North Fork of the Red River System Model Naturalization Update

Oklahoma Water Resources Board

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Submitted To:

Oklahoma Water Resources Board
Elise Sherrod, Hydrologist
Water Rights Administration Division
3800 N Classen Blvd
Oklahoma City, OK 73118

Submitted By:

Lynker Technologies, LLC
Graeme Aggett, Principal and
Chief Scientist
3002 Bluff Street, Suite 101
Boulder, Colorado 80301

Boulder, Colorado **DC—Metro** **Pacific—Oahu**

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1. Introduction

1.1. Background

This report describes the development of a water allocation model of the North Fork of the Red River in southwestern Oklahoma for the Oklahoma Water Resources Board (OWRB). The North Fork of the Red River Model (NFRR Model) represents the stream flows, reservoirs and surface water and groundwater uses within the North Fork of the Red River System. It simulates the allocation of water to water rights and simulates the operation of reservoirs according to historical, current or expected water use and operating rules. The model analyses show the extent to which water rights are satisfied under a number of different scenarios and will be used to inform the OWRB as it considers water availability and water management options for the river system. Additionally, the updated Red River model will be used for comparison against a Firm Yield analysis being conducted by the US Bureau of Reclamation (USBR) for Tom Steed and Lugert Altus reservoirs. Lynker worked closely with OWRB and the USBR to make model changes including several new future scenarios to evaluate reservoir firm yield.

The NFRR model was originally developed by AMEC in 2012 for the OWRB to provide guidance in water supply planning. A fully implemented model was delivered to OWRB in 2016 including naturalized flows, surface and groundwater permits, reservoirs and a number of planning scenarios. In 2017 Lynker Technologies was hired to make a number of changes to the model naturalization and scenarios.

This introduction describes the model domain, the objectives of the model and the general approach used by the model in simulating the river system. Subsequent sections describe the facilities in the system, the available water use data and the available streamflow data, the assumptions that were adopted for the model, the process by which streamflows were naturalized and subsequently updated, the operating rules and controls for water use and reservoir operations, and the model scenarios that have been developed.

1.2. Model Objectives

The OWRB uses water allocation models to help it estimate water availability for planning purposes and when evaluating applications for new water rights permits. As such, a principal objective of the model is that it provides a reliable estimate of the overall water budget at each monthly time step. Limitations on the accuracy of the monthly water budget arise primarily from limitations in the data, particularly regarding diversions and consumptive use, and the degree to which alluvial groundwater use may impact streamflows. Additional uncertainty arises from the obvious difficulty of predicting future water use practices of existing permit holders, and predicting the level of development of water use under Oklahoma’s set-aside for domestic use (which essentially provides a super-priority for self-supplied use by rural homes). The model is also projecting future conditions (year 2060) based on a range of future ground- and surface water development scenarios.

Secondary objectives of the model relate to the ability of OWRB staff to use it to conduct their required analyses.

1.3. Model Spatial and Temporal Domain

The North Fork of the Red River watershed is shown in Figure 1. It comprises four 8-digit hydrologic units, the Elm Fork (11120304), Lower Salt Fork (11120202), Lower North Fork (11120303) and Middle North Fork (11120302). A large portion of the upper watersheds of the Elm Fork, Lower Salt Fork and

Middle North Fork of the Red River are located within Texas, and were not modeled in the same manner as were the regions located within Oklahoma. Further details regarding the modeling of individual basins within the North Fork of the Red River System are provided in Section 6 of this report. The North Fork of the Red River System contains 93 12-digit hydrologic units that fall entirely or partially within Oklahoma, 112 active Oklahoma surface water permits, 732 active Oklahoma groundwater permits, the Lugert-Altus Irrigation District (LAID) and two major reservoirs. The two major reservoirs actively modeled include Lake Altus and Tom Steed Reservoir.

The model is developed around 12-digit “hydrologic units” (HUs), developed by the U.S. Geological Survey (USGS) to delineate sub-regions within larger watersheds. The HUs are drawn around hydrologic boundaries. Each HU is designated by a numerical code which is referred to as a “hydrologic unit code” (HUC). The level of spatial detail (12-digit HUs) and temporal detail (monthly time step) were adopted to allow sufficient detail for the types of analyses that OWRB expects to undertake without incurring undue development and maintenance costs. The HUC system is hierarchical, meaning that the entire watershed is under one 4-digit HUC (i.e. 0730). In Figure 1, 8-digit HUC watersheds are colored, and inside of each are the smaller HUC 12 basins.

The model simulation period extends from January 1950 through December 2012. The model uses a monthly time step. The use of a monthly time step allows for the evaluation of seasonal or shorter administration approaches while also allowing for the use of readily available data without the need to represent routing.

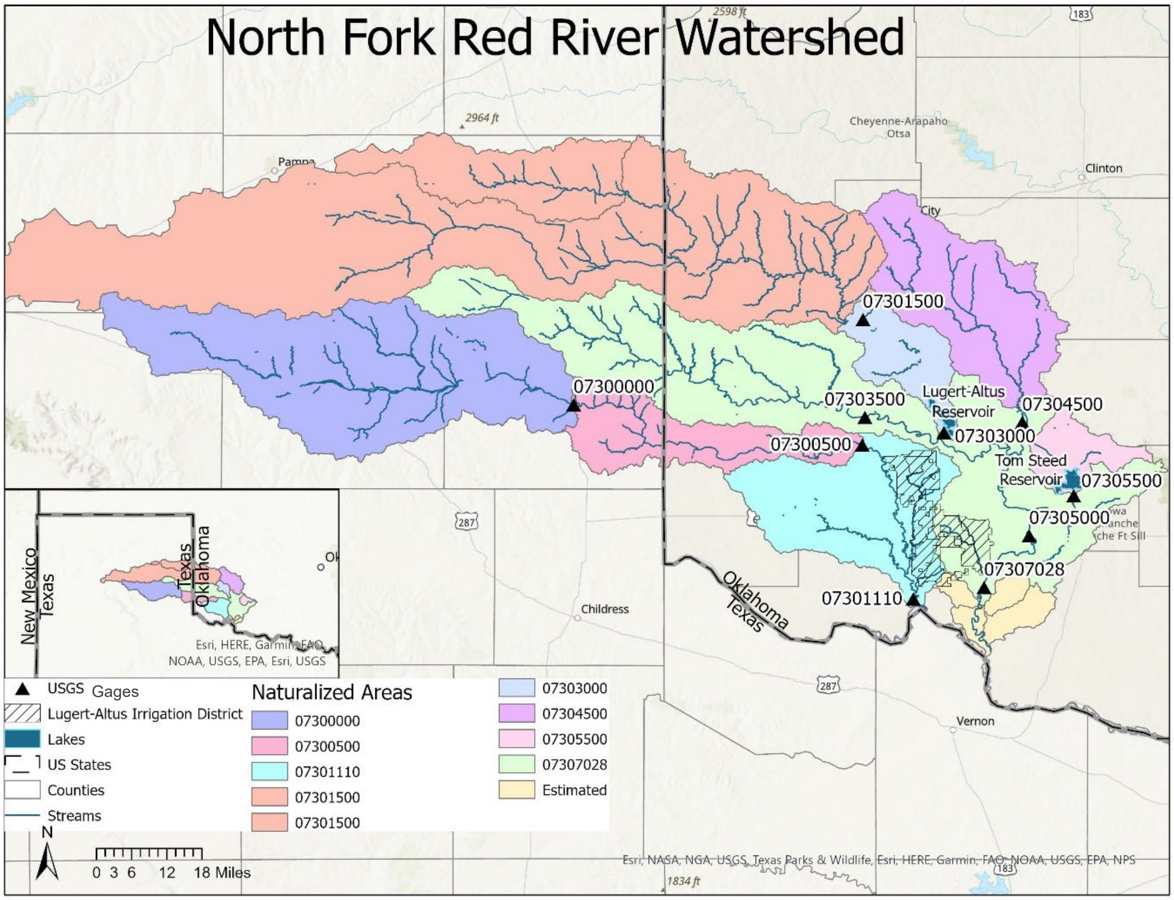

Figure 1. North Fork of the Red River model domain

2. Summary of Modeling Approach

The NFRR Model is based on a time series of naturalized flows, upon which a specified set of system operations is imposed. These operations include priority diversions to Oklahoma water rights permits and operation of reservoirs and canals. Several simulation scenarios have been developed and can be selected by the user. These scenarios may be modified and new scenarios created. This section provides a brief overview of the modeling approach and of the process of developing the model. The important elements of the model and their development are described in more detail in subsequent sections.

2.1. Naturalized flows

The NFRR Model uses as input a set of time series of “naturalized flows”, and then superimposes on those flows the effect of water management operations such as diversions, return flows and reservoir storage and releases. Naturalized flows represent the conditions that would have occurred without the effect of human activities on the stream. They are developed by adjusting gaged flows to remove the impact of human activities. For example, reservoir operations are “backed out” of the gage flow by adding to the gaged flow the observed change in storage (where an increase in storage is a positive value) and the amount of evaporation from the reservoir surface. (The process of naturalization is described in more detail in Section 7.)

Naturalized flows are used because the objective of the model is to simulate future river conditions given certain assumptions about water management practices and future hydrology. However, the past pattern of development and past management practices will not repeat themselves, which is why flows must be naturalized to provide a “clean slate” for simulation of future management practices. For example, when a water use begins or changes during the historical period, that change is embedded in observed streamflows, so studies intended to understand future conditions must adjust for that change. The most straightforward and flexible way to do that is to base the simulation on naturalized flows. Hydrologic conditions may also change. The conventional approach to modeling water resources systems has been to assume that the magnitude, frequency and arrival sequence of future flows will be similar to those of the past. Under this assumption, the historical sequence of flows has been used to represent expected future conditions. The growing scientific understanding of the potential effects of climate change has called this assumption into question. Techniques to represent projected conditions in a water resource system in the face of changed climate require adjustment to naturalized flows (and consumptive uses), generally using hydrologic models; observed flows cannot be adjusted directly to reflect the effect of future climate conditions. Accordingly, the use of naturalized flows provides the soundest and most flexible basis for simulation of a water resources system.

2.2. Simulation of Operations

Simulation of operations takes place in two principal phases. The first phase is simulation of diversion of water under Oklahoma water rights permits. In this phase, operations are based solely on the priority of the permitted diversion, including both direct diversions to use and reservoir storage (by either on-channel or off-channel reservoirs). The second phase simulates non-priority operations, such as releases from a reservoir for contracted uses, and consists of one or more “operational steps”. In some cases, such as the NFRR Model, it is possible to simulate reservoir deliveries without using the operational steps of the second phase. More detail about the simulation of operations and the structure of the NFRR Model can be found in Section 8.

2.3. CRAM Simulation Framework

The NFRR Model has been developed in Lynker’s Excel Central Resources Allocation Model (CRAM) network modeling system. CRAM is a simulation framework adapted for the use in water resources applications. CRAM has the capability to simulate efficiently the priority-based allocation of water to water rights, and to simulate the operation of facilities, such as reservoirs, using operating rules.

CRAM uses a "pure network" algorithm to simulate a water budget for each time step. Like linear programming, pure network flow algorithms solve for a set of dependent variables that provide for the maximum or minimum value of a system-wide objective function subject to a set of constraints. In network flow programming, the problem is stated as a directed graph constructed of a set of arcs, connected by nodes. The dependent variable is the "flow" through the arcs, which are "capacitated" with constraints representing the upper and lower bounds of flow. Arcs are "directed", that is they have a "from" node and a "to" node, though this does not necessarily limit flows to one direction, as negative lower bounds on flow are allowed. Additional constraints are continuity at the nodes. The objective function is the system-wide "cost", of all flows in the system. Costs are assigned to each arc and are applied to each unit of flow in the arc. Networks amenable to solution by pure network formulations must be "circulating". This means that there can be no dead-end arcs in the system and that no flows enter or leave the network. This fundamental aspect of pure networks means that the solution algorithm guarantees mass balance. River networks are tree-shaped and are converted to circulating networks by the addition of hidden arcs. For example, all of the water diverted for beneficial use is “recirculated” to inflows.

Application of pure network algorithms to water resources problems requires that the real-world water resources system, its operating rules and its constraints be expressed in a form amenable to solution by the network. CRAM provides code that allows the user to use fairly high-level constructs (e.g. inflows, demands, reservoirs) to formulate a water resources problem, and additional code that translates that high-level formulation into a form that can be solved by the network algorithm.

In formulating a network, arcs are used to represent river reaches, canals and other elements. Arc capacities are used to represent real-world facility or reach capacities or diversion, demand or storage targets. Arc costs are mapped to water rights or system operation priorities. Note that while network flow algorithms are optimization algorithms, CRAM does not use the algorithm to prescribe an optimal set of operations. Rather, CRAM uses the optimization capabilities of the network flow algorithms to simulate water rights or operations that are based on priorities.

In CRAM a discrete network (which may include iterative solutions) is used to simulate conditions in a single time step. The system state variables (i.e., reservoir storage, return flows from previous time steps) are used at the beginning of each time step to initialize the network.

A fundamental assumption of the network approach is that flows within a single network and, thus, a single time step in our application, are in equilibrium. In practical terms this means that routing is not considered and all flows within a single time step are available at all points in the network. This means that if the length of the time step used to solve a system is less than the longest travel time between any two points in the system some errors will be introduced in the solution. In real-world systems, the presence of reservoirs often serves to minimize the significance of these errors. AMEC has applied network flow solutions to systems with simulation time steps as short as one day.

CRAM embeds a network-flow-algorithm-based simulation system in Microsoft® Excel. The network solver and simulation codes are provided in a Dynamic Link Library (DLL). Code that manages model simulation steps and most of the input and output is written in VBA, the scripting language native to Excel. This provides for a simulation environment where the model inputs and outputs can be managed in a familiar spreadsheet program. Code to simulate special operations can be written in VBA.

CRAM provides for the following standard network elements (not all of these elements have been used in the NFRR Model):

Links—Links are general-purpose elements most often used to simulate river or canal reaches. A link is represented in the low-level network by a single arc. By default, the upper limit on flow is set to an "infinite" value, the lower limit on flow is set to zero and the cost is set to zero. These link parameters can also be set by input data or code to simulate part or all of a variety of system features. The distinction between the term arc and link is used to maintain the conceptual difference between the low-level representation of the network actually solved by the algorithm and the higher-level representation that is accessible to the modeler. In CRAM a Link object may not be connected to or from a mass-balance node.

Inflows—An inflow is represented in the low-level network by a single arc. The upper and lower limits on flow are equal and are set to the known value of inflow, and the cost is set to zero. Most often, the inflows used in a model are known completely before the simulation begins. In some cases, such as gains, inflows are calculated or adjusted dynamically within the model. If the flow is unable to enter the network and maintain mass balance at all of the nodes in the network the model will declare the network to be infeasible. In CRAM an Inflow object may not be connected to a mass-balance node.

Demands—A demand is represented in the network algorithm by a single arc. The upper limit on flow is set to a value that represents the target delivery, the lower limit is set to zero and the cost is set to a value that maps to the priority scheme used in the model. Demands are generally known before the start of a simulation but may be set dynamically. In CRAM a Demand object may not be connected from a mass-balance node.

Decree—A decree is represented in the low-level network by a single arc. By default, the upper limit on flow is set to an "infinite" value, the lower limit on flow is set o zero and the cost is set to zero. Decree elements have two additional properties. The first is called an Capacity and the second is an Admin Day. The annual limit is used to limit the amount of flow which can pass through the decree element in one year. The Admin Day is used to reset the tracked flow amount through the decree back to zero. This element can be used to represent the limits on total annual diversion to canals, to set annual filling limits on water rights into reservoirs, or to limit supplemental water to an annual limit without having to determine in which months it might be needed. Like a Link a Decree object may not be connected to or from a mass-balance node.

Return flows—Return flows represent water that leaves the surface water system at one location but then returns at another location and possibly another time. This element is designed to represent the un-consumed fraction of water applied to a farm or field that returns back to the river. Water can be consumed in irrigation operations by evapotranspiration or percolation to deep, non-tributary groundwater. When simulating an irrigation operation in CRAM, the total application of water to a farm is represented by a demand arc, and the un-consumed portion by a return flow arc which is a function of the demand. Return flows are allocated to one or more future time steps by a normalized table of "lag factors" that define what fraction of the un-consumed water in a time step accrues in each subsequent time step. To calculate the return flow in any time step all the contributions from previous time steps are summed.

Fixed Gains and Losses—Fixed gains are represented with inflow arcs. Fixed losses are represented by demands that are preset to certain values. These are generally known at the start of a time step.

Flow-dependent losses—These are simulated using a demand with the amount of the demand set dynamically by code.

Reservoirs—Reservoirs are simulated using a multi-arc construction to represent the various aspects of a surface water storage system.

The storage arc (or arcs) contains the information describing inlet capacity of the reservoir and the priorities and limits of storage water rights that allow the reservoir to divert water into storage.

The basic reservoir storage arc is a unique network arc in that it allows water to be lost to evaporation. This arc also contains information related to reservoir capacity, reservoir evaporation rates, and the reservoir's volume-area curve.

The carry-over arc(s) represent water left in storage after previous time steps and available in the current time step. It also allows multiple entities to store water in a single reservoir via arcs representing individual storage accounts. The carry-over arc(s) can have priorities assigned that allow certain pools of water to be released before others or that allow releases only when the priority of a downstream demand reaches a prescribed threshold.

More detail about CRAM and its operation is provided in the *North Fork Red River System Model User's Manual* and the electronic help files linked to the software. Model elements are illustrated and described in Appendix 2.

2.4. Model Development Steps

Generally, model development proceeds according to the following steps:

- *Collect data representing the basin*. This includes spatial data describing the basin, the stream network, the location of permits and reservoirs; historical water use data; historical reservoir operations data; and historical streamflow data.
- *Develop the model network*. A model network is constructed based on the spatial data. The inflow structure is based on 12-digit USGS hydrologic units (HUs). Water uses are located according to permit information. Reservoir capacities and area-volume-elevation curves are set.
- *Develop water use inputs*. Water use data are refined to fill in missing data and establish seasonal patterns of use based on type of use and reported annual use.
- *Develop operating rules*. Based on historical reservoir operations, operating rules are inferred for the modeled reservoirs. Priorities are assigned to water use based on permit date.
- *Naturalize the flows*. Using historical water use data (as refined), historical reservoir operating rules, reservoir area-volume-elevation curves and estimates of historical evaporation rates, historical gaged streamflows are adjusted to remove the influence of modeled water use and operations.
- *Develop modeling scenarios*. Develop model scenarios for verification and for simulation of future conditions.
- *Verify model.* The model is verified by comparing the results of a run using historical water use and reservoir operating rules against observed gaged streamflows.

The model is set up to operate with five different model scenarios as outlined in Table 1. Model naturalization was validated through use of the constrained historic scenario. The naturalization process is outlined in Section 7.

Table 1: Summary of Model Scenarios

Scenario Num	Name	Purpose	Description
0	Constrained Historic Scenario	Validation of flow naturalization	Demands operate based on historic uses. Missing demand values are filled with average historical demands (water user will have no demand for years prior to date of permit issue). Reservoir targets are actual historic reservoir contents.
1	Normal Historic Scenario	Baseline for all other scenarios	Demands operate based on historic uses. Missing demand values are filled with average historical demands (water user will have no demand for years prior to date of permit issue). Reservoir targets are average monthly historic contents.
2	Full Permit Scenario	Highest possible use case for permitted uses	Permitted amount used for all water users for all simulation years
3	Current Use Scenario	Current use case for permitted uses	Average reported use for all water users for all years
4	Full Permit Scenario 2	Possible use case for users determined by location along river	Water allocated from upstream to downstream.

The Nash-Sutcliffe Efficiency values were calculated for the “normal” historical scenario (Scenario 1) and for a “constrained” historical scenario (Scenario 0). In the normal scenario, reservoirs and canal diversions were simulated using full filling targets for reservoirs without any further constraints. The “normal” scenario tests the skill of the generalized reservoir targets. It shows wildly different results at the gages immediately downstream of the diversion and delivery locations of the Bretch and LAID canals since it was not possible to infer accurately the rules governing their historic operations, and because operations changed over time in the system. In the “constrained” historical scenario, reservoir contents and canal diversions were constrained to equal observed historical contents. This validation scenario eliminates error introduced by generalizing reservoir and diversion operating rules and tests the validity of the flow naturalization and disaggregation.

3. Facility data

Several major pieces facilities are simulated in the NFRR Model, including Lake Altus, Tom Steed Reservoir, the Altus Main Canal, the Lugert-Altus Irrigation District canals, the Bretch Diversion Canal that supplies Tom Steed Reservoir, permitted surface water diversions and permitted wells. Some data was available for all listed pieces of infrastructure, but in some cases the data were incomplete.

A summary of the reservoirs modeled in the NFRR Model is provided in Table 2. Reservoir storage records were obtained from the United States Bureau of Reclamation (USBR) for the entire period of record for each reservoir (1947-2017 for Lake Altus and 1975-2017 for Tom Steed Reservoir). Pan evaporation records for each reservoir site were obtained from the United States Army Corps of Engineers (USACE) for the entire period of record for each reservoir. For the post-reservoir-construction model period, reservoir evaporation losses were calculated by multiplying monthly pan evaporation measurements by a free surface coefficient factor of 0.7 to obtain a monthly net evaporation rate for the reservoir. The monthly net evaporation rate was then multiplied by the reservoir surface area to obtain monthly evaporative losses out of Lugert-Altus and Tom Steed Reservoirs. For the pre-reservoir-construction model period, evaporation was calculated through a combination of linear regression with measured evaporation at nearby weather stations and/or by adjusting post-construction evaporation with pre-construction recorded precipitation.

Table 2: Summary of Modeled Reservoirs

Reservoir Name	Impoundment Date	Start of Data Record
Lake Altus	November 1947 *(a)*	November 1947
Tom Steed Reservoir	June 1975 *(b)*	June 1975

(a): Average annual reservoir storage from 1947 to 2017.
(b): Average reservoir storage from 1975 to 2017.

Other small reservoirs exist in the North Fork of the Red River Watershed, but no data was available for these locations. A more detailed description of the simulated reservoirs is provided in the following sections.

3.1. Lake Altus

Lake Altus is located on the mainstem of the North Fork of the Red River and was impounded in November 1947, which is also when data records began (USBR, 2013). The lake is within the naturalized watershed of stream gage 07303000, North Fork Red River below Altus Dam near Lugert, OK. The average storage, the average evaporation rate and the estimated evaporation volume are provided in Table 3. Lake Altus and the Lugert-Altus Irrigation District are shown in Figure 2.

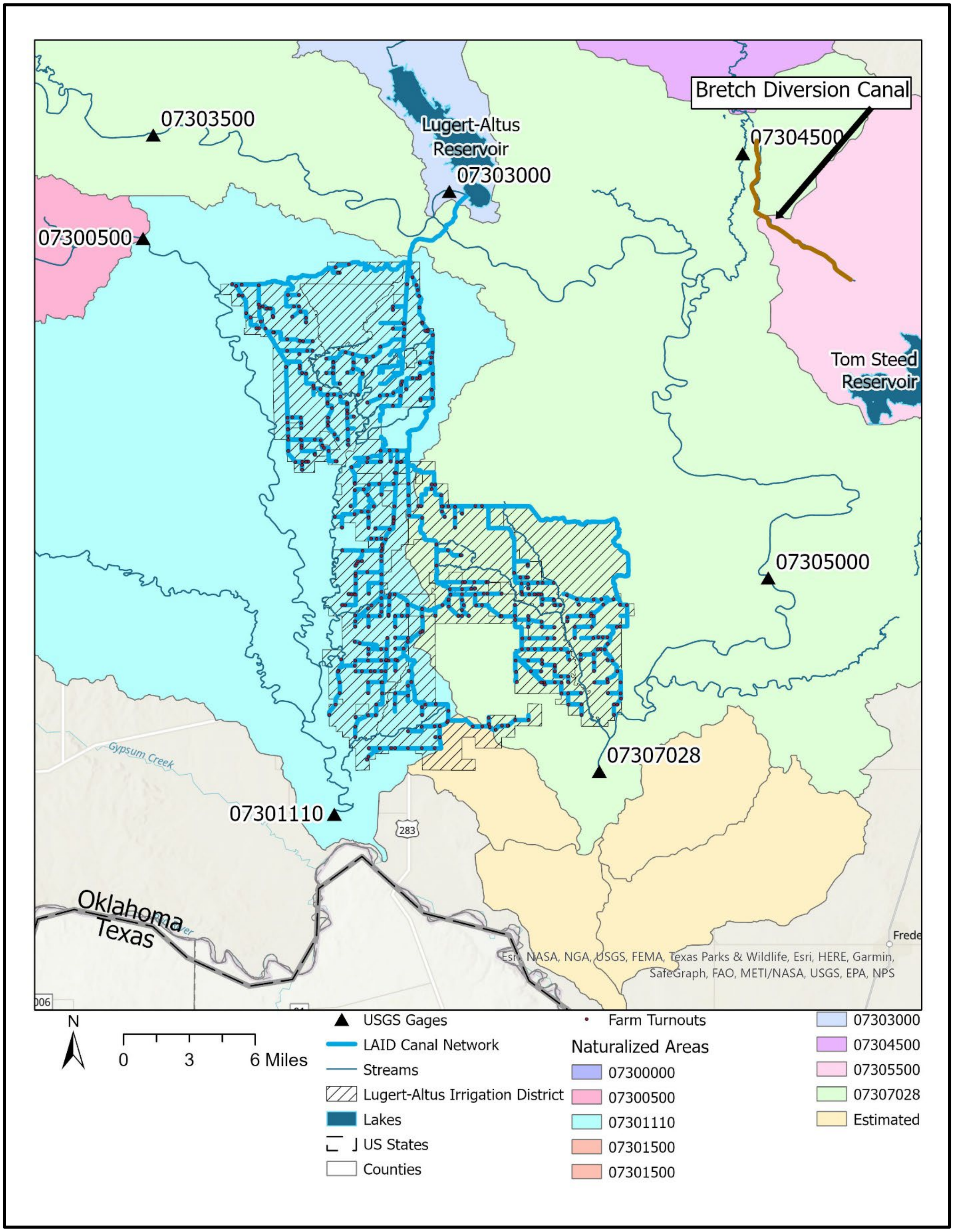

Figure 2 : Diagram of Lake Altus and Lugert-Altus Irrigation District

Table 3: Monthly Average Values for Lake Altus

Month	Average Storage (acre-feet)	Average Evaporation Rate (foot/month)	Average Evaporation Volume (acre-feet)
January	73,500	0.25	1,100
February	77,500	0.29	1,400
March	81,400	0.48	2,300
April	86,300	0.67	3,300
May	99,100	0.77	4,000
June	101,600	0.92	5,000
July	82,400	1.07	5,600
August	60,400	0.99	4,500
September	59,000	0.69	2,800
October	63,500	0.54	2,200
November	65,200	0.32	1,400
December	68,500	0.27	1,100

3.2. Altus Main Canal and Lugert-Altus Irrigation District

The largest water demand in the North Fork of the Red River system is the Lugert Altus Irrigation District (LAID) with an average annual permitted historical diversion amount of 54,244 Acre-ft. The LAID receives its water from diversions down the Altus Main Canal, which takes water directly from Lake Altus.

The areal bounds of the LAID and diversions on the Main Canal were provided by USBR. Surface water permit amounts and the locations of permits within the LAID were provided by the OWRB.

3.3. Tom Steed Reservoir

Tom Steed Reservoir is located on West Otter Creek and is approximately 20 miles southeast of Lake Altus. Tom Steed Reservoir Lake was impounded in July 1975, when the data record began (USBR 2010). The lake is within the naturalized watershed of stream gage 07305500, West Otter Creek at Snyder Lake near Mt Park, OK, though approximately 20% of its annual water supply is diverted down the Bretch Canal from the watershed of stream gage 07304500; Figure 3 shows a detail of Tom Steed Reservoir and the Bretch Canal.

Average monthly storage, the average evaporation rate and the average evaporation volume for Tom Steed Reservoir are shown in Table 4.

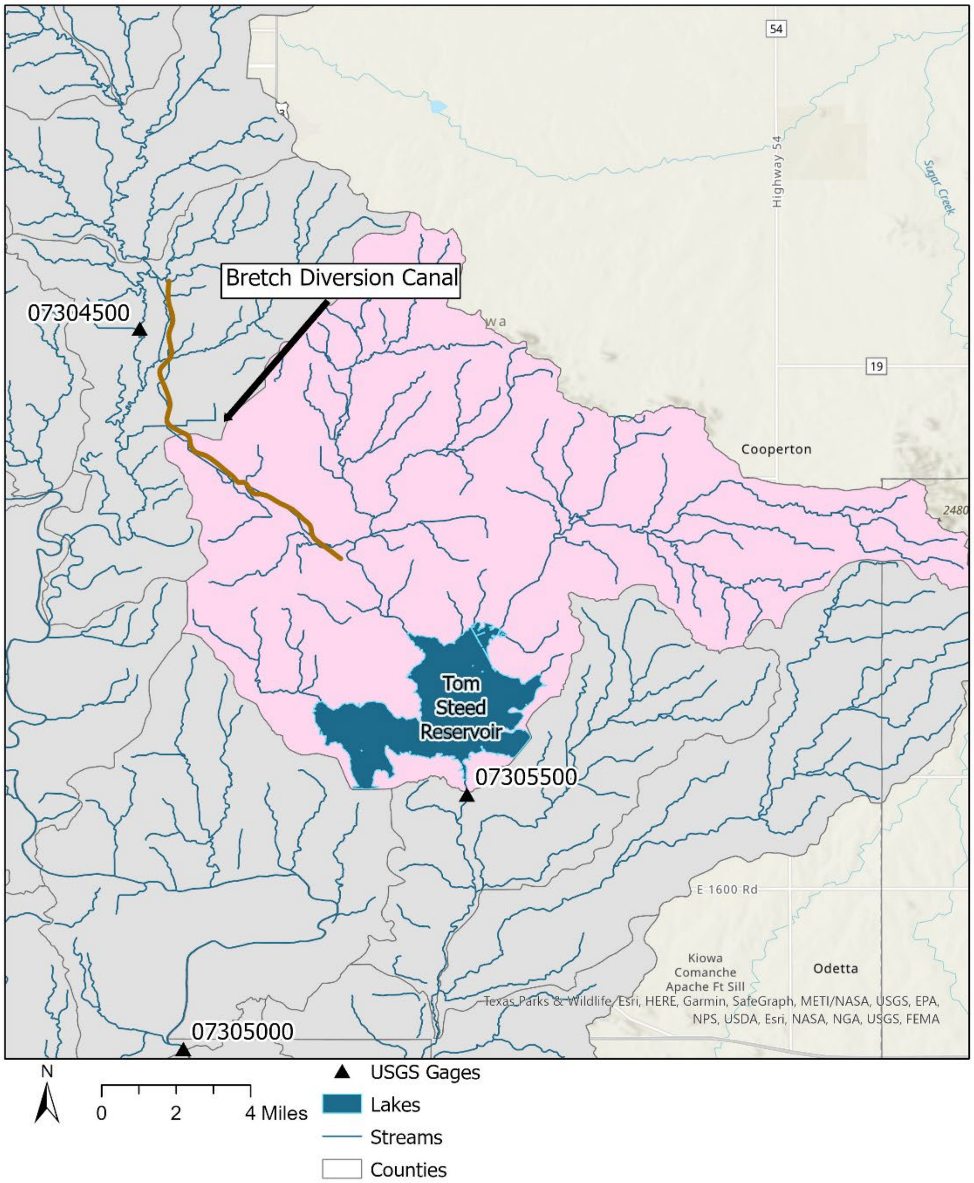

Figure 3: Tom Steed Reservoir Detail

Table 4: Monthly Average Values for Tom Steed Reservoir

Month	Average Storage (acre-feet)	Average Evaporation Rate (foot/month)	Average Evaporation Volume (acre-feet)
January	65,000	0.16	830
February	64,800	0.23	1,200
March	65,900	0.44	2,300
April	66,500	0.65	3,400
May	72,100	0.76	4,000
June	73,800	0.91	5,000
July	69,100	1.07	5,700
August	66,400	0.94	4,900
September	65,600	0.69	3,600
October	66,100	0.50	2,600
November	65,500	0.31	1,600
December	64,900	0.18	910

3.4. Bretch Diversion Canal

The Bretch Diversion Canal diverts water from Elk Creek and delivers it to Otter Creek, in the basin upstream of Tom Steed Reservoir and USGS gage 07305500. Diversions down the Bretch Canal can only happen when Elk Creek has a monthly volume greater than 100 af, and are limited by its hydraulic capacity of 1000cfs (USBOR, 2011). Tom Steed is in place to serve a large Municipal and Industrial water use at the Mountain Park Conservancy District (Permit 19670671L); since the deliveries to this use from Tom Steed Reservoir are in a different basin than the diversion point, it is assumed that these demands are 100% consumptive. The Bretch Diversion Canal location is shown above in Figure 3.

Monthly Bretch Canal diversion records were used to naturalize the flows in Elk Creek since reservoir construction. Measurements of divertible flow were taken at the diversion dam and are assumed to be reduced by 5.8% due to canal losses and evaporation before reaching the reservoir. Daily flow data from the USGS gage 07304500 was used to determine the maximum divertible flow in Elk, the details of which are included in the Tom Steed Reservoir Yield Report (USBR, 2010). For several of the modeling scenarios, maximum divertible flows in Elk Creek were calculated based on a minimum streamflow requirement below gage 07304500.

Bretch Divertable flows were estimated using USBR data from 2/11/2018 of historic diverted flows from Elk Creek. These flows were multiplied by 0.058 to incorporate a monthly loss of 5.8%. This process was used to calculate naturalized flows at 07305500. See Appendix 1 that describes the process of naturalizing 07305500.

4. Water Use data

4.1. LAID

An initial comparison of surface water permits and total diversions down the Altus Main Canal showed that the permitted surface water amounts accounted for only 30% historic canal diversions. Discussion with the OWRB, LAID and USBR clarified that diversions to farm turnouts within LAID are made under the LAID permit and in accordance with the operational rules applicable to Lake Altus. Some lands within the LAID also have Oklahoma water rights permits that allow diversion from streams. However, water in these streams comes from occasional rainfall events or from tail water from LAID deliveries, both of which supplies are sporadic. (Personal communication, Tom Buchanan, 2013) Accordingly, water use under Oklahoma water rights permits within the LAID was not simulated.

The Altus Main Canal Diversions data was provided by OWRB from a USBR report for the period 1946-2012 (USBR 2013). Approximately 30% of the water released into the Main Canal is lost to percolation or evaporation. (Personal communication, Maria Moreno, 2013)

4.2. Wells

Permitted amounts and permit dates for wells within the North Fork of the Red River system were obtained from the OWRB. All wells fell into one of two categories, Public Supply or Irrigation. Table 6 shows the breakdown of well permits by location and usage type. Since annual usage data was not available, a time series was developed for each well assuming that well always diverted its full permitted amount, beginning in the year of its permit. Figure 4 shows the locations of all permitted wells and surface water diversions.

4.3. Surface water permits summary

Permitted water depletions were obtained from the OWRB for 1950 to 2016. The water depletions represent the water use reported to the OWRB by the water user. For modeling purposes, it has been assumed that the reported water depletions are accurate and representative of the historical record. In some cases, permitted uses on the North Fork of the Red River System did not have an annual value recorded, in which case the average of all of the recorded annual uses was used to fill in water use for the missing years. The locations of these water depletions and the spatial extent of the North Fork of the Red River System were also obtained from the OWRB. The annual and monthly consumptive use amounts for different permitted use types were provided by OWRB.

Table 6 shows the breakdown of permitted amounts for well permits and Table 7 shows the breakdown of permitted amounts for surface water diversions by category for the various areas of the North Fork of the Red River system. Figure 4 shows the locations of all permitted wells and surface water diversions.

Table 5. Demand nodes added and removed from model and naturalization

Permit	Name	Downstream Naturalized Gage
Permits Added		
19520595A	Briscoe, Donald	07301110
19680119	Tolbert Farms	07307028
20020003C	Hendershot, Brent C	07301500
20020003D	Hendershot, Brennan J	07301500
20020003B	Hendershot, Vicki Ruth	07301500
Permits Removed		
19720294	Callen, Lottie P	07307028
19750027	Triple R Farms LLC	07304500
20010016	Quartz Mt Youth Camp	07305000
19540866	Mong, Joe & Faye	07301500
19780088	Quartz Mt Youth Camp	07305000
20020003	Hendershot, Brent C	07301500
19520096	Hook N Horns LLC	07301110
19520595	Briscoe, Donald	07301110

Table 6: Breakdown of Well Permits by River System

River System	Usage Type	Total Number of Well Permits	Total Permitted Diversion By Wells (AF, 2012)
LOWER NORTH FORK RED RIVER (1-15-1)	Public Supply	17	3,328.30
	Irrigation	381	47,037.70
UPPER NORTH FORK RED RIVER (1-15-2)	Public Supply	22	4,291.00
	Irrigation	163	27,529.00
SALT FORK RED RIVER (1-16)	Public Supply	10	2,242.30
	Irrigation	95	21,043.50
ELM FORK RED RIVER (1-18)	Public Supply	1	15.00
	Irrigation	32	4,170.00
TOTALS	**Public Supply**	**50**	**9,876.60**
	Irrigation	**671**	**99,780.20**
TOTAL FOR ALL WELL PERMITS		**721**	**109,656.80**

Table 7. Breakdown of Surface Water Permits by River System

River System	Usage Type	Total Number of Permits	Total Permitted Diversion (AF, 2012)
LOWER NORTH FORK RED RIVER (1-15-1)	Public Supply	3	17,831.00
	Irrigation	34	6,371.00
	Recreation, Fish, Wildlife	3	825.00
UPPER NORTH FORK RED RIVER (1-15-2)	Public Supply	1	4,800.00
	Irrigation	8	86,510.50
	Recreation, Fish, Wildlife	2	152.00
SALT FORK RED RIVER (1-16)	Public Supply	0	-
	Irrigation	55	8,653.00
	Recreation, Fish, Wildlife	2	223.30
ELM FORK RED RIVER (1-18)	Public Supply	0	-
	Irrigation	3	768.00
	Recreation, Fish, Wildlife	0	-
TOTALS	**Public Supply**	**4**	**22,631.00**
	Irrigation	**100**	**102,302.50**
	Recreation, Fish, Wildlife	**7**	**1,200.30**
TOTAL FOR ALL SURFACE WATER PERMITS		**111**	**126,133.80**

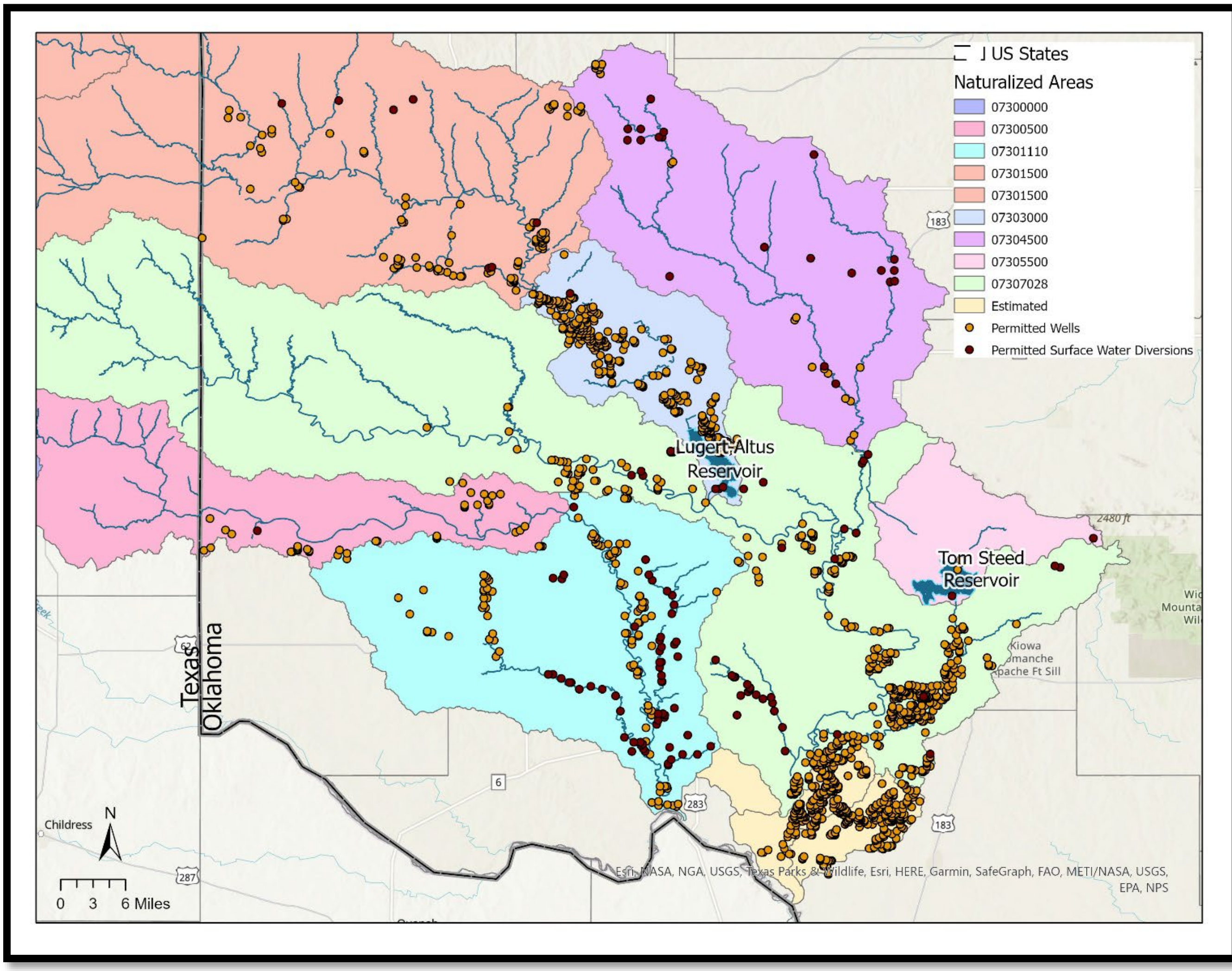

Figure 4: Location of Permitted Surface and Groundwater Diversions

4.4. Calculation of groundwater development adjustments

Pumping scenarios representing future groundwater development were provided by the USGS as part of an ongoing groundwater impact study for the Red River Basin (Report, 2017). A MODFLOW model was developed for portions of the Red River Basin near and upstream of Lugert-Altus and Tom Steed reservoirs. The MODFLOW model represents historic, current and future groundwater impacts as a series of steady-state runs. Runs were performed on a monthly or annual timestep for a 50 year stress period. Figure 5 shows the modeled aquifer boundary. Table 8 shows which MODFLOW model scenarios were extracted and incorporated into the NFRR model.

Table 8. MODFLOW scenarios included in the NFRR model

Scenario	Description
nopump	No pumping in MODFLOW model
avgpump	Average historical conditions
2013pump	“Current” pumping conditions representing 2013 pumping demands
growthpump	Current permitted pumping demands plus 20% growth
20, 40, 50 pump	Pumping rate coincident with full groundwater development at a 20, 40 and 50

	year time horizon

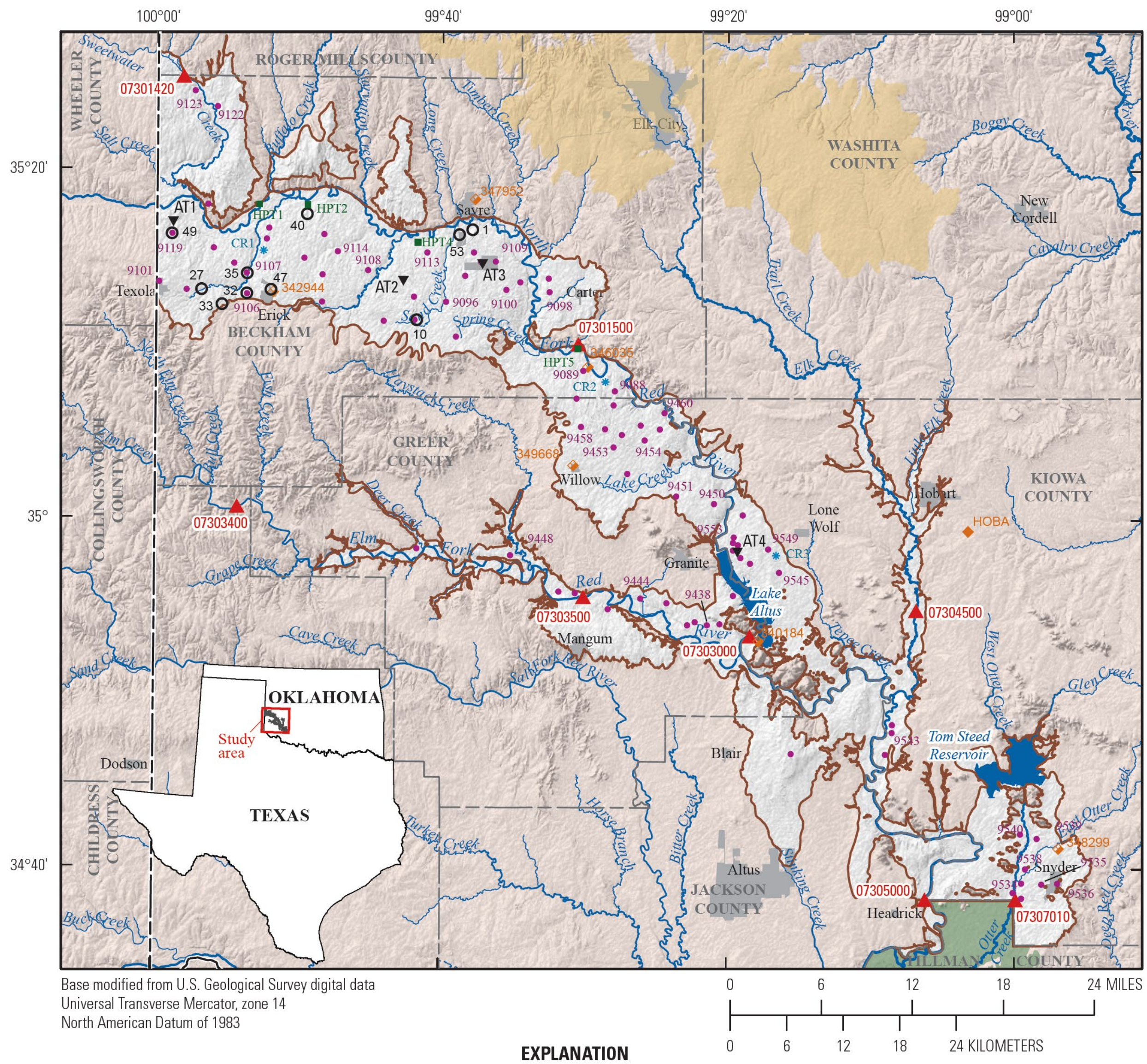

Figure 5. Aquifer modeled in USGS study (USGS, 2017)

The NFRR model does not differentiate between surface and groundwater so groundwater reductions were expressed as relative changes (usually decrease) in natural flow for each impacted HUC. Impacted natural flows were developed for the areas upstream of gages 07302000 and 07304500. Flows at gage 07304500 represent changes in flows available upstream of the Bretch canal diversion. The Bretch Canal that diverts from Elk Creek into Otter Creek is a source for Tom Steed Reservoir. Gage 07302000 was not modeled in the NFRR model, but it sits at the upstream end of Lake Altus. All HUCs upstream of Lake Altus (represented at gage 07303000) had groundwater impacts applied based on the modeled results from gage 07302000. Due to the firm yield modeling goals of USBR and OWRB, no groundwater impacts were applied downstream of Lake Altus or Tom Steed Reservoir, even though the USGS model domain extends that far.

Groundwater reductions for each pumping scenario were provided as monthly or annual baseflows upstream of a particular stream gage. 12 monthly values for each HUC were extracted from each MODFLOW run representing the total flow difference between a particular scenario and the "nopump" scenario at either the last year or last 12 months of the model stress period. Some of the model scenarios were only available as annual data, so those scenarios were split into monthly values using the monthly percent baseflows from the last 12 months of the stress period for the "avgpump" scenario.

Figure 6 and Figure 7 show the total impacts (monthly Acre-Feet) of groundwater pumping under the different modeled scenarios at gages 07304500 and 07302000, respectively. Since these offsets were calculated as a relative change between a scenario and the "avgpump" scenario, there are no calculated impacts applied in the model. Also, for gage 07304500, there was no difference in modeled groundwater impact between the "avgpump", "2013pump" and "growthpump" scenarios, so those offsets are also 0 for all months.

In the NFRR, groundwater impacts were represented as changes in natural flow to individual HUCs. It was assumed that future groundwater development is most likely to occur in the HUCs where groundwater use is currently permitted. The 12 monthly values generated for each study gage were weighted by the percent of total permitted groundwater use that fell in a particular HUC.

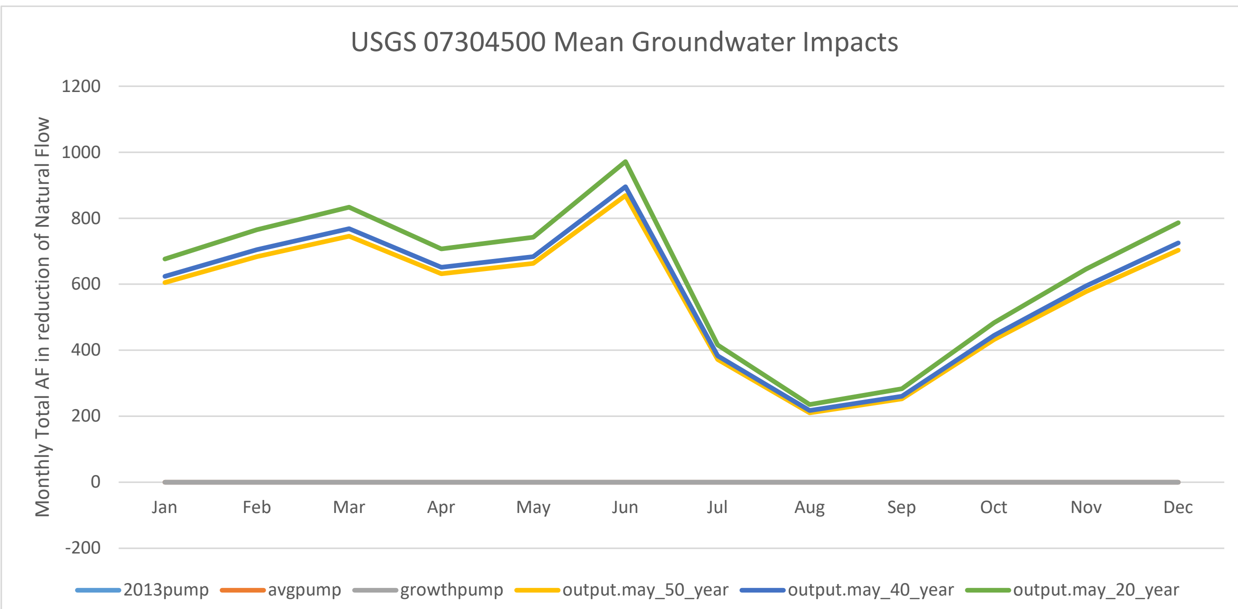

Figure 6. Total MODFLOW groundwater impact at gage 07304500

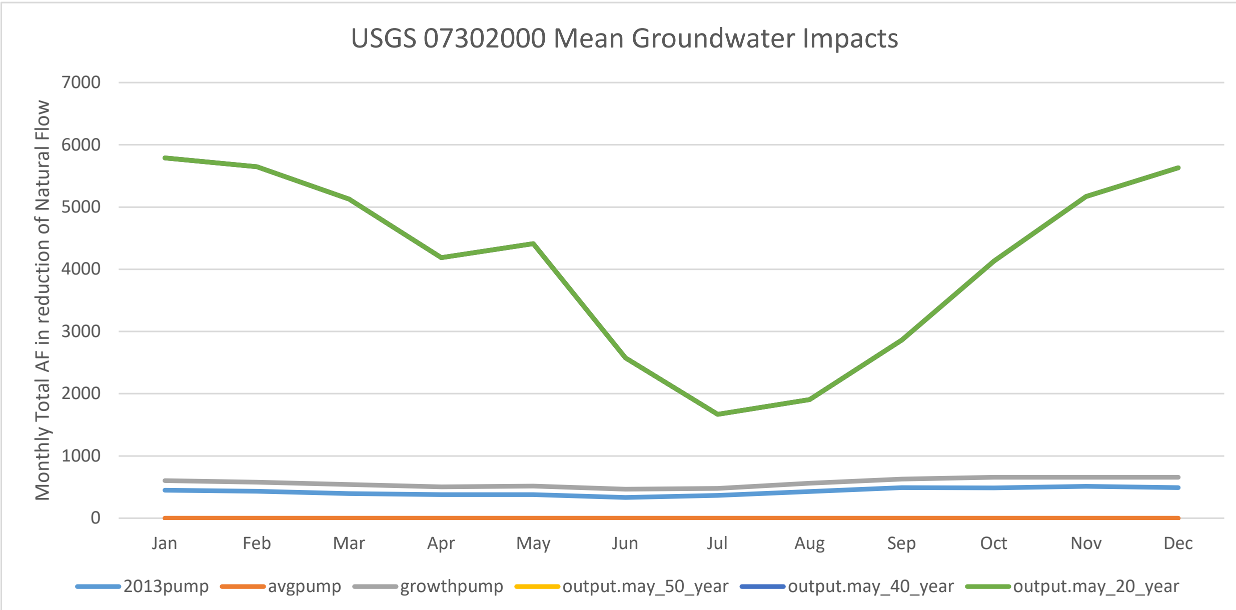

Figure 6. Total MODFLOW groundwater impact at gage 07302000

4.5. Groundwater rights and mainstem flows

All surface and groundwater demands in the original Red River model were designed to divert water available within the 12-digit HUC in which they were placed. This is realistic for surface water users since they cannot divert more than what is in the river. Groundwater users, on the other hand, can divert more water than what flows in the nearest river by drawing down the local water table, which is either supplied by recharge from local runoff or by drawing water from a nearby HUC. In the model this limitation is primarily an issue for groundwater permits in a HUC not on a river mainstem.

To represent this impact, any groundwater permits not on a mainstem HUC were connected, and allowed to divert water from, the nearest mainstem HUC. For each groundwater permit, the priority for this additional linkage was set slightly junior to their use of water in the HUC where they are located. The links in yellow in Figure 8 show an example of how a groundwater demand is connected to a mainstem location.

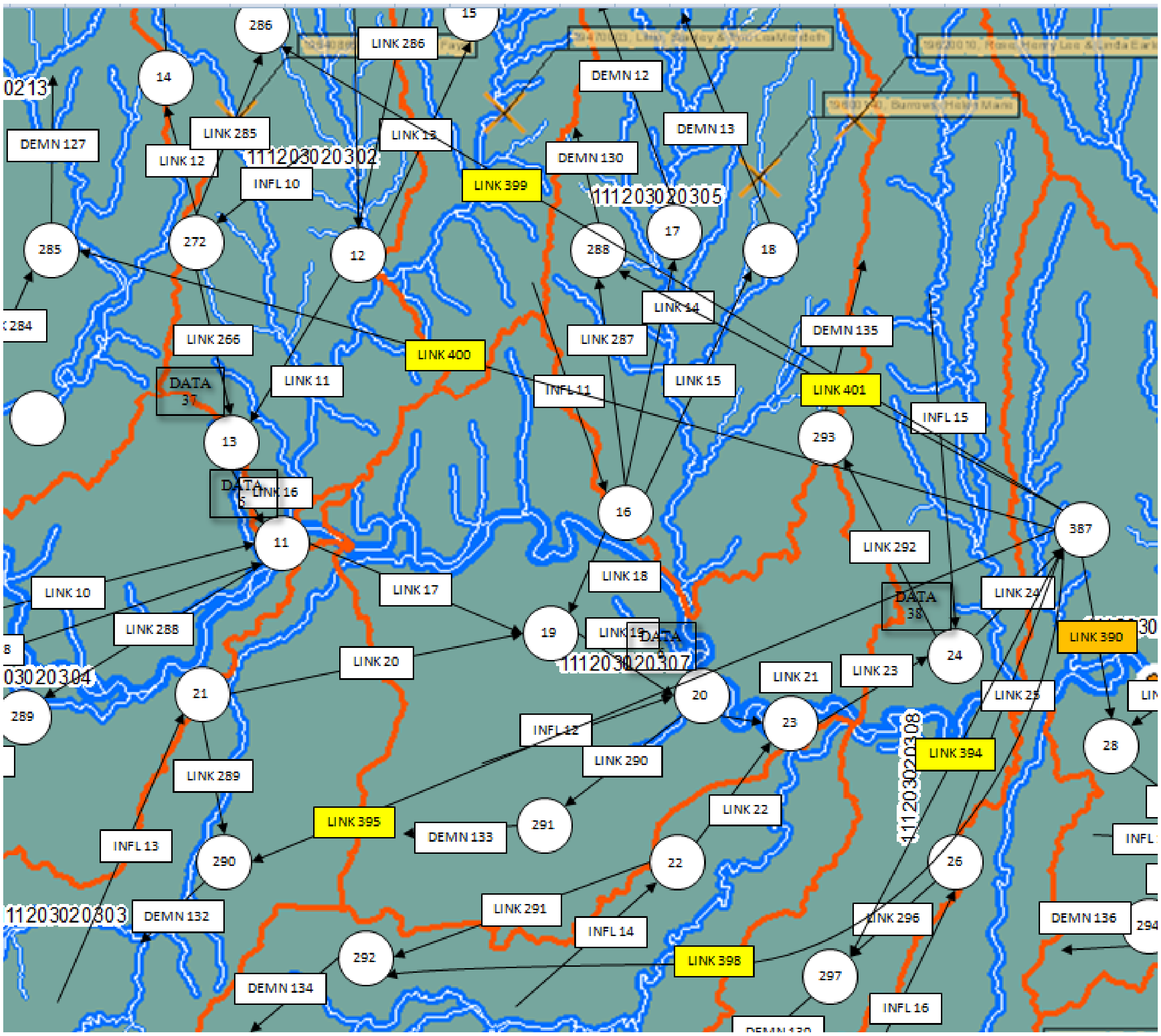

Figure 8. Links connecting the mainstem HUCs to groundwater demands shown in yellow. Mainstem reach is link 390 in peach color.

5. Streamflow data

The NFRR Model represents the amount of water entering the model domain either at the headwaters of tributaries along the basin boundary ("rim inflows") or at the Oklahoma-Texas state line ("cross-border inflows) or as stream gains at interior locations within the model domain. Stream gains represent the incremental amount of gain (or loss) that occurs in a specified reach of a stream.

Rim inflows and stream gains are represented at each 12-digit HUC within the model domain. If a hydrologic unit lies along the perimeter of the model domain then it will consist of one stream gain, possibly one or more water demands, and an outflow. A hydrologic unit (HU) that lies in the interior of the model domain or along the Oklahoma-Texas state line will consist of an inflow (the outflow from the HU immediately upstream), one gain, possibly one or more water demands, and an outflow. An HU that represents a confluence will have two or, rarely, more inflows. Accordingly, the streamflow data that are described in this section must be disaggregated to the scale of the 12-digit HUs. This process occurs after naturalization and is described in Section 7. The structure of the model elements that represent flows and gains in a hydrologic unit are illustrated and described in Appendix 2.

Stream gage records were obtained from the United States Geological Survey (USGS) covering the period from 1950 to 2016. In cases where flow data was missing, missing flows were filled using a linear regression. Twenty-two stream gage stations were within the North Fork of the Red River System and ultimately eight gages were used to develop naturalized flows and gains within Oklahoma and one gage was used to represent upstream flows entering the model domain. These stream gages are listed in Table 9 and shown in Figure 9. The naturalized stream gages used in the CRAM model are summarized in the following sections.

Table 9: USGS Stream gages within the North Fork of the Red River System

USGS Stream gage Station Number	Description	Record Start	Record End
Oklahoma Stream Gages Used for Naturalization			
07300500	Salt Fork Red River at Mangum, OK	1950	2017
07301110	Salt Fork Red River near Elmer, OK	1979	2017
07301500	North Fork Red River near Carter, OK	1950	2017
07303000	North Fork Red River below Altus Dam near Lugert, OK	1977	2017
07304500	Elk Creek near Hobart, OK	1950	1993
07305000	North Fork Red River near Headrick, OK	1950	2017
07305500	West Otter Creek at Snyder Lake near Mt Park, OK	1950	2003
07307028	North Fork Red River near Tipton, OK	1983	2017
Stream Gages Used for Boundary Inflows			
07300000	Salt Fork Red River near Wellington, TX	1952	2011
Stream Gages Not Naturalized			
07300530	Bitter Creek near Martha, OK	1998	2005
07300580	Bitter Creek West of Altus, OK	1998	2005
07301100	Turkey Creek at Olustee, OK	1960	1963
07303400	Elm Fork of North Fork Red River near Carl, OK	1959	2011
07303420	Elm Fork of North Fork Red River near Reed, OK	1965	1967
07303500	Elm Fork of North Fork Red River near Mangum, OK	1950	1976
07306500	Otter Creek at Mountain Park, OK	1950	1951
07307010	Otter Creek near Snyder, OK	2000	2008
07301420	Sweetwater Creek near Sweetwater, OK	1986	2011
07301481	North Fork Red River near Sayre, OK	1978	1984
07302000	North Fork Red River near Granite, OK	1950	1944

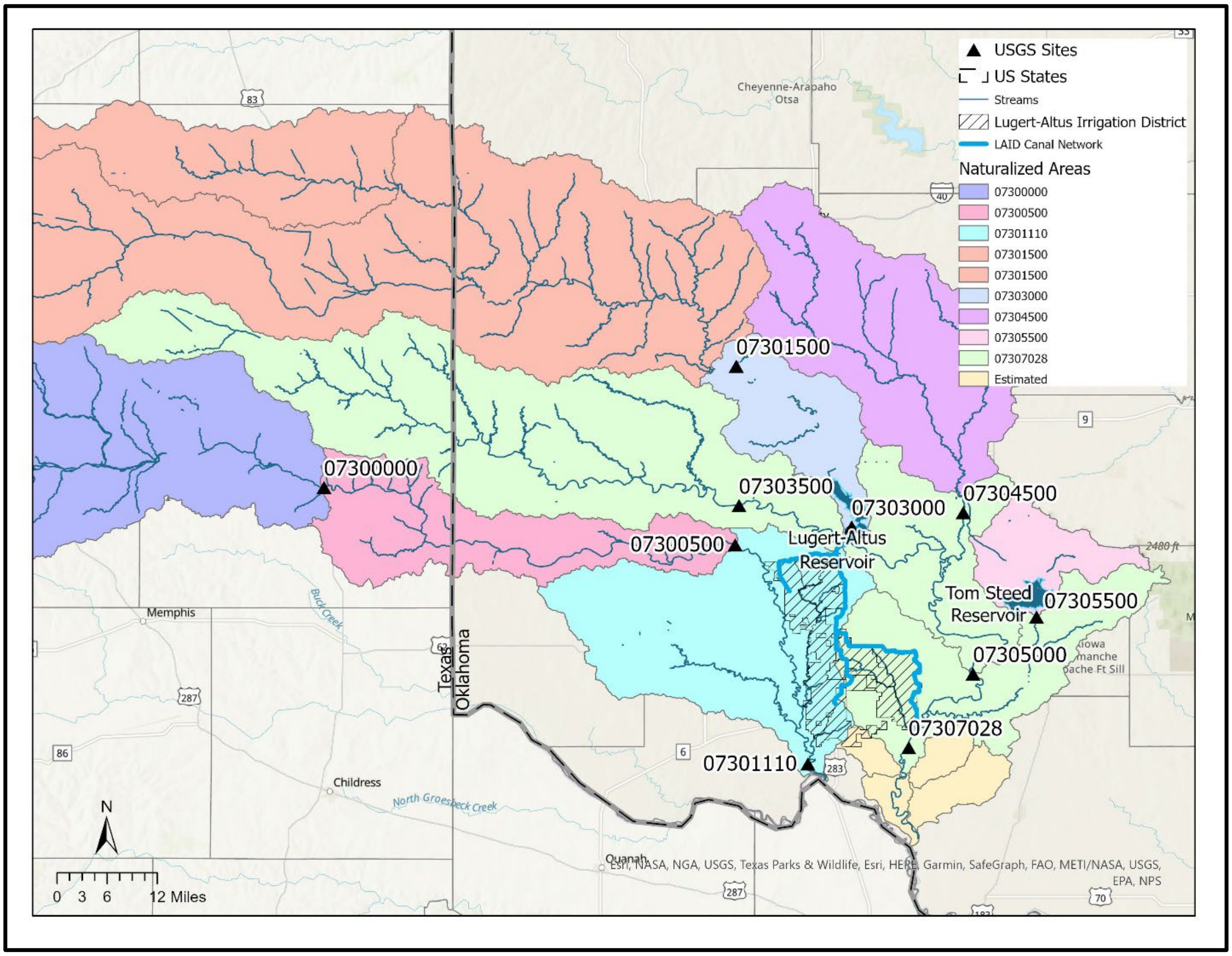

Figure 7: Gages in North Fork of the Red River System as Modeled in CRAM

The gages used to develop naturalized streamflows were chosen based on the availability of daily average stream flow over the model temporal domain (1950 to 2016), the location within the watershed, the size of the drainage area, and the proximity to other gage stations. In Figure 9 these gages are marked with a black triangle.

USGS stream gages 07300500, 07301500, and 07305000 fulfilled all these criteria, but the area covered by these gages was insufficient to naturalize the entire basin effectively and to account for all water management structures, so to improve the representation of streamflows flows were naturalized using other gages. Stream gage 07301110 was added to account for return flows below LAID and to provide a location for naturalization of flows at the lower end of the Lower Salt Fork of the Red River. The flow record at this gage was nearly complete (1979 to 2017). USGS stream gage 07303000 is located immediately below the dam at Lake Altus and has a sufficiently long period of record for naturalization (1977-2017); this gage was added to account for the water balance of Lake Altus. Stream gage 07304500 has a period of record from 1950-1993 and provides good flow coverage of the Lower North Fork of the Red River. USGS stream gage 07305500 is located immediately below Tom Steed Reservoir and has a long enough period of record to be used for naturalization (1950-2003). USGS stream gage 07307028 provides coverage at the lower end of the North Fork of the Red River as well as accounting for return flows for approximately half of the Lugert Altus Irrigation District.

USGS stream gage 07300000 was used to represent upstream inflows from Texas watersheds. Since no information about past, current or future water management activities in Texas was available, these gages were assumed to represent all flows crossing the state line.

Gages were not used for naturalization if the period of record for the gage was less than 10 year or contained too many discontinuities to be useful. Gages 07303400 and 07303500 (not pictured on map above) were used for model validation for the periods where they had data available. The model validation results are presented in Section 8.

6. Assumptions and data gaps

6.1. Filling missing streamflow data

In cases where flow data was missing, missing flows were filled using a linear regression. When filling a missing period at a target gage, other predictor gages were first identified that have data for the period when data are missing at the target gage, and linear regression functions were developed between the naturalized flows at the predictor gages and the naturalized flows at the target gage for an "overlap period" when two gages both have data. Usually, the relationship for the predictor gage with the best coefficient of determination (R^2) was used to estimate missing data.

6.2. Cross-border inflows

Measured flows at one gage was used to represent flows entering Oklahoma from Texas (see Section 5 and Table 9). This approach carries with it an implicit assumption that water management practices in Texas, including the development of infrastructure such as reservoirs, will occur in the future just as they have in the past. This includes the evolution of water use, management practices and infrastructure. This assumption is virtually certain to be strictly false, but it has been adopted for practical reasons. According to the Texas Region A Water Plan (draft TWDB, 2021), encompassing Subbasin I of the Red River Compact, which includes tributaries to the NFRR, little to no growth is projected in this area within Texas, water supplies are provided almost exclusively by groundwater, and development of surface water supplies are not anticipated. Therefore, it was assumed that no further future impacts would occur from Texas-based development upstream of either Lugert-Altus Reservoir or Tom Steed Reservoirs. Should it become evident that water management in Texas will change to a significant and important degree then it may become necessary to simulate water management practices in Texas.

6.3. Estimation of Reservoir Evaporation

The NFRR Model reservoir evaporation was estimated using the following approach. Area-volume curves, time series of reservoir contents and pan evaporation were provided for both Lake Altus and Tom Steed Reservoir by the USBR. Reservoir surface area was estimated from historical storage volumes using the area-volume curves and multiplied by the appropriate monthly evaporation rate to obtain a time series of monthly evaporation volumes in acre-ft per month for the entire period of record for each reservoir. See Section 3 for more additional information on evaporation data.

6.3.1. Changes in reservoir calculations

Volume-Area curves were provided by USBR for Tom Steed and Lugert Altus reservoir. As part of the process to validate NFRR flow naturalization as well as validating the NFRR model against the Firm Yield model developed by USBR, Lynker used two different sets of Volume-Area curves representing current conditions and those representing projected sedimentation by 2060. For Lugert-Altus Reservoir, the 2007 sediment survey showed that the sedimentation rate was 414 acre-ft/year. For Tom Steed Reservoir, the 2009 sediment survey showed that the sedimentation rate was 165 acre-ft/year. These sedimentation rates were used to project changes in Volume-Area curves out to the year 2060.

Additionally, during the naturalization process and during simulation, observed monthly pan evaporation rates were used in place of monthly average pan evaporation rates. When available for the post-reservoir-construction model period, pan evaporation measurements were used to calculate evaporation losses out of the reservoir. For the pre-reservoir-construction model period, monthly evaporation rates were calculated through a combination of linear regression with measured evaporation at nearby weather stations and/or by adjusting post-construction monthly average evaporation rates with pre-construction recorded precipitation.

Figure 10 shows the Volume-Area curves used for the NFRR model update for Lake Altus; Figure 11 shows the same curves for Tom Steed Reservoir. In both plots, the “Current (2007) Area/Volume” curve (in blue) was used to develop natural flows. The “2060 Area/Volume” curve (in green) was used for all other scenarios that were used for validation of USBR’s Firm Yield model.

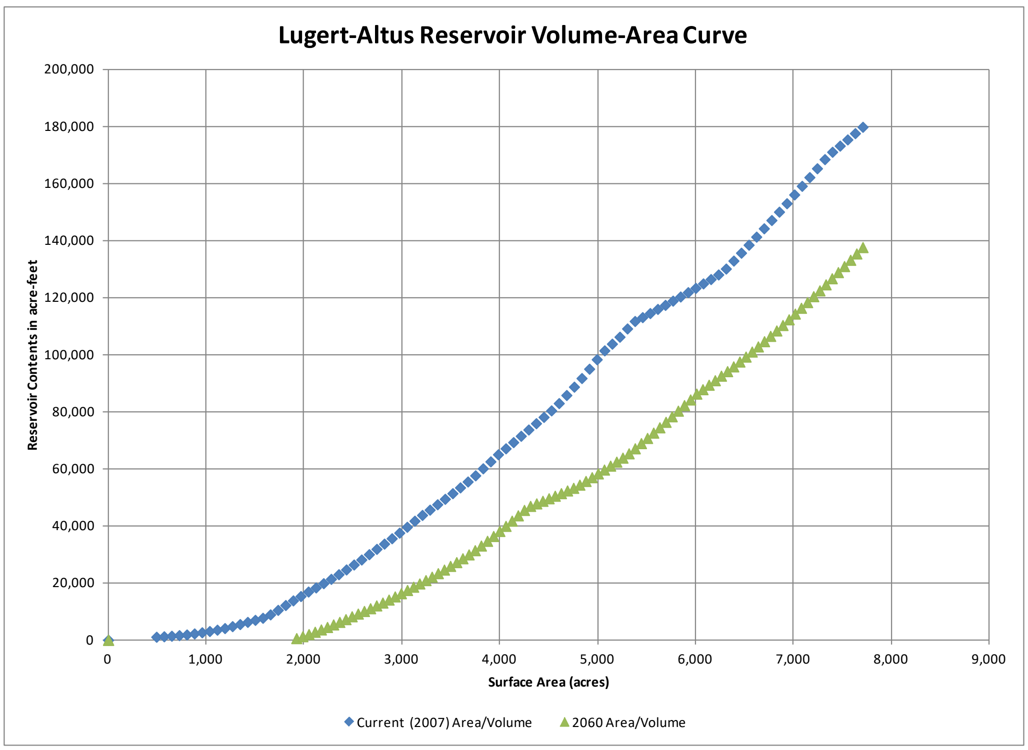

Figure 8. Reservoir area-volume curves used for Lugert-Altus Reservoir

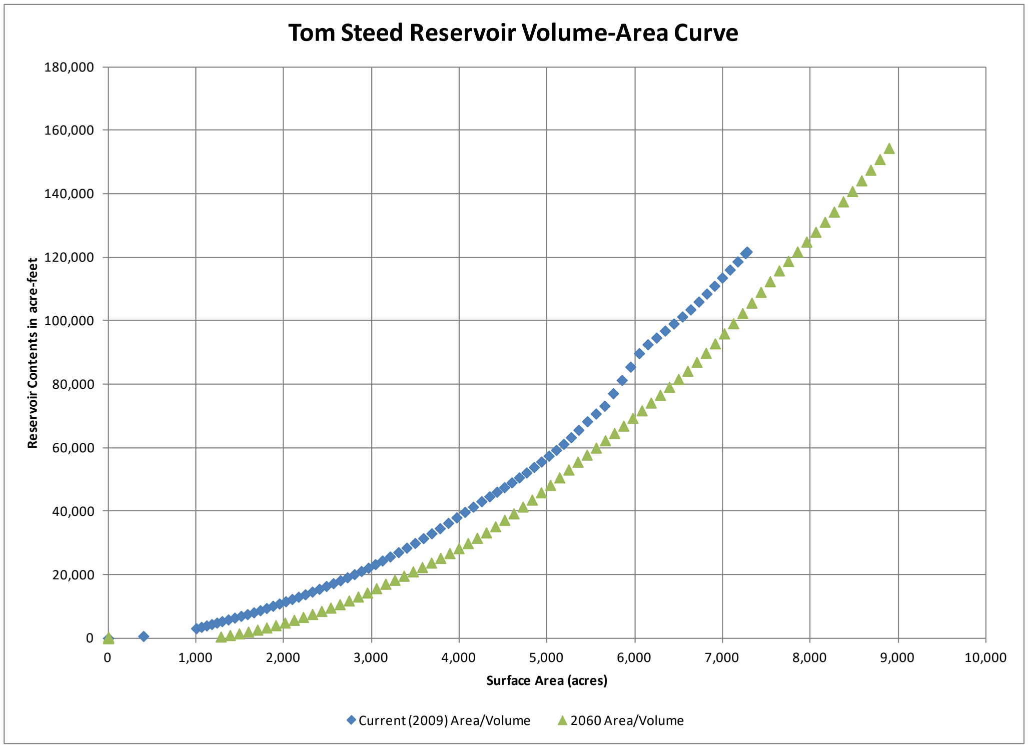

Figure 9. Reservoir area-volume curves used for Tom Steed Reservoir

6.4. LAID Canal Losses and Return Flows

Water is released from Lake Altus into the Altus Main Canal to deliver water to the lands within Lugert-Altus Irrigation District (LAID). For the purposes of flow naturalization and simulation, deliveries to individual farm turnouts in LAID were not simulated. Rather, the LAID was divided into three sub-areas; northwest, southwest and southeast. Water use and water demands for each of the three sub-areas were allocated based on the relative acreage that area. Historic use in each sub-area was calculated based on the total diversions by the Lugert Main Canal, minus canal losses, multiplied by the percentage of LAID area within the sub-area. The fractional areas of each sub-area are shown in Table 10.

Table 10: Percentage of Total Use for Sub-Areas of LAID Irrigated Lands

LAID Controls	
NW % of total area	28%
SW % of total area	32%
SE % of total area	40%

Because return flows arising from diversions in the LAID main canal accrue to three points (one for each sub-area) and accrue over approximately three months, consumptive use and return flows at LAID required formal simulation in the NFRR model.

Efficiency at LAID was assumed to be 70% over the life of the District—30% of the water applied to the lands returned to the stream--and that efficiency is a default for simulating future conditions. Efficiency at LAID has increased substantially over time (Personal communication, Tom Buchanan, 2013) so adoption of a constant efficiency will cause natural flows in the earlier part of the study period to be overestimated.

The return flows from the northwest and southwest areas of the LAID are returned to the naturalized watershed of USGS gage 07301110 while return flows from the southeast area of the LAID are returned to the naturalized watershed of USGS gage 07307028.

In addition to being returned to different watersheds, the return flows were lagged in such a way that 50% of the LAID deliveries to each the sub-areas was returned to the river in the first month, 30% in the second month and 20% in the third month (Table 11).

Table 11: LAID Return Flow Lagging Percentages

Month after diversion	Percentage of diversion reaching the river in the month
0 (Flows returned In Same Month)	**50%**
+1	**30%**
+2	**20%**
All months	100%

6.5. Estimation of Consumptive Use

A number of assumptions were made about groundwater and surface water demands to generate a time series of data for use as demands in the model. Groundwater demand data was only provided in terms of the permitted date and a maximum pumping amount for a given well location. For modeling purposes, the annual time series of groundwater demands for individual wells were aggregated within each HUC-12 watershed. Also, although it is understood that there are a number of unreported groundwater demands in parts of the basin demands were only modeled if a permitted date and amount were available. A time series of annual data was available for each permitted surface water diversion. Missing data were filled with historic annual averages for the same permit.

Since the model runs on a monthly basis, annual surface and groundwater permitted demands are converted to monthly time series. Monthly demand patterns have been established for each of the demands included in the model, based on the type of water use. It is important to note that the annual demands are changing but the monthly pattern is always assumed to be the same. Table 12 outlines the demand types and their consumptive use and Table 13 shows the monthly patterns of consumptive use. The demand patterns themselves can be found in the InputControls sheet of the model; these patterns can be adjusted depending on new information about usage percentages (see the NFRR Model User's Manual).

Table 12: Consumptive Use Percentages

Name	Description	Consumptive use percentage
Irrigation Pattern	Usage pattern by Irrigation	70.0%
LAID Irrigation Pattern	Usage Pattern from Historic LAID Data	70.0%
M & I Pattern	Municipal and Industrial Usage Pattern	50.0%
M & I Fully Consumptive Pattern	Fully Consumptive Municipal and Industrial Usage Pattern	100.0%
Other Pattern	Other Patterns of Demand	75.0%
Evaporation Pattern	Evaporation Pattern Based on Historic Data	100.0%
Thermal Electric Pattern	Usage Pattern by Thermoelectric Power Plants	62.0%

Table 13: Monthly Pattern of Use

	Monthly Fraction of Annual Water Use, Percent											
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Irrigation Pattern	0	0	0	0	0	25	33	29	13	0	0	0
LAID Irrigation Pattern	0	0	0	0	0	1	46	50	4	0	0	0
M & I Pattern	7	7	7	7	9	10	12	12	10	8	7	7
Other Pattern	8	8	8	8	8	8	8	8	8	8	8	8
Evaporation Pattern	0	0	0	1	0	24	33	29	12	0	0	0
Groundwater	0	0	0	0	0	25	33	29	13	0	0	0
Thermal Electric Pattern	8	7	5	6	6	8	11	17	9	9	6	7

6.6. Impact of Groundwater Use on Streamflows

Groundwater use is represented as a withdrawal from the Red River within the 12-digit HUC where the well(s) are located. For purposes of flow naturalization, groundwater use was simulated according to the use pattern for irrigation (see Table 13) and 100% of the consumptive use associated with each well was simulated as impacting streamflows. Different assumptions can be adopted for simulation (using the input controls sheet), but if the assumption used in modeling differs from the assumption used in naturalization, some error will be introduced into the simulation during later years (when a greater number of well permits existed and thus greater groundwater was assumed to have occurred.)

7. Flow Naturalization and Disaggregation

Generally, the process of developing inflow data involves first naturalizing historical gage data to remove the influence of those withdrawals and operations that will be represented in the model, and then disaggregating flows and gains to the level of detail appropriate for the level of spatial resolution required by the model. The adjustments made to gage flows include the effect of depletion changes in reservoir storage and reservoir evaporative losses; and the net effect on base flows of groundwater extraction and recharge by irrigation seepage losses. Flows are only partially naturalized because no adjustments are made for the effect of minor water uses that are expected to continue as they have historically.

The net effect of diversions is calculated as the difference between diversions and surface and sub-surface return flows to the stream. Because the model will use a monthly time step, surface return flows and virtually all sub-surface return flows can be considered to return in the same time step as the diversion, so the effect of a diversion can be calculated using a water budget approach. Losses to the surface water system would be depletions (evapotranspiration) and the effect of delayed return flows from lands distant from the river (which are represented explicitly in the model). Absent delayed return flows, the net impact of a surface water diversion in any single time step is the amount of the depletions. The gaged flows were adjusted by adding the net impact into all measured flows below the point of impact.

The effect of reservoirs is calculated by adding all changes in storage (increased storage is a positive value) and all estimated evaporation. Seepage losses will generally accrue in the same time step and are not explicitly represented in the water budget. These adjustments are added into all measured flows below the reservoir.

Once the flows have been naturalized at gages, they are spatially disaggregated to the each 12-digit hydrologic unit on an areal basis. The flow or gain associated with a HU is in proportion to the flow or gain at the downstream gage as the area of the HU is to the total contributing area of the downstream gage. At each gage, an areal flow is calculated, in units of acre-feet per square mile. This areal flow is then multiplied by the area of the HU to get the flow or gain in the HU.

Eight USGS stream gages within Oklahoma were naturalized using USGS and USACE reservoir data and water depletion data provided by OWRB. A summary of the naturalized USGS stream gages is provided in Table 14: Naturalized Stream gages in the North Fork of the Red River Watershed

USGS gage Number	Gage Description	Record Start[1]	Record End[1]	Naturalized Drainage Area (square miles)[2]	Major Upstream Reservoir	Number of Surface Water Permits	Number of Groundwater Permits
07300500	Salt Fork Red River at Mangum, OK	January 1, 1950	December 31, 2017	344	None	1	18
07301110	Salt Fork Red River near Elmer, OK	October 1, 1979	December 31, 2017	534	None	22	87
07301500	North Fork Red River near Carter, OK	January 1, 1950	December 31, 2017	2050	None	7	54
07303000	North Fork Red River below Altus Dam near Lugert, OK	October 1, 1977	December 31, 2017	178	Lake Altus	4	137
07304500	Elk Creek near Hobart, OK	January 1, 1950	September 30, 1993	549	Lake Altus	11	12
07305000	North Fork Red River near Headrick, OK	January 1, 1950	December 31, 2017	1160	Lake Altus	9	80
07305500	West Otter Creek at Snyder Lake near Mt Park, OK	January 1, 1950	June 30, 2003	132	Tom Steed Reservoir and Lake Altus	2	1
07307028	North Fork Red River near Tipton, OK	June 28, 1983	December 31, 2017	315	Tom Steed Reservoir and Lake Altus	5	120

1 – Streamflow gage records may be available before January 1st, 1950 and end after December 31st, 2011 but were clipped to the modeling timeframe

2 – Drainage areas shown are incremental areas between the gage in question and the next upstream gage

Monthly pan evaporation data and reservoir surface areas were used to calculate monthly reservoir evaporation volume (acre-feet per month) over the period of available data. Monthly pan evaporation rates (feet/month) were available for Lake Altus and Tom Steed Reservoir from a 2009 study. Lake Altus pan evaporation data was available from Jan 1926 to Dec 2016, while Tom Steed reservoir had data available from Oct 1959 to Dec 2016. The reservoir surface area was estimated from the reservoir volume using area-capacity curves. The monthly pan evaporation rate (foot per month) was multiplied by the surface area (acres) corresponding to the average monthly contents for each reservoir to obtain an evaporation volume (in acre-feet) for each month.

For gages where flow is impacted by upstream canal diversions and deliveries, the net canal diversion out of basin was added to the gaged flow as part of the naturalization process. In the North Fork of the Red River watershed, there were two large canal systems that were incorporated into the naturalization process. The Altus Main Canal diverts water directly from Lake Altus to supply irrigation demands in the Lugert-Altus Irrigation District (LAID). Diversion records were provided by the Bureau of Reclamation for the LAID canal from December 1946 through December 2016.

The Altus Main Canal diversion removes water from the naturalized watershed above USGS Gage 07303000 and delivers water via groundwater return flows to the watersheds of USGS gages 07301110 and 07307028. Further discussion of the calculation of these return flow amounts can be found in Section 6.

The Bretch Diversion canal diverts water from Elk Creek in the watershed of USGS gage 07304500 and delivers water to Otter Creek in the watershed of USGS gage 07305500. Diversion records for the Bretch Diversion Canal were provided by the Bureau of Reclamation from June 1975 through present day.

One stream gages in Texas was used to characterize flow from Texas-contributing portions of the upper watershed. This gage was not naturalized; rather its historical records were used to represent flows from Texas-contributing watersheds. It is important to note that all Texas watersheds are treated the same. A summary of the Texas gage is provided in Table 15.

. Naturalized flows were calculated according to the following formula:

$$\begin{aligned} &\mathit{Naturalized\ Flow} \\ &\quad = \mathit{Stream\ gage\ flow} + \mathit{Reservoir\ change\ in\ storage} + \mathit{Reservoir\ evaporation} \\ &\quad + \mathit{Depletions} + \mathit{Exports\ out\ of\ basin} - \mathit{Stream\ gage\ flow\ of\ upstream\ gages} \end{aligned}$$

Once the flows have been naturalized at gages, they are spatially disaggregated to each of 12-digit hydrologic units above the gage on an areal basis. The flow or gain associated with a HU is in the same proportion to the total flow or gain at the downstream gage as the proportion of the area of the HU to the total contributing area of the downstream gage. At each gage, an areal flow is calculated, in units of acre-feet per square mile. This areal flow is then multiplied by the area of the HU to get the flow or gain in the HU.

$$\begin{aligned} &\mathit{Areal\ Naturalized\ Flow} \\ &\quad = \frac{\mathit{Naturalized\ Flow}}{\mathit{Total\ drainage\ area\ of\ gauge} - \sum \mathit{Drainage\ areas\ of\ all\ upstream\ gauges}} \end{aligned}$$

Table 14: Naturalized Stream gages in the North Fork of the Red River Watershed

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2 – Drainage areas shown are incremental areas between the gage in question and the next upstream gage

Monthly pan evaporation data and reservoir surface areas were used to calculate monthly reservoir evaporation volume (acre-feet per month) over the period of available data. Monthly pan evaporation rates (feet/month) were available for Lake Altus and Tom Steed Reservoir from a 2009 study. Lake Altus pan evaporation data was available from Jan 1926 to Dec 2016, while Tom Steed reservoir had data available from Oct 1959 to Dec 2016. The reservoir surface area was estimated from the reservoir volume using area-capacity curves. The monthly pan evaporation rate (foot per month) was multiplied by the surface area (acres) corresponding to the average monthly contents for each reservoir to obtain an evaporation volume (in acre-feet) for each month.

For gages where flow is impacted by upstream canal diversions and deliveries, the net canal diversion out of basin was added to the gaged flow as part of the naturalization process. In the North Fork of the Red River watershed, there were two large canal systems that were incorporated into the naturalization process. The Altus Main Canal diverts water directly from Lake Altus to supply irrigation demands in the Lugert-Altus Irrigation District (LAID). Diversion records were provided by the Bureau of Reclamation for the LAID canal from December 1946 through December 2016.

The Altus Main Canal diversion removes water from the naturalized watershed above USGS Gage 07303000 and delivers water via groundwater return flows to the watersheds of USGS gages 07301110 and 07307028. Further discussion of the calculation of these return flow amounts can be found in Section 6.

The Bretch Diversion canal diverts water from Elk Creek in the watershed of USGS gage 07304500 and delivers water to Otter Creek in the watershed of USGS gage 07305500. Diversion records for the Bretch Diversion Canal were provided by the Bureau of Reclamation from June 1975 through present day.

One stream gages in Texas was used to characterize flow from Texas-contributing portions of the upper watershed. This gage was not naturalized; rather its historical records were used to represent flows from Texas-contributing watersheds. It is important to note that all Texas watersheds are treated the same. A summary of the Texas gage is provided in Table 15.

Table 15: Texas Stream gage modeled, but not naturalized in the North Fork of the Red River Watershed

USGS gage Number	Gage Description	Record Start[1]	Record End[1]	Drainage Area (square miles)[2]	Major Upstream Reservoir	Number of Water Depletions
07300000	Salt Fork Red River near Wellington, TX	July 1, 1952	December 31, 2016	1,222	N/A	N/A

N/A: Water demands and reservoirs are not available for Texas. The model is simulated for Oklahoma operations.
[1] – Streamflow gage records may be available before January 1st, 1950 and end after December 31st, 2016 but were clipped to the modeling timeframe
[2] – Drainage areas shown are incremental areas between the gage in question and the next upstream gage

7.1.1. Gages selected

Gage data from USGS gages was used as the basis for developing natural flows in the original NFRR model. Additional data was obtained to extend the model period and a variety of methods were used to fill in gage data. Table 16 shows the list of gages in the model as well as the gages used to fill in missing data. Refer to Figure 9 for a map of the location of each gage.

Table 16. Gages used to complete natural flow record

Gage	Gage used for Filling	Period Filled
07300500	07305000	1/1950-6/1952
07301110	07305000	1/1950-10/1979
07301500	07305000	10/1962-7/1964
07303000	07305500	10/1962-7/1964
07303500	VIC Model Data	1/1950-12/2016
07304500	07305500 (Alternate method)	9/1993-12/2016
07305000	07301500	10/1993-12/2016
07305500	USBR Dataset	Replaced
07307028	07305000	1/1950-6/1983

7.1.2. Gage filling

The Red River model uses as its basis, a set of monthly natural flows developed at each streamflow gage in units of Monthly Acre-Ft per Square Mile. Natural flows represent streamflow minus any human interventions including reservoir contents changes, evaporation, consumptive use demand, diversions and other impacts.

Once unit area natural flows are complete, missing data is filled in so all gages have data for the entire model period of record. For each gage, 12 monthly equations were developed using regression between sets of natural flows and were used to fill in periods where no gaged flow was available. Refer to Appendix A-1 for in-depth description of filling approach for each gage.

When the Red River model was extended, the gage flows used as the starting point for the naturalization process were reviewed. Several discrepancies were discovered in the gage data at USGS gage 07305500. These discrepancies were due to the gage being below a low-head dam where no inflow or contents were available. Lynker replaced the data at that gage with a timeseries developed by USBR through a correlation between flow data and a rainfall gage at the Roosevelt site in the basin for 07305500.

The initial approach to filling natural Elk Creek gage (07304500) data gave poor results, so the Lynker team came up with an alternative process. Monthly linear regressions were created for five different methods for filling the flows at Elk Creek and were compared to find the method with the best R-squared and the lowest RMSE. The best approach was by subtracting gaged flows at 07303000 from gaged flows at 07305000 in order to remove the effects of Lake Altus releases. This modified set of gage flows was then used as the predictor to fill in the natural flows at 07304500. Refer to Appendix A-1 for additional descriptions of gage filling processes.

7.1.3. Using the VIC model to fill the natural flows

Instead of filling gage 07303500 in the way the other gages were, the Variable Infiltration Capacity (VIC) model was used to weight the flows at 07305000 to represent accurately how physical hydrology varied from place to place.

As part of a previous climate change impact effort, Lynker had conducted VIC runs on a 1/8th degree gridded basis with a monthly timestep across the Red River basin. These model runs were developed in 2010 as part of the Oklahoma Climate Change Assessment project.

These results included a baseline dataset that represents current hydrology. The process below was used to develop modeled flows for 07303500 using the VIC baseline results:

1. 07305000 was naturalized for as much of its period of record as data was available. This was dependent on upstream gages at 07303000 and 07304500.

2. Basin weighting factors were created for the naturalized drainage of 07305000 by multiplying the modeled VIC runoff in each grid cell by the percentage of the entire 07305000 drainage represented by that grid cell. Those weighted runoff values were summed for the entire 07305000 drainage. Figure 12 shows the basins and the relevant grid cells (hatched) used to generate the weighting.

3. The same basin weighting technique was used to calculate the basin-wide weighted runoff for the entire drainage of 07303500 as well as the drainage of 07305000 downstream of 07303500 (this basin is 07305000_Local).

4. The basin-wide weighted runoff for 07303500 was divided by the basin-wide weighted runoff for the naturalized drainage of 07305000 to generate a timeseries of monthly runoff factors. These factors represent the percent of natural flow at 07305000 in a given month that can be contributed to HUCs upstream of 07303500.

5. These monthly factors were then multiplied by the unit-area natural flow calculated in the initial naturalization of 07305000. The result of this step is a set of monthly unit-area natural flows at 07303500. This same weighting process was applied to the 07305000_Local drainage.

6. The results were checked and the sum of the modeled runoff at 07303500 and the smaller 07305000 basin were equal to the total flow at the bottom of the 07305000 drainage.

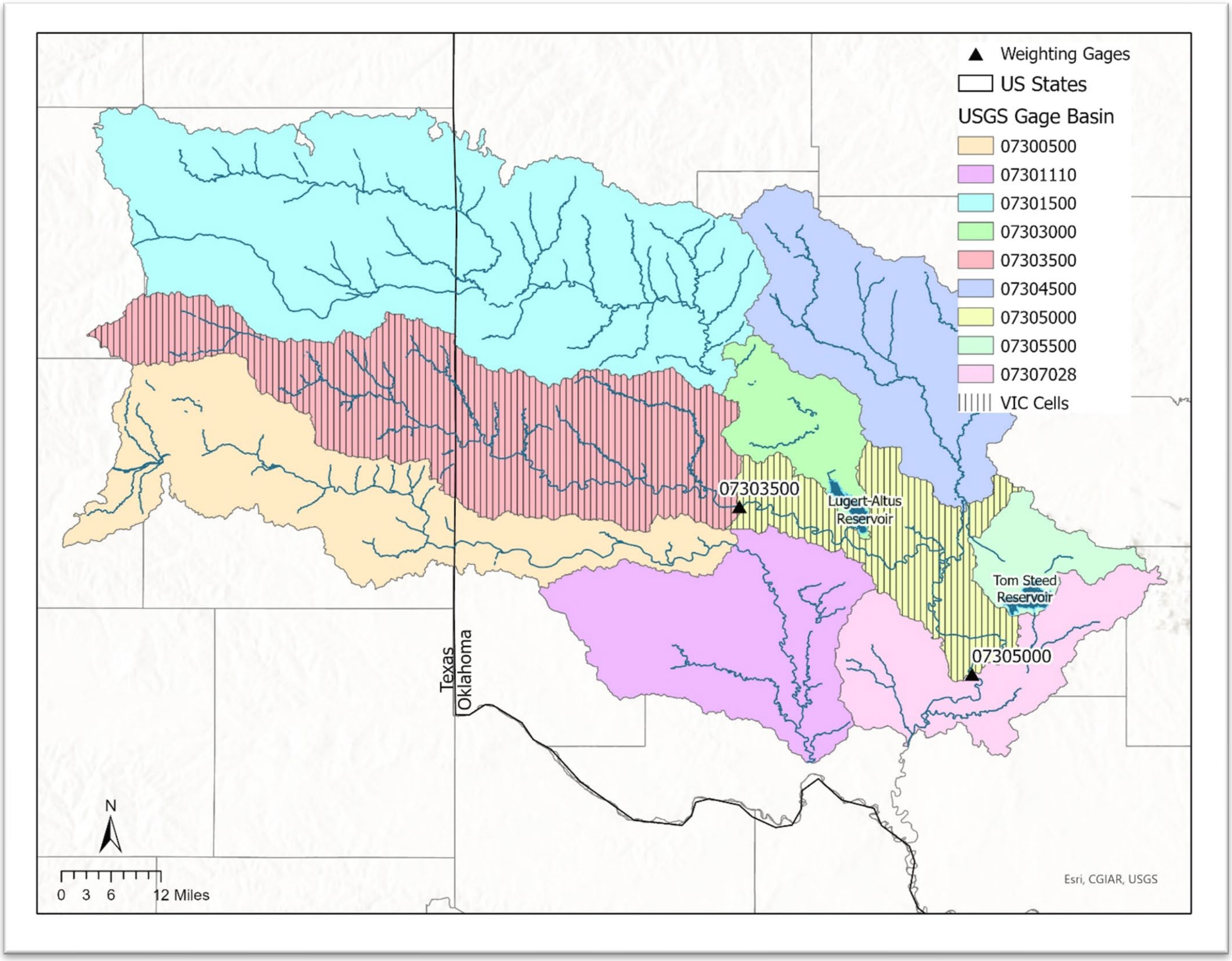

Figure 10. Basins with VIC weighting applied

8. Model Scenarios

Model scenarios show the possible outcomes of the model given a set of changing inputs. These inputs include the historic data as well as future possible changes including development and growth, permitting changes, and canal operations.

8.1. Historical Scenarios

The constrained historical scenario in the model is designed to validate the naturalization process. Historic data are used for targets for demands, canal diversions and reservoir contents. Reservoirs, canals and demands only appear in the system in the years when they existed historically.

Output from historical runs of the CRAM model was compared to the historical gage records to check the accuracy of the model fit. Historical runs are intended to replicate closely the observed behavior of the system. Accordingly, the historical runs use historical annual patterns of water use, canal diversions and bring reservoirs into the simulation in the year and month in which they were constructed. No reservoir operations rules were used since, in the validation scenario, modeled reservoir contents were contrained to equal historical reservoir contents. Accuracy of the modeled results was determined using the Nash-Sutcliffe Efficiency (NSE) value, which is calculated according to the following formula:

$$NS = 1 - \frac{\sum(Q_o - Q_m)^2}{\sum(Q_o - Q_{avg})^2}$$

Where: *A-Q_o is observed flow*
A-Q_m is modeled flow
A-Q_{avg} is average observed flow

A perfect match between the observed flow values and the modeled flow values would produce a result of 1, whereas a result of 0 would indicate that modeled results are as accurate as the mean observed flow. A result of less than 0 would show that the model provides less useful estimates of conditions than would average values. For this project, NSE values equal to or greater than 0.95 were the objective. The Nash-Sutcliffe Efficiency values were calculated for the “normal” historical scenario (Scenario 1) and for a “constrained” historical scenario (Scenario 0). In the normal scenario, reservoirs and canal diversions were simulated using full filling targets for reservoirs without any further constraints. The “normal” scenario tests the skill of the generalized reservoir targets. It shows wildly different results at the gages immediately downstream of the diversion and delivery locations of the Bretch and LAID canals since it was not possible to infer accurately the rules governing their historic operations, and because operations changed over time in the system. In the “constrained” historical scenario, reservoir contents and canal diversions were constrained to equal observed historical contents. This validation scenario eliminates error introduced by generalizing reservoir and diversion operating rules and tests the validity of the flow naturalization and disaggregation.

It was expected that gages used for naturalization would model very closely to the historic record in the constrained historical scenario. Less agreement is expected at gages that were filled by linear regression or that were not naturalized and for which flows in their contributing area were estimated using areal flows from another gage.

Under the normal model scenario 10 of 12 stream gages had Nash-Sutcliffe Efficiency (NSE) values above 0.90; and 6 of those values were greater than 0.95. Under the constrained historic reservoir scenario all naturalized stream gages had NSE values greater than 0.90 and 10 of 10 naturalized gages had NSE values greater than 0.95. The results of the two historical scenarios show that if the reservoir storage and canal diversions are constrained to historic behavior then modeled stream gage flows correspond very closely to historic stream gage flows. Much of the difference between modeled stream gage flows and historic stream gage flows in the normal mode run can therefore be attributed to the generalization of reservoir and canal operations. The Nash-Sutcliffe values are presented in Table 17.

Table 17. Nash-Sutcliffe Efficiency Values for Selected Stream gages

USGS gage ID	Nash-Sutcliffe	
	Constrained Historical Scenario (Scenario 0)	Normal Model Scenario (Scenario 1)
Naturalized gages		
USGS 07300500	0.9688	0.9688
USGS 07301110	0.9919	0.9895
USGS 07301500	0.9984	0.9984
USGS 07303000	0.9692	0.4093
USGS 07304500	0.9946	0.9082
USGS 07305000	0.9599	0.9492
USGS 07305500	0.9598	-0.3896
USGS 07307028	0.9812	0.9669
Texas gages		
USGS 07300000	1.0000	1.0000
USGS 07301410	1.0000	1.0000
Validation gages		
USGS 07303400	0.1871	0.1871
USGS 07303500	0.3477	0.3477

Where there are differences between Nash-Sutcliffe values for the normal model scenario and the constrained historical scenario these differences represent error arising from using generalized operating rules. The Nash-Sutcliffe Efficiency value is very sensitive to outliers, which can be common when simulating using generalized rules that do not replicate anomalous historical operations. The differences in Nash-Sutcliffe values for gages 07303000, 07303400, 07303500, 07304500, 07305000 and 07305500 are discussed below.

USGS gage 07303000 has a Nash-Sutcliffe value of 0.4093 for the normal model scenario, which is much lower than the 0.95 objective. This gage is immediately below Lake Altus and is impacted by changes in reservoir storage as well as diversions down the LAID Main Canal, which comes directly out of Lake Altus. The average annual historic flow at this gage is 36,492 AF and the average annual diversion of the LAID canal is 52,833 AF. This means that minor changes in timing and quantity of diversions down the LAID canal can have very large impacts on gage flows. To emphasize this point, the constrained historic scenario for the same USGS gage has a Nash-Sutcliffe of 0.9692.

The flow at USGS gage 07305500 has a Nash-Sutcliffe value of -0.3896 for the normal model scenario, the negative value indicates that the mean flow does a better job of predicting values than the modeled flow. Flows at this gage are used to naturalize a very small watershed above Tom Steed reservoir. In addition to the natural inflows and the reservoir operations of Tom Steed, the watershed of this gage is fed by the Bretch Canal diversion from Elk Creek. The average annual flow at USGS gage 07305500 is 11,603 AF and the average annual diversion down the Bretch canal is 5,256 AF; the large influence of the canal diversions and reservoir operations on this small watershed accounts for the poor fit when using the normal historical model scenario. For the constrained historic scenario the Nash-Sutcliffe score is 0.9598 which indicates a fair fit and that the natural flows used in that basin are representative of the physical reality.

USGS gages 07303400 and 07303500 had Nash-Sutcliffe values of 0.1871 and 0.3477 for both the normal and constrained model scenarios; these values are much lower than the 0.95 threshold for acceptable values. There are several possible reasons for the poor performance of these gages—the return flows were not lagged; diversions are done on a monthly basis; or other operations within this basin affecting the results. These gages were not naturalized but were used exclusively for validation purposes. The per-unit-area gains at both gages were assigned based on the values at USGS gage 07305000; the next downstream tributary gage.

The average monthly hydrographs of observed flow gage records and modeled flow gage records were analyzed as a part of the validation scenario and are presented in Appendix 1. Each hydrograph includes the average monthly observed flow record from USGS stream gages, the average monthly modeled stream flow with constrained historical scenario, and the average monthly modeled stream flow under the normal model scenario. These average monthly hydrographs are calculated based on the years where gage data was available for both the naturalized gage and any upstream gages that were subtracted as part of the incremental naturalization process.

The Nash-Sutcliffe Efficiency values for the observed stream flow and the constrained historical scenario stream flow as well as between the observed stream flow and the normal model scenario stream flow are provided on each chart, along with the average annual volume for observed flow, constrained historical scenario flow and normal model scenario flow. Finally, the ratios of average annual flow for modeled constrained historical scenario to observed conditions as well as the average annual flow for the normal model scenario flow to observed conditions are included on each chart. These charts are provided in the Appendix 1 in Figures A-1 through A-21.

8.2. Firm Yield Scenarios

Firm yield scenarios are necessary for identifying possible outcomes based on various growth and development scenarios, permitting, and any other future changes to the heuristics regime of the basin. Table 18 shows the scenarios provided by USBR for their firm yield modeling that were then developed for NFRR.

Table 18. Firm yield model scenarios from USBR

Scenario	Model Options	Model Settings Description
Scenario 1	(1) No Diversions Natural Flow Only	All permits, groundwater demands and reservoirs set to zero. Natural flow in river.
Scenario 2A	(2A) Observed Historic	Demands operate based on historic uses. Missing demand values are filled with average historical demands (water user will have no demand for years prior to date of permit issue). Reservoir targets are historic contents.
Scenario 2B	(2B) Observed Historic with Seniority	Demands operate based on historic uses. Missing demand values are filled with average historical demands (water user will have no demand for years prior to date of permit issue). Reservoir targets are historic contents. Water Rights are enforced.
Scenario 6A	(6A) Observed Historic Full MTN PARK and LAID	Demands operate based on historic uses. Missing demand values are filled with average historical demands (water user will have no demand for years prior to date of permit issue). Reservoir targets are historic contents. Mtn Park demand at 16,100 AFY, LAID at Full Permitted
Scenario 6B	(6B) Observed Historic FULL MTN PARK and LAID with Seniority	Demands operate based on historic uses. Missing demand values are filled with average historical demands (water user will have no demand for years prior to date of permit issue). Reservoir targets are historic contents. Mtn Park demand at 16,100 AFY, LAID at Full Permitted.
Scenario 6C	(6C) Observed Historic Full MTN PARK and LAID with Operations	Demands operate based on historic uses. Missing demand values are filled with average historical demands (water user will have no demand for years prior to date of permit issue). Reservoir targets are historic contents. This uses the Operations for LAID to determine deliveries.
Scenario 6D	(6D) Observed Historic FULL MTN PARK and LAID with Seniority	Demands operate based on historic uses. Missing demand values are filled with average historical demands (water user will have no demand for years prior to date of permit issue). Reservoir targets are historic contents. Mtn Park demand at 16,100 AFY, LAID as allowed by Operational Rules.
Scenario 3A	(3A) Current or Full use of Current Permit scenario	Permit amount used for all water users for all simulation years with Water Rights enforced.
Scenario 3B	(3B) Current or Full use of Current Permit scenario with Seniority	Permit amount used for all water users for all simulation years with Seniority
Scenario 3C	(3C) Current or Full use of Current Permit scenario and LAID Operations	Permit amount used for all water users for all simulation years. This run includes LAID operations.
Scenario 3D	(3D) Current or Full use of Current Permit scenario with Seniority and LAID Operations	Permit amount used for all water users for all simulation years with Seniority with LAID operations
Scenario 4A	(4A) 2060 (OCWP Projected Growth)	Permit amount used for all water users for all simulation years with Water Rights enforced.
Scenario 4B	(4B) 2060 (OCWP Projected Growth) with	Permit amount used for all water users for all simulation

Scenario	Model Options	Model Settings Description
	Seniority	years with Seniority
Scenario 4C	(4C) 2060 (OCWP Projected Growth)	Permit amount used for all water users for all simulation years with Water Rights enforced. With LAID Operations
Scenario 4D	(4D) 2060 (OCWP Projected Growth) with Seniority	Permit amount used for all water users for all simulation years with Seniority with LAID Operations
Scenario 5A	(5A) Future (Base on Full Development under Existing Law/Rules)	Full Development: 0.59 AF/A (20 yr EPS), Fully permitted surface water
Scenario 5B	(5B) Future Full GW / Current SW with Seniority (Base on Full Development under Existing Law/Rules)	Full Development: 0.59 AF/A (20 yr EPS), Fully permitted surface water with Seniority
Scenario 5C	(5C) Future (Base on Full Development under Existing Law/Rules)	Full Development: 0.52 AF/A (40 yr EPS)
Scenario 5D	(5D) Future (Base on Full Development under Existing Law/Rules) with Seniority	Full Development: 0.52 AF/A (40 yr EPS) with Seniority
Scenario 5E	(5E) Future (Base on Full Development under Existing Law/Rules)	Full Development: 0.52 AF/A (50 yr EPS)
Sceanrio 5F	(5F) Future (Base on Full Development under Existing Law/Rules) with Seniority, Full use of Surface Permits	Full Development: 0.52 AF/A (50 yr EPS) with Seniority
Scenario 5G	(5G) Future (Base on Full Development under Existing Law/Rules) with LAID Operations	Full Development: 0.59 AF/A (20 yr EPS), Fully permitted surface water LAID Operations
Scenario 5H	(5H) Future Full GW / Current SW with Seniority (Base on Full Development under Existing Law/Rules)	Full Development: 0.59 AF/A (20 yr EPS), Currenet Surface Water uses (average) with Seniority with LAID Operations
Scenario 5I	(5I) Future (Base on Full Development under Existing Law/Rules)	Full Development: 0.52 AF/A (40 yr EPS) with LAID Operations
Scenario 5J	(5J) Future (Base on Full Development under Existing Law/Rules) with Seniority	Full Development: 0.52 AF/A (40 yr EPS) with Seniority with LAID Operations
Scenario 5K	(5K) Future (Base on Full Development under Existing Law/Rules)	Full Development: 0.52 AF/A (50 yr EPS) with LAID Operations
Scenario 5L	(5L) Future (Base on Full Development under Existing Law/Rules) with Seniority, Full use of Surface Permits	Full Development: 0.52 AF/A (50 yr EPS) with Seniority with LAID Operations
Scenario FYSTEED_A	(FYSTEED_A) Fully Permitted MPMCD Run 1	USBR Firm Yield for Tom Steed at 16,100 AFY Mountain Park Demand
Scenario FYSTEED_B	(FYSTEED_B) Fully Permitted MPMCD Run 2	USBR Firm Yield for Tom Steed at 13,900 AFY Mountain Park Demand
Scenario FYALTUS	(FYALTUS) Fully Permitted M&I for LAID	USBR Firm Yield for Lake Altus at 11,100 AFY LAID Demand

8.3. Scenario validation

8.3.1. Nash-Sutcliffe values for the stream gages in the historic validation scenario

Table 19 shows model validation statistics from the historical run. Nash-Sutcliffe values were calculated by comparing modeled gage flow with gaged flow for the periods when observed (not filled) data was available. Per the project scope, all gages are calibrated to a N-S value of >0.95. The high NSE values are due to the scenario chosen for comparison. The constrained historical scenario (Scenario 0) has very little operational flexibility since it is primarily for historical validation. Natural flows are developed from observed demands and reservoir contents, and the constrained historical scenario uses this same data. This method is intended to validate that all data is being used as expected and does not have any major errors or gaps.

Table 19. Final Nash-Sutcliffe Values of Gage Flow for Historical Model Run

USGS Gage	Gage Period	Nash-Sutcliffe	R-Squared
07300500 Salt Fork Red River at Mangum, OK	1953-2016	0.978	0.981
07301110 Salt Fork Red River near Elmer, OK	1979-2016	0.994	0.995
07301500 North Fork Red River near Carter, OK	1965-2016	1.000	1.000
07303000 North Fork Red River blw Altus Dam nr Lugert, OK	1977-2016	0.996	0.996
07303500 Elm Fork of North Fork Red River nr Mangum, OK	1965-1976	0.989	0.992
07304500 Elk Creek near Hobart, OK	1950-1993	1.000	1.000
07305000 North Fork Red River near Headrick, OK	1977-1993	0.994	0.995
07305500 West Otter Creek at Snyder Lk nr Mt Park, OK	1952-1993	0.999	0.999
07307028 North Fork Red River near Tipton, OK	1983-1993	0.965	0.974

8.3.2. Lugert-Altus Reservoir validation

Lugert-Altus Reservoir historic to modeled comparison has an R-squared value of 0.9996 (Figure 13).

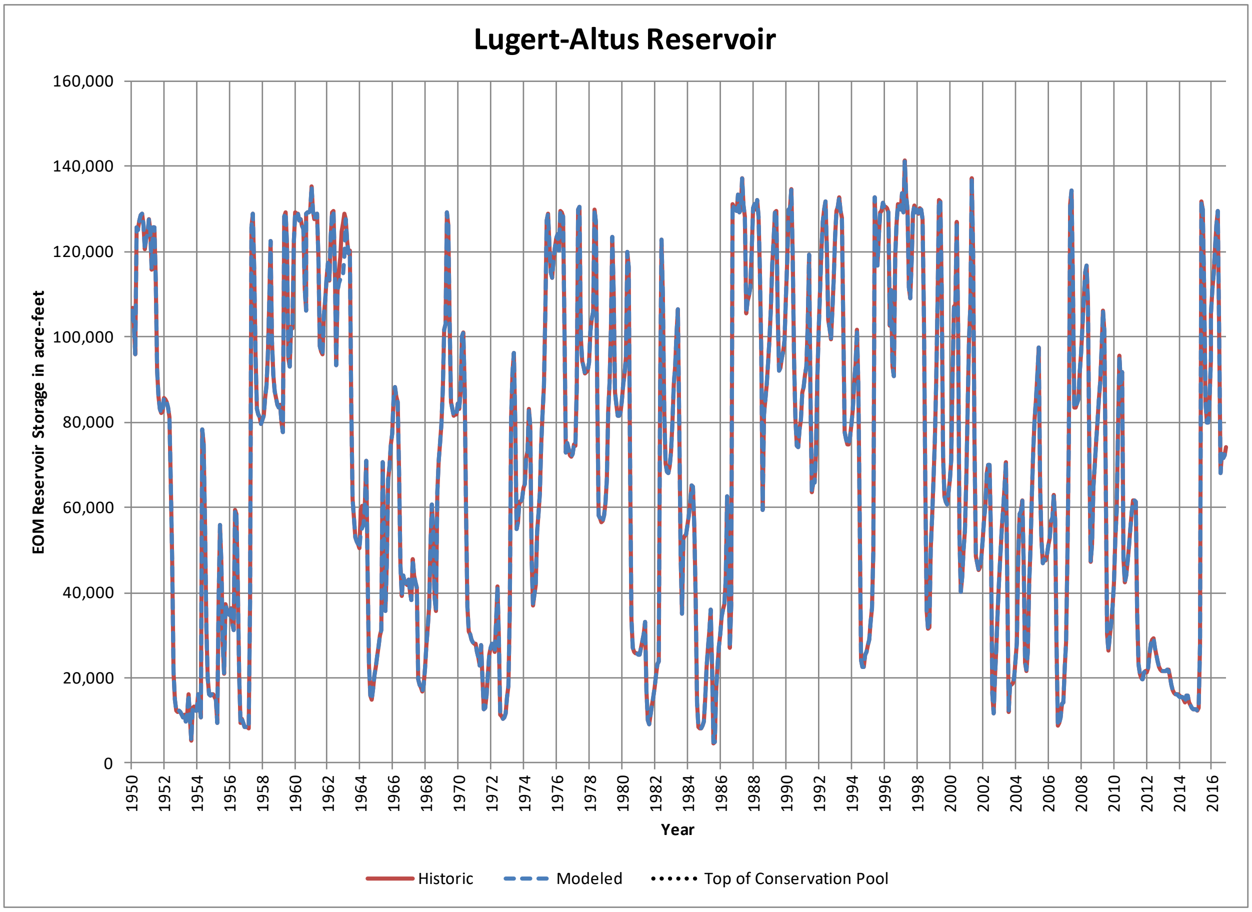

Figure 11. Observed vs modeled historic contents for Lugert-Altus Reservoir

8.3.3. Tom Steed Reservoir validation

Tom Steed Reservoir Historic to Modeled comparison has an R-squared value of 0.9999 (Figure 14).

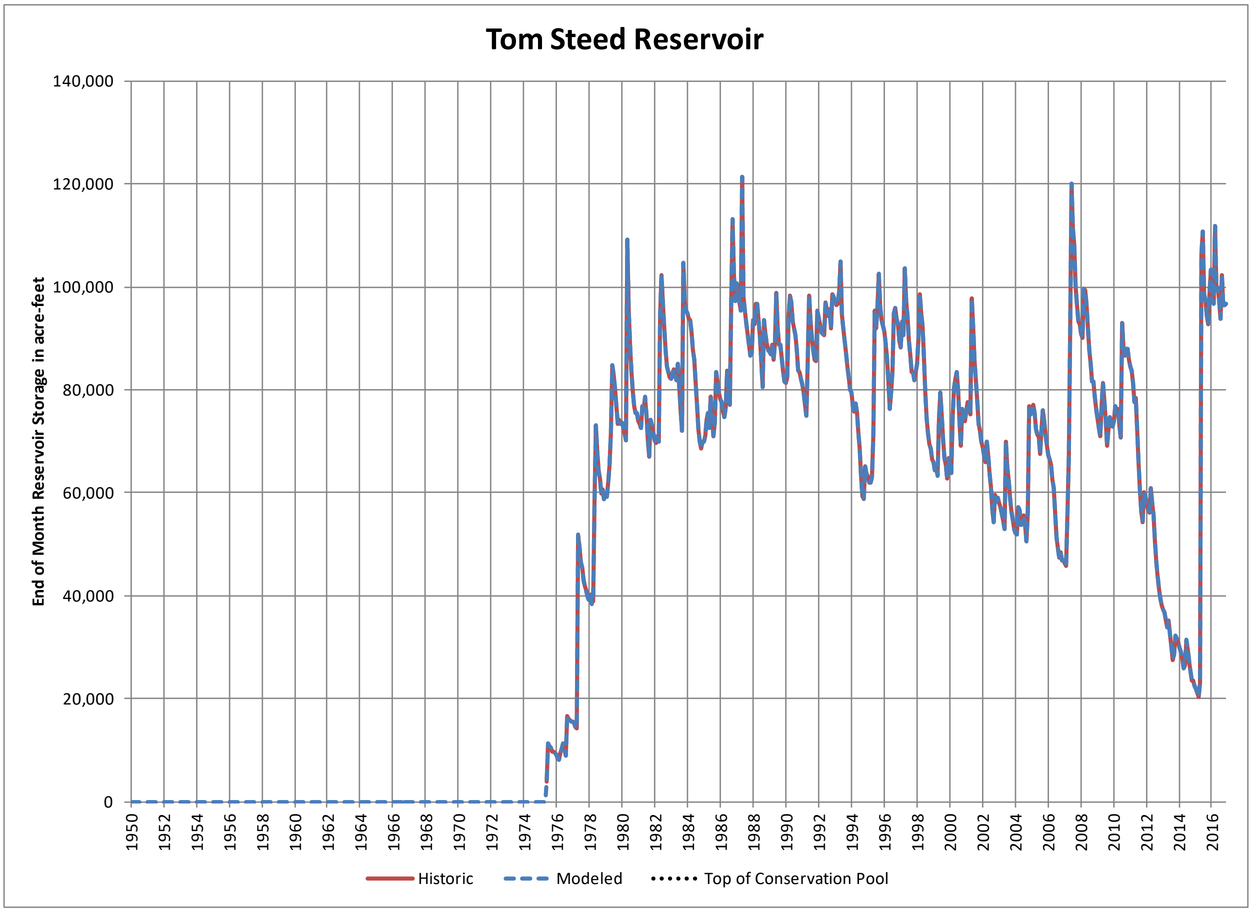

Figure 12. Observed vs modeled historic contents for Tom Steed Reservoir

9. Conclusion

In 2011 Lynker built a water resources model in CRAM to represent the hydrology, demands and system operations of the Red River basin in southwestern Oklahoma under a contract with the Oklahoma Water Resource Board (OWRB). This model, the North Fork of the Red River model (NFRR), included surface water, groundwater, canal and reservoir operations. OWRB provided Lynker with surface and groundwater demand data, reservoir area-volume-elevation curves, and inflow data to Tom Steed Reservoir. This data was used to calculate naturalized flow data for eight gages. Any incomplete gage records were filled using monthly linear regressions. In 2017, OWRB hired Lynker Technologies to update that model to extend the model period, incorporate new data and run additional model scenarios. The model was validated through a comparison of modeled gage and reservoir contents from the historical run.

One of the goals of this modeling work was to develop scenarios that could be used in direct comparison to an existing US Bureau of Reclamation (USBR) model. Several datasets were modified to match the assumptions in the USBR model including modified observed gage flows and elevation-area-volume curves. Lynker developed dozens of runs representing a range of future operations and groundwater development. The final model was validated against existing firm yield models developed by USBR and NFRR results will be incorporated into OWBR and USBR's planning process for the region.

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A-1 Appendix 1 – Flow Naturalization

USGS gage 07300500

USGS gage 07300500 is located on the Salt Fork Red River and was active from 1937 to present day. The naturalized watershed area is approximately 344 square miles, contains one permitted surface water depletion and 18 groundwater permits, and includes no major reservoirs. The stream gage has been operated continuously from October 1937 to present day. Since the upstream USGS gage 07300000 was operated from 1952 to present day, watershed was naturalized for that period according to the following formula.

$$07300500\ Naturalized\ Flow\ (Monthly\ AcreFt\ per\ sqmi) = \frac{\sum Stream\ Gage\ 07300500 + \ Depletions - \ Stream\ Gage\ 07300000}{Incremental\ area\ from\ 07300500\ to\ 07300000}$$

For the period prior to the operation of the upstream stream gage (January 1950 to December 1952), flows in the watershed were calculated using the areal unit natural flow from USGS stream gage 07300500. Figure A 1 shows the naturalized area for USGS gage 07300500.

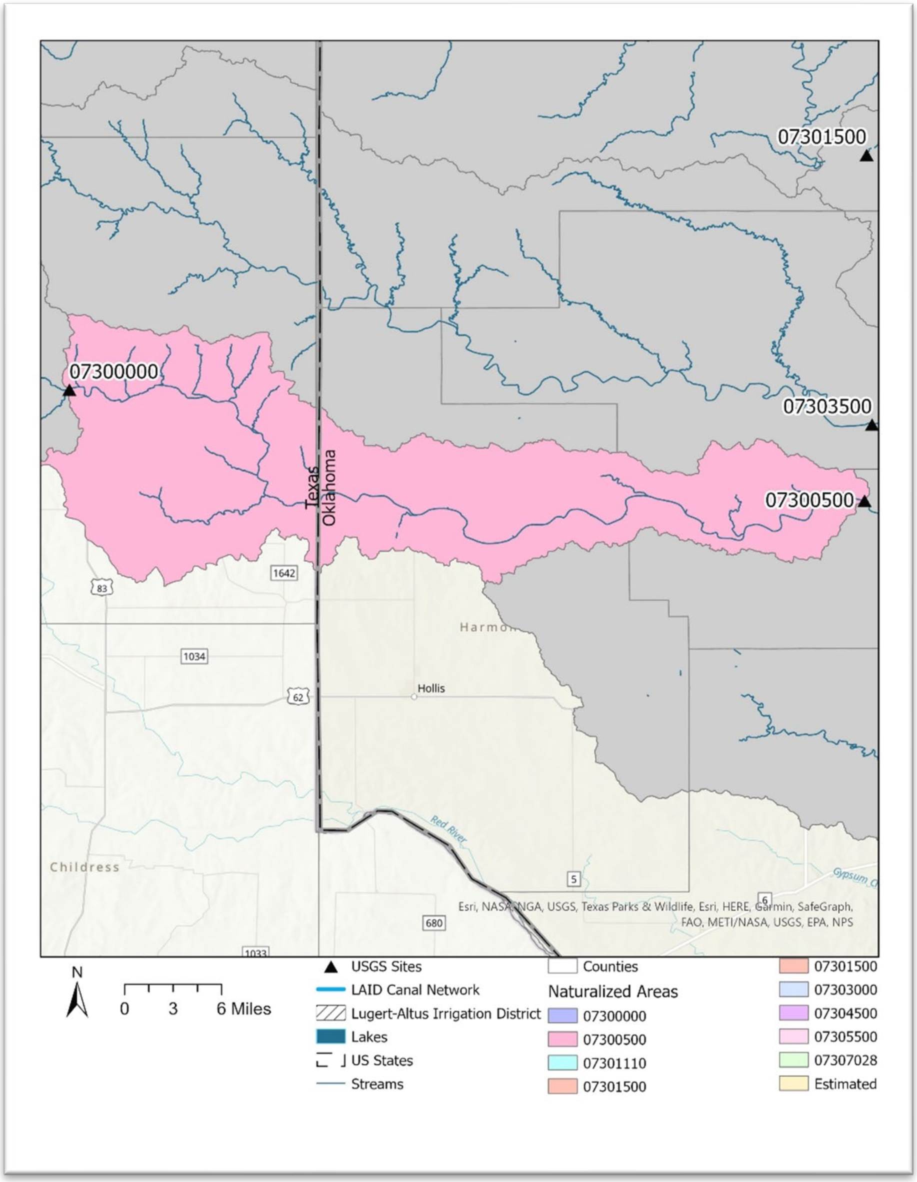

Figure A 1 USGS Stream 07300500 Naturalized Watershed

USGS gage 07301110

USGS stream gage 07301110 is located on the Salt Fork of the Red River with a naturalized watershed area of approximately 533 square miles. There are 19 permitted surface water permits and 87 groundwater permits within the naturalized watershed of USGS gage 07301110; approximately 60% of the land area of the Lugert-Altus Irrigation District falls within the naturalized watershed of this gage as well. Figure A 2 shows the naturalized watershed of USGS gage 07301110.

Gage 07301110 was naturalized by converting average daily USGS flow rates to monthly flow volumes in acre-feet. The upstream data from gage 07300500 was subtracted from the flow at gage 07301110. Monthly lagged return flows for the northwest and southwest portions of the Lugert-Altus Irrigation District were subtracted from the flow at gage 07301110. Section 6 has a discussion on calculation of Lugert-Altus Irrigation District return flows. The following equations were used to calculate naturalized flows for USGS gage 07301110.

$$\begin{aligned}
&07301110\ Naturalized\ Flow = \\
&\quad = \sum Stream\ Gage\ 07301110 - Stream\ Gage\ 07300500 \\
&\quad - Lagged\ Return\ flows\ to\ the\ Northwest\ and\ Southwest\ portions\ of\ the\ LAID \\
&\quad + Depletions
\end{aligned}$$

$$07301110\ Naturalized\ Flow\ (Monthly\ AcreFt\ per\ sqmi) = \frac{07301110\ Naturalized\ Flow}{Incremental\ area\ between\ 07301110\ to\ 07300500}$$

Streamflow data at USGS gage 07301110 was only available for the period from October 1979 to December 2011, so a linear regression was used to fill in monthly naturalized flow values for the years outside the period of record. Annual naturalized flows at USGS gages 07300500 and 07301110 were compared for the period of overlapping data (October 1979 to December 2011). The relationship between the two gages was used to predict the total annual runoff for the years with missing data for gage 07301110. The monthly naturalized flow for missing months was calculated by multiplying the predicted total annual runoff by the historical average percent of monthly flow at USGS gage 07301110 for the month being predicted.

$$\begin{aligned}
&07301110\ Naturalized\ Flow\ for\ missing\ months \\
&\quad = Total\ Annual\ flow\ predicted\ by\ regression\ with\ USGS\ gauge\ 07300500 \\
&\quad * Average\ percent\ of\ annual\ naturalized\ flow\ at\ gauge\ 07301110
\end{aligned}$$

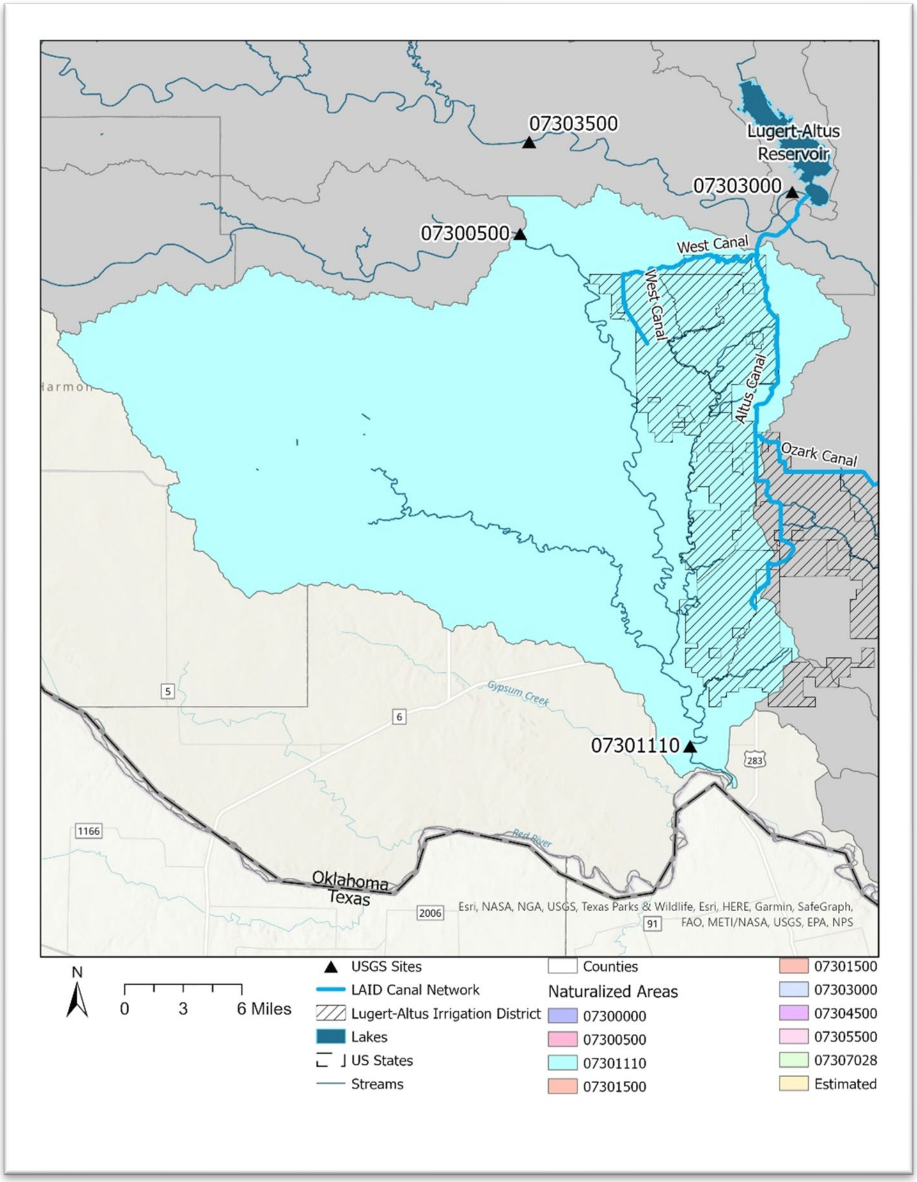

Figure A 2. USGS Stream gage 07301110 Naturalized Watershed

USGS gage 07301500

USGS gage 07301500 is located on the North Fork Red River and was active from 1944 to present day. The naturalized watershed area is approximately 2,050 square miles, contains seven permitted surface water depletion, 54 groundwater permits, and includes no major reservoirs. Figure A 3 shows the naturalized area for USGS gage 07301500.

$$07301500\ Naturalized\ Flow\ (Monthly\ AcreFt\ per\ sqmi) = \frac{\sum Stream\ Gage\ 07301500 + \ Depletions}{area\ above\ 07301500}$$

For the period prior to the operation of the upstream stream gage (January 1950 to December 1964), a linear regression was used to fill in monthly naturalized flow values. Annual naturalized flows at USGS gage 07301500 and the raw gage flows at 07301500 were compared for the period of overlapping data (January 1965 to December 2011). The relationship between the naturalized and raw flows was used to predict the total annual runoff for the years with missing naturalized flow data for gage 07301500. The monthly naturalized flow for missing months was calculated by multiplying the predicted total annual runoff by the historical average percent of monthly naturalized flow at USGS gage 07301500 for the month being predicted.

$$07301500\ Naturalized\ Flow\ for\ missing\ months$$
$$= \ Total\ Annual\ Naturalized\ Flow\ predicted\ by\ regression\ with\ raw\ flows\ at\ gauge\ 07301500$$
$$*\ Average\ percent\ of\ annual\ naturalized\ flow\ at\ gauge\ 07301500$$

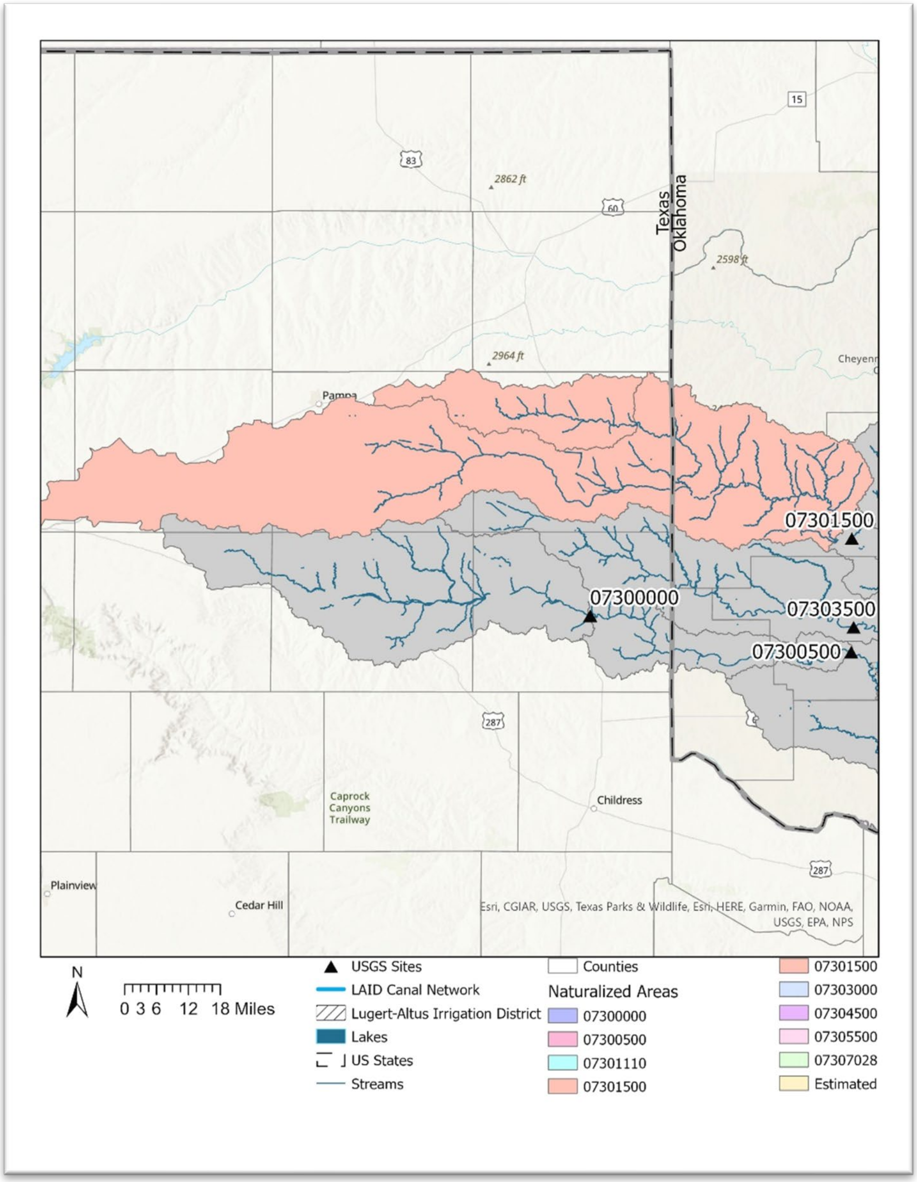

Figure A 3. USGS Stream gage 07301500 Naturalized Watershed

USGS gage 07303000

USGS stream gage 07303000 is located on the North Fork of the Red River with a naturalized watershed area of approximately 178 square miles and was active from October 1977 to present day. The upstream watershed contains Lake Altus, the diversion point of the Altus Main Canal, 5 permitted water demands and 137 groundwater permits. USGS gage 07303000 was naturalized by first subtracting the average daily flow from the upstream gage 07301500 and then converting average daily flow rates into monthly volumes. Increases in monthly reservoir storage were added to the stream gage and decreases in monthly reservoir storage were subtracted from the stream gage. Monthly evaporation from Lake Altus was added to the stream gage as were diversions by the Altus Main Canal, permitted water depletions and groundwater permits upstream of USGS gage 07303000. A map of the naturalized watershed is provided in Figure A 4.

$$\mathbf{07303000\ \mathit{Naturalized\ Flow}} = \sum Stream\ Gage\ 07303000 - Stream\ Gage\ 07301500 + Lake\ Altus\ Change\ in\ Storage + Lake\ Altus\ Evaporation + Depletions + Diversions\ by\ Altus\ Main\ Canal$$

$$\mathbf{07303000\ \mathit{Naturalized\ Flow}\ (\mathit{Monthly\ AcreFt\ per\ sqmi})} = \frac{07303000\ Naturalized\ Flow}{Incremental\ area\ between\ 07303000\ to\ 07301500}$$

For the period prior where data was not available for USGS gage 07303000 or the upstream gage 07301500 (January 1950 to September 1977), a linear regression was used to fill in monthly naturalized flow values. Annual naturalized flows at USGS gages 07303000 and 07305000 were compared for the period of overlapping data (October 1977 to December 2011). The relationship between the naturalized and raw flows was used to predict the total annual runoff for the years with missing naturalized flow data for gage 07303000. The mon7thly naturalized flow for missing months was calculated by multiplying the predicted total annual runoff by the historical average percent of monthly naturalized flow at USGS gage 07303000 for the month being predicted.

$$07303000\ Naturalized\ Flow\ for\ missing\ months = Total\ Annual\ Naturalized\ Flow\ predicted\ by\ regression\ with\ gauge\ 07305000 * Average\ percent\ of\ annual\ naturalized\ flow\ at\ gauge\ 07303000$$

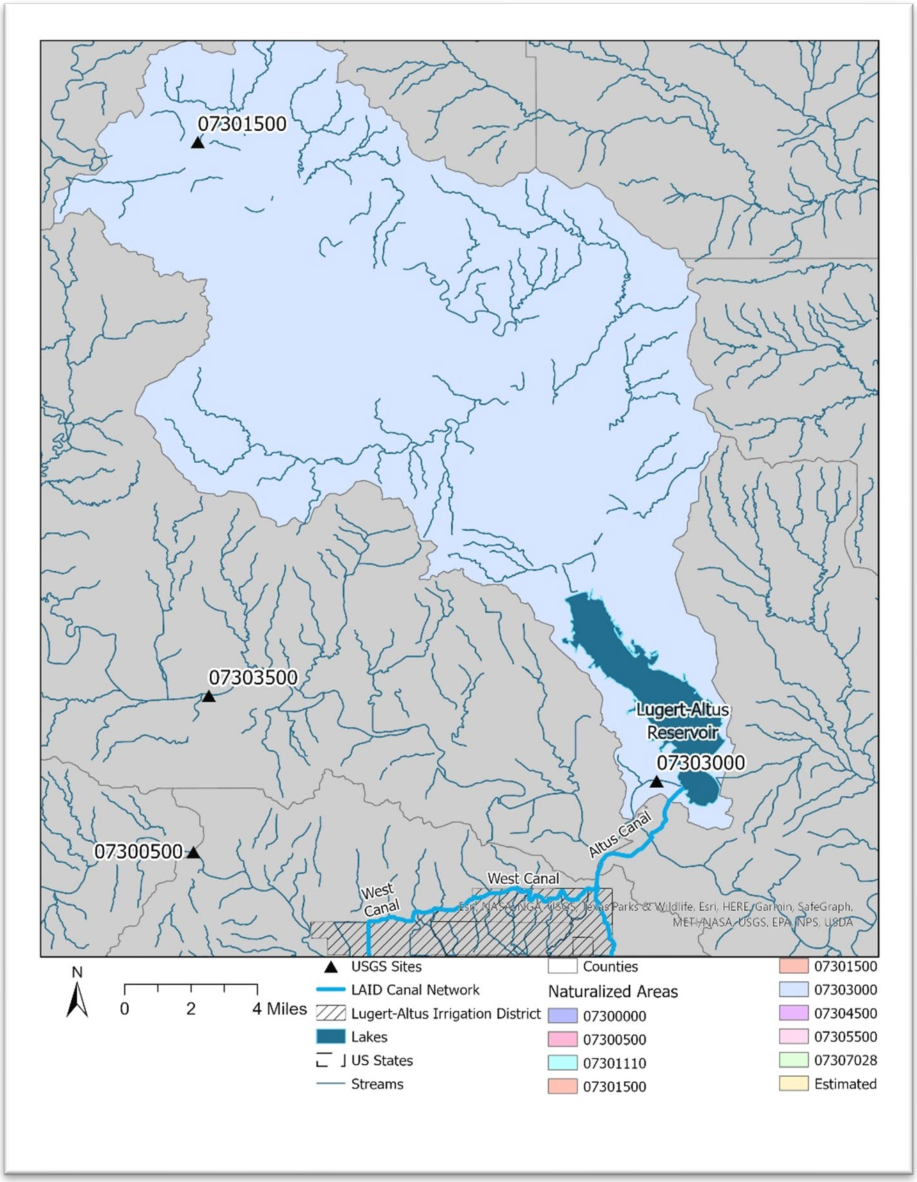

Figure A 4. USGS Stream gage 07303000 Naturalized Watershed

USGS gage 07304500

USGS gage 07304500 is located on Elk Creek in the North Fork Red River watershed and was active from 1950 to 1993. The naturalized watershed area is approximately 549 square miles, contains 11 permitted surface water depletions, 12 groundwater permits, and includes no major reservoirs. Figure A 5 shows the naturalized area for USGS gage 07304500. The watershed of USGS gage 07304500 was naturalized in two steps. Since the diversion records for the Bretch Canal were incomplete, the 07304500 was naturalized from 1950 to 1974 (prior to the construction of the Bretch Canal) according to the following formula.

$$07304500\ Naturalized\ Flow\ (Monthly\ AcreFt\ per\ sqmi) = \frac{\sum Stream\ Gage\ 07304500 + Depletions}{Watershed\ area\ of\ 07304500}$$

For the period when the Bretch Canal has been in operation (1975 to 2011), a linear regression was used to fill in monthly naturalized flow values. Monthly linear regressions were created for five different methods for filling the flows at Elk Creek and were compared in order to find the method with the best R-squared and the lowest RMSE. The five datasets each method used were:

- Natural flows at 07305500 (method described below)
- Gaged flows at 07305000
- Gaged flows at 07305000 minus gaged flows at 07303000 (removing Lake Altus operations)
- Monthly PRISM rainfall over the 07304500 basin
- Sentinel rain gage timeseries

After testing linear regressions using each of the 5 independent variables above, the best performing was found to be the gaged flows at 07303000 minus the gaged flows at 07305000. This independent variable was fit against calculated natural flows for the period where the two datasets overlapped (1950-1993). Once this linear regression was completed, additional constraints were added to the final set of natural flows to remove any mass balance and operational issues. The resulting formula for developing natural flows is the following:

$$07304500\ Naturalized\ Flow\ for\ missing\ months =$$

$$MAX(Bretch\ Canal\ Diversions + Total\ Upstream\ Demands, Natural\ Flow\ Data\ Developed\ from\ Monthly\ m * b - b\ regression, 0)$$

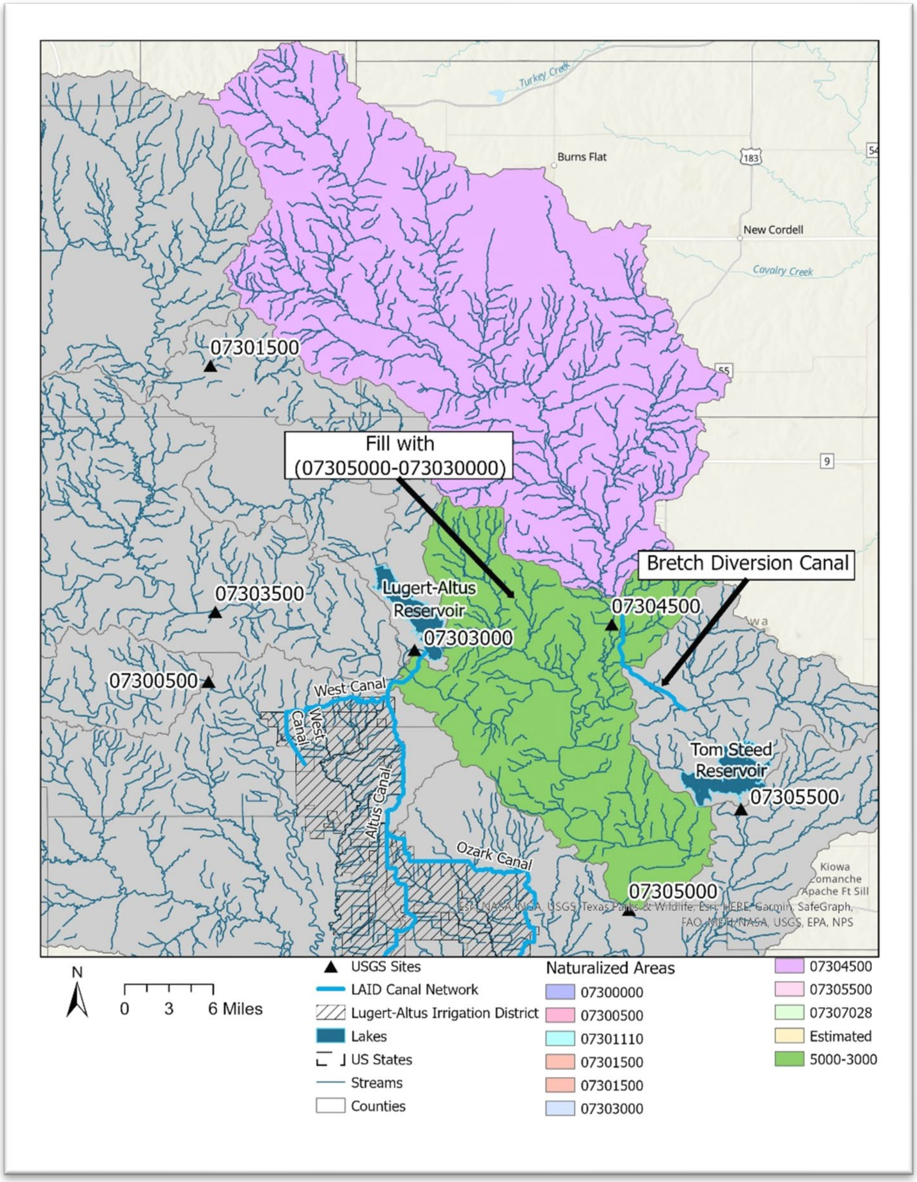

Figure A 5. USGS Stream gage 07304500 Naturalized Watershed

USGS gage 07305000

USGS gage 07305000 is located on the North Fork Red River and was active from 1905 to present day. The naturalized watershed area is approximately 1,160 square miles, 9 permitted surface water depletions, 80 groundwater permits, and includes no major reservoirs. Figure A 6 shows the naturalized area for USGS gage 07305000.

USGS gage 07305000 was naturalized by first subtracting the average daily flow from the upstream gages 07304500 and 07303000 and then converting average daily flow rates into monthly volumes. Monthly permitted water depletions and groundwater permits upstream pf the stream gage were added in.

Since the overlapping period of record for gage 07305000 and the upstream gages 07304500 and 07303000 was limited to October 1977 to September 1993, the watershed of USGS gage 07305000 was naturalized for that period according to the following formula.

$$
\begin{aligned}
07305000\ Naturalized\ Flow \\
&= \sum Stream\ Gauge\ 07305000 + \ Depletions - \ Stream\ Gauge\ 07304500 \\
&- Stream\ Gauge\ 07303000
\end{aligned}
$$

For the period where one or more upstream gages did not have data available (January 1950 to September 1977 and October 1977 to December 2011), a linear regression was used to fill in monthly naturalized flow values. Annual naturalized flows at USGS gage 07305000 and the raw gage flows at 07305000 were compared for the period of overlapping data (October 1977 to September 1993). The relationship between the naturalized and raw flows was used to predict the total annual runoff for the years with missing naturalized flow data for gage 07305000. The monthly naturalized flow for missing months was calculated by multiplying the predicted total annual runoff by the historical average percent of monthly naturalized flow at USGS gage 07305000 for the month being predicted.

$$
\begin{aligned}
&07305000\ Naturalized\ Flow\ for\ missing\ months \\
&= \ Total\ Annual\ Naturalized\ Flow\ predicted\ by\ regression\ with\ raw\ flows\ at\ gauge\ 07305000 \\
&* Average\ percent\ of\ annual\ naturalized\ flow\ at\ gauge\ 07305000
\end{aligned}
$$

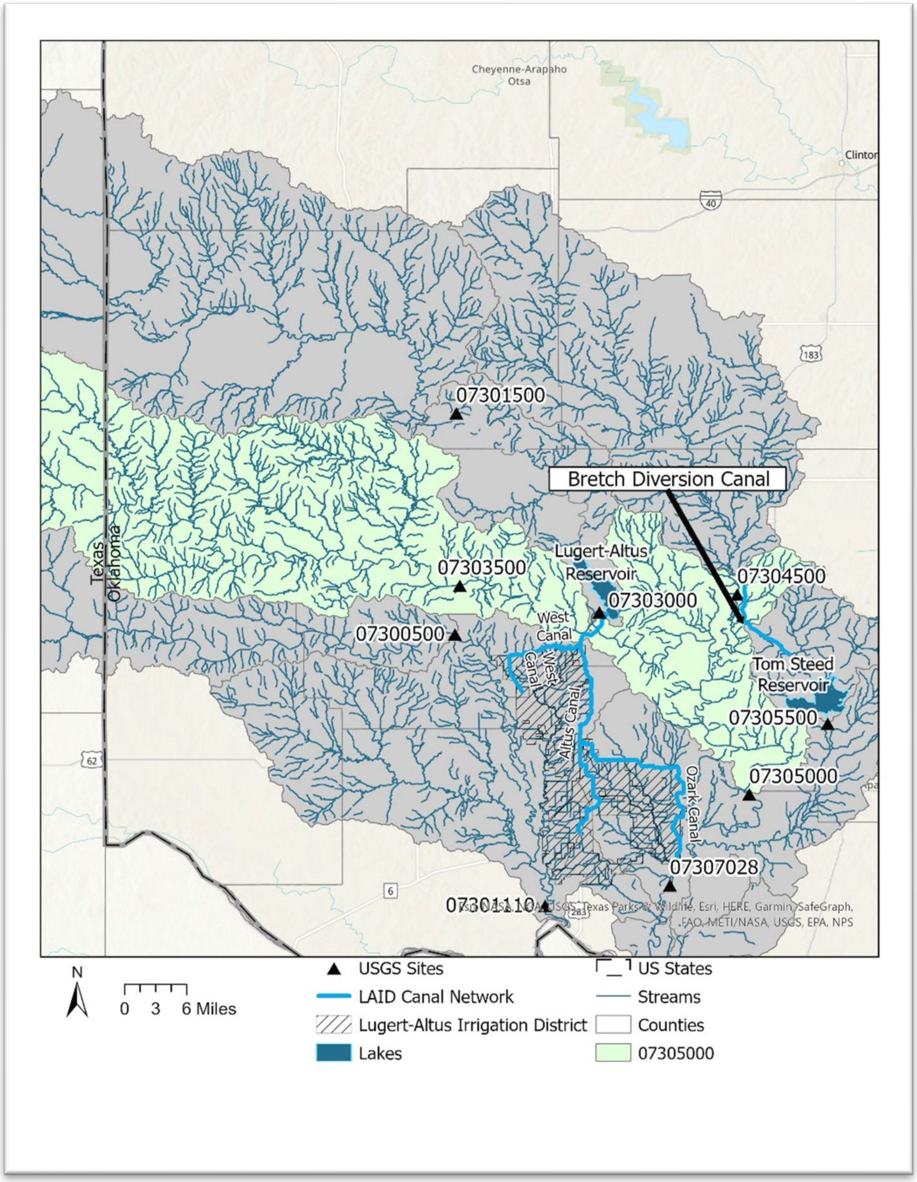

Figure A 6. USGS Stream gage 07305000 Naturalized Watershed

USGS gage 07305500

USGS stream gage 07305500 is located on West Otter Creek in the North Fork of the Red River watershed with a naturalized watershed area of approximately 132 square miles. Gage 07305500 was active from April 1903 through June 2003 though prior to 6/1975, that gage data is considered unreliable. USBR provided Lynker with an alternate set of gage data prior to 6/1975 based on a regression with a nearby rain gage.

The watershed upstream of 07305500 contains Tom Steed Reservoir, the delivery point of the Bretch Diversion Canal, 2 permitted water demands and 1 groundwater permit. USGS gage 07305500 was naturalized by converting average daily flow rates into monthly volumes. Increases in monthly reservoir storage were added to the stream gage and decreases in monthly reservoir storage were subtracted from the stream gage. Monthly evaporation from Tom Steed Reservoir was added and deliveries by the Bretch Diversion Canal were subtracted from the stream gage. Permitted water depletions and groundwater permits upstream of USGS gage 07305500 were added to the stream gage as well. A map of the naturalized watershed is provided in Figure A 7.

$$\mathbf{07305500\ \mathit{Naturalized\ Flow}} = \sum Stream\ Gage\ 07305500 + Tom\ Steed\ Reservoir\ Change\ in\ Storage + Tom\ Steed\ Reservoir\ Evaporation + Depletions - Bretch\ Canal\ Diversions$$

$$\mathbf{07305500\ \mathit{Naturalized\ Flow}\ (\mathit{Monthly\ AcreFt\ per\ sqmi})} = \frac{07305500\ Naturalized\ Flow}{Watershed\ area\ of\ 07305500}$$

Annual naturalized flows at USGS gage 07305000 and 07305500 were compared for 01/1950 to 6/1977. The relationship between 07305000 and 07305500 was used to predict the total annual runoff for 7/1975-12/2016 for gage 07305500. The monthly naturalized flow for missing months was filled in using the per-area naturalized flows at gage 07305000. These per-area flows were multiplied by the ratio of the average monthly flows between gages 07305500 and 07305000.

$$07305500\ Naturalized\ Flow\ for\ 7/1975 - 12/2016 = Monthly\ Naturalized\ Flow\ at\ 07305000 * \frac{Average\ monthly\ naturalized\ flow\ at\ gauge\ 07305500}{Average\ monthly\ naturalized\ flow\ at\ gauge\ 07305000}$$

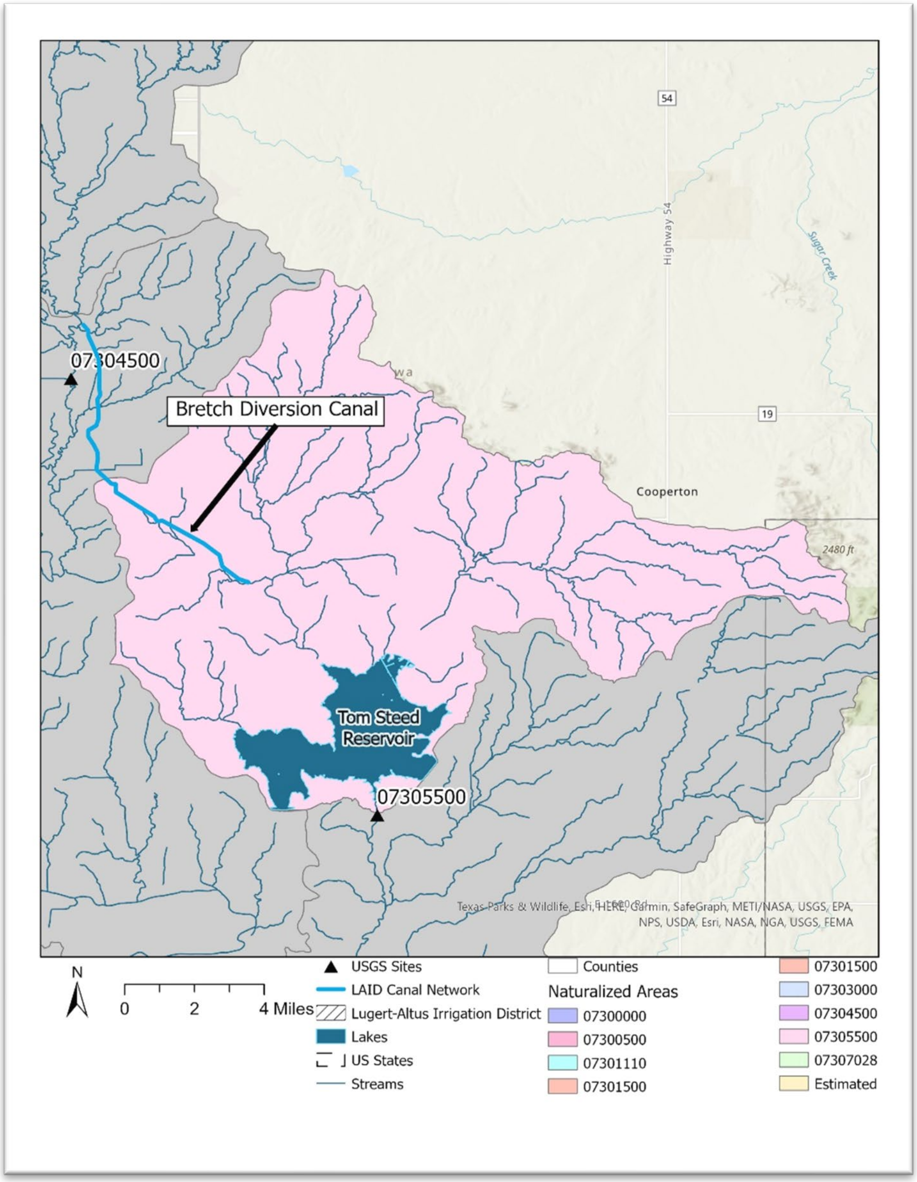

Figure A 7. USGS Stream gage 07305500 Naturalized Watershed

USGS gage 07307028

USGS stream gage 07307028 is located on the North Fork of the Red River with a naturalized watershed area of approximately 315 square miles. Gage 07307028 was active from 7/1983 to 12/2011 though data is missing for a short period from 10/1997-9/1998. There are 5 permitted surface water permits and 120 groundwater permits within the naturalized watershed of USGS gage 07307028; approximately 40% of the land area of the Lugert-Altus Irrigation District falls within the naturalized watershed of this gage as well. Figure A 8 shows the naturalized watershed of USGS gage 07307028.

Gage 07307028 was naturalized by converting average daily USGS flow rates to monthly flow volumes in acre-feet. The upstream data from gages 07305000 and 07305500 were subtracted from the flow at gage 07307028. Monthly lagged return flows for the portion of the Lugert-Altus Irrigation District were subtracted from the flow at gage 07307028 as well. Section 6 has a discussion on calculation of Lugert-Altus Irrigation District return flows. The following equations were used to calculate naturalized flows for USGS gage 07307028.

$$\mathbf{07307028\ \mathit{Naturalized\ Flow}} \\ = \sum Stream\ Gage\ 07307028\ - Stream\ Gage\ 07305000 \\ -\ Stream\ Gage\ 07305500 \\ - Lagged\ Return\ flows\ to\ the\ Southeast\ portion\ of\ the\ LAID +\ Depletions$$

$$\mathbf{07307028\ \mathit{Naturalized\ Flow}\ (\mathit{Monthly\ AcreFt\ per\ sqmi})} \\ = \frac{07307028\ Naturalized\ Flow}{Incremental\ area\ above\ 07307028\ and\ below\ 07305000\ and\ 07305500}$$

For the periods where data was not available for USGS gage 07307028 (1/1950-6/1983 and 10/1997-9/1998), linear regression was used to fill in monthly naturalized flow values. Two different linear regressions were used to fill in the different periods of missing data. Annual naturalized flows at USGS gage 07305500 and 07307028 were compared for 7/1983-12/2011. The relationship between 07305500 and 07307028 was used to predict the total annual runoff for 1/1950-6/1983 for gage 07307028.

Annual naturalized flows at USGS gage 07301110 and 07307028 were compared for 7/1983-12/2011 as well. The relationship between 07301110 and 07307028 was used to predict the total annual runoff for 10/1997-9/1998 for gage 07307028. The monthly naturalized flow for missing months was calculated by multiplying the predicted total annual runoff by the historical average percent of monthly naturalized flow at USGS gage 07307028 for the month being predicted.

$$07307028\ Naturalized\ Flow\ for\ 1/1950 - 6/1983 \\ =\ Total\ Annual\ Naturalized\ Flow\ predicted\ by\ regression\ with\ gauge\ 07301110 \\ * Average\ percent\ of\ annual\ naturalized\ flow\ at\ gauge\ 07307028$$

$$07307028\ Naturalized\ Flow\ for\ 10/1997 - 9/1998$$
$$= Total\ Annual\ Naturalized\ Flow\ predicted\ by\ regression\ with\ gauge\ 07305500$$
$$* Average\ percent\ of\ annual\ naturalized\ flow\ at\ gauge\ 07307028$$

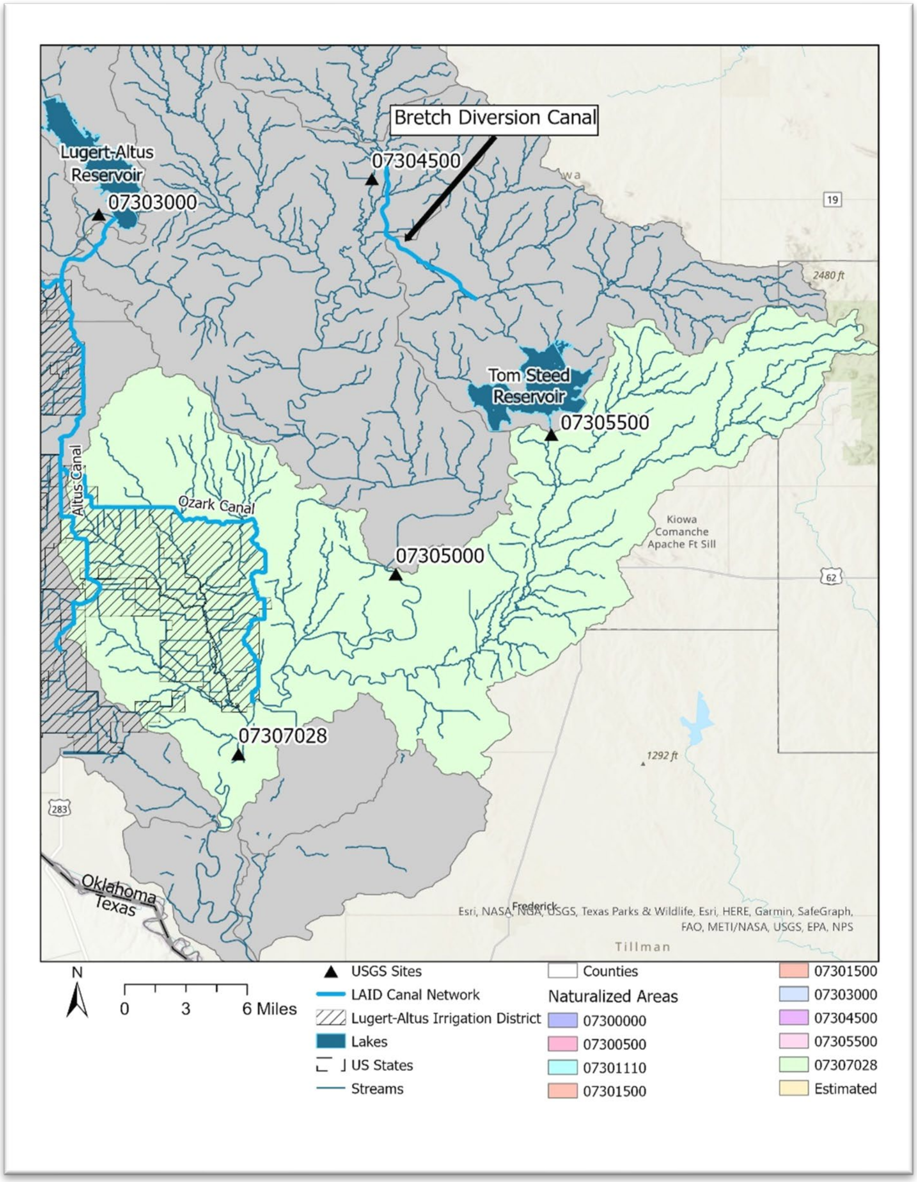

Figure A 8. USGS Stream gage 07307028 Naturalized Watershed

Downstream North Fork of the Red River Naturalization

The furthest downstream naturalized section of the North Fork of the Red River watershed did not have a stream gage from which to naturalize the watershed. Therefore, the areal unit naturalized flows (acre-foot/square mile) for the USGS Gage 07307028 was used every month of each year for these farthest downstream 12-digit hydrologic units. A map of the naturalized watershed is provided in Figure A 9.

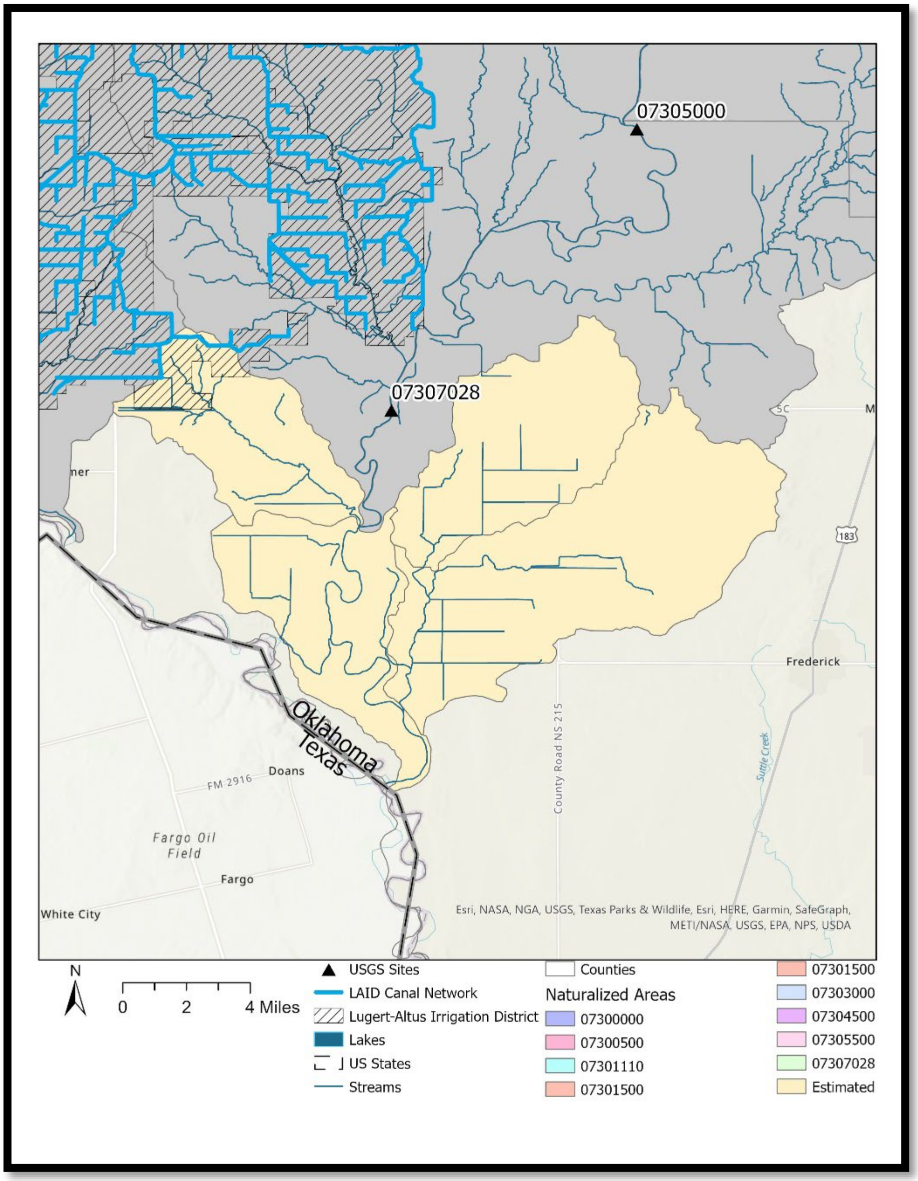

Figure A 9: Furthest Downstream Naturalized North Fork of the Red River Watershed

Naturalization Analysis

The areal naturalization values (acre-foot/square mile) from each of the naturalized stream gages were compared to analyze differences between the drainage areas within the North Fork of the Red River System. The results are presented in Table A-1, and a map of the average monthly area flow values is Figure A 10. The naturalized areal values cover a broad range, reflecting the varied hydrology of the study area, but some of the variability between gages is due to uncertainty about water use which results in error in the naturalization process.

In Table A-1, gage 07303000 appears to be an outlier with a very high naturalized flow per unit area. This discrepancy is likely caused due to the reporting accuracy on the large amount of water transferred out of that basin by the Altus Main Canal. Further discussion of the basin above gage 07303000 can be found below.

Table A 1: Average Monthly Areal Flow Values for North Fork of the Red River System

Month	Naturalized Stream gages (acre foot/square mile)							
	USGS Gage 07300500	USGS Gage 07301110	USGS Gage 07301500	USGS Gage 07303000	USGS Gage 07304500	USGS Gage 07305000	USGS Gage 07305500	USGS Gage 07307028
January	2.9	7.8	2.2	9.8	3.8	2.6	4.8	6.9
February	3.6	8.6	2.6	13.7	4.2	1.7	7.8	7.9
March	3.7	14.0	3.4	22.3	6.8	5.1	16.0	12.4
April	5.8	15.6	4.1	26.4	8.0	3.6	18.6	10.1
May	18.6	31.5	8.2	35.0	31.8	16.5	53.4	16.3
June	10.8	40.2	6.3	54.2	19.5	21.0	41.0	28.9
July	5.2	11.1	2.0	39.6	8.9	6.3	14.8	13.2
August	3.8	10.9	1.7	37.8	4.0	5.1	11.5	11.3
September	5.4	7.6	1.7	20.4	10.3	6.8	19.4	12.4
October	5.9	12.4	2.2	20.2	16.9	10.6	19.8	12.3
November	2.2	11.7	1.7	14.4	5.9	4.6	7.9	11.3
December	2.7	7.4	1.9	12.7	4.3	3.3	6.2	9.6
Average	**5.9**	**14.9**	**3.2**	**25.5**	**10.4**	**7.3**	**18.4**	**12.7**

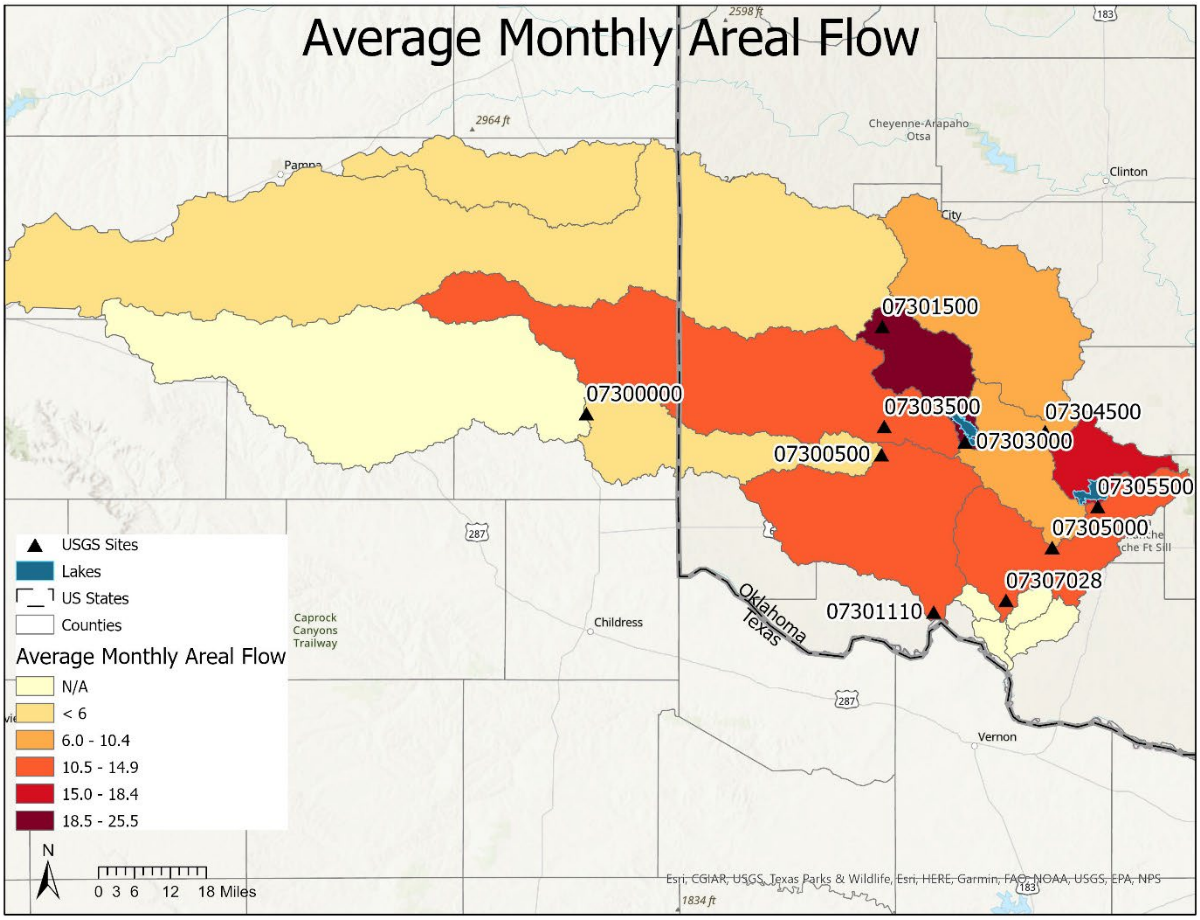

Figure A 10. Monthly Average Areal Flow values for each basin (blue) in af/sq

Comparing the naturalized gains per unit area across all the different gages shows behavior consistent with the annual patterns of local rainfall (PRISM 2012). Figure A-11 compares the annual pattern of naturalized gains with the pattern of annual precipitation. In this context, gains refer to runoff that occurs in the drainage area between the naturalized gage and the next gage upstream. Therefore, it is expected that exact patterns of naturalized gains will vary from basin to basin based on size, and local rainfall behavior. Although these gages cover a wide area, almost all hydrographs show the same bimodal behavior as the rainfall with peaks in early summer and early fall.

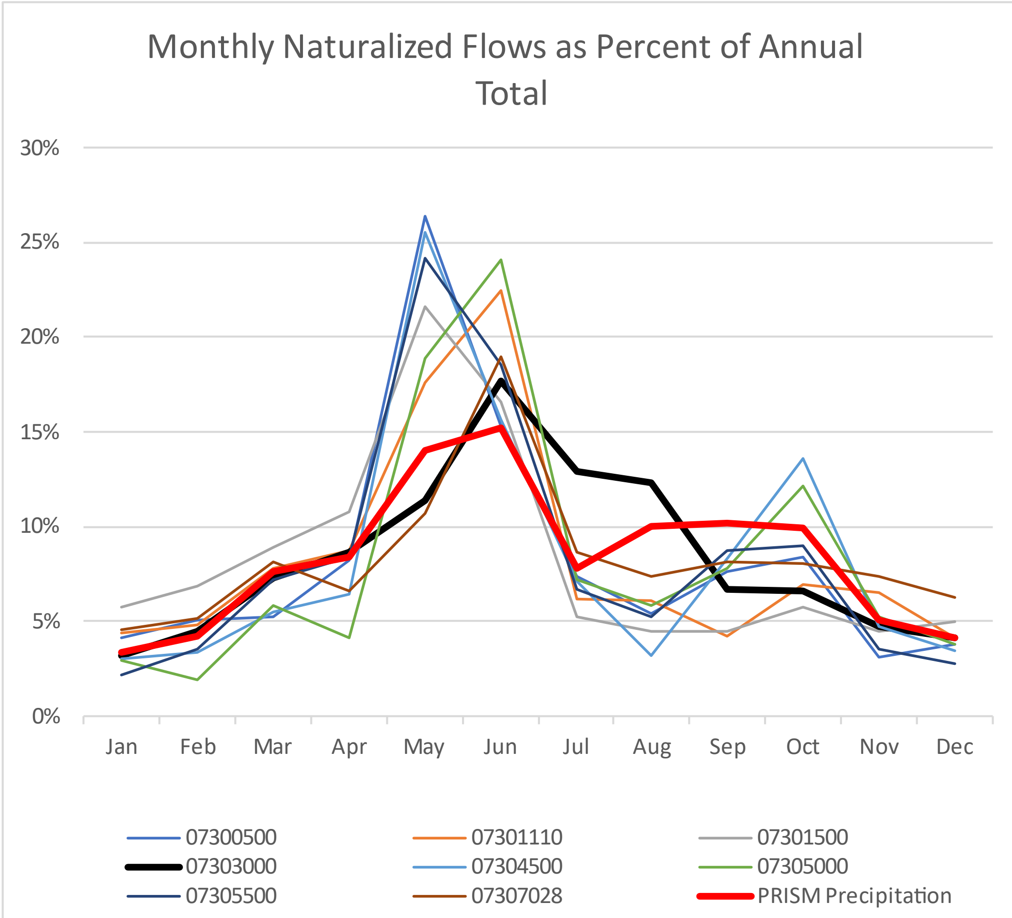

Figure A-11: Naturalized Flow as a Percent of Annual Totals for All Basins

Naturalized flows for gage 07303000 appear to be an outlier since they have no second peak in fall and show higher than normal flows during the irrigation season (June to September). This behavior is most likely caused by reporting accuracy for the various component flows and demands used in the naturalization process for the incremental drainage basin of 07303000.

Gains above gage 07303000 appear in a heavily managed basin that is impacted by diversions down the LAID canal as well as the operations of Lake Altus. Figure A 12 shows the monthly average hydrographs of the different components that are combined to produce the naturalized flows in the basin of gage 07303000. The most striking element of Figure A 12 is that the monthly change on storage in Lake Altus and the deliveries down the LAID canal are several times larger than the naturalized flows. In addition, the peak LAID diversions and volume change in Lake Altus occur during July and August. During July and August, the final naturalized flow at gage 07303000 is ~20% of the diversions by the LAID canal. Looking back at Figure A-11, July and August are the months where the relative naturalized flows for gage 07303000 vary from the two-peaked hydrograph seen at all other naturalized gages and in the pattern of local precipitation.

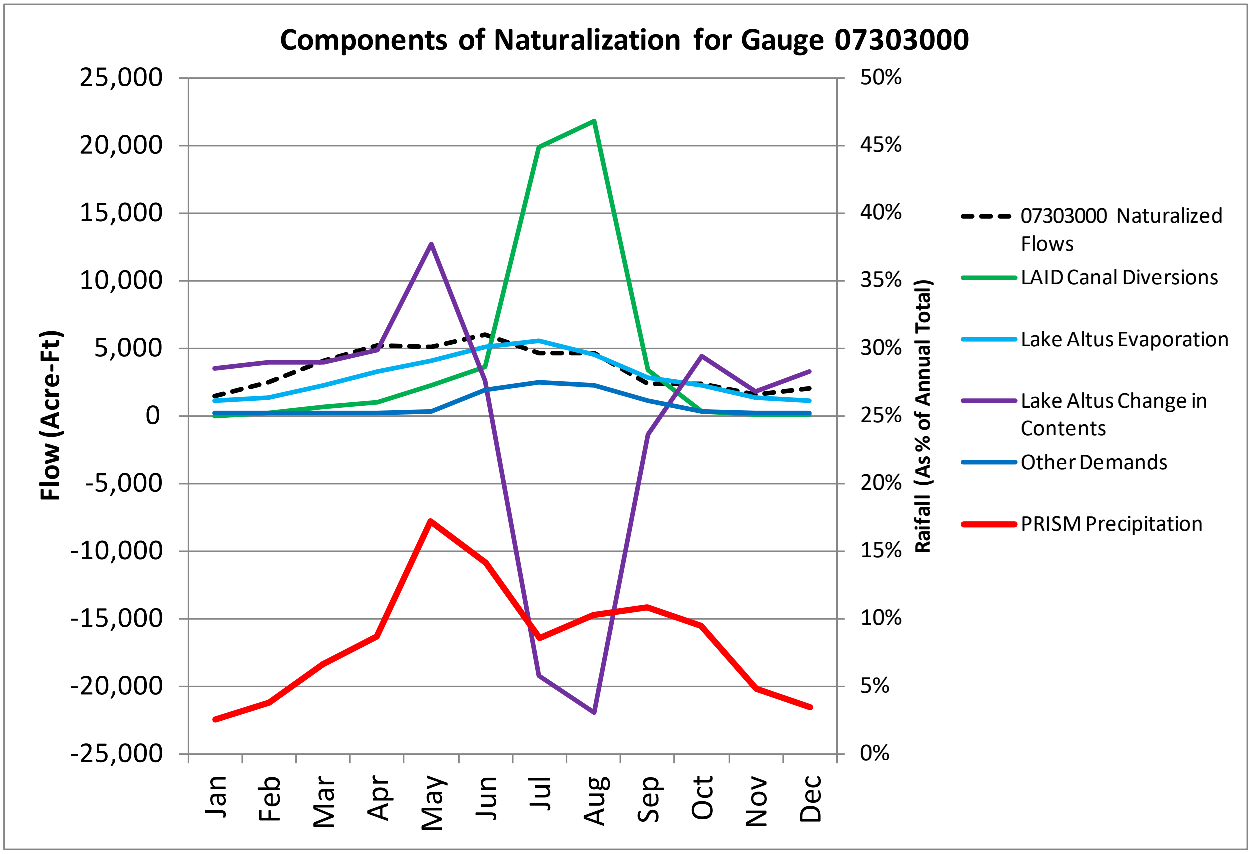

Figure A 12: Components of the Naturalization Process for Gage 07303000

Based on this information about the naturalization, a reasonable hypothesis for the variation in the naturalized gage flows at 07303000 is due to measurement accuracy for either the LAID canal diversions or the end of month contents at Lake Altus. A small variation in either of these measurements could lead to a large percentage change in the naturalized flows in this basin.

Although Figure A-11 shows there is a significant variation in the monthly percentage of flow at gage 07303000, Figure A 13 shows that the absolute magnitude of the gains at gage 07303000 are small enough to have only a minor impact on the behavior of the entire basin.

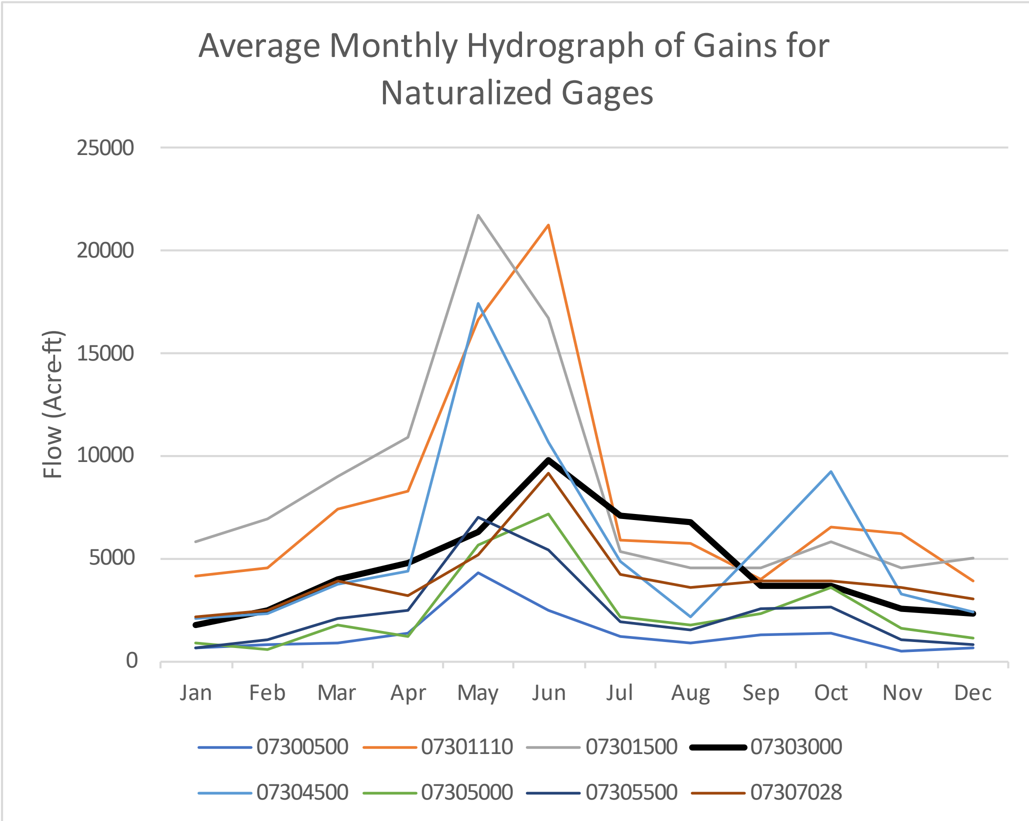

Figure A 13: Average Monthly Natural Flows at Naturalized Gages

Flow graphs

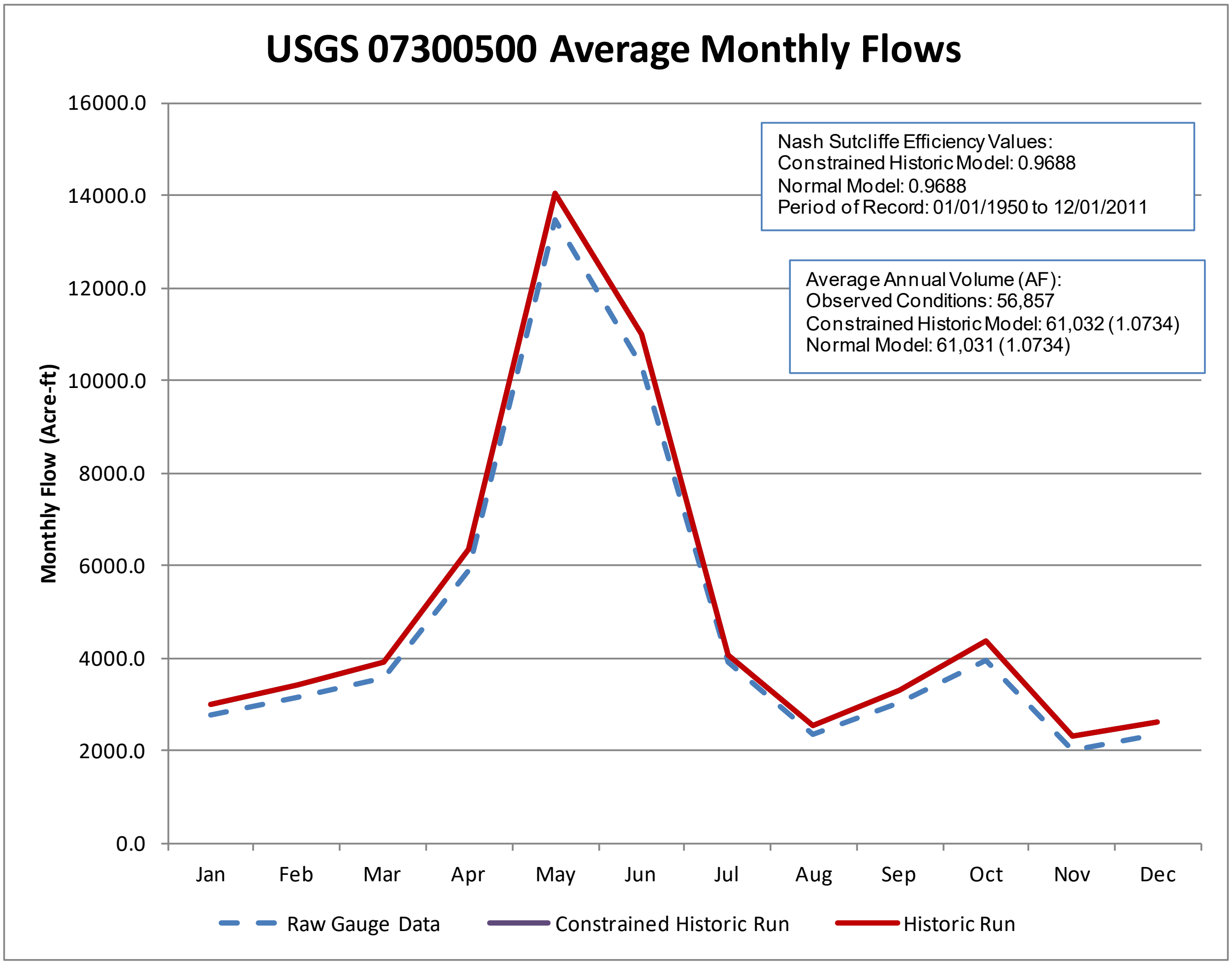

Figure A 14: Average Monthly Hydrograph for USGS 07300500

Notes: This gage was naturalized. It is a headwater gage influenced primarily by demands. Constrained historic run (purple) is directly behind the historic (red) line.

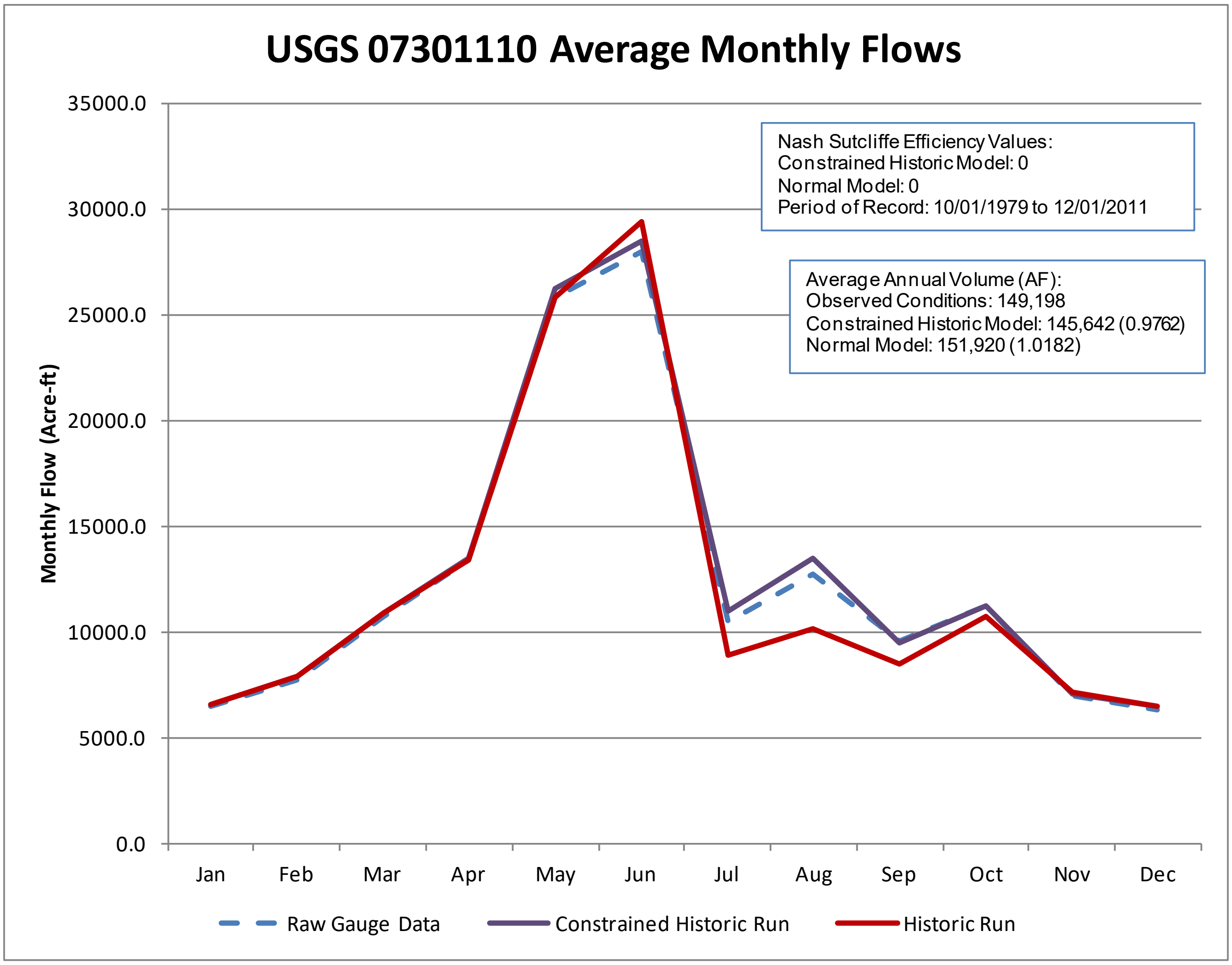

Figure A 15: Average Monthly Hydrograph for USGS 07301110

Notes: This gage was naturalized. It is influenced by return flows from the Lugert Altus Irrigation District. The estimated monthly average return flows from LAID irrigation to the watershed of this gage are 11% of the monthly average gage flow.

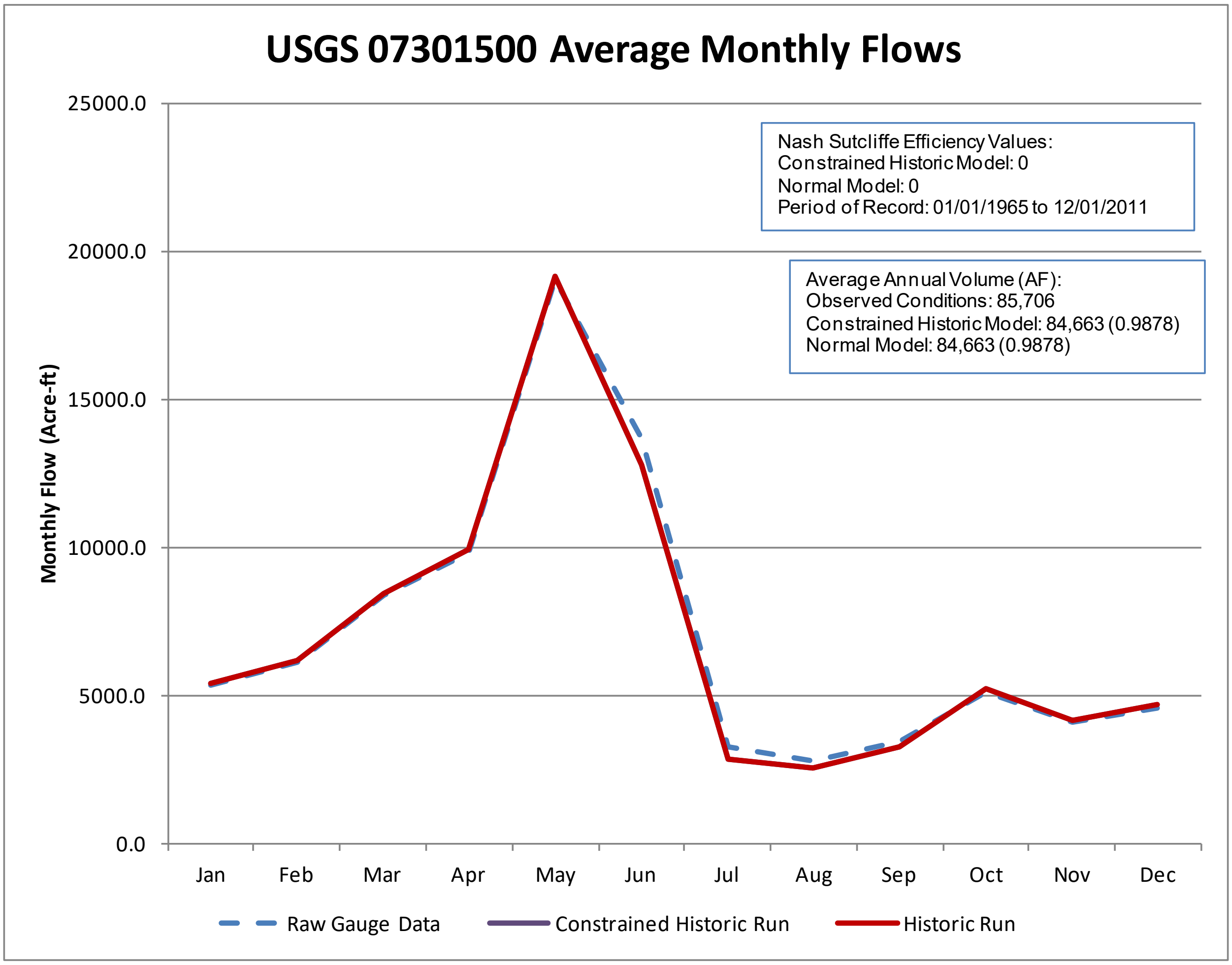

Figure A 16: Average Monthly Hydrograph for USGS 07301500

Notes: This gage was naturalized and is influenced primarily by upstream groundwater and surface water demands. Constrained historic run (purple) is directly behind the historic (red) line.

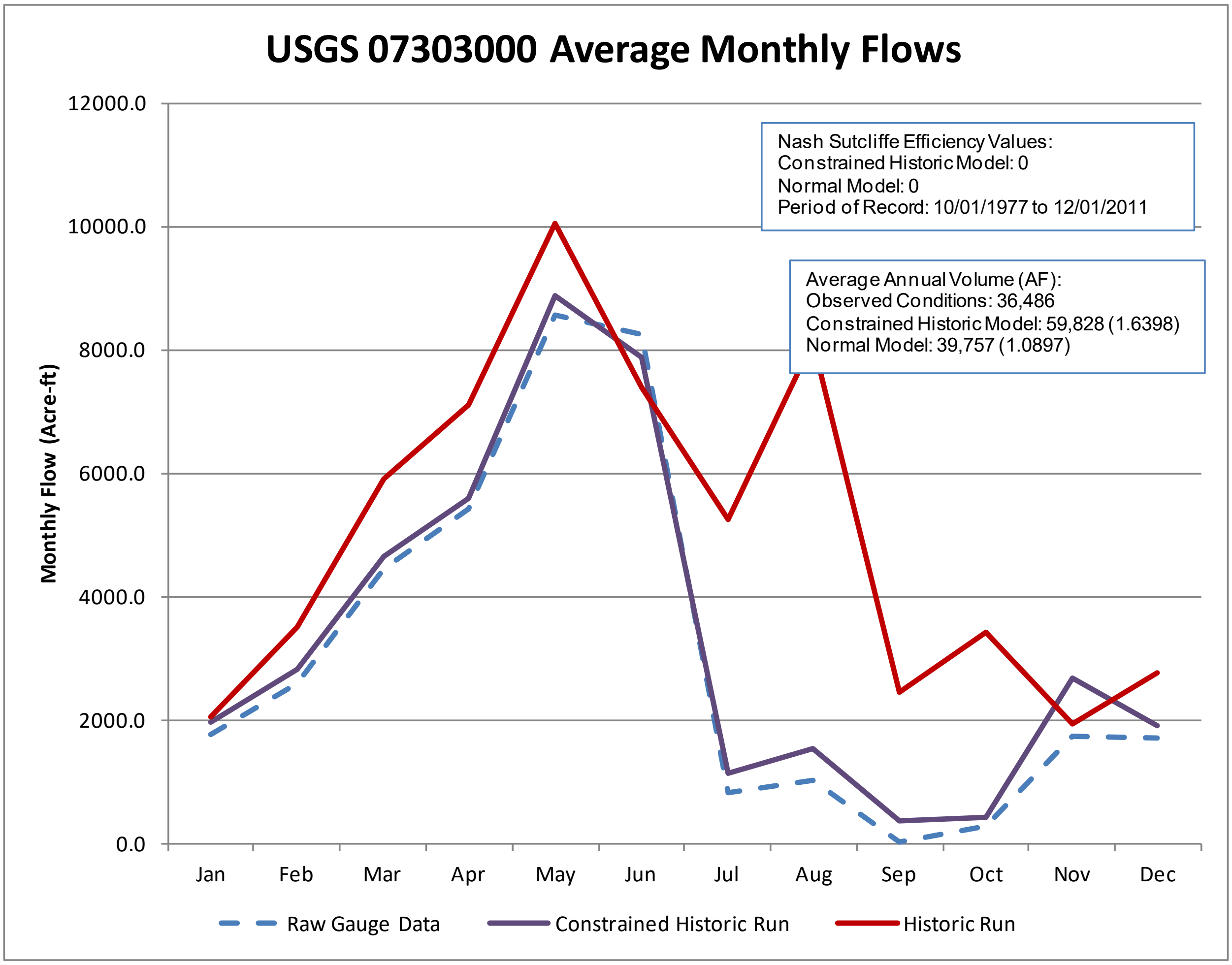

Figure A 17: Average Monthly Hydrograph for USGS 07303000

Notes: This gage was naturalized. It is influenced by Lake Altus and the Lugert Altus Irrigation District Canal. The average absolute value of monthly change in storage at Lake Altus is approximately 144% of monthly average gage flow, reservoir evaporation is approximately 94% of monthly average gage flow and average monthly diversions down the LAID canal are approximately 290% of monthly average gage flow.

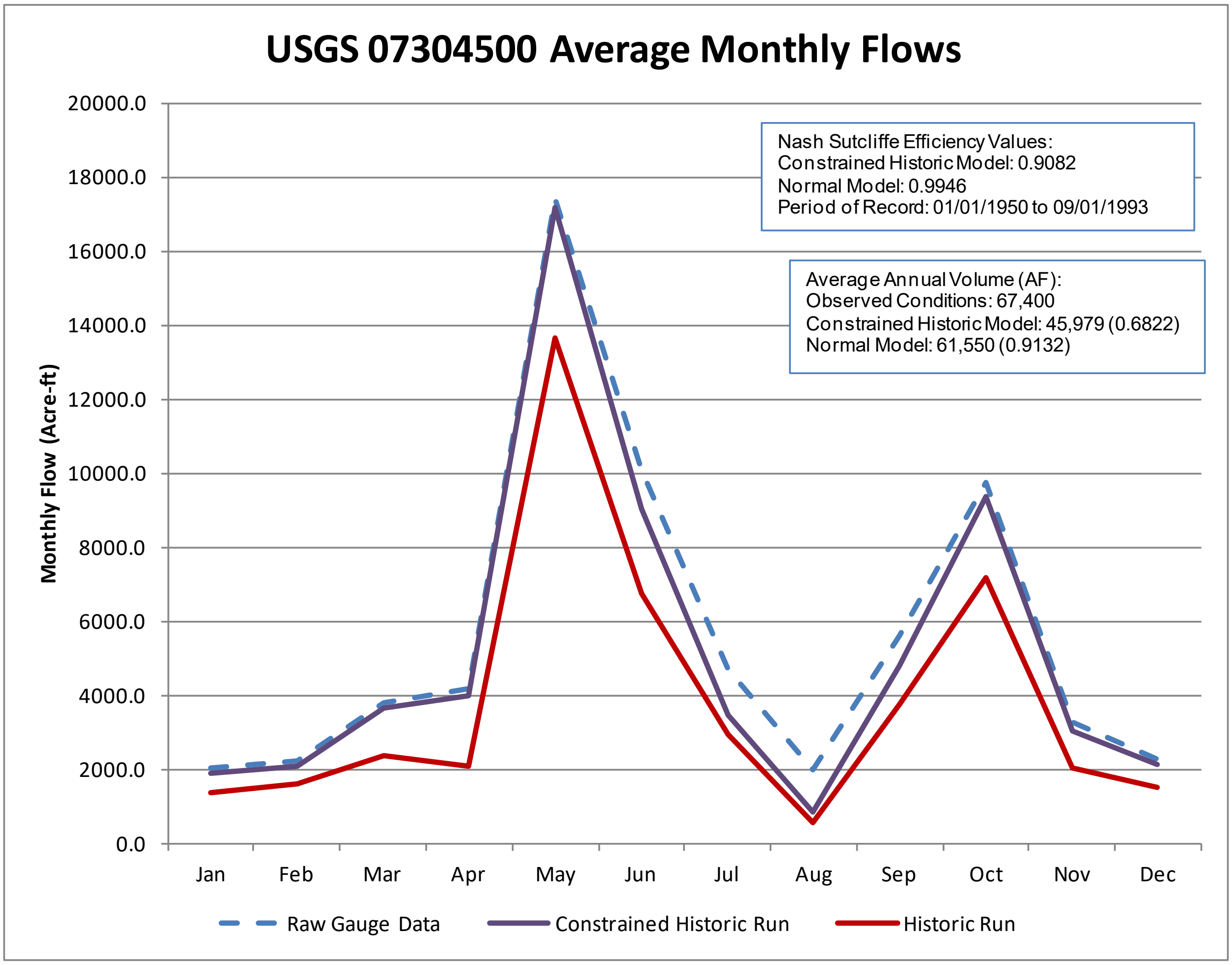

Figure A 18: Average Monthly Hydrograph for USGS 07304500

Notes: This gage was naturalized. It is influenced by diversions down the Bretch Canal. Average monthly diversions down the Bretch Canal are 21% of the average monthly gage flow.

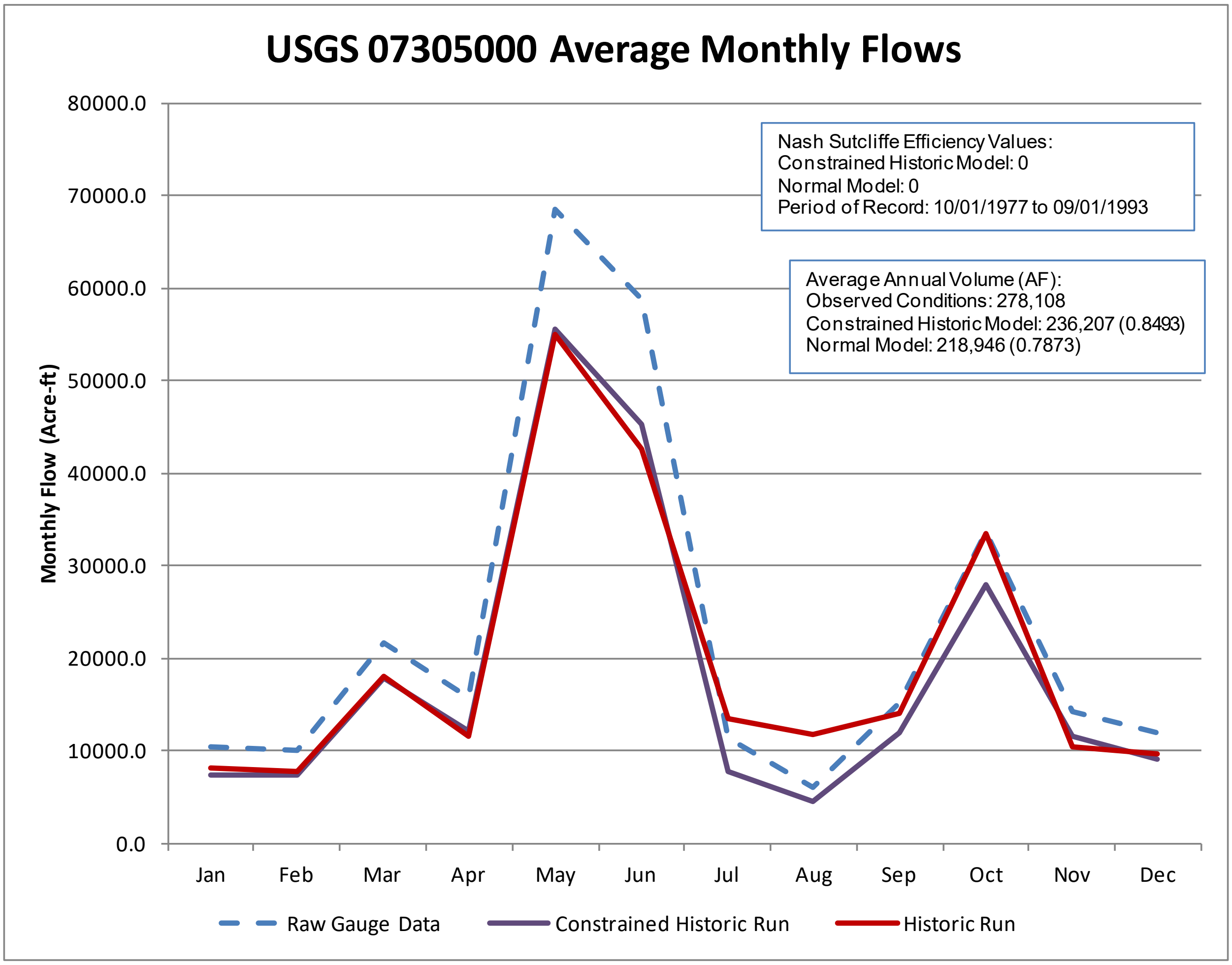

Figure A 19: Average Monthly Hydrograph for USGS 07305000

Notes: This gage was naturalized and is primarily influenced by surface and groundwater demands.

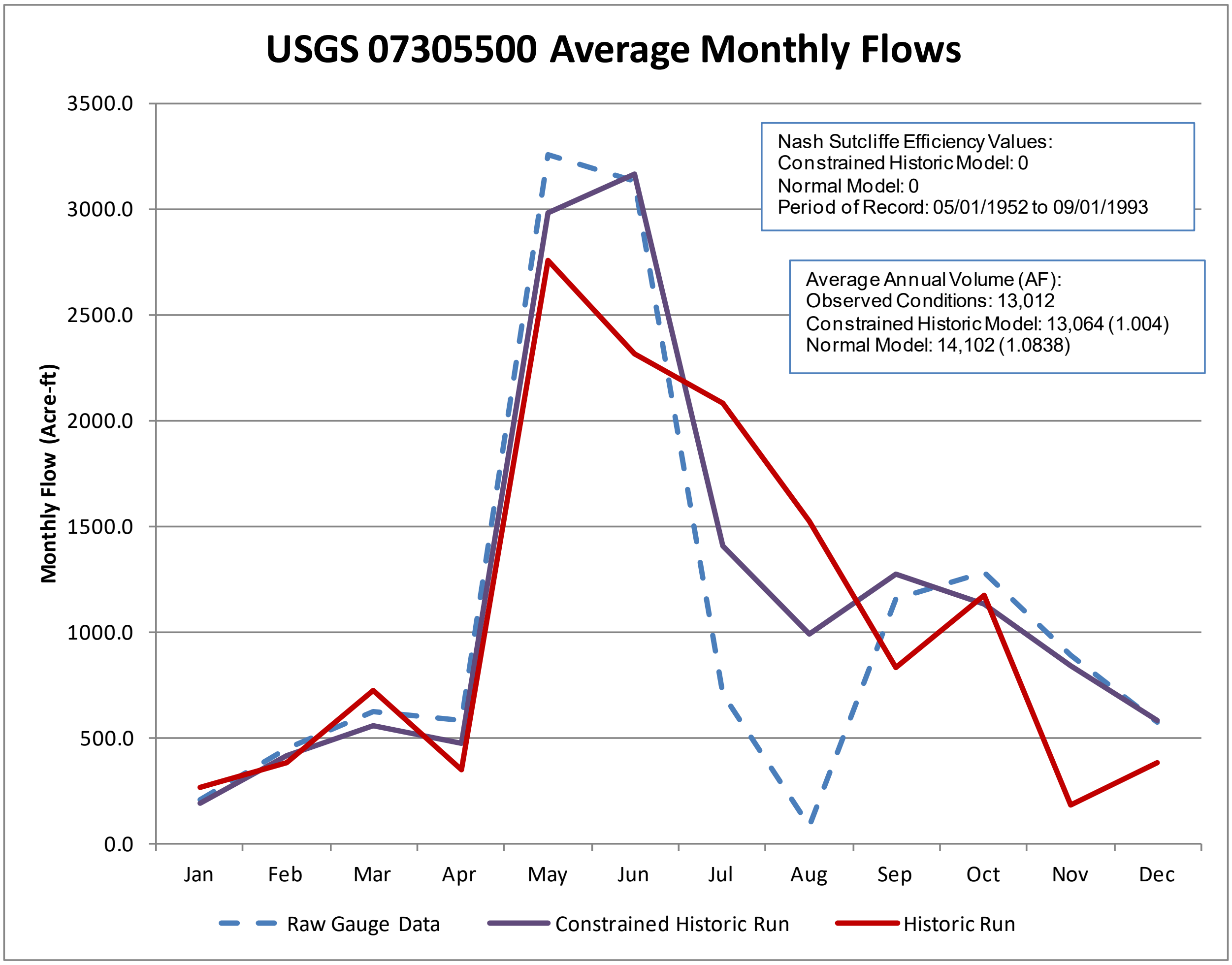

Figure A 20: Average Monthly Hydrograph for USGS 07305500

Notes: This gage was naturalized. The flows at this gage are influenced by Tom Steed Reservoir. Average monthly reservoir evaporation is 310% of gage flow, and the average absolute value of monthly change in reservoir storage is 370% of gage flow.

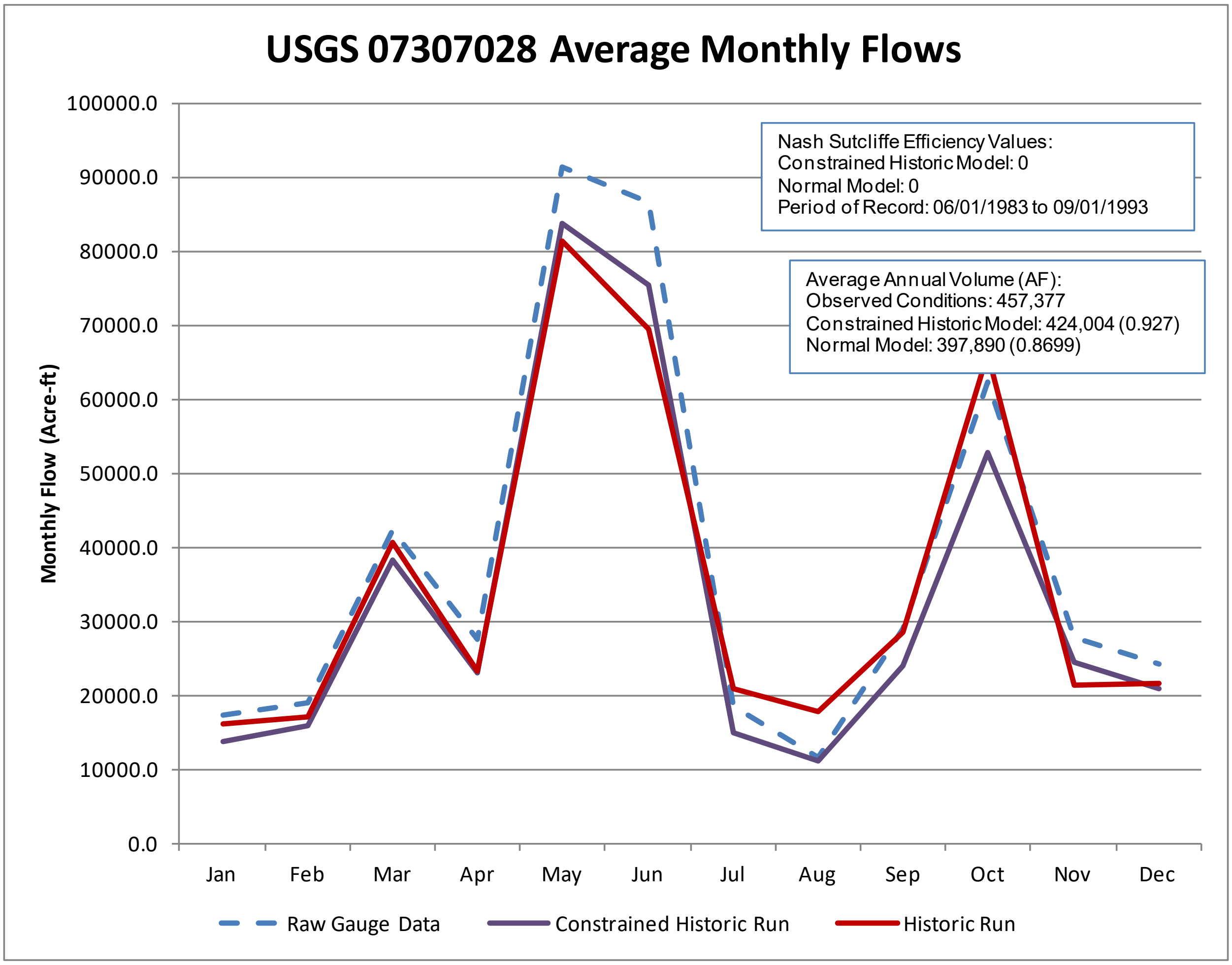

Figure A 21: Average Monthly Hydrograph for USGS 07307028

Notes: This gage was naturalized. This gage is influenced by return flows to the eastern portion of the Lugert Altus Irrigation District. Estimated average monthly return flows are 11% of average monthly gage flow.

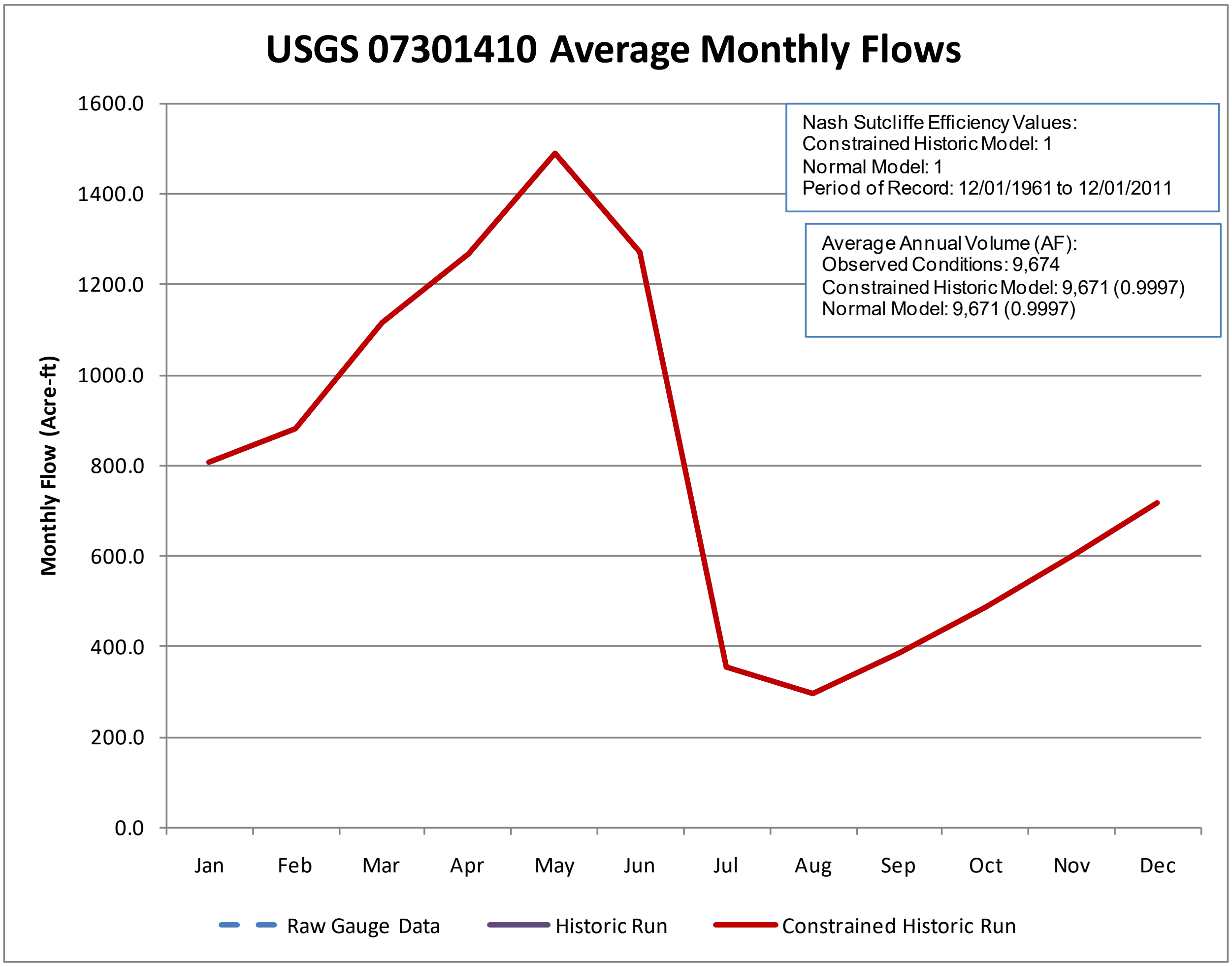

Figure A 22: Average Monthly Hydrograph for USGS 07301410

Notes: This gage was not naturalized. This gage represents inflows from Texas.

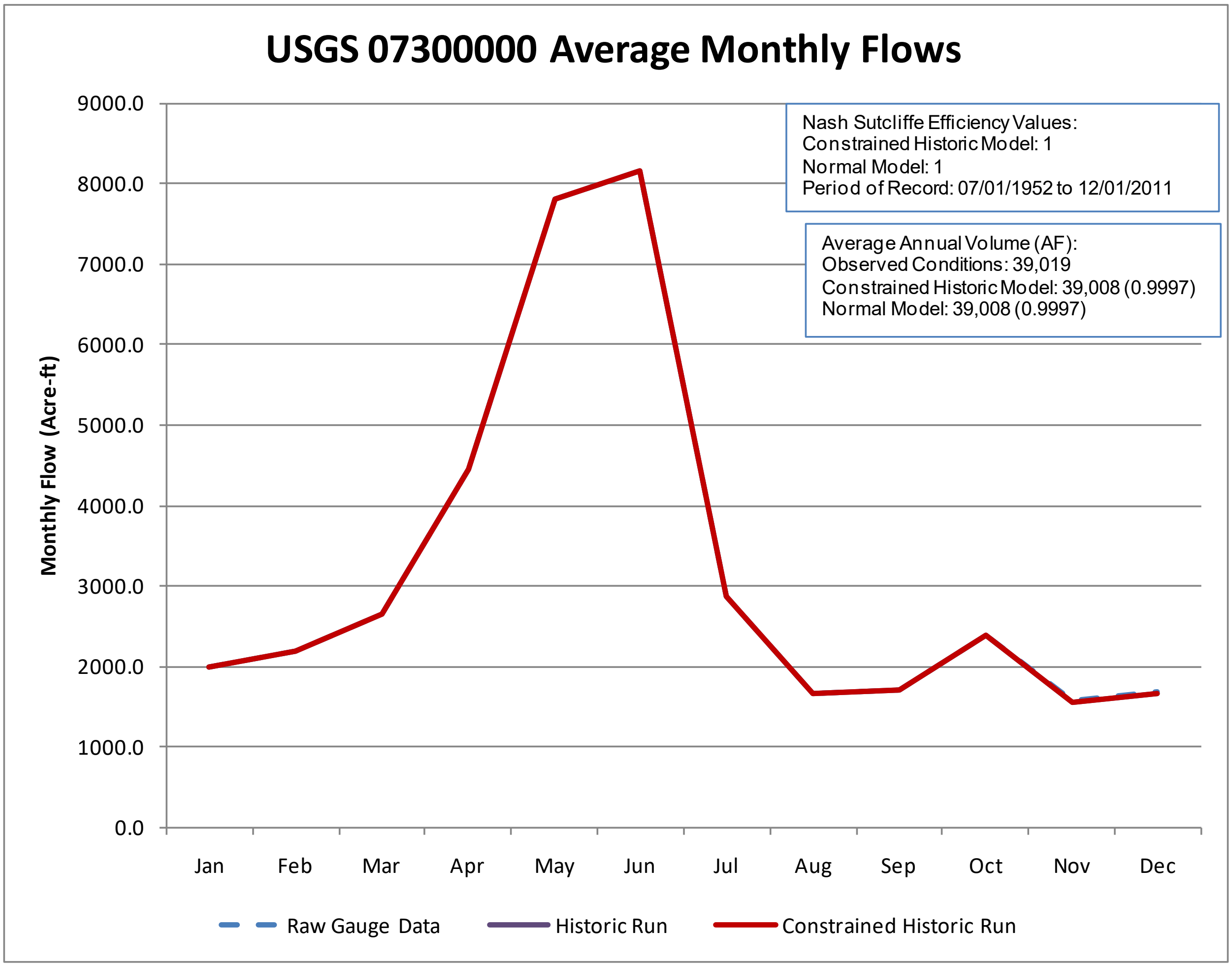

Figure A 23: Average Monthly Hydrograph for USGS 07300000

Notes: This gage was not naturalized. This gage represents inflows from Texas.

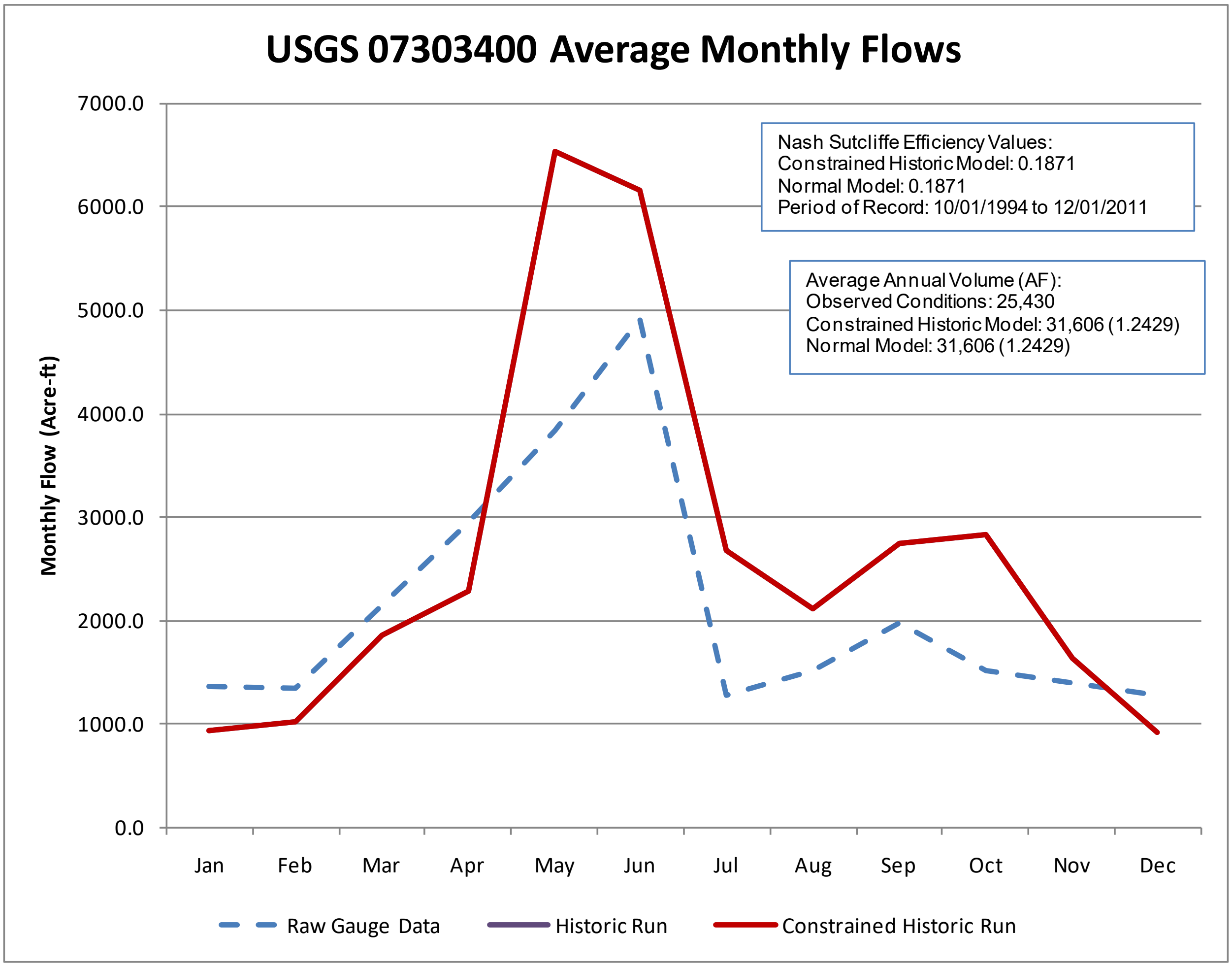

Figure A 24: Average Monthly Hydrograph for USGS 07303400

Notes: This gage was not naturalized; it was used as a validation gage. Discrepancies arise since the period of record of raw data does not match the period of record of raw data at the gages used to generate the modeled flows.

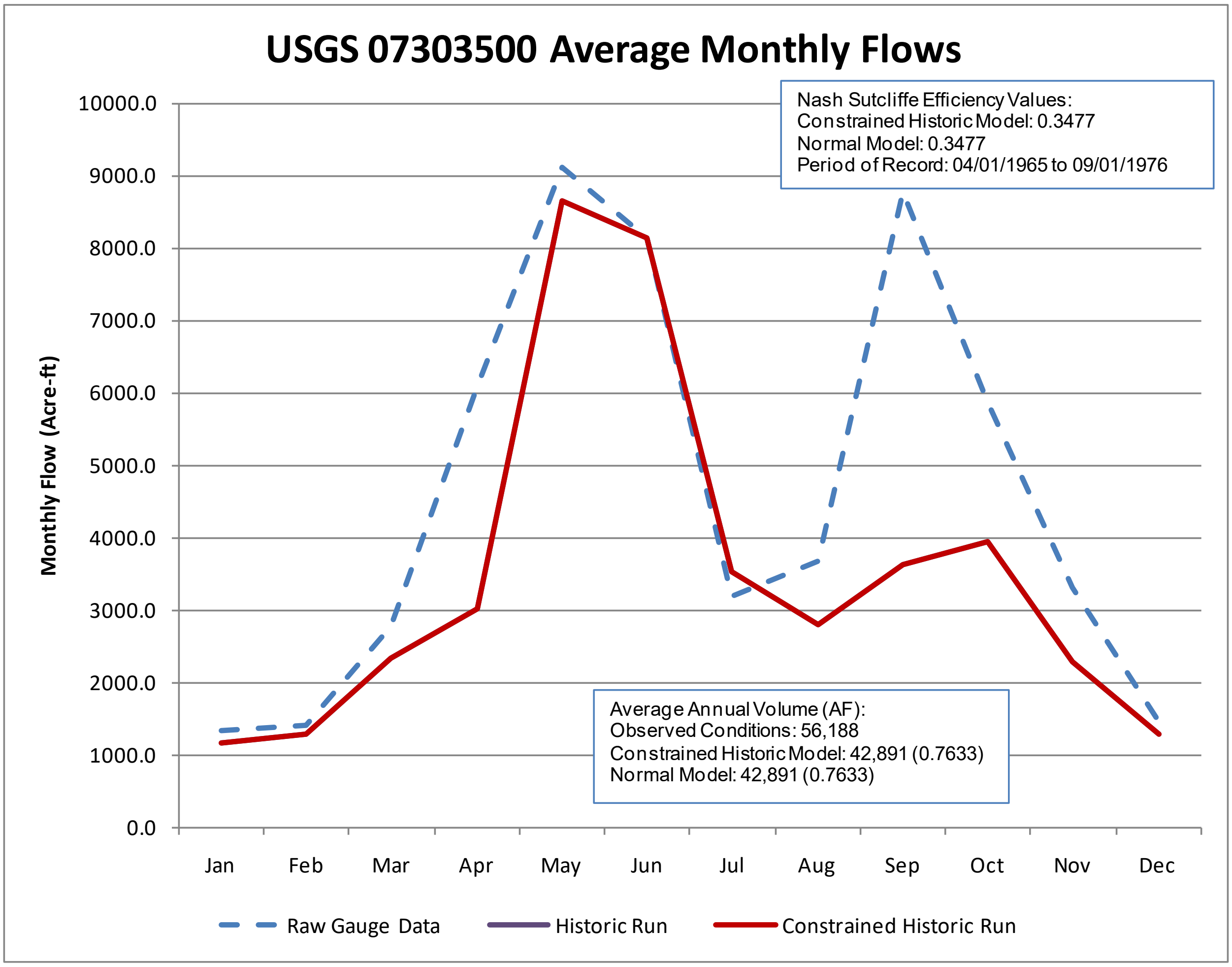

Figure A 25: Average Monthly Hydrograph for USGS 07303500

Notes: This gage was not naturalized; it was used as a validation gage. Discrepancies arise since the period of record of raw data does not match the period of record of raw data at the gages used to generate the modeled flows.

A-2 Appendix 2 – Description of Model Elements

Hydrologic Unit Gains

Each HU in the model should have an Inflow arc (rectangle) going to a node in the middle of the HU which represents the areal unit gain calculated in the flow naturalization process for the HU and the number of square miles in the HU. This inflow should be created in the HU with the appropriate relationship to a *Stream Gage* link (see Section 2.4). If the HU has an inflow from a higher HU (see discussion below), water use permits in the HU that are located above approximately one half of the HU's drainage area, should be located to draw water from the HU from a node above the node at which the HU Gains are introduced.

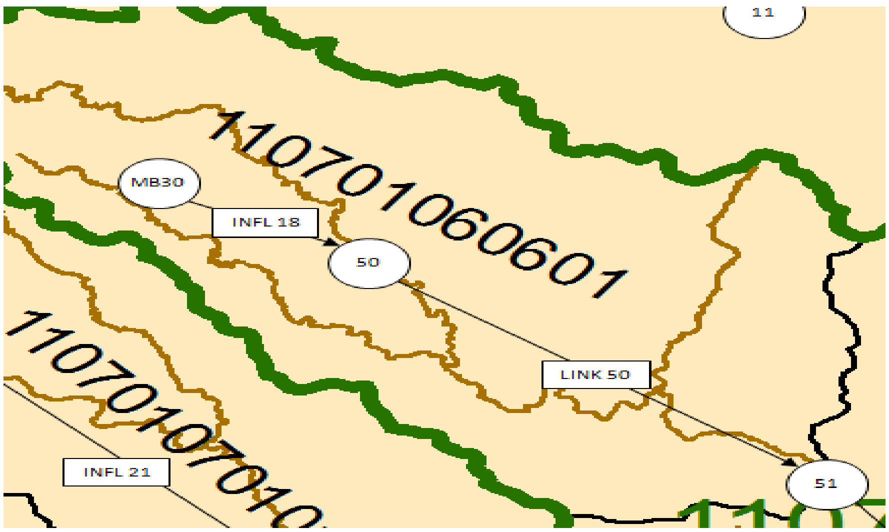

Figure A 26. Hydrologic Unit Gain Network Structure

Figure A 26 shows Inflow 18 (rectangle) which is the HU Gain for HU 110701060601. Link 50 is the *HU Outflow* link for the HU.

Hydrologic Unit Inflows

An HU Inflow represents all of the water entering the HU from upstream HUs or from a perimeter flow such as the flows entering the system from areas in Kansas. If there is no upstream HU or perimeter flow, then the HU Inflow is not needed. If upstream flows enter the HU from different sides and would be difficult to sum using a node and a link, the *HU Inflow* may be represented by a Data Object that adds together the flows in two or more Links to get a *Combined HU Inflow*. Extra VBA code has to be added to the *PostMinorTimeStepHook()* procedure whenever a Data Object is used to compile the inflows into an HU. There are fourteen such constructs in the Verdigris River model.

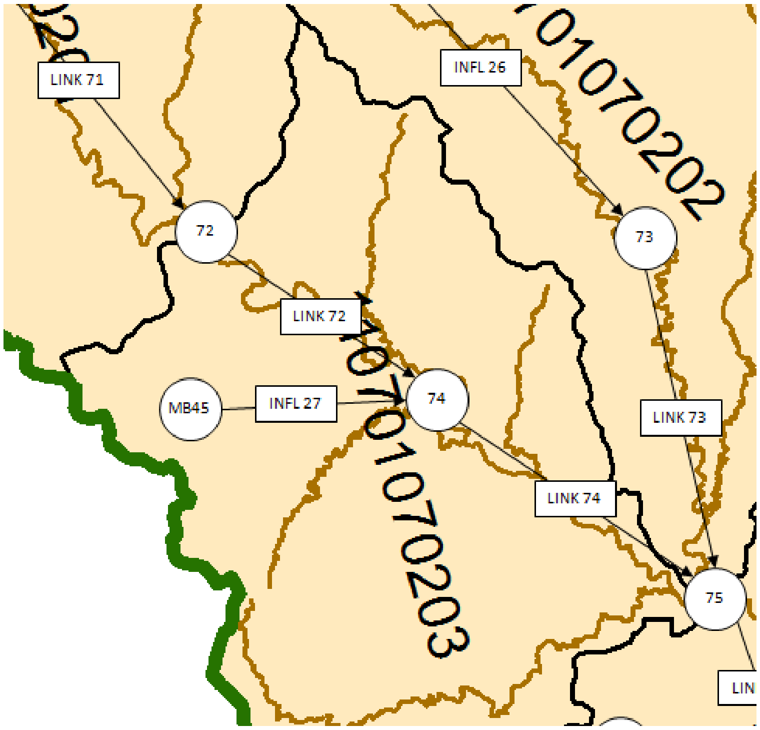

Figure A 27: Hydrologic Unit Inflow Network Structure

Figure A 27 shows the structure of an HU inflow. The HU Inflow in Figure A 27 is Link 72 (rectangle). The HU Gains are represented by Inflow 27 and the HU Outflow is represented by Link 74.

Water Use Permits

A permit construct is attached to a river reach. The construct consists of a link going from a node on the HU river reach, either above or below the *HU gains*, to a node to which a demand is connected.

The demand name is set to the numeric value of the permit date. The comments field of the demand should contain the permit holder's name, purpose (Public Supply, Irrigation, etc.), and total annual diversion in acre-feet for the permit, all separated by semi-colons (;). These values will be used to populate the *Demand Patterns* worksheet by the *Process Network Schematic* button.

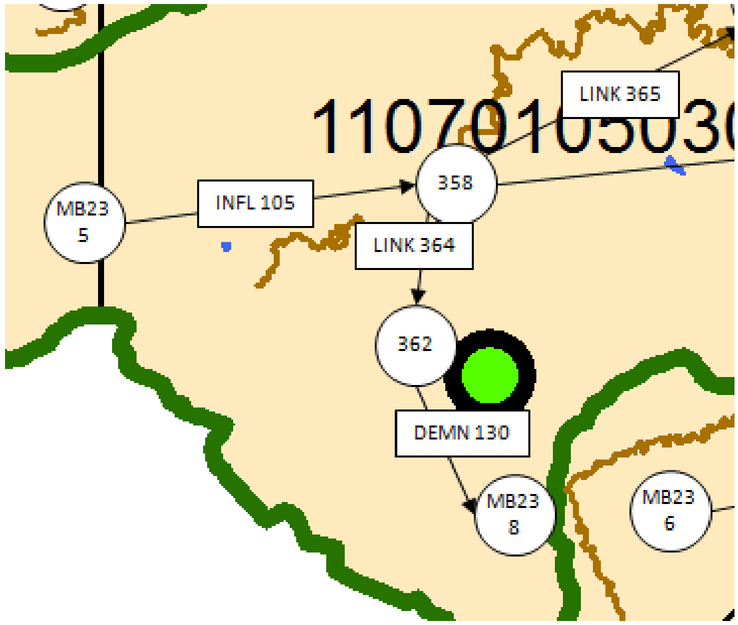

Figure A 28: Water Use Permit Network Structure

The structure of a water use permit is illustrated in Figure A 28. The water use permit is represented by the Link 364 and Demand 130 which takes water from node 358 in the network. Inflow 105 represents the HU Gains and Link 365 is part of another water use permit within the HU.

Hydrologic Unit Outflows

An *HU Outflow* is a link that represents the net flow out of a 12-digit HU after the accrual of the *HU Gains*, storage in reservoirs, and deliveries to water use permits within the HU. This Link should be set up as the last link in an HU. It may be put in series with a *Stream Gage Link* (see below) if the HU has a gage at the bottom.

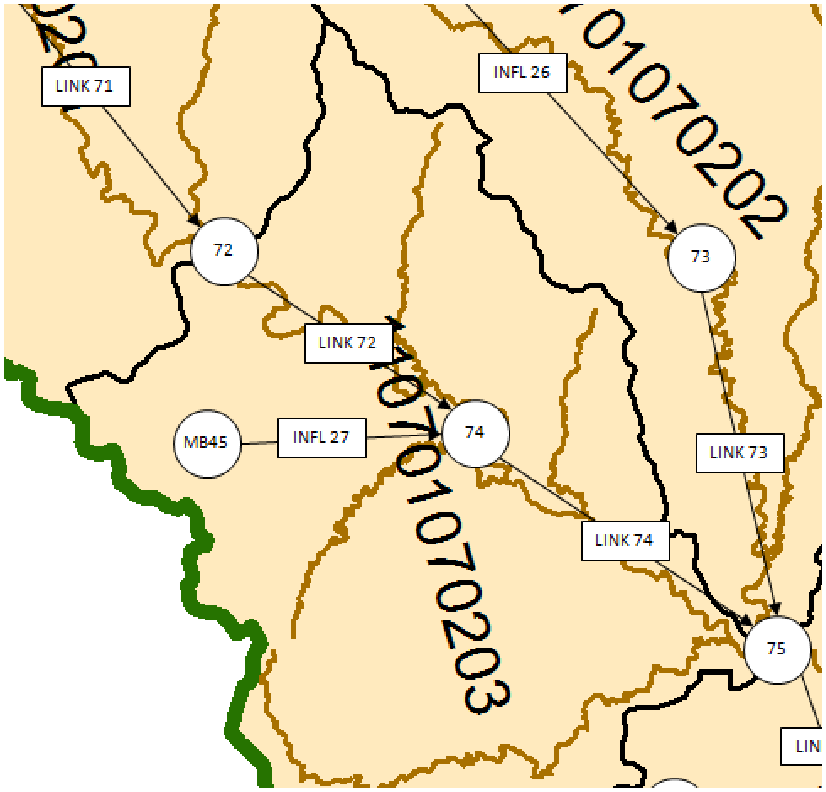

Figure A 29: Hydrologic Unit Outflow Network Structure

Figure A 29 illustrates the network structure for an HU outflow. The HU Outflow in Figure A 29 is Link 74. The HU Gains are represented by Inflow 27 and the HU Inflow is represented by Link 72.

Stream Gage Link

A stream gage is represented in the model by a link that passes all of the upstream flows which would normally pass the stream gage in the basin (i.e. it is on the flow path representing the river reach). If the real-world location of the gage is above one-half of the area of the HU, then the *Stream Gage* link should be placed upstream of the HUC inflow, otherwise the *Stream Gage* link should be downstream of the HUC inflow. *Stream Gage* links are positioned on the map where they are measured in the real world. Because gage watersheds don't always correspond exactly with the HU boundaries, some bias is introduced in simulations of gage flows.

Reservoirs

A Reservoir construct represents potential storage in the HU. If the Reservoir spans more than one HU it should be located in the most downstream HU so it can capture gains from all of the upstream HUs. The reservoir should be constructed with a link that bypasses the *Into Storage* link and comes in above the *Releases from Storage* link. The reservoir should have two carry over links one a *Target Storage* link and the other a *Carry Over* link that allows the reservoir to store water to a specific target volume and potentially store water in times of surplus into the flood control pool, up to the capacity of the reservoir, via the *Carry Over* link.

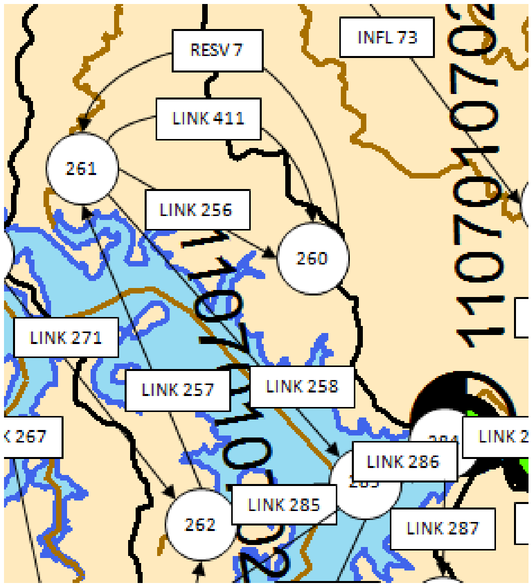

Figure A 30: Reservoir Network Structure

Figure A 30 illustrates the network structure for a reservoir. The reservoir is represented by the Reservoir 7 construct, the *Carry Over* Link 256, the *Target Storage* link 411, the *Into Storage* link 257, the *Releases from Storage* link 258 and the *Reservoir Bypass* link 285.

Formulation of Operating Rules

The principle operating rule for stream water withdrawals is priority allocation of water. Additional rules are required for simulation of reservoirs.

Water use permits

Priority allocation of water rights is simulated using the inherent capabilities of the ExcelCRAM network optimization approach.

Priorities were assigned to water uses based on their permit dates. The most senior water use was assigned a priority value of 5000 and each of the rest of the water uses were assigned a priority value of 10 less than the previous water use permit priority in order from oldest to newest. The newest permit was assigned a priority value of 3,420.

Reservoirs

Reservoir operating rules simulate storage and release of water in the reservoirs. Reservoir operating rules can be constrained to replicate historical storage volumes or can be generalized to represent expected future operations. For the generalized operating rules, for each month a reservoir has a target storage value. Under non-flood conditions the reservoir tries to store water up to its target volume, but will release water to supply any use below it that is short of water. During flood conditions storage will occur above the target volume up to the capacity of the reservoir.

Capacities and priorities on links were set in the model so that the reservoirs would provide water to any downstream water user who needed water, then store water up to the capacity of the *Target Storage* links, then bypass water to the bottom of the Basin until the flow at the bottom of the basin exceeded 1.4 maf in a month, at which point the reservoirs would begin filling flood control space in the reservoirs up to reservoir capacity. This would occur as long as the flow at the bottom of the basin was at or above 1.4 maf/month. When the flows at the bottom of the river basin would drop below 1.4 maf/month the reservoirs would evacuate the flood control pools until they reached their target storage levels.

The Target Storage values for the reservoirs were estimated on a monthly basis using the average end of month historical reservoir contents for the period after the reservoir had initially filled. These monthly storage targets were used as a repeating pattern for every year in the model run except in the constrained historical scenarios and for the initial reservoir filling period in the Historic Use scenario. The flood threshold at the mouth of the Verdigris (1.4 maf/month) was determined by calibration by matching modeled operations to historical operations after filling periods.

Reservoir starting contents were set to the ending contents at the end of the Historical Use run for the current condition scenario and the full permit scenarios. For the Historical Use scenario the reservoirs were started empty except for Bluestem and Claremore which were started full at the beginning of the model run.

Model Mechanics, Rules, & Controls

Model operations and water deliveries are based on the relative priorities of individual demands. Priorities for individual water demands and links are established based on permitted dates. Lake Altus delivers flow to the Lugert-Altus Irrigation District based on the priority of the Altus Main Canal (Permit Number 19390023). Diversions down the Altus Main Canal are distributed to three nodes within the LAID, corresponding to the irrigated lands in the Northwest, Southwest and Southeast sub-areas of the LAID, as described in Section 6. A diagram of the Lake Altus and LAID system is shown in Figure 2, above.

The majority of the water delivered to Tom Steed reservoir comes down the Bretch Canal. For the model to operate properly, the priority associated with the storage target for Tom Steed Reservoir is set to the same priority as the permit associated with the Bretch Canal (19670671U). The priority on the Bretch Canal is set to a slightly negative value so no water is diverted unless it is called down the canal to meet the targets of Tom Steed Reservoir. There is a small instream flow (Link 392) placed below the diversion with a priority higher than the target for Tom Steed. This instream flow amount is currently set at 100AF/month minimum flow for Elk Creek; the amount is based on the physical limitations of the Bretch Canal diversion structure, which were not precisely known at the time of this writing. These assumptions can be adjusted to reflect better information. The priorities for the Tom Steed Reservoir system are set so that water is diverted down the Bretch Canal to fulfill only the requirements at Tom Steed Reservoir itself and no extra water is bypassed. The Tom Steed Reservoir System is shown in Figure 3, above.

The user interface of the model can be found in the *InputControls* Tab of the model spreadsheet. Variables that can be modified easily by the model user are the demand patterns and consumptive use amounts for each of the different demand types, the model scenario, the losses at the LAID and the percentage of Altus Canal deliveries that go to each sub-area of the LAID. The assumed impact of groundwater on streamflows can also be set in this Tab. Changes to the return flows for the individual portions of the LAID must be done in the *Return Flow Sheet* Tab.

Many scenarios including different water rights priorities, reservoir targets, and demand assumptions were developed and run. The section below highlights these changes, with more detail provided for those where it is not obvious how they were developed.

New model scenario controls

The screen capture below shows the new model scenario controls added to the “InputControls” worksheet. These controls can be operated independently to make scenarios for the model, or the top dropdown box can have a scenario set selected and all values loaded by clicking the Load button on the “Premade Scenarios Controls” dialog box. This is accessed by clicking on the “Scenario Selection” button on the User Controls worksheet. The choices of Scenario Settings are “Historic”, “Fully Permitted MPMCD Run 1”, “Fully Permitted MPMCD Run 2”, “Fully Permitted M&I for LAID” and “Fully Permitted Irrigation for LAID”. Additional scenarios can be added to the list of sets in cells Q69:Q74 and then the code to set the settings would be found in the macro attached to the “Scenario Selection” button. The labels for the settings will take the user to the worksheets where the settings take effect.

Scenario Selection		
Last Scenario Loaded	(2A) Observed Historic	
Scenario	1	
Reservoir Target	Historic Contents	
Lugert-Altus 2060 Conservation	106,812	disabled
Tom Steed 2060 Conservation	88,881	disabled
Lugert-Altus Storage Priority	-	
Tom Steed Storage Priority	-	
Reservoir Curves	2017	
Use Historic Reservoir Start	TRUE	
Start Lugert-Altus Contents	0.0%	disabled
Start Tom Steed Contents	0.0%	disabled
Bretch Canal Diversions	Historic	
Allocate Water Upstream to Downstream	TRUE	
Surface Water Users	Historic	
Surface Water above Reservoirs	Historic	
Groundwater Users	Historic	
Reduce HUC Base Inflows	FALSE	
Base Flow Reduction Scenario	avgpump	disabled
Disable GW Demands	FALSE	
Use Mountain Park USBR	TRUE	
Use LAID Irrigation Historic	TRUE	
LAID Irrigation Annual	0	disabled
Use LAID M&I Historic	TRUE	
LAID M&I Annual	0	disabled
LAID Irrigation Dynamically Calculated	FALSE	
Tom Steed M&I Annual Demand	Historic	
Add Shortage Adjustment	FALSE	
Add GW Shortage by HUC	TRUE	
Scenario Reruns	0	
Skip in Batch Run Mode	FALSE	

Figure A 31. New scenario controls on "InputControls" worksheet

The following bullet points are different reservoir control options that can be implemented in the model run based on different initial scenarios.

- **Reservoir Target:**
    - Historic Contents – reservoir tries to fill to the historic contents.

- Up to Flood Pool – reservoir fills to the top of the conservation pool.
- Full Capacity – reservoir tries to fill to maximum capacity.

- **Lugert-Altus 2060 Conservation** – Volume of Lugert-Altus reservoir when the reservation pool is filled in 2060. This will be disabled as shown to the right if the reservoir target is set for Historic Contents or Full Capacity.

- **Tom Steed 2060 Conservation** – Volume of Tom Steed reservoir when the reservation pool is filled in 2060. This will be disabled as shown to the right if the reservoir target is set for Historic Contents or Full Capacity.

- **Lugert-Altus Storage Priority** – Sets the priority on storing water in Lugert-Altus reservoir. This changes the allocation of water in the model depending on whether you are running an upstream to downstream simulation or a Seniority simulation. If you are running an upstream to downstream simulation this priority is set to zero while in a Seniority allocation scenario the priority is set to a value just below the water right which uses the reservoir.

- **Tom Steed Storage Priority** – Sets the priority on storing water in Tom Steed reservoir. This changes the allocation of water in the model depending on whether you are running an upstream to downstream simulation or a Seniority simulation. If you are running an upstream to downstream simulation this priority is set to zero while in a Seniority allocation scenario the priority is set to a value just below the water right which uses the reservoir.

- **Reservoir Curves** – Selects the volume/area/elevation curves for the simulation. Options available are 2017 and 2060

- **Use Historic Reservoir Start** – Start the simulation with the reservoirs at their historic starting contents (0.68493586 * reservoir capacity for Lugert-Altus, 0 for Tom Steed Reservoir). If this is false, the reservoirs use the starting contents in the next two controls (Start Lugert-Altus Contents and Start Tom Steed Contents).

- **Start Lugert-Altus Contents** – Percentage of full capacity to use as a starting content for Lugert-Altus reservoir if non-historic starting contents are used.

- **Start Tom Steed Contents** – Percentage of full capacity to use as the starting contents for Tom Steed reservoir if non-historic starting contents are used.

- **Bretch Canal Diversion** – The capability for the Bretch Canal to divert water to Tom Steed.
  - Historic – divert the historic amount diverted down the Bretch Canal.
  - Potential – divert the maximum potential amount of water to Tom Steed per USBR estimate
  - Maximum – divert the maximum amount to Tom Steed, respecting the minimum flow below the canal
  - None – no diversions into the Bretch canal.

- **Allocate Water Upstream to Downstream –** True makes the model allocate water without using seniority or water rights. Permit users take water as it passes, reservoirs store water opportunistically. False makes the model enforce water rights. Groundwater users are the most senior users on the river. This settings requires a change in the Lugert-Altus Storage Priority and Tom Steed Storage Priority controls so that the reservoirs perform correctly.

- **Surface Water Users**
  - Historic – divert historical uses for each surface water permit. Missing years of record are filled in with average usage.
  - Average – divert the average historical usage for each surface water right permit.
  - Full Permit – divert the fully permitted amount for each surface water right.
  - None – no surface water diversions.
- **Surface Water above Reservoirs** – this applies to surface water rights that are located above Tom Steed or Lugert-Altus reservoirs.
  - Historic – divert historical uses for each surface water permit. Missing years of record are filled in with average usage.
  - Average – divert the average historical usage for each surface water right permit.
  - Full Permit – divert the fully permitted amount for each surface water right.
  - None – no surface water diversions.
- **Ground Water Users** – this applies to all groundwater users but can be modified by the setting of the control Disable GW Demands
  - Historic – divert historical uses for each HUC based on all groundwater permits within the HUC. Missing years of record are filled in with average usage.
  - Average – divert the average historical usage for each HUC based on all groundwater permits within the HUC.
  - Full Permit – divert the fully permitted amount for each HUC based on all groundwater permits within the HUC.
  - None – no surface water diversions.
- **Reduce Base HUC Inflows** – True activates the baseflow reduction scenarios generated by Reclamation in the control below.
- **Base Flow Reduction Scenario** – this specifies which base flow reduction scenario to apply to the groundwater demands above the reservoirs. The details of how these groundwater impacts are applied are outlined below.
  - Output.May_50_year
  - Output.May_40_year
  - Output.May_20_year
  - 2013pump
  - avgpump
  - growthpump

- **Disable GW Demands** – turns off all groundwater demands in the model. This will override the setting of the Ground Water Users control.
- **Use Mountain Park USBR** – used the Bureau of Reclamation's demands for Tom Steed M&I uses. This is permit 19670671L. The demand starts in June of 1967.
- **Use LAID Irrigation Historic** – Settings this to FALSE allows the control below (LAID Irrigation Annual) to take effect. These controls effect water rights: 19390023_NW_LAID, 19390023_SW_LAID and 19390023_SE_LAID.
- **LAID Irrigation Annual** – This sets a value for LAID irrigation if it is not using Historic values.
    - Full Permitted – uses the fully permitted amount for LAID irrigation deliveries.
    - 0 – turns off LAID irrigation deliveries.
- **Use LAID M&I Historic** – This determines if the control below is active. If set to TRUE LAID M&I use their historic uses. Otherwise they use the demand in the next control.
- **LAID M&I Annual** – the annual amount of demand for the LAID M&I use.
    - 10000 – The use takes 10,000 af of water each year.
    - 11100 – The use takes 11,100 af of water each year.
    - 15000 – The use takes 15,000 af of water each year.
    - Full Permitted – the fully permitted amount of water is taken each year.
    - 0 – The use takes no water.
- **LAID Dynamically Calculated** – a True value here has the model calculate an annual amount for LAID M&I and LAID Irrigation demands based on the contents of Lugert-Altus reservoir at the start of May per the USBR provided rules.
- **Tom Steed M&I Annual Demand** -This sets the M&I use from Tom Steed reservoir. This is the 19670671L permit.
    - Historic – Set the M&I annual demand to historic levels.
    - 15700 – Sets the M&I annual demand to 15,700 af/year.
    - 16100 – Sets the M&I annual demand to 16,100 af/year.
    - 13900 – Sets the M&I annual demand to 13,900 af/year.
    - 6800 – Sets the M&I annual demand to 6,800 af/year.
    - 0 – Sets the M&I annual demand to zero.
- **Add Shortage Adjustment** – If this is set to TRUE, this control adds flow to basin gains per square-mile based on shortage values recorded for the basin.
- **Add GW Shortage by HUC** – This control enables adding a fixed amount of water to a HUC based on shortage found on the MONTHLY_ANALYSIS worksheet for a groundwater demand in the HUC. The values form the MONTHLY_ANALYSIS worksheet that are pasted to the Inflow worksheet as values. These represent additional inflows added to HUCs on a case-

by-case basis due to shortages to ground water uses in the model calibration process. The additional inflows compensated for the runoff per square mile values being constant over a basin.

- **Scenario Reruns** – A control that identifies how many times a saved scenario needs to be run to have the reservoir storage targets updated for actual evaporation in the reservoir. For the historic scenario where the historic contents is the target, this is not needed but for other scenarios this needs to be at 1 (re-run the model 1 additional time after the first solution.)
- **Skip In Batch Run Mode** – Set to TRUE to skip the saved scenario when running the model in batch mode which runs the model for all scenarios on the ScenariosPremade worksheet. Note: The first scenario cannot be skipped.

Reservoir target, reservoir curves, and reservoir starting contents

The Reservoir Target sets the storage capacity targets for Lugert-Altus Reservoir and Tom Steed Reservoir. The storage target can be set to either Historic Contents, Up to Flood Pool, or Full Contents. The suggested settings for this control for each of the 6 scenarios is shown to the right of the control.

Adjustment of inflows for groundwater demands

A control was added to the "InputControls" worksheet to add inflows to HUCs with groundwater shortages sufficient to balance out the shortages. This additional inflow is consumed by the groundwater demand in the HUC and not transmitted downstream. It can be disabled on the "InputControls" worksheet by changing the value in the field from TRUE to FALSE.

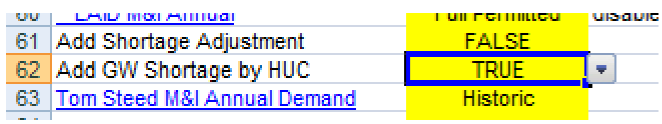

Figure 13. Adding groundwater shortage to HUC control

The additional inflows were derived from the "MONTHLY ANALYSIS" worksheet where all demands in the model can be evaluated for shortages and then added on the Inflow *NN* Timeseries Data worksheet for the corresponding HUC.

New worksheets in model

The following titles in **bold** are the names of the tabs that have been added to the model.

Worksheet Dictionary lists all worksheets in the model and provides a hyperlink in column A to take the user to a worksheet from this dictionary, allows the users to specify which worksheets should be visible and which should be hidden for different user levels. It also provides a cell to document the description of each worksheet. The Update List button on this worksheet will scan the workbook and add any new worksheets to the dictionary. It does not remove worksheets that have been deleted.

User Controls worksheet contains buttons to control the visibility of model components, start a simulation, and save or load a set of model controls for a scenario. The worksheet can also have more custom buttons added to the worksheet.

InputControls worksheet contains the current options set for the model to use during the next execution of the model. The values on this worksheet are validated using data validation rules on each cell, the cells are referenced by named ranges and the value here can be saved to the ScenariosPremade worksheet as a “scenario” using the “Scenario Selection” button on the User Controls worksheet.

The **ScenariosPremade** worksheet holds a set of InputControls for different scenarios run in the model. This list can be added to using the Scenario Selection button on the User Controls worksheet. Scenarios require unique names to have different values.

Gages Comparisons contains formulas comparing the latest model run to the historic gage values, calculating a Nash-Sutcliffe and R-squared value for each item.

HistoricReservoirContents

DynamicAllocationCheck

ZResultsTracking contains the results of the gage Nash-Sutcliffe analysis, reservoir R-squared values vs historic contents, and shortages by basin.

ANNUAL ANALYSIS contains formulas summarizing the latest model runs by yearly totals.

MONTHLY ANALYSIS contains formulas organizing the permits by basin and reservoir contents, evaporation and flows in canals. This worksheet is exported in the mass model run.

HUC Baseflow Reductions contains the data provided by the Bureau of Reclamation for reduction of baseflows above the reservoirs from groundwater modeling performed by the USGS. These are annual net changes in inflows by HUC.

Demand 224 Lake Altus Other Dem contains an additional demand on Lake Altus found in the USBR data.

New summarizing worksheets

Several new worksheets were added to the model to perform summarization of the raw model output to facilitate analysis by the Bureau of Reclamation. The MONTHLY ANALYSIS worksheet (Figure A 32) generates results sorted by HUC basins and organized by USGS gages to show the amount of shortage, highs (the full demand), reservoir contents and inflows around the reservoirs in the model on a monthly timeseries.

	A	B	C	D	BJ	BK	BL	BM	
1									
2									
3									
4									
5			Acres in HUC		62.54		42.13	45.44	
6									
7			SW %						
8			GW %						
9									
10			INFLOW #		inflow 17 Timeseries Data		inflow 19 Timeseries Data		
11			Total SW						
12			Total GW						
13			Total						
14									
15		DEMAND TOTAL			1,957	917	40,779	-	
16									
17					Groundwater	Groundwater	Groundwater	Groundwater	Groundw
18				Basin	07301500 Basin Flows	07301500 Basin Flows	07301500 Basin Flows	07301500 Basin Flows	073015 Flows
19									
20				HUC	111203020402	111203020403	111203020403	111203020404	111203
21				DEMAND	200	202	206	192	
22				COLUMN	351	354	357	360	
23				Permit Number	111203030304_GW	111203030305_GW	111203030306_GW	111203030401_GW	1112030
24		Year	Month	PARAMETER	Demand_200_Sho	Demand_202_Sho	Demand_206_Sho	Demand_192_Sho	Deman
25		1950	1	1/1/1950	0	0	0	0	
26		1950	2	2/1/1950	0	0	0	0	
27		1950	3	3/1/1950	0	0	0	0	
28		1950	4	4/1/1950	0	0	0	0	
29		1950	5	5/1/1950	0	0	0	0	
30		1950	6	6/1/1950	0	0	0	0	
31		1950	7	7/1/1950	0	0	0	0	
32		1950	8	8/1/1950	0	0	0	0	
33		1950	9	9/1/1950	0	0	0	0	
34		1950	10	10/1/1950	0	0	0	0	
35		1950	11	11/1/1950	0	0	0	0	
36		1950	12	12/1/1950	0	0	0	0	
37		1951	1	1/1/1951	0	0	0	0	
38		1951	2	2/1/1951	0	0	0	0	
39		1951	3	3/1/1951	0	0	0	0	

Figure A 32. MONTHLY ANALYSIS Worksheet Table of Shortages by Permit

The ANNUAL ANALYSIS worksheet (Figure A 33) shows the shortages, highs (full demands) or flows for years in the model simulation. This worksheet summarizes the uses in each HUC for surface and groundwater uses.

	A	B	C	D	EF	EG	EH	EI	EJ	EK	EL	EM	EN	EO	EP	EQ	ER	ES
1																		
2		SHOW THIS PARAMETER BELOW						Missing from Naturalization										
3			Shortage															
4																		
5		Acres in HUC				43.35		58.14				46.74			40.17		56.69	30.21
6																		
7			SW %															
8			GW %															
9																		
10			INFLOW #															
11			Total SW	9,590										91				
12			Total GW	65,215		53389						34669		-				
13			Total	75,817										1,103			334,670	
14																		
15		DEMAND TOTAL																
16																		
17					Groundwa		Groundwa	Groundwa				Groundwater			Groundwa	Groundwa	Groundwa	
18				Basin	07305000	07305000	07303000	07305000	07305000	07305000	07305000	07305000	Basin Flo	07305500	07305500	07305500	07305500	07305500 E
19											07305000 Basin Flows			07305500 Basin Flows		07305500 Basin Flows		
20				HUC	111203030404	111203030404	111203020410	111203030405	111203040305	111203040305	111203040305	111203040305		111203030301	111203030301	111203030303	111203030302	111203030303
21				DEMAND	194	104	195	201	39	40	41	160		34	197	198	199	35
22				COLUMN	366	177	369	372	183	42	114	450		123	342	345	348	93
23				Permit Number	111203030403_G	20060062	111203030404_G	111203030405_G	20110035	19551387	19780028	111203040305_GW		19820113	111203030301_G	111203030302_G	111203030303_G	19720294
24				PARAMETER	Demand_	Demand_	Demand_	Demand_	Demand_	Demand_	Demand_	Demand_	160_Short	Demand_	Demand_	Demand_	Demand_	Demand_3
69				1994	0	0	0	0	0	0	0	0		0	0	0	26	0
70				1995	0	0	0	0	0	0	0	0		0	0	0	26	0
71				1996	0	0	0	0	0	0	0	0		0	0	0	26	0
72				1997	0	0	0	0	0	0	0	0		0	0	0	23	0
73				1998	0	0	0	0	0	0	0	0		0	0	0	23	2
74				1999	0	0	0	0	0	0	0	0		0	0	0	26	0
75				2000	0	0	0	0	0	0	0	0		0	0	0	26	0
76				2001	0	0	0	0	0	0	0	0		0	0	0	26	0
77				2002	0	0	0	0	0	0	0	0		0	0	0	26	0
78				2003	0	0	0	0	0	0	0	0		0	0	0	26	0
79				2004	0	0	0	0	0	0	0	0		0	0	0	26	0
80				2005	0	0	0	0	0	0	0	0		0	0	0	26	3
81				2006	0	0	0	0	0	0	0	0		0	0	0	26	1
82				2007	0	0	0	0	0	0	0	0		0	0	0	26	3
83				2008	0	0	0	0	0	0	0	0		0	0	0	23	0
84				2009	0	0	0	0	0	0	0	0		0	0	0	26	0
85				2010	0	0	0	0	0	0	0	0		0	0	0	26	0
86				2011	0	0	0	0	0	0	0	0		0	0	0	26	0
87				2012	0	0	0	0	0	0	0	0		0	0	0	26	0
88				2013	0	0	0	0	0	0	0	0		0	0	0	26	0
89				2014	0	0	0	0	0	0	0	0		0	0	0	26	0
90				2015	0	0	0	0	0	0	0	0		0	0	0	19	0
91				2016	0	0	0	0	0	0	0	0		0	0	0	23	0
92																		
93	Total	75,817			0	0	0	0	0	0	0	0		3	0	0	1012	88
94	Total - LAI	75,817																
95																		
96																		
97																		

Reservoir Output / Basin Outflow / MassGenerate / Worksheet Output Template / old HUC-Inflow Areas / ZResultsTracking / ANNUAL ANALYSIS / MONTHLY

Figure A 33. ANNUAL ANALYSIS Worksheet Table of Shortages by Permit

The ZResultsTracking worksheet reports the R-squared values for the USGS gages, the R-squared values for Lugert-Altus and Tom Steed reservoirs and any shortages in the regions above the USGS gages for the most recent run.

Additional input worksheets

The model now contains additional worksheets that are used to modify inflow or demand data in the model. The worksheet "HUC Baseflow Reductions" contains a table of baseflow reduction values for the different HUCs in the model. The values in table are populated with data from the USGS ModFlow modeling.

A new demand template was created for generating demands for groundwater users. The worksheet "gw demand timeseries template" contains formulas, fields to lookup demand uses and volumes which will apply to all groundwater demands in the model.

The worksheet “Reservoir 1 Altus Evap Rates” and “Reservoir 2 Steed Evap Rates” contain the timeseries values for monthly evaporation for the two reservoirs.

The worksheet “VolumeAreaOptions” contains the volume area information for Lugert-Altus and Tom Steed for the different time periods. The model uses VBA code to load the data on this worksheet into the Reservoirs Sheet prior to the model run.

Geodatabase

10.1.1.1. MDB Tables

The standard tables for the OWRB River Basin models were exported to the target Geodatabase when the model is run. They include a table of Permits in an HU, USGS Gages in the model, and Reservoirs in the model.

10.1.1.2. MDB Queries

The standard set of queries for the OWRB River Basin models were exported and executed as expected to the target Geodatabase when the model is run. They include building tables of permits with shortages, permits with 10 of the months in shortage as well as other pre-defined queries.

VBA Customization

Some additional VBA macros were added to the Verdigris Basin model to allow for Climate Change modeling (see further discussions in Sections 3 and 6). The VBA module *LoadDataSets* was added to the model to automatically load sets of time series data like the HU-12 inflows from ASCII text files to allow whole sets of inflow data for the entire basin to be swapped into the model with a single call.

The subroutine ExportInflowTime seriesToASCII was added to the *moddataProcessingUtility* module to export the naturalized allocated HU-12 inflows from the model to ASCII text files so they could be modified by the Excel workbook CalculateMonthlyHUCOutflows.xlsm to produce the ten sets of inflow files for the ten climate change scenarios.

Code was added to the PreBatchSimulationHook and PostBatchSimulationHook to allow all ten climate change scenarios and the baseline to be run and have the results stored in ASCII files.

A-3 Appendix 3 – List of OWRB Surface Water permits

Permit	Entity Name	Purpose	Permitted (AF)
LOWER NORTH FORK RED RIVER			
19320051	Hobart, City of	Public Supply	631.0
19520051	Kelly, Joe T	Irrigation	40.0
19520414	Tipton Home Inc, The	Irrigation	77.0
19520580	Trent, D H	Irrigation	18.0
19550353	Spieker, Jimmy & Carol	Irrigation	7.5
19600053	Sanders, Otis J	Irrigation	108.0
19640061	Abernathy, Charles	Irrigation	24.0
19640399	Leverett, Darill L	Irrigation	134.0
19640530	Winters, Lorin J	Irrigation	39.0
19641018	Triple R Farms LLC	Irrigation	160.0
19650245	Hicks, Margie Koester	Irrigation	15.0
19650249	Elk City, City of	Recreation, Fish, Wildlife	800.0
19650553	Oklahoma Space Industry Dev Auth	Irrigation	149.0
19670671	Mt Park Master Conservancy Dist	Public Supply	16100.0
19720294	Callen, Lottie P	Irrigation	20.0
19740306	Hill, J C	Irrigation	20.0
19750027	Triple R Farms LLC	Irrigation	109.0
19810055	Winters, Lorin J	Irrigation	37.0
19810156	Mills, Marie	Irrigation	19.0
19820014	Fowler, J C	Irrigation	25.0
19820113	U S Fish & Wildlife Service	Recreation, Fish, Wildlife	10.0
19850022C	Butchee, Iverna	Irrigation	56.5
19870018	Elks Golf & Country Club	Irrigation	25.0
19910024	Leverett, Darill L	Irrigation	502.0
19940057	Abernathy, Charles	Irrigation	157.0
19950008	Nichols Family Partnership Limited	Irrigation	208.0
19950015	Robbins Farms Inc	Irrigation	213.0

Permit	Entity Name	Purpose	Permitted (AF)
19960036	Warrick, Robert E & Noleen E	Recreation, Fish, Wildlife	15.0
19970006	Hobart, City of	Public Supply	1100.0
19970010	Morris, Jeffrey R & Jana S	Irrigation	297.0
19980025	Moore, Pat	Irrigation	1338.0
20000029	Carder, Bob	Irrigation	43.0
20010016	Quartz Mt Youth Camp	Irrigation	6.0
20020015	Abernathy, Clint & Kim	Irrigation	250.0
20030007	Fike, Susan	Irrigation	217.0
20030029	Coy, Noble	Irrigation	100.0
20040022	Williams, Randall R	Irrigation	121.0
20060043	Freeman II, Charles R & Carrie	Irrigation	1470.0
20060062	Hahn, Kenneth & Bonnie	Irrigation	320.0
20090008	McElroy, Johnny R & Dana D	Irrigation	46.0
UPPER NORTH FORK RED RIVER			
19260006	Altus, City of	Public Supply	4800.0
19390023	Lugert - Altus Irrig District	Irrigation	85630.0
19470003	Little, Stanley & Tani LeaMerideth	Irrigation	84.0
19540866	Mong, Joe & Faye	Agriculture	4.0
19600140	Burrows, Helen Marie	Recreation, Fish, Wildlife	150.0
19620010	Rose, Henry Lee & Linda Earlene	Irrigation	110.0
19660220	Smith, John W	Irrigation	53.0
19740253	Dusek, Pamela A	Irrigation	11.0
19780088	Quartz Mt Youth Camp	Recreation, Fish, Wildlife	2.0
19900029	Tourism & Recreation, Dept of	Irrigation	100.0
19950037A	Hendershot, Ruth	Irrigation	80.0
20020003	Hendershot, Brent C	Irrigation	442.5
ELM FORK RED RIVER			
19551387	Corrections, Dept of	Irrigation	248.0

Permit	Entity Name	Purpose	Permitted (AF)
19780028	Corrections, Dept of	Irrigation	200.0
20110035	Hahn, James & Nancy Webster	Irrigation	320.0
SALT FORK RED RIVER			
19480184	Drury, Tim & Lisa	Irrigation	96.0
19490098	Olson, John P	Irrigation	50.0
19490150	Cargal, Ricky and Imogene	Irrigation	52.0
19520061	Shelby, Jerry	Irrigation	100.0
19520096	Hook N Horns LLC	Irrigation	97.0
19520122	Shelby, Jerry	Irrigation	160.0
19520231	Jones, Gary A	Irrigation	63.0
19520286	Vinyard, Harold	Irrigation	30.0
19520331	Davis, Kathleen Holt	Irrigation	101.0
19520331	Davis, Kathleen Holt	Irrigation	101.0
19520595	Briscoe, Donald	Irrigation	31.0
19530271	Shelby, Jerry	Irrigation	320.0
19540091	Wildlife Conservation, Dept of	Recreation, Fish, Wildlife	167.0
19560788	Bailey, J Mack	Irrigation	50.0
19640321	Jameson, W H	Irrigation	70.0
19640402B	Givens Farms Inc	Irrigation	8.0
19640483	Olson Land Company LLC	Irrigation	172.0
19640499	Ballew, Norman Weber	Irrigation	60.0
19640503	J P W Farms Inc	Irrigation	558.0
19640524	Garrison, Roy	Irrigation	35.0
19640756	Taylor, Delbert	Irrigation	36.0
19670357	Hollenback, Byron C	Irrigation	14.0
19710179	Hat Mc, Inc	Irrigation	240.0
19740078	Crow, Jr, Herschal H	Irrigation	34.0
19740169	Doughten, Wendell	Irrigation	10.0

Permit	Entity Name	Purpose	Permitted (AF)
19740224	Abernathy, Clint D & Kimberly K	Irrigation	100.0
19790142	Tipton Home Inc, The	Irrigation	320.0
19800150	Lewis, Kit Ray	Irrigation	34.0
19860006	Wallace, Cary Pat & Rhonda	Irrigation	420.0
19900008	Mock, Paul H	Irrigation	175.0
19910034	Vaughan, Randal S	Irrigation	98.0
19910051	Vinyard, Harold	Irrigation	230.0
19910057	McLeod, Owayne	Irrigation	131.0
19910060	Fox, Jr, Raymond H	Irrigation	60.0
19920003	Worrell, Harold D	Irrigation	66.0
19920004	Worrell, Harold D	Irrigation	33.0
19920009	Scoggins, E B	Irrigation	165.0
19920010	Caldwell, Martin	Irrigation	115.0
19920012	Jordan-Richards Trust, Mary Jane	Irrigation	120.0
19930008	Holsey, Frankie Lucille	Irrigation	272.0
19930041	Aboussie, Josephine	Irrigation	47.0
19940052	Shadid, Ned	Irrigation	139.0
19940056	Crow, Herschal H	Irrigation	756.0
19950011	Olson, William G & Shirley L Family Trust	Irrigation	207.0
19950021	McLeod Farms Inc	Irrigation	95.0
19950031	S & D Farms Inc.	Irrigation	68.0
19950045	Olson, William G & Shirley L Family Trust	Irrigation	289.0
19970018	Hawthorne, W B	Irrigation	152.0
19980007	Altus Land & Cattle Co	Irrigation	75.0
19980045	McLeod, James R	Irrigation	95.0
20010037	McMahan, John	Recreation, Fish, Wildlife	56.3
20020025	McMahan, John Boyd	Irrigation	167.0
20030009	S & D Farms Inc.	Irrigation	154.0

Permit	Entity Name	Purpose	Permitted (AF)
20030010	Vinyard Farms Inc	Irrigation	240.0
20040024	Pryor, James H	Irrigation	622.0
20090018	Hat Mc, Inc	Irrigation	400.0
20110015	Dunn, Darrell & Debora	Irrigation	320.0