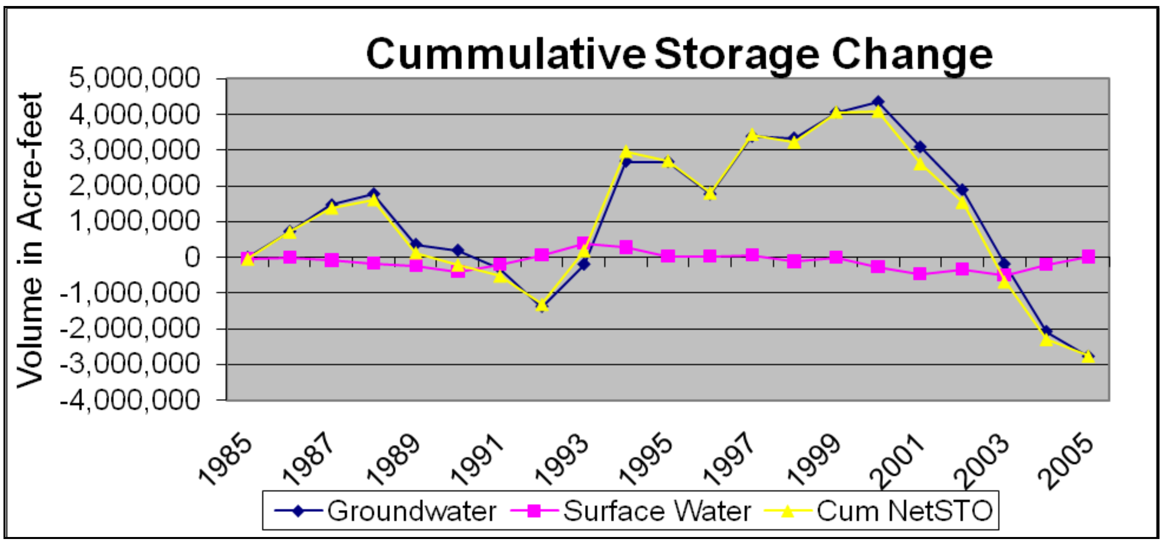
COHYST 2010

2010

Observation Wells and Polygon areas used for Aquifer Storage change







Data compiled here will be used to guide future activities according to the COHYST 2010 workplan that is currently in development. The data compiled here will also provide external constraints on the Phase II models currently under development as part of the COHYST 2010 workplan. The principal function of the models will be to define internal quantities of water moving from one part of the system to another, and to provide a means of calibration to total measured fluxes, reducing uncertainties associated with techniques used to estimate the component quantification of the model fluxes (such as baseflow separation). This is possible by combining baseflow from the groundwater component and surface flow from the routing component to compare with total measured flow from the whole system. The annual variability shown here gives an indication of the dynamic nature of the history that will be produced by the models.