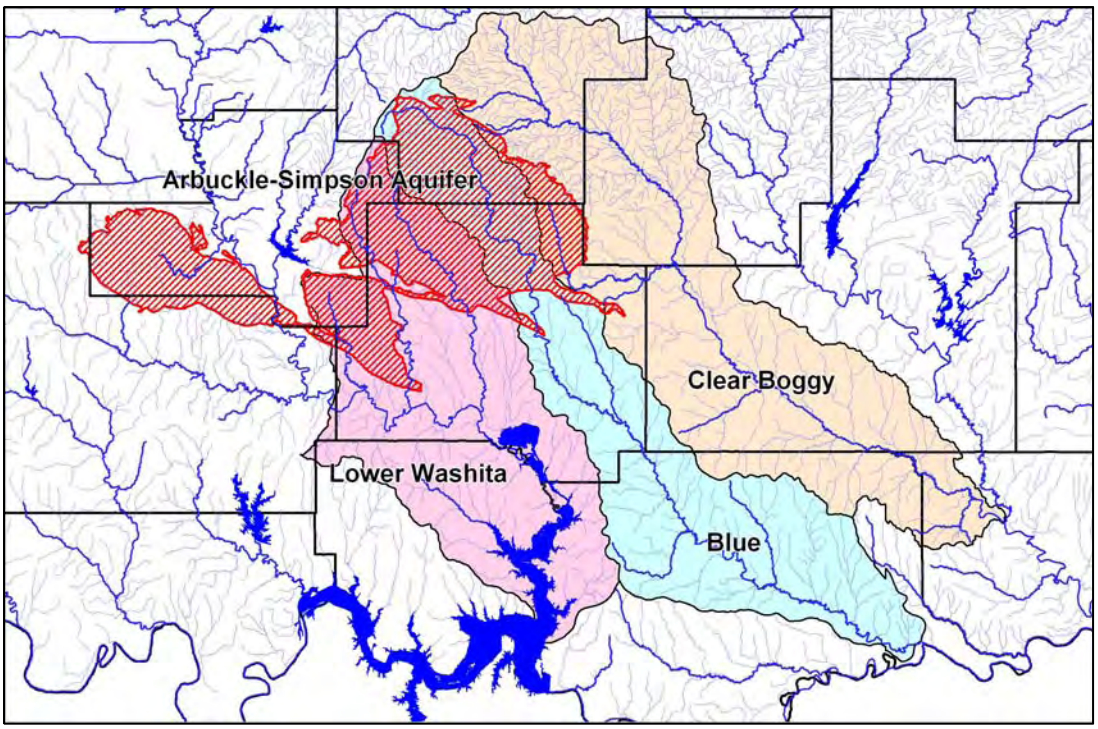
Arbucke Simpson Aquifer Special Study

Stream Water Management Network Model

Prepared for

The Oklahoma Water Resources Board



HYDROSPHERE
Resource Consultants

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The Oklahoma Water Resources Board issues permits for water use and administers water rights within the state of Oklahoma.

The Arbuckle-Simpson Aquifer contributes base flow to the Blue River, the Clear Boggy River and parts of the Lower Washita River watersheds. Pumping from the Arbuckle-Simpson Aquifer is expected to reduce base flows in these watersheds.

In order to determine the potential impact of ground water withdrawals on downstream permit holders, the Board contracted with Hydrosphere Resource Consultants to develop a network model of surface water and water rights along the three watersheds. This report describes the development and preliminary results of the modeling effort, and provides recommendations for actions of the Water Resources Board.

Objectives

The objective of this work is to develop a network flow model of the water rights in the Clear Boggy, Blue and Lower Washita river basins. The Oklahoma Water Resources Board will use the model to develop recommendations for the management of the Arbuckle-Simpson aquifer and to evaluate applications for new water permits in the river basins. The model has the capability to:

1. Determine the available water for existing water rights and new water rights applications by allocating water to water rights according to priority;

2. Calculate the impact of ground water withdrawals on the availability of stream water to senior water rights;

2. Evaluate individual applications for stream water rights to determine their impact on in-stream flow restrictions and their potential interference with senior stream water rights; and

4. Quantify the impact of drought on the availability of water to stream water rights, utilizing historic or current stream flow data.

Specifications for the model are shown in Appendix A.

Model Construction

The surface water rights model for the basins is required to address two primary questions:

- What will be the result of priority administration of water rights on a monthly basis for current and future stream water rights, and

- What will be the effect on water availability for existing water rights of changes in base flow brought about by pumping from the Arbuckle-Simpson Aquifer.

Modeling Approach and System

A network flow water rights modeling approach was selected because of its ability to allocate water in priority. The ExcelCRAM network flow modeling system was used to develop the model. More information about the ExcelCRAM modeling system can be found in {ExcelCRAM users guide}.

Period of Record

The minimum period of record for the surface water model was specified in the scope to include the years 1950 through 1959 and 1994 through 2006. The 1950's were to be included to cover the drought of record, and the period since the mid-1990s is to represent the recent water operations.

The model was constructed to operate over the years 1943 through 2006. The longer period of record provides additional hydrologic variability and therefore enables a more robust calculation of hydrology statistics than the shorter period would allow. Gage data is available from 1929 to 2006 for the Washita River basin, 1937 to 2006 for the Blue River, and 1943 to 2006 for the Clear Boggy River basin.

While the longer of periods of record are were included in the model for the Blue and Washita basins, the model was constructed to run from 1943 through 2006 to maintain a consistent base period.

Timestep

The model was constructed with a monthly timestep. Because of the size of the basins, the travel times are considered to occur within each timestep, which in turn means that the model does not have to incorporate routing routines. Without routing, the model executes faster than one which requires a routing algorithm.

Network Topology

The physical model domain and water use permit locations is shown in Figure 1.

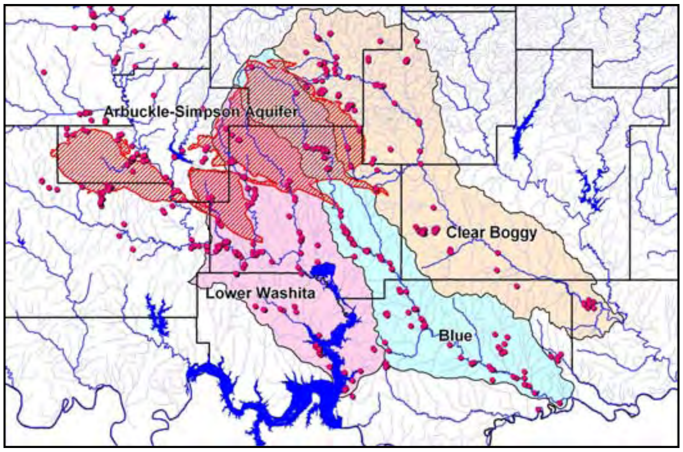

Figure 1. Watersheds with permit locations.

Though the surface water systems of the three basins do not influence one another, all three basins are included in one model network for simplicity's sake. The model was constructed with three sub-networks, one for each of the main river basins. Each sub-network has tributary inflows and surface water diversions. The three sub—networks are depicted on the Network Schematic sheet roughly in their actual relative orientation.

Because stream flow data are not routinely measured on the tributaries in the basins, the model was consolidated, with each of the river basins divided into ten to twelve sub-basins, each of which was represented as a tributary in the network. An inflow was added to the upper end of each tributary to represent the tributary flow, and the demands included within the sub-basin were placed on the tributary according to their actual spatial relationships.

Generally speaking, each water use permit was represented by a single demand node in the model, including permits with multiple diversion points. Where a single permit had multiple diversion points that were sequentially located along the stream (with no intervening inflows or water rights) the diversions were consolidated to a single demand. When other water rights were interspersed between a multiple diversion points (for a single permit), the diversion was located in the reach with the most points of diversion.

Reservoir Storage

The physical model domain includes the Lake of the Arbuckles, the northern arm of Lake Texoma, 14 municipal reservoirs, and more than 450 flood control reservoirs that are located in the three watersheds.

Figure 2. Lake of the Arbuckles (USBR)

In the Washita basin, the current model actively simulates the Lake of the Arbuckles, Mountain Lake, and a reservoir representing the composite of Jean Neustadt, Rock and Ardmore reservoirs. In the Clear Boggy basin, the model has 10 reservoirs, representing the flood control reservoirs in each sub-basin. There are no reservoirs represented in the Blue River basin.

As shown in 1, diversions in the Washita basin come from upstream of Lake Texoma, from the lake itself, or from Turkey Creek, a tributary to the lake that is not affected by flows from the Arbuckle-Simpson aquifer. Water permits on Turkey Creek were not included in the model because streamflows are not influenced by water from the Arbuckle-Simpson aquifer. Lake Texoma was not included in the model because the flows in the Washita River will not measurably affect the physical availability of water for diversions that withdraw water from the lake.

The Lake of the Arbuckles, Mountain Lake, and a reservoir representing the composite of Jean Neustadt, Rock and Ardmore reservoirs are included in the model in the Washita basin. Because operational rules and historical data were essentially unavailable for these reservoirs, they are operated in the model to divert the water to remain full all the time. The model constructs have area-capacity curves, and they evaporate water. The reservoirs are operated such that they fill to replace evaporated water whenever excess water is available. They make releases to meet downstream demands whenever the natural flows are insufficient to meet demands.

In the Clear Boggy basin, the model includes ten reservoirs, one in each of the model's sub-basins. These reservoir constructs represent a composite of the NRCS flood control reservoirs located in the basin. These reservoirs, in physical reality, do not formally operate, but rather fill with surface runoff and then seep and evaporate water over time. Because there were no reliable data about the number, capacity or surface area of these reservoirs, the composite reservoirs were constructed by summing the surface area of the reservoirs in the GIS coverage for each sub-basin and assuming the reservoirs had an average depth of 5 feet. This depth was chosen in order to approximate the total storage in the Clear Boggy basin as reported by the OWRB. These reservoirs were originally included in the model to evaporate water from the stream system. However, because the reservoirs are expected to continue to store and evaporate water as they have historically, the losses from these reservoirs were not added back into the gage record as part of the flow naturalization process and the evaporation for these reservoirs is currently set to zero in the model. Because the reservoirs are not operated in any manner, they have no effect on simulated streamflows, and they are currently disabled. They are provided in the model for possible future use if and when more data become available regarding the physical characteristics and operating rules.

Historical Diversion Records

Surface water permit holders are expected to submit records of their water diversions to the OWRB each year. Permit holders who fail to submit records for seven consecutive years are legally considered to have abandoned the water right. Despite these requirements, many permit holders do not submit annual records to the OWRB.

All available surface water diversion records for the three basins were obtained from the OWRB. The records were delivered in a database which was keyed to the permit numbers. Some of the users report their use as monthly totals while some report it only as an annual total. Since the monthly reported use was totaled by permit owner (a given owner can have multiple permits) and was not able to be separated by permit, this data was ignored as the model requires permit specific information. Diversion data that were reported as an annual amount were disaggregated using standard monthly demand patterns. Because most of the permits have reported use in at least some years, missing data were filled in using the average of the reported data.

Demand Patterns

Demand data reported on an annual basis were disaggregated using monthly demand patterns. The model uses two patterns, one for irrigated agriculture and one for all other uses. The monthly distribution of the two patterns is shown in the following table.

Table 1. Monthly demand patterns

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Irrigation Pattern	0.0%	0.0%	2.1%	5.4%	13.7%	17.2%	18.4%	16.5%	15.7%	9.4%	1.5%	0.0%	100%
M & I Pattern	8.3%	8.3%	8.3%	8.3%	8.3%	8.3%	8.3%	8.3%	8.3%	8.3%	8.3%	8.3%	100%

The municipal and industrial (M&I) pattern was assumed to be flat throughout the year to account for indoor, industrial and commercial uses. This pattern under-represents summer use due to lawn watering. When a monthly distribution for municipal users that includes landscape irrigation becomes available the existing M&I distribution could be adjusted or a third demand pattern could be added to the model to represent the distribution of lawn watering demands.

Because most water uses consume only a part of the water diverted, and because the return flows are assumed to reach the stream within the same month they are diverted, the model demands were modified to divert only the consumptive use portion of the diversion. The consumptive use factor is applied to the historical demand data in the same step as the monthly demand patterns. The percentage of consumptive use can be set by the user for the two demand patterns.

System Inflows

Stream flow data was obtained from the U.S. Geological Survey (USGS) for each of the three basins for the period of record available. The USGS gages used included:

- 7331000 Washita River near Dickson, OK (1928-2007)
- 7328500 Washita River near Pauls Valley, OK (1937-2007)
- 07332500 Blue River at Blue, OK (1936-2007)
- 07335000 Clear Boggy Creek near Caney, OK (1942-2007)

Figure 1. Blue River at Blue, OK (NOAA)

Figure 2. Washita River nearPauls Valley, OK (Wikipedia)

Daily streamflow data were naturalized by adding in the historical permitted diversions above the gage location. Because the many soil conservation reservoirs are assumed to operate as they have historically, the evaporation from these small reservoirs was not added to the gage record.

Because detailed information about tributary inflows is not available, the naturalized streamflows were proportioned to each sub-basin using the watershed area. These inflows can be easily refined as more data becomes available.

Model Scenarios

The model was constructed to simulate three particular scenarios. These are:

1. Running the historical record of inflows and water use. Results from this scenario should come very close to recreating the historical gage records.

2. Modeling current conditions over the period of record. This scenario uses average historical diversion data for permit demands, and runs these current demands across the historical hydrology. This allows the user to compare how specific water rights would fare under current conditions for the historical hydrology.

3. Modeling the permitted amounts over the period of record. This scenario allows the user to see how specific water rights would be affected if all users took their permitted amounts.

Model Results

Analysis of model output has shown that while the model is not a perfect representation of the basin, the model is able to provide useful information regarding the system. This section summarizes the general findings rather than specific model results.

Model Limitations

Examination of the model results shows that the model is limited in two major ways.

First, for a lack of better data, the inflows were generated by proportionately scaling naturalized gage records based on drainage basin area. The result of this method is that there are places where there are insufficient flows to satisfy records of historical diversions. The allocation of streamflow to specific stream segments can be improved through the use of synoptic study data, which will show the locations of ground water inflows into the stream systems.

Second, the historical records of water rights data are frequently missing. While the record of these diversions can be improved in the future, historical modeling is limited by the availability of data.

Availability of Water

The model results, using the historic scenario, show that water is generally available to all rights the vast majority of the time. As shown in Figure 3 below, shortages typically occur very infrequently and for very short periods of time. According to the data, shortages occur only on the months of August – October and only in those years that are in the bottom 10% by total annual flow. This implies that storage could be used by either existing junior water users or new permit holders to provide water through dry periods.

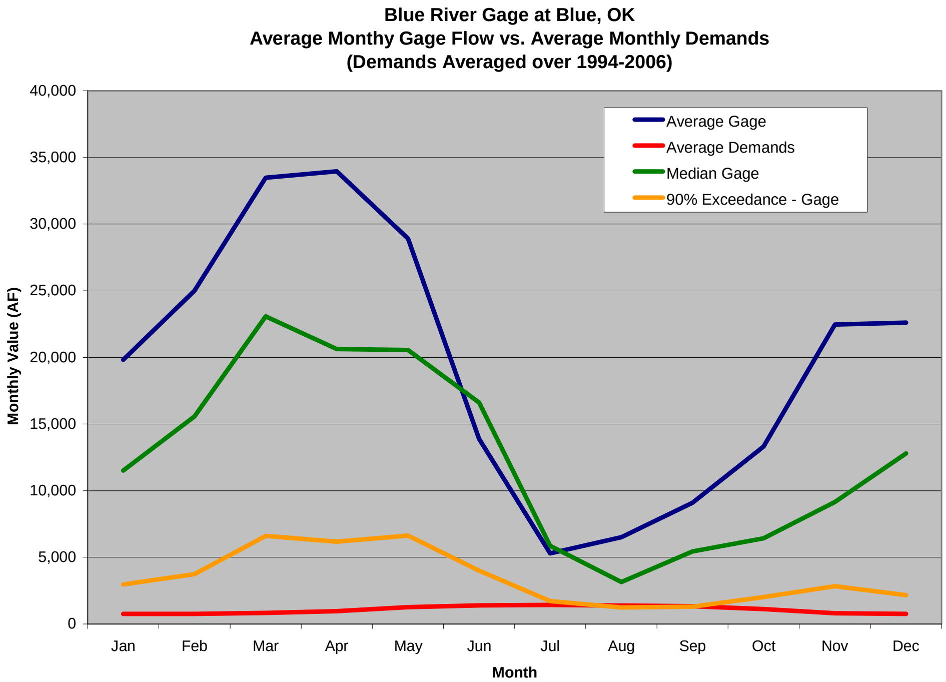

Figure 3: Supply vs Demand on the Blue River

Recommendations

As a result of constructing and testing the surface water model for the Arbuckle-Simpson aquifer project, Hydrosphere has developed a series of recommendations for the OWRB and the water users of the Washita, Blue and Clear Boggy river basins.

Recommendation No. 1 –Diversion Records

In compiling water diversions for use in the model, we found many water users fail to report historical water use. Requiring better reporting will provide numerous benefits, including:

- Providing defensible documentation that establishes the level of use of each user;
- Compiling data for future revisions of the model's historical use data set;
- Documenting compliance or exceedance of diversions with water rights permits.

We recommend that the OWRB be provided the enforcement tools necessary to enforce the reporting of diversions, the staffing and/or instrumentation to record the diversions for itself, or some combination of the two.

Recommendation No. 2 – Streamflow Records

While building the inflow data set for the model, we found there are few long-term gages in the three basins studied. Installing gages and maintaining them long-term will provide data for:

- Determining the gains and losses on each stream;
- Spatially disaggregating streamflows;
- Spatially and temporally disaggregating groundwater inflows;
- Providing long-term data sets for hydrological trend analyses, such as ground water pumping, climate change or other factors.

We recommend that the OWRB determine strategic locations for at least 5 more stream gages in each of the three basins receiving water from the Arbuckle-Simpson aquifer and begin a long-term stream-gaging program, or provide funding to the USGS to conduct stream gaging on its behalf.

Recommendation No. 3 – River Administration

From our conversations with the OWRB staff, it is apparent that Oklahoma is on the cusp of having to administer streamflows in some parts of some basins. If demand for water increases and/or the availability of water decreases, administration will become a routine function of the OWRB. Administration will allow:

- Senior water users to divert the water they are entitled to;
- Provide the opportunity to educate water users about the prior appropriation system before water supplies become critically constrained;

We recommend that the OWRB select a stream segment where water conflicts occur and begin routine enforcement of water rights. Expand on this experience to establish what resources will be required to enforce the prior appropriation system in other parts of the state and budget time and staff accordingly.

Appendix A. Model Specifications

To ensure that the model is capable of performing all the tasks required, the OWRB developed a set of model specifications. These specifications include:

Spatial Domain

The model represents the Blue River basin, the Clear Boggy Creek basin, and the Lower Washita River basin of Oklahoma. Hydrologic detail of the basin will have to be sufficient to include surface and ground water inflows, surface water rights that divert from stream systems, and the impact that ground water pumping in the Arbuckle-Simpson Aquifer has on surface water flows.

Surface Water Rights

From the ORWB database, 179 stream water rights divert an average of 82,162 acre-feet per year from 295 diversion points in the Lower Washita, 55 stream water rights divert an average of 33,393 acre-feet per year from 100 diversion points in the Clear Boggy basin, and 51 water rights divert an average of 16,261 acre-feet per year from 97 diversion points in the Blue River basin. There are 52 NPDES discharge outfalls within the three stream systems.

The model was constructed to include these diversions, though were modeled results would not be affected, diversions were amalgamated into a single diversion point.

Ground Water Withdrawals

There are 40 permitted ground water rights which withdraw approximately 72,000 acre-feet per year from the Arbuckle Simpson Aquifer. Ground water use in the watershed outside of the Arbuckle Simpson aquifer was not considered.

Ground Water Flow

A principal objective of the modeling study is to understand and quantify the influence of present and future ground water development on the flows of the Blue River, Clear Boggy Creek, and portions of the Lower Washita River. Accordingly, the model represents the changes in streamflows caused by changes in the dynamics of ground water flow. Because the wells are used as primary supplies rather than as supplemental sources, the amount and timing of ground water withdrawals are not dependent on surface water conditions, and the ground water representation need not be coupled to the surface water system.

Surface Water Transport

The model will account for all surface water in the system, including inflows and gains from ground water around the perimeter of the model. Surface water flows will be available for diversion, use and storage. The model will track and account for all water in the system, and the model will maintain mass balance at all points. Because the model model will operate on a monthly timestep, the model will not be required to route flows.

Reservoir operation

The Lake of the Arbuckles and upper reaches of Lake Texoma will be represented in the model. In addition there are approximately 14 city reservoirs or large lakes in the watershed of the Lower Washita basin which should be represented in the model.

In addition to the operated reservoirs, there are approximately 130 additional flood control structures with 11,100 acre-feet of storage in the in Clear Boggy Creek watershed, 25 flood control structures with 4,200 acre-feet of storage in the Blue River watershed, and 309 flood control structures with 89,500 af storage in the Lower Washita River watershed. These structures, constructed by the National Resources Conservation Service, are operated rather informally. Typically these structures fill and stay full, or drain out over long periods of time, or water is withdrawn from them late in the irrigation season by pumping. The model should be constructed to include potential operation of these reservoirs.

Temporal domain

The model will represent a minimum of two periods, 1950 through 1959 and 1994 through 2006. The earlier period represents a critical drought period for this stream system. The model should be constructed so that as additional data become available, the model will be extended beyond 2006.

The model will operate on a monthly time step. This selection of time step will allow the evaluation of seasonal or shorter administration approaches while also allowing the use of readily available data. A monthly timestep will also allow routing to be intrinsically incorporated into the model.

Boundary Conditions

Boundary conditions consist of inflows at the boundary from Stream Sub-System 1-8-2 into Stream Sub-System 1-8-1, the upper Washita into the Lower Washita basin, and the watersheds of the Blue River and Clear Boggy Creek.

Historical Base Flows

Base flows represent the contribution to the streams and rivers from the ground water system. To the extent possible, base flows will be determined through surface water run-off modeling to be done by the Dr. Baxter Vieux, University of Oklahoma. Gage data, for the time periods described in the temporal domain section, will be naturalized to represent the conditions without the impact of human activities (e.g. irrigation seepage and ground water extraction) that will be represented in the model. Other adjustments (e.g. to compensate for growth of un-permitted domestic wells) may be necessary Adjustment of actual base-flows during the 1950s will not be conducted due to the lack of any significant information on water use during that period. Initial ground water boundary conditions are defined as the current base flow regime, which is assumed to be in equilibrium.

Future Base Flows

The impact of future development and regulation of aquifer development on base flows will be quantified by ground water modeling. Variations in ground water flow predicted by modeling will be incorporated into the surface water model through aggregated adjustment factors to ground water inflows.

System surface inflows

Surface inflows at the boundaries of the surface water system must be estimated at points above all surface withdrawal points.

Historical Data

Historical water use data

Because of inconsistent reporting, records of water use are incomplete and vary in quality. It will be necessary to reconstruct missing records for some withdrawals. Some records will have to be disaggregated from annual values and some records of municipal water use may have to be corrected to reconcile duplicate entries. Good data do not generally exist for irrigated acreage and cropping patterns in cases where water use data are missing, so in many cases hydrologic techniques cannot be used to estimate irrigation volumes. In those cases where such data are unavailable, statistical methods will be used to fill in missing data and to disaggregate annual data to monthly data. These methods will be based on the relationship between local weather and irrigation volumes.

Historical reservoir storage data

Historical reservoir storage data will be obtained for the two principal reservoirs in the system. Water withdrawals from the soil conservation reservoirs will be assumed to empty the reservoir prior to runoff.

Inflow data and boundary conditions

The process of developing inflow data will involve 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.

A first step in naturalizing conditions will be to develop a complete database of historical stream flows. There is one stream gage on a major spring and one gage below the confluence of Clear Boggy Creek with Muddy Boggy Creek; two stream gages on Blue River, and seven stream gages within the Lower Washita River with varying study periods.

When a complete database of water withdrawals has been assembled, it will be used as the basis from which partially naturalize the historical flows will be calculated. Flows will only be partially naturalized because water uses that will continue as they occurred historically will be left in the gage record.

The process of naturalizing flows involves adjusting the observed flows to remove the influences of human activities. These influences include the net effect of diversions; reservoir storage, releases, and evaporative losses; and the net effect on base flows of ground water extraction and recharge by irrigation seepage losses.

The net effect of diversions is calculated as the difference between diversions and surface return flows to the stream. Because the model will use a monthly time step, 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 mass balance equation. Losses to the surface water system will be depletions (evapotranspiration) and seepage losses, which will accrue to the river through the ground water system and will be addressed separately. The net impact of a surface water diversion is the amount of the losses. The gaged flows will be adjusted by adding this net impact into all measured flows below the point of impact.

The observed record will be adjusted to eliminate the impact of reservoir operations adding all changes in storage (increased storage is a positive value) and all estimated evaporation or seepage losses. Seepage losses will be addressed in the ground water system. These adjustments are added into all measured flows below the reservoir.

Human-caused changes in base flows are subtracted from the record at appropriate points (anthromorphologic increases in base flow are positive values.) Changes in base flow are calculated by using the ground water model discussed below to estimate the base flows that would have occurred in the intervening reaches between gages had the relevant human activities not been present (e.g. irrigation recharge/return flow, ground water extraction.) The observed base flow is subtracted from this estimated natural base flow to quantify the changes in base flow due to human activities.

Once the flows at these gages have been naturalized they will be disaggregated to the level required to represent flows, and thus water availability, in all critical reaches of the river. Disaggregation will be done using parametric and non-parametric statistical techniques and hydrologic modeling, as appropriate, coupled with GIS methods. Flows will be disaggregated at each water withdrawal point, reservoir or other point of interest.

Operating rules

The principle operating rule for stream water withdrawals will be priority allocation of water. Additional rules will be required for management of Lake of the Arbuckles and for as many municipal lakes as operating data can be obtained. The small flood control reservoirs do not have the ability to bypass flows, so they will be operated according to their individual water budgets.

Simulation approach

The modeling objectives suggest the following requirements for the simulation methodology:

- A monthly time step is sufficient
- Routing need not be represented (within a time step a steady-state representation is sufficient.)
- Representation of ground water extractions can be uncoupled or only loosely coupled with the representation of surface water conditions
- Dynamic simulation of physical hydrology is not required
- Priority allocation of water to numerous water rights is required
- Representation of operating rules is required

Formulation of network

The topology of the network will be based on the stream network derived from the [stream reach dataset]. The network will extend to the highest withdrawal on each tributary. Reaches initially will be delineated only where a water withdrawal, significant gain or confluence occurs—further refinement can be made as necessary.

Lake of the Arbuckles, Lake Texoma, and municipal lakes will be represented independently. The soil conservation reservoirs may be consolidated or treated individually as appropriate.

If return flows from surface water withdrawals are determined to accrue to the river immediately downstream of the withdrawal point and within the same month as the withdrawal, then water uses will be represented as the consumptive use portion of the withdrawal. If this is not the case then water uses will be represented as the withdrawal coupled with an explicit representation of the resulting return flow.

Over 190 water demands were represented, including 124 irrigators and 17 public water supplies. The model included 36 inflow points and 178 river reaches.

Formulation and Analysis of Scenarios

The modeling objectives encompass two primary questions:

- What will be the effect of priority administration on water availability for current and future stream water rights?
- What is the effect of the changing relationship between base flows and runoff?

Priority administration

Current water rights administration on the North Fork only addresses surface water rights, which are administered only on annual withdrawals. The model will be used to investigate the issues and benefits arising from administering all rights on a monthly basis. In this evaluation, which will serve as the baseline condition for other scenarios, each water right will be assigned a water demand representing its full supply or allocation. The water rights system will be operated in priority and the actual water available to each right will be determined, along with depleted streamflows and reservoir conditions.

Changes in base flow

Recent flow records indicate that base flow from ground water is providing a larger fraction of streamflow than in the past. An increase in the percent of base flow has implications for water rights administration as it allows a longer period during which direct flow diversion is possible and increases the amount of direct flow diversion at the expense of reservoir storage. This will change administration of water rights in the basin.

If data are available, the effect of increased base flows will be assessed by adjusting historical naturalized flows such that the entire period reflects the recently observed relationship between base flow and runoff.