System Dynamics Model of Southwestern New Mexico Hydrology to Assess Impact of the 2004 Arizona Water Settlements Act

Amy Sun, Vince Tidwell, Geoff Klise, Len Malczynski, Will Peplinski, and Jim Brainard
Sandia National Laboratories[1], Albuquerque, New Mexico

Abstract

Water resource management requires collaborative solutions that cross institutional and political boundaries. As key technical contributors to solving critical resource and security problems on a national scale, Sandia National Laboratories are well positioned to team with federal, state, and local water experts to model growing water concerns in the country. Unlike the traditional approach of compartmentalization of tasks and expertise, Sandia utilizes a collaborative modeling approach that is inclusive, multidisciplinary, quantitative, and transparent to all interested parties. A system dynamics (SD) approach forms the basis for the simulation models. We illustrate this process with a water balance model of the Gila-San Francisco River Basin (Gila Basin) in southwestern New Mexico. Teaming with key stakeholders over a course of eighteen months, a system-dynamics hydrologic model is built in response to the terms of 2004 Arizona Water Settlements Act to assess the existing use of water in the region and the potential impact of additional withdrawal based on the legal requirement of the 2004 Arizona Water Settlements Act. The model has enhanced the overall understanding of the intricate coupling between water resources and demands and helped structure dialogue around potential the human and ecological impact on the river health in the context of the new settlement.

Introduction

In the U.S. Supreme Court litigation *Arizona v California*, 376 U.S. 340 (1964), the State of New Mexico presented evidence of present and past uses of water from its tributaries in the Lower Colorado River Basin including the Gila River and its tributaries. In addition, New Mexico presented a water supply study showing how the state could apply and use the water it claimed as its equitable share of the Gila River (Figure 1). In the resulting report of the Special Master, it was found that New Mexico should be allowed present uses as an equitable apportionment of the waters of the Gila Basin, but did not make an apportionment of water to New Mexico to provide for future uses.

Subsequently, the 1968 Colorado River Basin Project Act, P.L. 90-537, which authorized the building of the Central Arizona Project (CAP) included allocation of 18,000 acre-feet of water to New Mexico. This water is in addition to the water awarded in the 1964 court decree (30,000 acre-feet of consumptive use per year). The allocation was effected through an exchange by the Secretary of the Interior of 18,000 acre feet of CAP water for an equal amount of diversions of Gila Basin water. However, the 1968 Act did not provide a means for New Mexico to divert the Gila Basin water without objection by senior downstream users. The 2004 Arizona Water Settlements Act amends the 1968 Act and together with the Consumptive Use and Forbearance Agreement (CUFA), provides both the ability to divert without objection by downstream parties and the funding to help. The CUFA sets forth the rights and responsibilities of all involved parties. The CUFA also describes the terms and parameters under which diversions by New Mexico may occur without objection by the downstream parties, because additional diversions in New Mexico will be junior to all Gila Basin rights existing as of September 30, 1968. It also describes how the Secretary of Interior will exchange CAP water for Gila Basin water and how disputes may be resolved.

Specifically, the 2004 Arizona Water Settlements Act provides New Mexico 140,000 acre-feet of additional depletions from the Gila Basin in New Mexico in any ten year period. In addition, the State of New Mexico will receive $66M for "paying costs of water utilization alternatives to meet water supply demands in the Southwest Water Planning Region of New Mexico, as determined by the New Mexico Interstate Stream Commission (NMISC) in consultation with the Southwest Water Planning Group (SWPG). Funds may be used to cover costs of an actual water supply project, environmental mitigation, or restoration activities associated with or necessary for the project. Further, if New Mexico decides to build a project to divert Gila Basin water in exchange for CAP water, the state will have access to an additional $34-$62 million. According to the settlement, New Mexico has until 2014 to notify the Secretary of the Interior about plans to divert water from the Gila Riverthat include a diversion.

Environmentalists have kept a wary eye on the negotiations due to concerns about possible environmental costs if New Mexico were to develop its entitlement to the Gila River, the last main stem river in New Mexico without a major water development project. They argue that whatever diversion technique is adopted will reduce water available for wildlife, vegetation, nutrient cycling and other vital river functions. The 2004 Act requires that the NEPA process must be completed with a record of decision by 2019. The legislation designates the U.S. Bureau of Reclamation as the lead federal action agency and provides that the State of New Mexico through the Interstate Stream Commission may elect to serve as joint lead. As such the Bureau (and NMISC) will plan the formal environmental compliance activities (e.g., NEPA).

In response, the NMISC, the Office of the Governor of the state of New Mexico, and SWPG have both adopted policies that "recognize the unique and valuable ecology of the Gila Basin." In considering any proposal for water utilization under Section 212 of the Arizona Water Settlements Act, full consideration will be given to "the best available science to assess and mitigate the ecological impacts on Southwest New Mexico, the Gila River, its tributaries and associated riparian corridors, while also considering the historic uses of and future demands for water in the basin and the traditions, cultures and customs affecting those uses."

Now with the necessary settlements in place, decisions are needed as to how best to use the additional 140,000 acre-feet of Gila water and the available funding, all before the applicable time limits expire. Ultimately, the NMISC will make that determination in consultation with the SWPG, the citizens of southwest New Mexico and other affected interests. The New Mexico Interstate Stream Commission has committed to a continuing process of public information and comment to help arrive at such determinations.

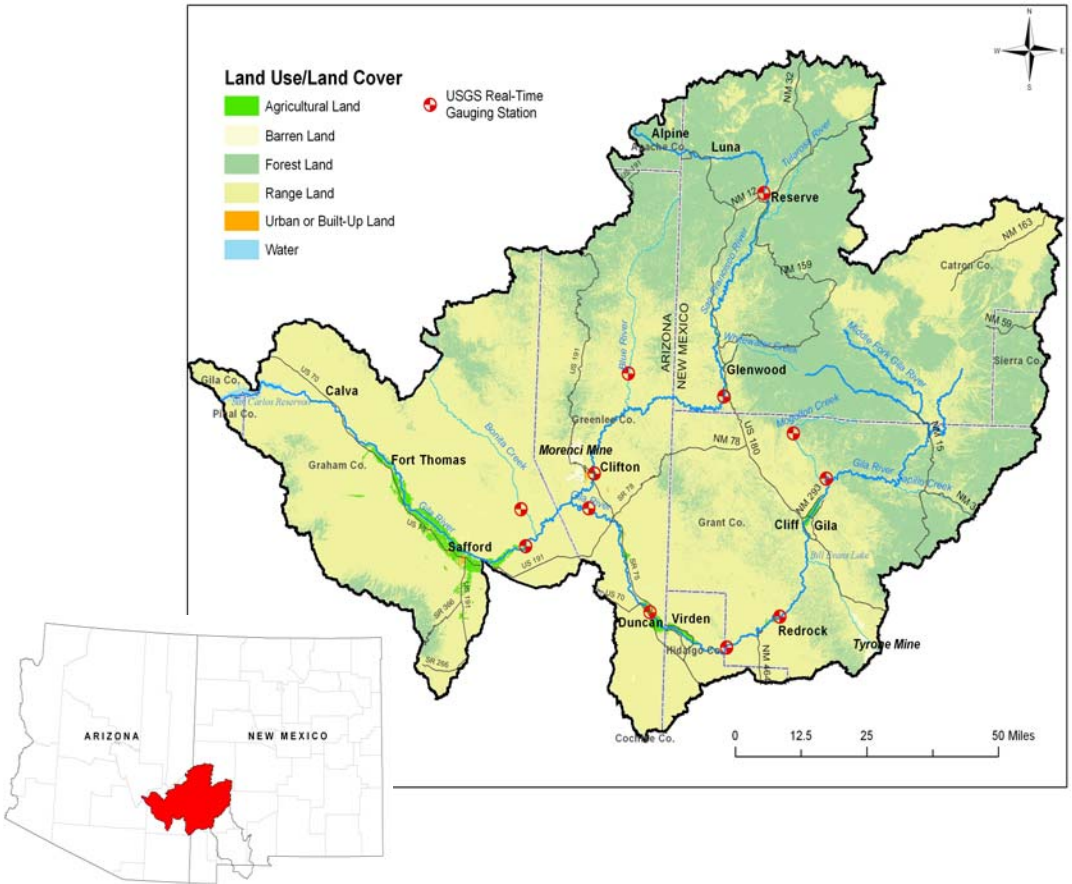


Figure 1: Map of the Gila and San Francisco River Basins. Shown are the major tributaries, gauges, and municipalities.

Collaborative, Stakeholder-driven Process

The watersheds we live in are comprised of a set of complex, highly interactive physical and social processes. These systems are continually evolving in response to changing climatic, ecological, and human conditions that span across multiple spatial and temporal scales. Thus, human intuition and experience alone are insufficient to effectively manage our watersheds. More importantly, developing watershed management models that are both scientifically sound and publicly acceptable is often fraught with difficulty. If such models are developed “behind closed doors,” their operation, application and utility can appear obscure to stakeholders. Rather, an open and participatory model development process can help overcome such problems by building familiarity, confidence and acceptance in the models, while allowing a more diverse group of participants to engage in the planning process.

To assist in decisions concerning implementation of the articles of the 2004 Arizona Water Settlements Act, The New Mexico Interstate Stream Commission (NMISC) has teamed with Sandia to develop an interactive decision support tool through a community mediated process. The model through collaborative development is a tangible manifestation of the common understanding of a wide range of stakeholders, who in turn feel a sense of common, shared ownership and confidence in the resulting model. In turn, this confidence will be conveyed to policy makers and the public contributing to widespread confidence in ensuing management decisions. Specifically, the project provides a model built from the collective knowledge and effort of a wide and disparate range of regional stakeholders, including hydrologists, ecologists, attorneys, agriculturalists, planners, policy makers, and the general public.

The NMISC, the U.S. Bureau of Reclamation (lead federal agency), and U.S. Fish and Wildlife Service constitute the statutory authority over the implementation of the New Mexico Consumptive Use and Forbearance Agreement (CUFA). The Gila Water Planning Group including representatives from the four-county region, the Nature Conservancy, the Town of Silver City, local concerned citizens, and a local conservation group named the Gila Conservation Coalition. Modelers from Sandia National Laboratories (SNL) are responsible for model development, while a professional facilitator and meeting note taker are responsible for managing the flow of each meeting. In all, there are roughly 20 active members on the team. The cooperative modeling team was formed in September 2005 and met bi-weekly until July, 2007.

The stakeholder driven, model building process consists of four parts: problem definition, conceptual design of the causal loop structure, refinement within each sector, and abstraction into system dynamics formalism. While these steps are sequential, iterations are necessary to build upon incremental understanding of the historical demands and supplies in the region. This open and participatory nature of the model development process also results in shared understanding from group with disparate backgrounds. A unique aspect of the cooperation was the use of web-based conferencing due to the geographically dispersed nature of the participants. The process and key feedback results have been documented in more details elsewhere [1].

System Dynamics Model of Southwestern New Mexico

Selection of the appropriate architecture for the decision model is based on two criteria. First, a model is needed that provides an “integrated” view of the watershed — one that couples the complex physics governing water supply with the diverse social and environmental issues driving water demand. Second, a model is needed that can be taken directly to the public for involvement in the decision process and for educational outreach. For these reasons we adopt an approach based on the principles of system dynamics [2,3]. System dynamics provides a unique framework for integrating the disparate physical and social systems important to water resource management, while providing an interactive environment for engaging the public.

The goal of the model, as drawn by the collaborative group, is to answer three important questions in the context of the New Mexico Consumptive Use and Forbearance Agreement.

- Given various constraints, how much water is available from where, when and to what purpose?
- Given various constraints, how much water is in demand from where, when and to what purpose?
- What are the tradeoffs among various approaches to managing this water?

<u>Overall Causal Loop Diagram</u>

The overall influence diagram for the model is shown in Figure 2. Elements in Figure 2 largely relate to unit volumes and unit flows of water. Intuitively, the major hydrologic units are surface water supply and groundwater supply. The groundwater supply is further broken down into two groups, shallow aquifer storage and deep aquifer storage. The other volumes to be considered are the amount of water demanded by human consumption, crop irrigation, riparian growth, industrial consumptive use, cattle growth, and finally, CUFA diversion. The various rates of change from natural or man-made processes reveal a complex diagram of interactions and feedback loops. As supply and demand vary spatially, the Gila Basin region is divided into seven interaction basins spanning uplands to the desert. Temporal variation is captured at a daily timestep extended over a twenty-year planning horizon.

The Consumptive Use (CU) water rights adjudicated in the 1964 Supreme Court decision represent the maximum allowable use of existing water. It consists primarily of mining rights, local farming and ranching, and domestic use. Nevertheless, rather than utilizing the full amount of water rights every year, an average consumptive use is calibrated against historical hydrographic surveys from the State Engineer's office in New Mexico [4]. Also noted in Figure 2, the water rights holders have the ability to supplement surface water diversion with groundwater pumping. The model uses these numbers as the upper bounds for usage by irrigated agriculture, cattle ranching, mining, domestic purposes, and commercial and industrial use in the region.

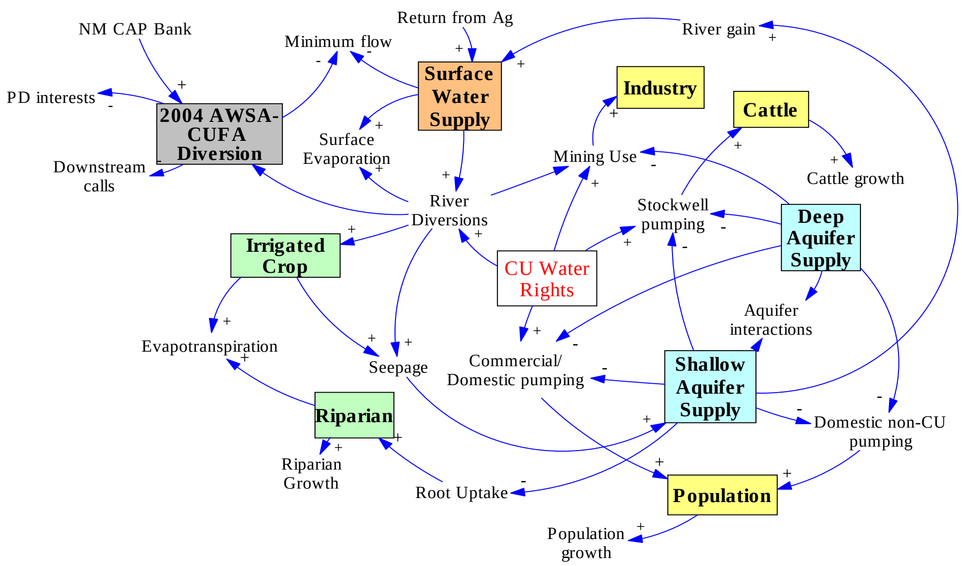


Figure 2 – Overall conceptual diagram.

<u>Agriculture sector</u>

The causal loop diagram specific to the agriculture sector is shown in Figure 3. The variables used for defining the rate equations are also noted in the diagram as “blue” keys. The irrigation demand is fueled by evapotranspiration of all the crops as well as seepage into the soil. For this study, the reference evapotranspiration is estimated from the Hargreaves equation, which utilizes combined temperature and solar radiation data in this region [5]. The Hargreaves equation combined with cultivated acres and crop growth yield the estimated water use by cultivated land. The surface evaporation and seepage from established conveyance also accounts for a part of the irrigation demand. These quantities require knowledge of conveyance morphology as well as conveyance efficiency. Typically, a concrete-lined diversion ditch has higher efficiency compared to earthen diversion ditch.

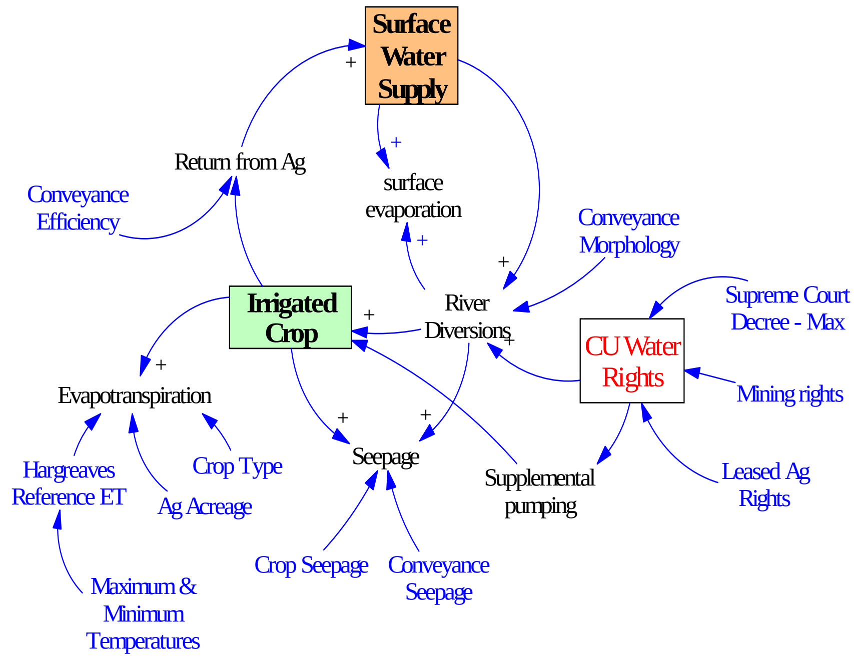


Figure 3 – Agriculture sector causal loop diagram. Variables shown in blue reflect the necessary inputs into the rate equations.

<u>Population Growth</u>

The causal loop diagram specific to population influence is shown in Figure 4. The population growth is refined further between rural and urban area growth rates. Interestingly, the highest growth area in population demand originates from the Mimbres basin, outside the Gila Basin. The collaborative team feels it is important to incorporate the population growth in this region as it represents an important demand on the additional water allocated under the 2004 Arizona Water Settlements Act. The population growth trends in the four county region are based on the trends assessed by University of New Mexico's Bureau of Business and Economic Research and recent water planning document prepared for southwestern New Mexico [6,7]. Water usage by the population can be categorized two ways: consumptive and non-consumptive use. The use of water for maintaining household living is considered non-consumptive use, such as laundry and bathing, and the state can issue well permits for that purpose for every family in the rural portions of the basin. The domestic consumptive use rights refer to water allocation for uses that include gardening, stockwells, and commercial operations, and they must be derived from the adjudicated rights. At the bequest of the Town of Silver City, this model also compartmentalized population growth and water demand for that municipality alone.

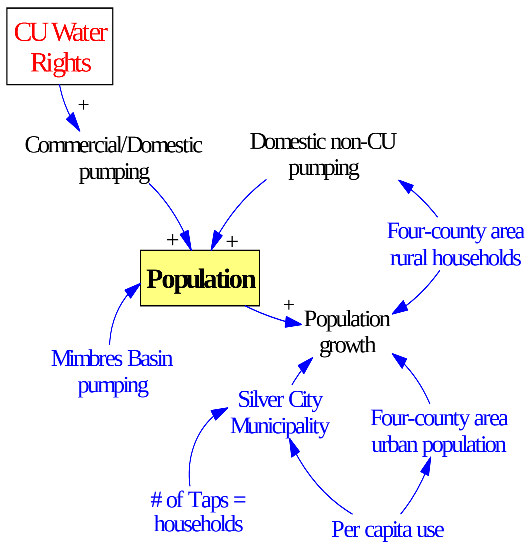


Figure 4 – Overall conceptual diagram for Population.

Mining Industry

The Gila-San Francisco area houses one of the world's oldest copper mines. The New Mexico State Engineer keeps a monthly record of water use in these commercial operations and the data are used in this model. When water rights held by the mining industry are not fully utilized, some can be leased back to crop irrigation. The collaborative team also determines the importance of abstracting that information into the model.

Cattle

Water use for cattle is tightly coupled to the water rights in the region. While the adjudicated water rights under domestic and stock well pumping form the basis for the amount available for cattle, a large fraction of the cattle population in the region also consumes water in the federally-owned forested land where springs or earthern dams are available for drinking.

Surface Water and Groundwater Interactions

The hydrologic feedback loop is the most important element in this water balance model and is shown in Figure 5. It consists of three types of supply: surface water, shallow (or alluvial) aquifer, and deep aquifer. Since the physical reality between the river and its corresponding shallow and deep aquifers requires details of hydrogeologic information that are incomplete for this region, this three-level abstraction crudely represents the intricate coupling between alluvial hydrology and groundwater storage.

The contribution of surface water into the shallow aquifer is through seepage in the conveyance system. The relative difference of hydraulic head and river stage controls the exchange rate at which the two stocks interact. Similarly, the exchange between shallow and deep aquifer supplies is controlled by the relative heads. Because of the large variability in the system, the rate constants are adjustable parameters in the model in order to calibrate the historical observations.

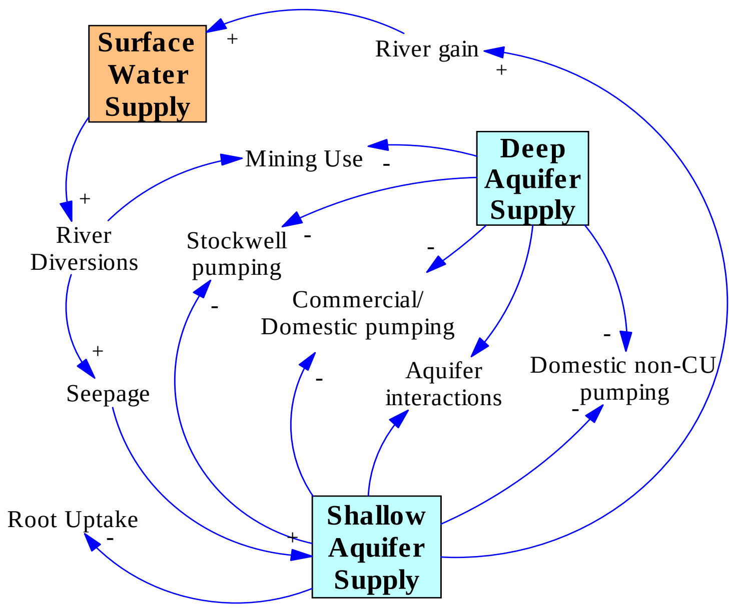


Figure 5 – Causal diagram of the surface and ground water supplies.

<u>Consumptive Use and Forbearance Agreement (CUFA)</u>

The most important feature of this decision support tool is to address the impact of additional diversions under the terms of 2004 Arizona Water Settlements Act. The CUFA is a legal document appended to the Settlements Act with specific hydrologic and demand conditions for allowing withdrawal to occur [8]. In the model, these are referred to as “tests” for CUFA diversion. Table 1 summarizes the requirements for withdrawal. As long as any one of the test fails in Table 1, no water can be used from either the Gila or San Francisco river.

Table 1 – Summary of CUFA conditions required for additional diversion of Gila-San Francisco rivers.

Test	Type	Description
Annual Total < 64,000 AF	Cumulative	Sum of Gila and San Francisco total consumptive use cannot exceed 64,000 AF per year.
Annual San Francisco Total < 4,000 AF	Cumulative	San Francisco annual consumptive use cannot exceed 4,000 AF annually.
10-yr running total < 140,000 AF	Cumulative	Running 10-yr total of Gila and San Francisco consumptive use cannot exceed 140,000 AF.
New Mexico CAP Water Bank < 70,000 AF	Cumulative	The CAP Water Bank, as maintained by the federal agency, must never exceed 70,000 AF
Gauged flow > Daily Diversion Basis (DDB)	Daily	DDB is the amount of water that the downstream users in Arizona are entitled to and must be satisfied before withdrawal is allowed.
San Carlos Reservoir > 30,000 AF	Daily	San Carlos Reservoir provides water use to its downstream users. Minimum storage amount in the San Carlos reservoir is required before any consideration for withdrawal.
Sum of withdrawal < 350 cfs	Daily	Combined withdrawal of rivers cannot exceed 350 cfs.
Gila Virden gauge > 120% of Duncan-Virden Valley call	Daily	Duncan-Virden valley straddles both New Mexico and Arizona and its daily irrigation requirement must be met. The USGS flow gauge near the town of Virden best indicates Gila river flow near the valley.
San Francisco gauges > required flow for Phelps Dodge	Daily	This section of the CUFA focuses on the water available for the mining company Phelps Dodge throughout the year.
Gauged flow > Potential flow	Daily	This is a New Mexico mandate which requires a specified minimum flow imposed on the Gila and San Francisco rivers

As outlined in Table 1, there are two types of constraints in the CUFA, daily constraint and cumulative constraint. Daily constraint such as the minimum storage requirement in San Carlos reservoir of 30,000 AF is enforced. On the other hand, cumulative constraint do not impact withdrawal until the amount reaches the ceiling specified in the CUFA, such as the 10-year running total of 140,000 AF of total diversion. Other than the 10-

year running sum, there are three other cumulative constraints: 64,000 AF of total annual withdrawal, 4,000 AF of annual San Francisco river withdrawal, and the annual maximum New Mexico CAP Water Bank Balance of 70,000 AF.

Sample Run

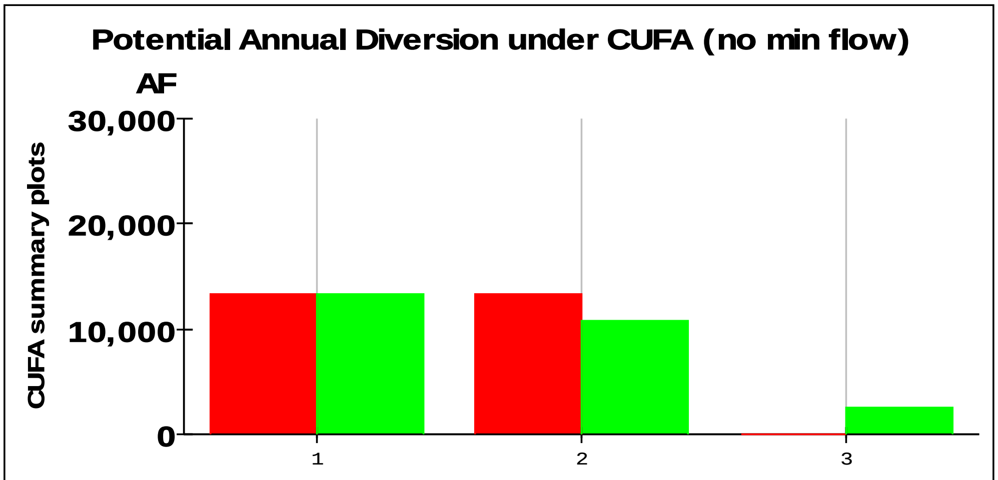
This paper does not provide the details of the iterative process for calibrating the hydrologic model that narrows the gap between model and historical data. This process is documented elsewhere [8]. This section illustrates a baseline run with its corresponding results from the model. The model is built on PowerSim Studio software [9]. The user interface is built to allow adjustments on parameters that are uncertain or interesting to the collaborative team. An example of the adjustment is the amount of minimum flow required in the river. This can vary depending on the season and or the local ecology in the area.

In any given run, tables and charts of surface and ground water usage are generated from the model that summarizes the consumptive use in yearly increments as well as the total volume. The overall water budget is further categorized according to its sector. Figure 6 shows a typical table of a twenty-year summary for Gila groundwater consumptive use. The rate information is averaged over a twenty-year period while the total volume shows the cumulative total.

Gila GW	Avg Annual Rate	Total Volume
Domestic Wells	20 AF/year	413 AF
DNC Wells	1,818 AF/year	35,483 AF
Municipality	657 AF/year	14,241 AF
GW to Mimbres	951 AF/year	17,865 AF
Commercial	2,183 AF/year	45,880 AF
Livestock	3,206 AF/year	67,283 AF
Mining	392 AF/year	8,367 AF
Supplemental Ag	2,948 AF/year	78,829 AF

Figure 6 – Tabular results of groundwater consumptive use over a 20-year horizon.

The CUFA results are also shown as tables and charts. The potential diversion is shown graphically relative to the baseline settings. This ensures an instantaneous comparison between the diversion under a "typical" condition versus a condition that experiences an external perturbation (such as temperature change).



	Total	Potential Gila	Potential SF
	13,333 AF	13,333 AF	0 AF
Baseline Summary	13,333 AF	10,749 AF	2,582 AF

Figure 7 – Summary of modeled CUFA diversion showing both the baseline diversion amount (red) and an amount that experiences a change in the model parameter (green). This case shows the result of total diversion when San Francisco River is not considered at all.

Current effort is focused on creating scenarios and understanding the sensitivities of results to various model parameters.

Summary

A decision support tool for assessing the impact of additional water allocation for New Mexico in response to the 2004 Gila Water Settlements Act is described in this work. In order to understand the implications of additional water withdrawal from the Gila and San Francisco Rivers, a hydrologic component must be built to represent the current water demand and supply. This involves coarse-grained abstraction of the current surface water and groundwater supplies and demand. A collaborative modeling process spanning over eighteen months integrated with system dynamics methodology has yielded a computer model that is accepted by the stakeholder group and the broader public. The model currently summarizes the consumptive use of water in the region as well as the potential CUFA diversion over a 20-year horizon. More scenario runs are needed to quantify the sensitivities of potential diversion relative to exogenous perturbations in human or ecological demands.

[1]Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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