University of Nevada, Reno

A Dynamic Decision Support System for Drought Resiliency and Climate Change

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in Hydrology

By

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Abstract

A water utility is tasked with perpetually supplying water to its customers, regardless of weather patterns and water supply. Simply put, there is no room for a shortage under any conditions. This can be most challenging in times of drought, when available water is slim and the utility system is most stressed. Across the west, these drought planning challenges are further exacerbated by ever increasing water demands, and a changing climate may be accentuating weather variability and drought severity. However, given information about plausible future conditions, it is possible for a water purveyor to evaluate management strategies and system limitations.

This study develops a decision support system (DSS) structured for the Truckee Meadows Water Authority (TMWA), northern Nevada's largest water purveyor. The DSS has been created to assist in long-term drought planning, and is able to identify situations when existing infrastructure or policies are insufficient to meet customer demands under drought conditions. The model uses a linear program, to solve the water supply and demand problem via a cost minimization algorithm. The model has been parameterized with current operating conditions, and is easily adjustable to analyze the effects of system upgrades or policy changes.

The model has been used to evaluate two drought scenarios, created by a partner project titled Water for the Seasons (USDA/NIFA Grant No. 1360505/1360506). Both scenarios are based on the same concatenation of two historic droughts, creating a 13-year dry period. One has been calibrated to current temperature profiles, and the other to projected temperatures for the time period 2051-2070. Results show that utility operations are drought resilient for both scenarios, but substantially more stressed under the future drought conditions; due to a shift in the timing of snowmelt and runoff.. Dynamic monitoring of snowpack and drought conditions could help to ease future difficulties, with the most beneficial actions related to the timing of reservoir storage accumulation. TMWA's current drought response plan was seen to be adequate for the near future, but with the potential to be explored further for greater drought resiliency.

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I. Introduction

Water resource management has perpetually been a challenge in the arid western United States. Competing stakeholders are often left vying for limited water supplies, under hydrologic conditions which can be highly variable and difficult to predict. For municipal water purveyors, overcoming these resource challenges is of utmost importance. Such an entity is tasked with perpetually providing reliable water supplies to its customers; to ensure their health, well-being, and economic vitality. Simply put, this leaves no room for a water shortage. A water purveyor must determine a safe annual yield of available water resources into the future, which can be delivered regardless of circumstance (TMWA, 2016). If that yield is not more than predicted future demands, then something must change for the utility: be it operations, system improvements, or water conservation.

This project analyzes these management challenges associated with drought and climate change, for a case study on the Truckee River. To accomplish this, a decision support system (DSS) has been created, which models operations for the Truckee Meadows Water Authority (TMWA). TMWA is the largest purveyor of water in Northern Nevada, and relies on the Truckee River for most of its supply. A linear program (LP) was thought to be the best mathematical approach for modeling this system, and optimizing utility operations within the DSS. The overall goal of this study is to evaluate the potential impacts of climate change on the system, and recognize what actions can and must be taken to mitigate future water supply risks. The setting of this study, methods used, and end results are all presented within this paper.

3.1 Problem and Setting

The following sections offer more detail on the Truckee River system, TMWA, and future supply difficulties associated with changing hydrologic conditions.

a). Water Resource Planning Challenges

Over time, change is inevitable in any system. For water resource managers, change comes in many forms, and must be accounted for to ensure that customer demands will continually be met. This isn't the easiest task, as even those customer demands are constantly changing, primarily driven by population growth. Thus, the challenge is to understand what amount of demand a system can accommodate. This maximum estimated demand is known as a commitment level, representing the largest annual water demand that can be reliably supplied. A maximum commitment level is generally approximated using a drought standard, which specifies near worst-case hydrologic conditions (Stoddard, 2006). Under the circumstance that an annual water commitment is less than current or near-future projected demands, the system needs to be evaluated and upgraded. Factors such as regulatory requirements, water rights, or facility capacities can change beneficially to accommodate that difference. Changes to factors such as a region's hydro-climatic regime may have the opposite effect, potentially worsening the drought standard and increasing the gap between supply and demand. As such, the role of water resource managers is to recognize and account for these changes, avoiding a water shortage through proactive rather than reactive management.

While many factors impact the sustainability of a water system, none are perhaps as unpredictable and pivotal as climate variability and climate change. Climate variability denotes fluctuations on a shorter time scale, including floods, wet periods, and especially droughts. Climate change refers to prolonged variability, both natural and anthropogenic, and is often associated with warming temperatures (Garbrecht and Piechota, 2006). Numerous studies have recognized widespread declines in snowpack across the western United States, which are linked to climate change (Scalzitti et al., 2016; Safeeq et al., 2016). This loss in snowpack has the propensity to affect both the timing and quantity of river flows in snowmelt dominated regions. Although these timing effects may potentially be dampened by storing water in upstream reservoirs, warming temperatures are also expected to increase evaporation and transpiration rates, exacerbating difficulties associated with reservoir use and maintenance of drought supplies (Barnet et al., 2005). A predicted increase in weather variability and intensity is also associated with climate change, introducing further concerns (Maurer, 2007; Reclamation, 2016).

It is therefore a combination of both climate variability and climate change, that has the greatest potential to cause water resource problems. Water supply systems are most stressed during extreme events, especially times of limited water. These future droughts may become more severe, exacerbated by climate change impacts. To manage for potential water shortages, a region's drought standard must be representative of plausible future droughts, and not simply historic conditions. A robust drought plan would therefore incorporate scientific information regarding climate change, meshed with an operational model (or DSS) that accurately represents the system and water demands as expected. It is the therefore the goal of this project to do so for the Truckee Meadows water Authority.

b). Case study – The Truckee River and TMWA

The Truckee River originates in California at Lake Tahoe, flows northeast for 119 miles, and eventually terminates on tribal lands at Pyramid Lake in Nevada (Figure 1.1). It's total basin size is approximately 3,060 square miles, with around 25 percent of that land in California and the remaining 75 percent in Nevada (Reclamation, 2016). Although a majority of the watershed is located in Nevada, most of the prepitation occurs in California, at headwater elevations up to 10,000 feet. The Truckee River is considered a

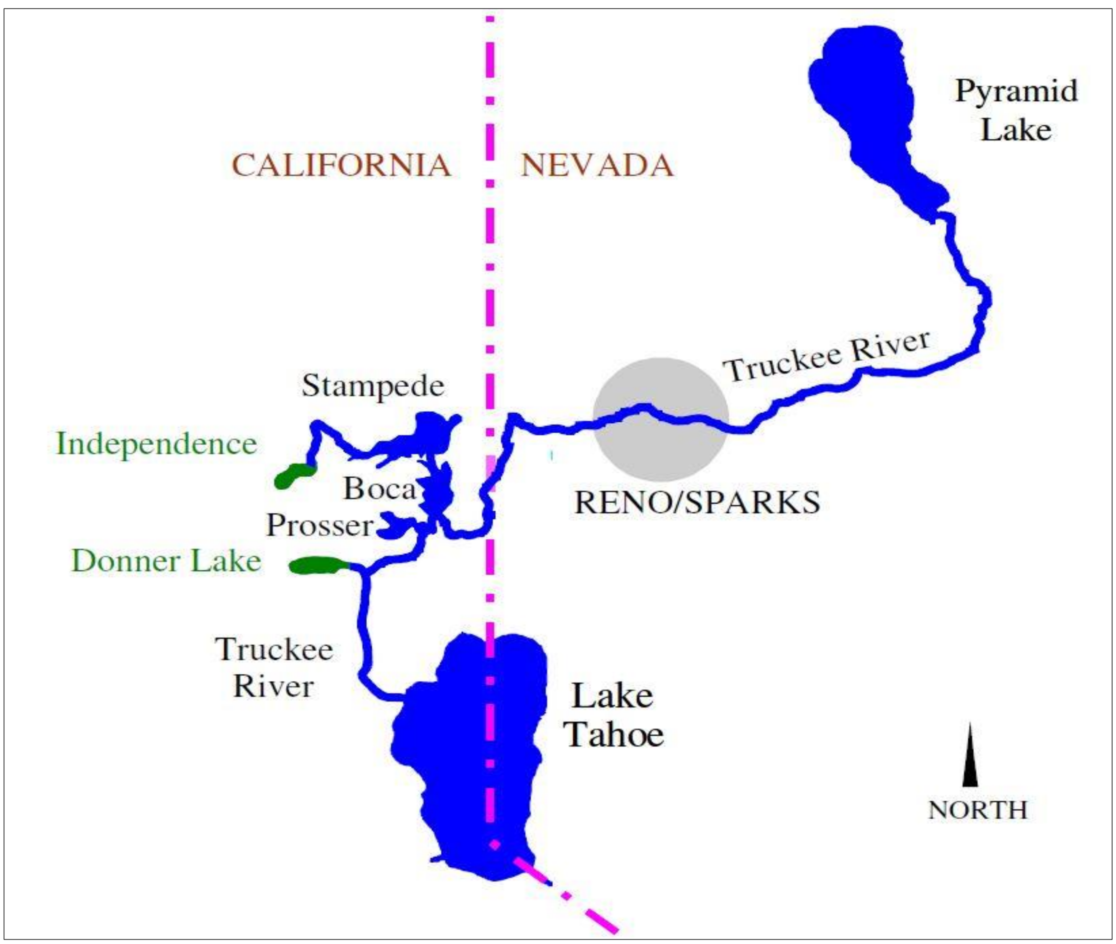


Figure 1.1: The Truckee River System. Source: TMWA

snow-fed arid-land river system, as most of the river's water comes from snowmelt in the Sierra Nevada Mountains. The regional climate is highly seasonal, with precipitation primarily occurring during the cooler months of late fall, winter, and early spring. During the wet season, much of that snow falls within only a few degrees of freezing, due to warm marine storms and relatively low headwater elevations. This makes the river system particularly susceptible to impacts associated with warming temperatures and climate change. Whydf

To store water and regulate river flows, seven reservoirs exist on the Truckee River (Figure 1.1). Five of these (Tahoe, Prosser Creek, Stampede, Boca, and Martis Creek) are federally operated, while the other two (Donner and Independence Lakes) are managed by the Truckee Meadows Water Authority (TMWA). Lake Tahoe is by far the largest reservoir on the system, with an average annual usable storage capacity of 557,100 acre-feet (AF), and a maximum capacity of over 700,000 AF. It is a somewhat unusual reservoir, in that a small dam controls only the top 6.1 feet of the lake. Thus, the managed portion of water is very wide compared to its depth, and annual evaporation losses are often substantial compared to the actual quantity of water stored. The other four federal reservoirs are more traditional in design, and collectively store approximately 237,300 AF in an average year (Reclamation, 2016). By comparison, the stored water in Donner and Independence Lakes is a relatively small quantity, at 9,500 AF and 17,500 AF respectively. The collective operation of all these reservoirs, as dictated by the Truckee River Operating Agreement (TROA), provides the vast majority of water flowing down the Truckee River.

TMWA is the largest purveyor of water in northern Nevada, and a primary stakeholder in the consumption of Truckee River Water. The utility provides water to a majority of the population in southern Washoe County, with a service area that encompasess most of the Reno/Sparks metropolitan area and surrrounding valleys (Figure 1.2). During normal years, TMWA's main suppply source is the Truckee River. Water is diverted from the river and and sent to two water treatment plants: Chalk Bluff and Glendale. When water consumption peaks during the hot and dry summer months, the capacity of these treatment plants is often insufficient to meet demands. During such times, groundwater supplies must be utilized to offset the difference. As of 2016, TMWA had 81 active prodcution wells which could perform that duty (Figure 1.2), supported by an adequate amount of water rights. The utility also actively engages in an aquifer storage and recovery (ASR) program, which improves regional aquifer health and could potentially provide extra supplies during a drought situation. 33 wells are currently equipped for recharge. As detailed above, this combination of river supplies, well use, and groundwater recharge constitutes standard TMWA operations (TMWA, 2016).

Drought is not a new phenomenon for northwest Nevada. Historically the area has experienced two eight-year droughts (with 1987-1994 the most severe), and numerous shorter dry spells. Currently, the region is in its second year of recovery from the worst four-year drought on record (2012-2015). TMWA's drought plan involves both "supply-side" and "demand-side" actions, which are implemented to conserve water when a drought situation is in effect. During a severe drought, the utility must also rely on water supply sources which are above and beyond normal operations. This includes privately owned stored water (POSW) in Donner and Independence Lakes, and M&I credit water (as specified by TROA) stored in the other Truckee River Reservoirs. These surface water supplies are managed conjunctively with groundwater pumping, and ASR water

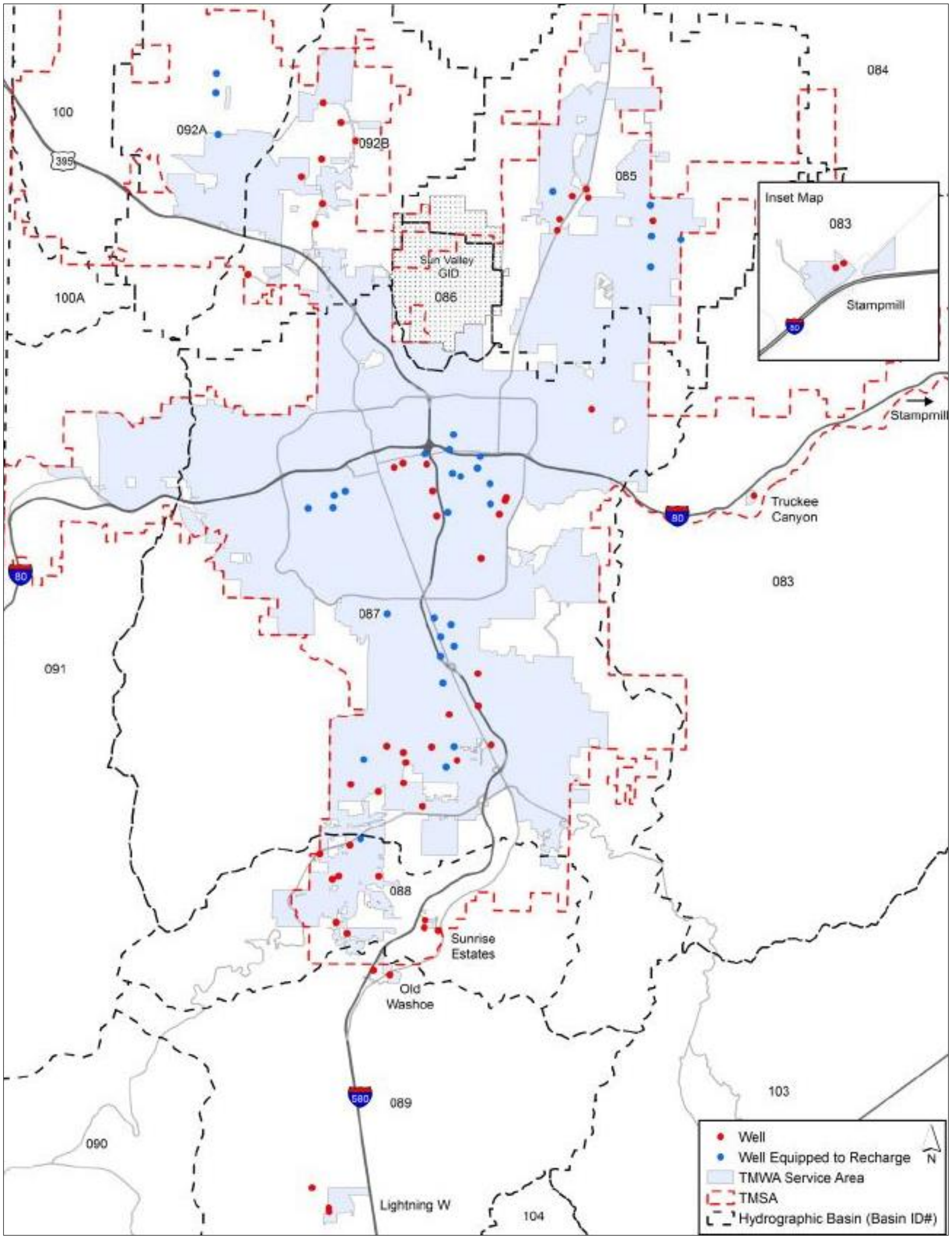


Figure 1.2: TMWA service area (TMSA) and groundwater resources. Source: TMWA

may be extracted during very dry years. To determine a maximum commitment level with these available water sources, TMWA's drought planning actions have been based off a combination of potential scenarios. A keystone is the 1987-1994 drought, generally considered the design drought and worst on record. Operations have been modelled and designed to withstand a repeat of those conditions. Other planning has involved hydrologic conditions from the 2012-2015 drought, blended with different water years or repeats of 2015 (TMWA, 2016). These scenarios have helped to develop a robust drought response plan, and show the maximum commitment level (119,000 AF) to be substantially above current demands (84,000 AF). However, these conclusions have all been based off historic data, and do not consider the implications of climate change.

In addition to changing climate and increasing population, TMWA has recently been affected by other fundamental changes to its water resources and management structure. In 2014, the utility completed its acquisition of two other regional water utilities, South Truckee Meadows General Improvement District (STMGID) and the Washoe Department of Water Resources (WDWR) . Among various impacts, the merge increased the number of customers, changed infrastructure, and nearly doubled TMWA's groundwater resources. In short, the aquistion has altered possible management strategies for the utility, and offers new resources which have not yet been fully considered. In addition to the physical changes offered by this merge, the Truckee River Operating Agreement (TROA) was finally implemented in 2015, ushering in a new operational strucutre for the entire river system. While retaining some of the old operational framework, TROA offers new flexibility in water storage practices, and was partially designed with drought resiliency at its forefront. Simply put, the impacts from both the merger and adoption of TROA have not yet been fully considered. It is likely that optimal drought management practices may be different than previously modeled, potentially leaving room for improvement. Using a DSS to optimize water management policies on the newly configured system, offers the ability to explore these changes and fully determine a best-case drought contingency plan.

3.2 Literature Review

The following sections include a further discussion about the aspects of this project, and the existing literature related to each.

a). Drought and Climate Change

Drought is a type of slow-moving natural disaster, related to a shortage in water supplies, that produces a complex web of impacts which can affect many sectors of the economy. It has been said that drought may be the most complex of all natural hazards, impacting more people than any other (Wilhite, 2007). These events occur all over the world, with varying degrees of severity, and the result is a rather vague definition of drought. More than anything, the exact qualities that define a drought are unique to a region.

Wilhite and Glantz (1985) categorized the many definitions of drought into four main classifications: meteorological, agricultural, hydrological, and socioeconomic. A meteorological drought is generally defined on the basis of dryness (or lack of precipitation), compared to a “normal” or average amount and the duration of the dry period. Meteorological drought is generally location specific, since these exact characteristics may vary from place to place. Agricultural drought links characteristics of meteorological drought to many different agricultural impacts. Basically, when crop yields are lessened due to a shortage of water, then an agricultural drought is occurring. Hydrological drought is generally defined by the effects of meteorological drought, on shortfalls to surface or subsurface water supply. This is often analyzed on a watershed or river basin scale. In addition, the timing of hydrological drought may often lag behind the other classifications, as it can take longer for precipitation deficiencies to show up in reservoirs, groundwater levels, streamflow, etc. Finally, socioeconomic drought regards the supply or demand of a good, and how those link with elements of the other drought types. Like agricultural drought, a socioeconomic drought occurs when the demand for an economic good exceeds supply, due to weather-related water shortages (Wilhite and Glantz, 1985). A fifth type of drought has also been recognized in more recent years. Known as induced drought, its defining conditions involve a water shortage due to over-drafting or overuse of the normal water supply (TMWA, 2016).

While all these drought types are closely monitored on the Truckee River system, TMWA and other stakeholders utilize a hydrologic drought definition to determine event severity and response. This definition measures drought by years, creating a drought determination for each water year, which is judged by the projected amount of Floriston Rate (FR) water in Lake Tahoe and the other Truckee River Reservoirs. Floriston Rate water is a type of stored regulated water, which is released to meet hydropower and water rights demands whenever natural river flows are not sufficient (typically every day, summer through late fall/winter in a normal year). That quantity of FR water stored in all the reservoirs is combined for supply accounting, and managed as if it were all kept in Lake Tahoe. A drought situation is then determined when the combined quantity of water would equate to a Lake Tahoe level of 6,223.5 feet Lake Tahoe Datum (approximately 0.5' above the natural rim), on or before the following November 15th (TROA, 2008; TMWA, 2016). TMWA then categorizes its drought response based on the date of that year, on which FR supplies are projected to run out. If the reservoirs and Lake Tahoe are relatively full beginning the first year of meteorological drought, it will generally take 2-3 years for the stored water level to reach that point. Conversely, it is not uncommon for the lake levels to fully recover from drought after one very wet year.

There has been a substantial amount of research done and material published on the topic of climate change. The subject refers to prolonged variability, driven by both natural and anthropogenic factors, which is most commonly associated with warming temperatures (Garbrecht and Piechota, 2006). For the western United States, this warming is already being seen in recorded temperatures. Studies show that much of the region has warmed by about 1.5^{0}C compared to historical records from 1901-1960 (Hoerling et al. 2013). Projections of future temperatures show the region continuing to warm by between 2.5^{0}C and 5^{0}C by the end of the century, depending on future rates of greenhouse gas emissions (Walsh et al., 2014; Dettinger et al., 2015; Reclamation, 2016). These warming temperatures are likely to cause an inflation of evaporation and transpiration rates, affecting the storage of water in both engineered and natural reservoirs. The discussed trends in warming and evaporation could also change the timing, form, and quantity of snowpack for the region (Barnet et al., 2005; Maurer, 2007; Safeeq et al., 2016; Scalzitti et al., 2016).

Changes to annual precipitation amounts are relatively uncertain, and have been projected to stay mostly the same within the northern Nevada region (Dettinger et al., 2015). However, the number of extreme weather events has been increasing compared to historical records, and that trend is expected to continue (Georgakakos et al., 2014). This increased variability includes more heavy precipitation events, as well as an increase in droughts. Dry spells are expected to lengthen in most regions, especially across the southern parts of the U.S. (Dai, 2013; Walsh et al., 2014). In addition, warming may already be impacting some extreme drought events. Studies show that climate change played a role in the most recent drought (2012-2015), with warmer temperatures reducing the potential snowpack and exacerbating conditions (Mao et al., 2015; Shukla et al., 2015).

To evaluate the effects of climate change and extreme hydrologic events on the entire Truckee River System, for all stakeholders (TMWA included), another ongoing study has currently taken aim at the issue. This study, titled Water for the Seasons (WftS), is a project funded under NSF/WSC Program jointly funded with USDA/NIFA Grant: 1360505/1360506. WftS is a broad scale basin-wide project, which focuses on the conjunctive management of both the Truckee and Carson River Systems. Similar to this project, WftS makes use of modeling to assess vulnerabilities of the system resulting from climate change, utilizing several plausible future climate scenarios for the region. These scenarios are based on past weather history coupled with future climatic predictions. The associated hydrologic data has been used for this project as well, and the two studies have had a sort symbiotic relationship by sharing data and results. The use of WftS hydrologic data is discussed thoroughly in section III, Data.

b). Linear Programming Methods

At the core of this project, the DSS is solved via a network-flow linear program (LP). LP has proven to be an effective and powerful tool for water resource management, with its usefulness being demonstrated through countless applications for large scale problems. There are many variations on the classic methods of linear programming, and numerous mathematically similar programming approaches which have been utilized for system optimization. These include integer linear programming, fractional linear programming, dynamic programming, evolutionary computation, genetic algorithm, and non-linear programming (Rani and Moreira, 2010). Despite the modelling differences these methods present, it has been concluded that optimization methods generally yield comparable results, with standard LP requiring the least expense and overall computation time (Mani et Al, 2016; Ayvaz and Karahan, 2008; Singh, 2012).

The original algorithm for solving LPs was developed in 1951 by George Dantzig. Called the simplex algorithm, this technique has been used to solve countless transportation and optimization problems since its creation, and is very computationally efficient (Georgakakos, 2012, Thie and Keough, 2008). As a further extension of Dantzig's work, network flow programming (NFP) was introduced by Ford and Fulkerson in 1962, and is essentially an organizational variant of the classic LP structure.

NFPs are considered computationally efficient, and are excellent for representing the movement of goods or materials over time. With NFP, the general configuration of a water supply and storage system can be represented as a capacitated network, with the overall goal to being maximize flow or minimize cost (Rani and Moreira, 2010).

The usefulness of LP and NFP for reservoir and water system optimization has been shown many times. In an early study, Crawley and Dandy (1993) created a deterministic LP for reliable dry-year management of Adelaide's water supply, located in the Murray-Darling basin of Australia. The study was highly effective, with model results ultimately implemented because they showed significant savings for the operating authority. In a similar approach as this project, Hsu and Cheng (2002) developed a network flow optimization model for long-term supply-demand analysis of basin wide water resource planning, within a river basin of North Taiwan. Their model input river flows and population demands, analyzing potential shortages and optimization techniques. While generally effective, the model itself lacked development of any conditional operating rules, which could ultimately represent decision-making by the managing authority. Similar modeling has also been used to approximate multiple-source water supply systems for California, concluding that reasonable water demand estimates are ultimately as important as water supply inputs (Georgakakos, 2012). A few studies have incorporated climate change predictions into the mix of model inputs, suggesting possible management strategies as well as staged improvements for their respective systems over time. These climate change conditions are generally based on local-level scenarios generated specifically for the watersheds or region of interest (Ray et al., 2012), as in this project. Linear programming has also proven to be an efficient tool when combined with simulation models, ultimately producing more reliable results. These model-integration methods have shown promise when applied to conjunctive surface/groundwater management (Mani et al., 2016), multi-objective modelling of reservoir storage and hydropower generation (Alemu et al., 2011), and drought resiliency (Sechi and Sulis, 2009). However, few studies have attempted a synthesis of drought resiliency planning, analysis of impacts from climate change, conjunctive surface water/groundwater management, and conservation/user feedback as this project does.

The most relevant piece of LP literature is a past study by Stoddard (2006), in which he created a DSS that TMWA's current drought contingency plan is based upon. In that research, Stoddard utilized a NFP which approximated various water supplies, storage, treatment, and distribution for the TMWA system. The model was structured to operating rules of the time, as well as existing infrastructure. Runs were performed in an implicit stochastic optimization (ISO) style, using all available historical streamflow records to infer best operating policies. These records included two eight-year drought cycles, allowing the model to analyze best operations for drought resiliency based on past hydrologic data. Although a thorough project, very little consideration was given to climate change, or to impacts from climate change on the regional water supply. Stoddard's model still exists, and its general framework is well documented. That existing model has been used as a rough blueprint for the work performed in this project.

c). The Truckee River System

Several different documents provide specific operating details about the Truckee River system, and TMWA operational parameters. Every five years, the utility publishes a water resource plan (WRP) which details the current state of infrastructure, operational planning, and future system predictions. The 2016 WRP was extensively researched prior to the start of this project. That plan includes critical details about system parameters, water rights, future projected demands, water conservation, drought response, and overall system operations. Much of the modelling performed was structured based off information provided in that plan (TMWA, 2016).

Although utility operations are ultimately structured from decisions within TMWA, there are also several legal documents which bind the potential options. These include orders by the state engineer, court rulings, legal agreements, and of course the Truckee River Operating Agreement (TROA). Apart from TROA, two smaller documents were researched and used extensively in this project. State Engineer Order 1161 restricts annual groundwater pumping for TMWA, dictating the amount of water that can be pulled from the groundwater basin 087 (Truckee Meadows) for both an annual and three-year period (Turnipseed, 2000). The second document, The Donner Lake Indenture, is a formal agreement that binds the operation of Donner Lake (Stone, 1943). The parameters specified by these documents, as well as those determined by the 2016 WRP, are discussed further in Section III, Data.

The document which ultimately dictates Truckee River system operations more than any other, is the Truckee River Operating Agreement. TROA was formally signed in 2008, but did not become officially implemented until nearly 2016. This agreement is unique and well thought out, allowing for increased flexibility of operations by all signatory parties. Flexibility is achieved through one of the document's central pillars: a credit water system. This allows major Truckee River shareholders to trade water rights, reservoir storage space, and timing of water releases; as overseen by an appointed administrator. For non-TMWA shareholders, this credit system is beneficial in that it provides enhanced flows for endangered fish species in Pyramid Lake, benefits river water quality, and offers credit water for other environmental concerns. TROA also resolves the interstate allocation of water between California and Nevada, protects water rights holders, and specifies an end to all previously existing litigation on the system. For TMWA, the agreement offers a completely new way to store and manage its drought supplies. Through the credit system, TMWA can accumulate dramatically more reservoir water than before. It is thought that TROA will allow the utility to be more resilient to droughts, increasing the potential maximum commitment level. The agreement truly represents a shift in water management for the local area, and is a milestone for water agreements everywhere. Since it has only recently been implemented, many of its policies have yet to be fully tested beyond their theoretical application (TROA, 2008).

II. Methods and Model

To answer the questions presented, a decision support system (DSS) was created, which has been parameterized for the Truckee Meadows Water Authority (TMWA). The DSS was based off another model, previously developed for TMWA by Stoddard (2006). A linear program mathematically solves the DSS, optimizing operations on a monthly scale over the full time specified (15 years). Outputs from this model include tables of water

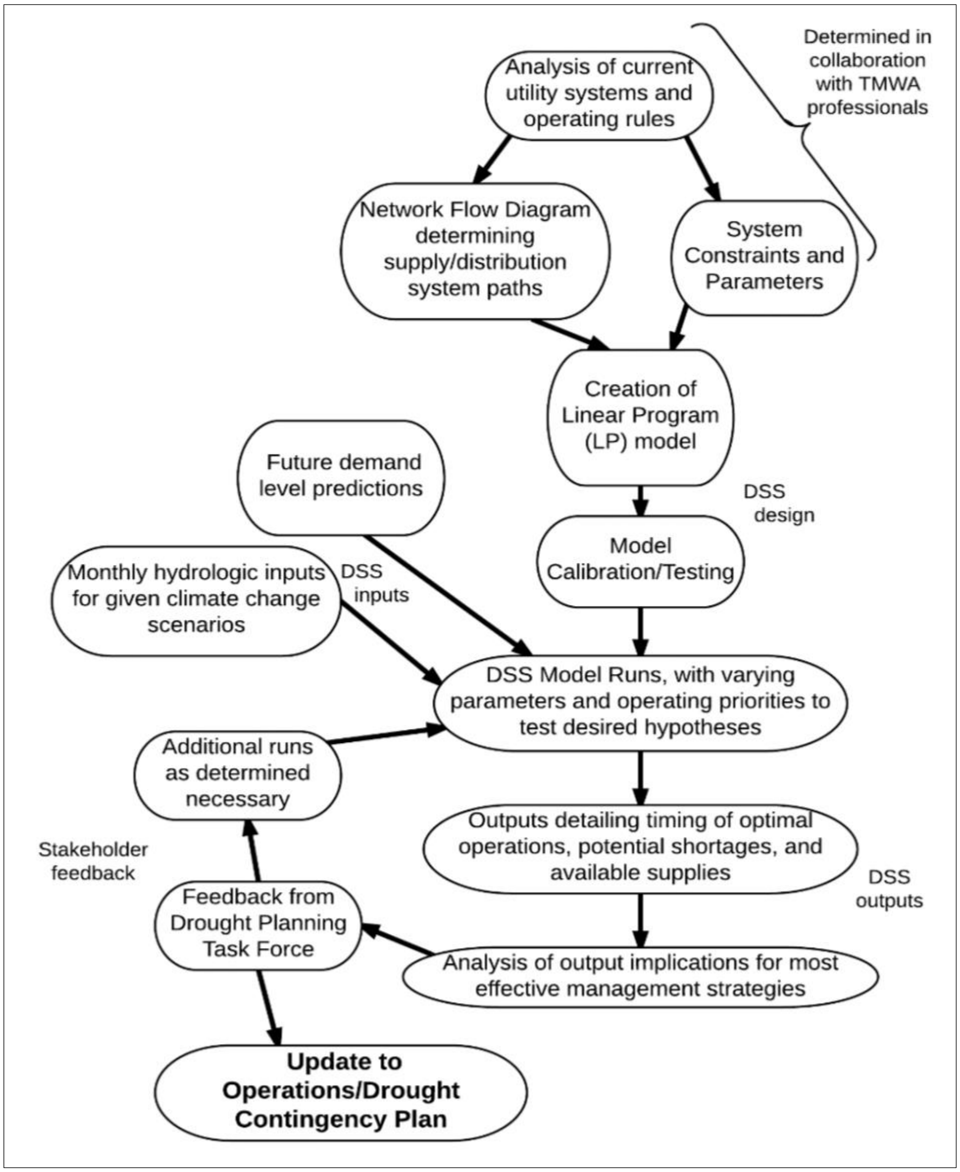


Figure 2.1: General structure of modeling process

sources, reservoir and groundwater quantities, and the timing of specific operations such as water storage or recharge. These outputs were then compared to determine effective operations, policies, and limits.

To fine tune the model and further determine which issues to examine, feedback was solicited from professionals within TMWA, and from other stakeholders in the local community brought together as a drought planning task force (DPTF). Through this interactive process, the model was more precisely parameterized, and the DSS ultimately became more user friendly. This process of refinement shaped the format of the DSS, in that it was modified to address the concerns of the Drought Planning Task Force, and became a less general model.

The following sections feature a detailed discussion of the model, stakeholder feedback process, and other methods used for this project (Figure 2.1).

2.1 DSS Construction

For a model to be useful in the practice of water resource planning and management, it must adequately represent the desired system, and provide outputs which can be interpreted to answer the desired questions. In many situations, interpretation is often the biggest struggle. A model may only be understandable to its creators, and not as much for the decision makers utilizing its outputs. In an attempt to remedy that gap, this DSS has been constructed in an easily modifiable and understandable framework using Microsoft Excel. It represents the system well, through two major components: the mathematical models and the visual user interface. Values are input into the visual user interface and link in to the mathematical model as constraints and rules. Following a run of the mathematical model, results are output once again into the visual user interface. These components and their interaction within the DSS are discussed in greater detail below.

a). General Theory, Network Flow Program

At the core of the DSS is a type of LP known as a network flow program. For a NFP, the mathematical setup is defined via a graphical network, consisting of nodes and arcs which represent the water resource system (figure 2.2). In this model, nodes designate water sources, reservoirs, diversion points, treatment facilities, and monthly customer demand. Arcs connect the nodes and represent river stretches, distribution infrastructure, or stationary flow from one time period to the next (water stored in reservoirs/aquifer). The arcs mathematically define flow through the system, and are limited by upper and

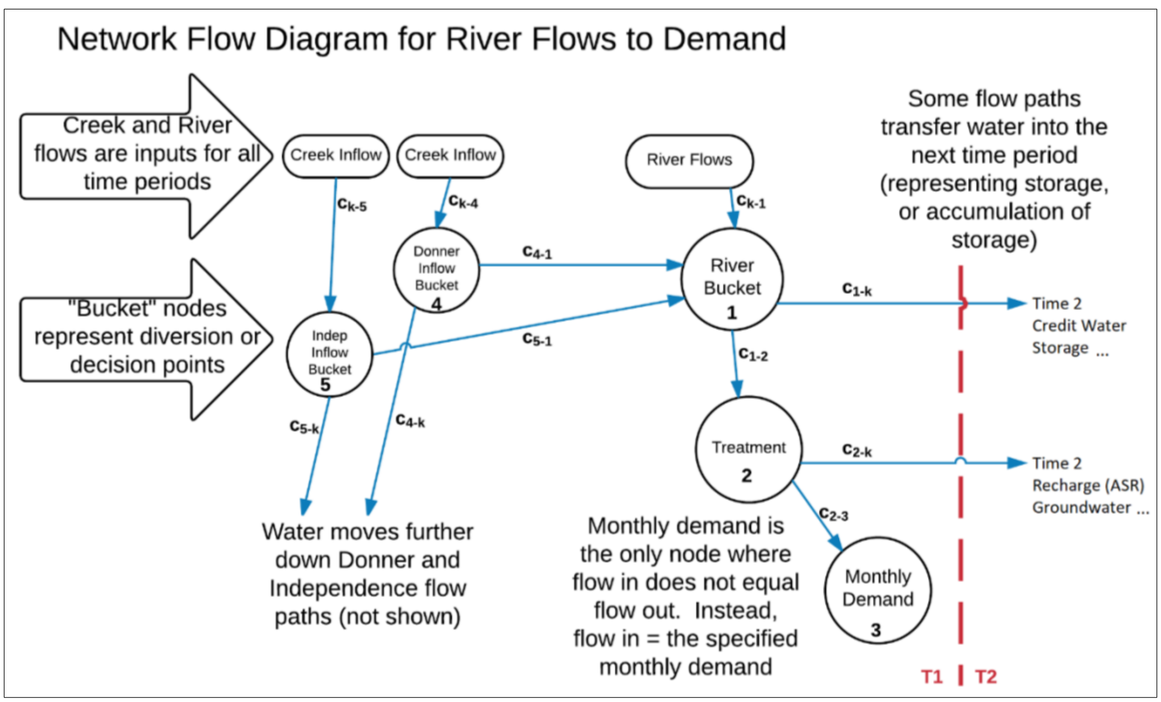


Figure 2.2: Flow path for river flows over one month illustrating nodes (numbered 1-5), arcs, and pseudo-costs associated with each arc (labeled c_k , etc.…). For simplicity sake, some arcs have been omitted

lower capacity constraints. Some also have flow multipliers, for incorporating gains or losses (such as evaporation or distribution loss).

In general, this particular network flow problem can be considered a transportation model. 180 terminal nodes represent customer demands (one for each monthly time period over 15 years), and the system of nodes and arcs is optimized to transport the necessary water to all those demand nodes. This optimization is achieved by assigning a unique unit pseudo-cost to water flows across each individual arc. The unit cost (or pseudo-cost) is non-monetary, and can be thought of like a penalty. These costs weight the desirability of using each water supply and its associated arcs (discussed more in section 3.7). The overall goal of the model is to minimize the total cost of flow through the system, while simultaneously meeting customer demands. An objective function defines this total cost relationship, and its possible values are bounded by a series of constraints. The network flow model can be represented by the following series of linear equations.

Minimize (objective function):

$$Z = \sum_{k=1}^{K} c_k q_k \tag{1}$$

Subject to:

Mass balance at each node n = 1, 2, …, N except customer demand nodes.

$$\sum_{k \in K_{in}} a_k q_k - \sum_{k \in K_{out}} q_k = 0 \tag{2}$$

Mass balance for customer demand nodes.

$$\sum_{k \in K_{in}} a_k q_k = customer\ demand\ for\ time\ period, m \qquad (3)$$

$$\sum_{k \in K_{out}} q_k = 0 \qquad (4)$$

Upper and lower capacity constraints for each arc k = 1, 2, …, K.

$$0 \leq l_k \leq q_k \leq u_k \qquad (5)$$

Where Z = total system cost (objective function value); K = total number of arcs; N = total number of nodes; q_k = flow in arc k; c_k = cost per unit of flow for arc k; a_k = flow multiplier for each arc k (generally a percentage loss); K_{in} = subset of arcs flowing into node n; K_{out} = subset of arcs flowing out of node n; l_k = lower bound for arc k; u_k = upper bound for arc k; m = any time period (Stoddard, 2006).

Year	Month	Time Period	Arc Num (x)	Origin (i)	Terminal (j)	Name	Flow (AF)	Lower Bounds	Upper Bounds	Per Unit Cost	Unit Gains/ Losses	Received Flow (AF)	Total Flow Cost
0	0	0	1		101	Donner Starting Balance	3,500.0	3,500.0	3,500.0	-	1.00	3,500.0	-
0	0	0	2		102	Independence Starting Balance	14,000.0	14,000.0	14,000.0	-	1.00	14,000.0	-
0	0	0	3		103	TROA Water Starting Balance	6,000.0	6,000.0	6,000.0	-	1.00	6,000.0	-
0	0	0	4		104	TMWA Emergency Drought Supply Starting	7,500.0	7,500.0	7,500.0	-	1.00	7,500.0	-
0	0	0	5		105	TRA ASR Starting Balance	50.0	50.0	50.0	-	1.00	50.0	-
0	0	0	6		106	TROA annual Groundwater Permit	15,950.0	15,950.0	15,950.0	-	1.00	15,950.0	-
0	0	0	7		112	Annual Extra GW Rights	11,000.0	11,000.0	11,000.0	-	1.00	11,000.0	-
1	1	1	8		100	River Supply to Collective River Bucket	3,959.7	-	34,147.6	-	1.00	3,959.7	-
1	1	1	9		107	Hunter Creek to Treatment	363.0	-	363.0	-	1.00	363.0	-
1	1	1	10		110	Creek inflow to Donner Inflow Bucket	-	-	1,163.67	-	1.00	-	-
1	1	1	11		111	Creek inflow to Independence Inflow Bucket	-	-	536.2	-	1.00	-	-
1	1	1	12		109	Shortage to TRA Demand	-	-	1,000,000.0	150.0	1.00	-	-
1	1	1	13		109	Policy to TRA Demand	-	-	-	55.0	1.00	-	-
1	1	1	14	100	107	River Bucket to Treatment	3,959.7	-	8,556.0	-	1.00	3,959.7	-
1	1	1	15	100	203	River Bucket to TROA t= 2 (changed diversion)	-	-	-	(2.0)	0.64	-	-
1	1	1	16	101	201	Donner To Donner t= 2	3,500.0	-	3,500.0	-	-	3,500.0	-
1	1	1	17	101	203	Donner to TROA t=2	-	-	9,000.0	(1.0)	1.00	-	-
1	1	1	18	101	107	Donner to Treatment	-	-	3,500.0	35.0	1.00	-	-
1	1	1	19	102	202	Independence to Indep. T=2	11,460.2	-	14,500.0	-	-	11,460.2	-
1	1	1	20	102	203	Independence to TROA t=2	2,539.8	-	10,000.0	(1.0)	1.00	2,539.8	(2,539.8)
1	1	1	21	102	107	Independence to Treatment	-	-	10,000.0	40.0	1.00	-	-
1	1	1	22	103	203	TROA Water to TROA Water t=2	6,000.0	-	119,000.0	-	0.9976	5,985.6	-
1	1	1	23	103	107	TROA Water to Treatment	-	-	119,000.0	45.0	1.00	-	-
1	1	1	24	104	204	TMWA EDS to EDS t=2	7,500.0	-	7,500.0	-	1.00	7,500.0	-
1	1	1	25	104	107	TMWA EDS to Treatment	-	-	7,500.0	130.0	1.00	-	-
1	1	1	26	105	205	TRA ASR to TRA ASR t=2	50.0	-	1,000,000.0	-	1.00	50.0	-
1	1	1	27	105	108	TRA ASR to wells	-	-	5,053.0	10.0	1.00	-	-
1	1	1	28	106	108	TRA GW to wells	100.0	-	5,053.0	-	1.00	100.0	-
1	1	1	29	106	206	TRA GW to TRA GW t=2	15,850.0	-	1,000,000.0	-	1.00	15,850.0	-
1	1	1	30	107	205	Treatment to TRA ASR t=2	620.0	-	620.0	(5.0)	1.00	620.0	(3,100.0)
1	1	1	31	107	109	Treatment to TRA Demand	3,702.7	-	8,556.0	(10.0)	1.00	3,702.7	(37,027.0)
1	1	1	32	108	109	TRA wells to Demand	100.0	-	5,053.0	15.0	1.00	100.0	1,500.0
1	1	1	33	110	100	Donner Inflow Bucket Flowthru to River	-	-	1,163.67	-	0.70	-	-
1	1	1	34	110	101	Donner Inflow Bucket to Donner Lake POSW	-	-	-	(1.0)	1.00	-	-
1	1	1	35	111	100	Indep Inflow Bucket Flowthru to River	-	-	536.2	-	0.10	-	-
1	1	1	36	111	102	Indep Inflow Bucket to Indep Lake POSW	-	-	-	(1.0)	1.00	-	-
1	1	1	37	112	108	Extra GW to Wells	-	-	5,053.0	-	1.00	-	-
1	1	1	38	112	212	Extra GW to Ex GW t=2	11,000.0	-	11,000.0	-	1.00	11,000.0	-

Table 2.1: Model arcs and flow parameters, as structured in the model, time period 1

Upper and lower capacity constraints are necessary for each arc. These are defined by system conditions such as monthly river flows, treatment plant capacities, reservoir storage rule curves, or water rights. Where lower bounds are not defined, the default value is always zero since water flow cannot be negative (Table 2.1). In addition to these single-arc constraints, there are several conditions which constrain the system through a combination of arcs. One such example would be yearly groundwater rights, in which the sum of all well use for one year (12 time periods), must be less than the annual groundwater pumping limits. Since the model has been written for a 15-year period, this creates 15 new constraints. For year one this constraint is written:

$$\sum_{k \in K_{wells1}} q_k = 22{,}000 \qquad (6)$$

Where K_{wells1} = subset of arcs flowing out of wells for year 1; and q_k is the flow in arc k. Other multiple-arc constraints include yearly limits (reservoir impound, water rights, etc), use of the same system infrastructure for two actions (ex: groundwater recharge and groundwater extraction), and other multi-month or multi-year limits. These constraints were evaluated on an individual basis, and have been translated as best as possible to be mathematically represented in the NFP set up.

There are many textbooks which have been written about operations research, linear programming, and network flow programs. Ragsdale (2001), thoroughly covers the topic of model development and network flow programs in his text *Spreadsheet Modeling and Decision Analysis*. Another text by Jensen and Bard (2003), provides many examples on the construction of models in Excel, and even includes its own NFP solving software.

Stoddard (2006) used these texts as a guide for his LP model of the TMWA water system. This DSS model and its associated NFP, builds substantially from the framework of Stoddard's, and follows the general structure outlined in the texts listed above. When combined with available software, an NFP is a very powerful platform for decision making and water resource management.

b). Solver Engine

A software package called Premium Solver Platform (V2016) has been used to mathematically solve the network flow program. This solver package was created by Frontline Solvers, and is essentially an upgrade to the basic Excel solver. It has been designed with many features to aid in solving and analyzing linear programs.

Once the NFP was written in Excel, it could be linked to Premium Solver. The solver requires an objective function cell to be designated, and constraints to be input. The solver also offers the choice of several different engines to be used, depending on the problem. For this DSS, the Large-Scale LP Solver Engine (V2016) was used. As its name might suggest, this engine has been designed to solve very large linear programming problems, such as the DSS. The Large-Scale LP Solver uses the simplex algorithm to minimize the objective function value. On average, model runs take about five minutes to reach a solution with this software. Once the model was configured and linked to Analytic Solver, it's conditions were saved in the program and multiple runs were easily performed. An example of the solver dialogue window and the specified conditions can be seen in Figure 2.3.

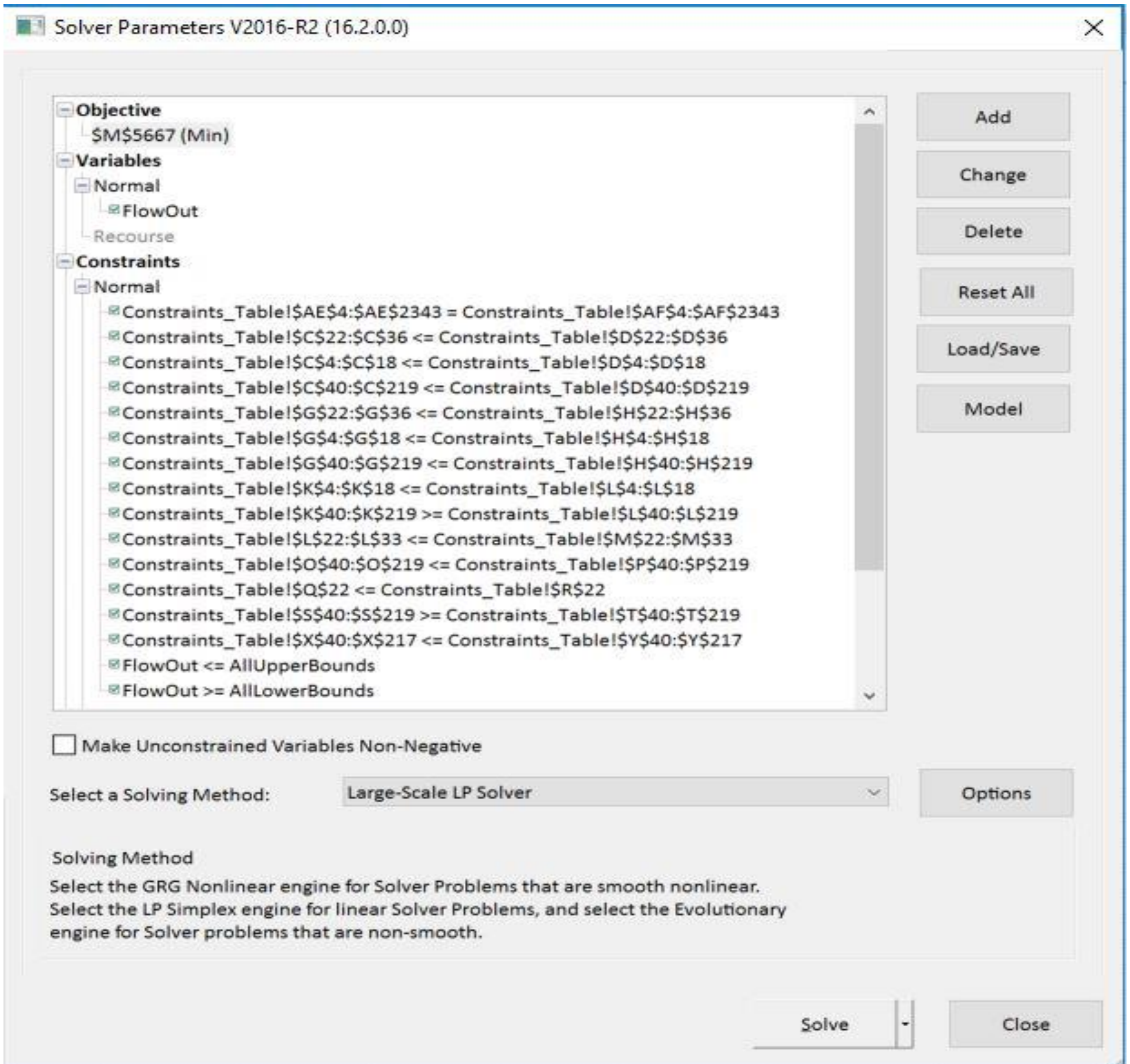


Figure 2.3: Premium Solver dialogue box and model set up

c). User Interface

The DSS has been completely structured in Excel, using a workbook format with multiple worksheets organizing its different sections (inputs, constraints, model, results, etc.). Utilizing Excel for model arrangement allows the DSS to be easily understandable and modifiable, for a large audience of resource managers. Excel also provides a wide range of data management functions, which have been used to further organize and link the model together.

Model Name:	TMWA Drought Decision Support System (TDDSS)
Version:	4.2
Creator:	Boyer, Stoddard, Christman
General Purpose:	1B run at 84K annual starting demand. Demand profile matches that of average (non-conservation) years production. Res storage = month 3, well cap = 64MGD
More Detail:	Scenario 1B. Good starting point for any 1B runs, with all River and Evap data input for scenario 1B (with M&I credit water accounted for per Riverware inputs)
Conclusions:	No EDS, conservation use not maximized. TROA M&I and POSW use extensive. Water supplies thin but adequate!
Model Creation Date:	7/15/2017
Run Date:	7/18/2017

Table 2.2: Example header page details, providing information about a model run using scenario 1B

Within the DSS, all data is stored in a series of tables. These tables include: physical system parameters, operating rules and regulations, customer demands, river and creek supplies by month, cost coefficients, reservoir evaporation, and others which define the operating system. The NFP itself is also a table, which can be quickly viewed and adjusted, or debugged as necessary. The main input tables link into the NFP, which has its own worksheet. The input tables have also been organized into two separate worksheets, presented at the beginning of the model. A header worksheet provides details about the individual model run, and allows space for notes and conclusions to be organized in a logical fashion (Table 2.2). After performing multiple runs, the header page was most commonly referenced to locate key results. This page provides the most detail about differences in each model run.

d). Outputs

A run of the DSS ultimately outputs sources of water supply for TMWA, at a monthly timestep over 15 years. Outputs also include available quantities of groundwater, reservoir levels (Figure 2.4), and potential recharge activities. These results from the

Example Model Output for Surface Water Storage

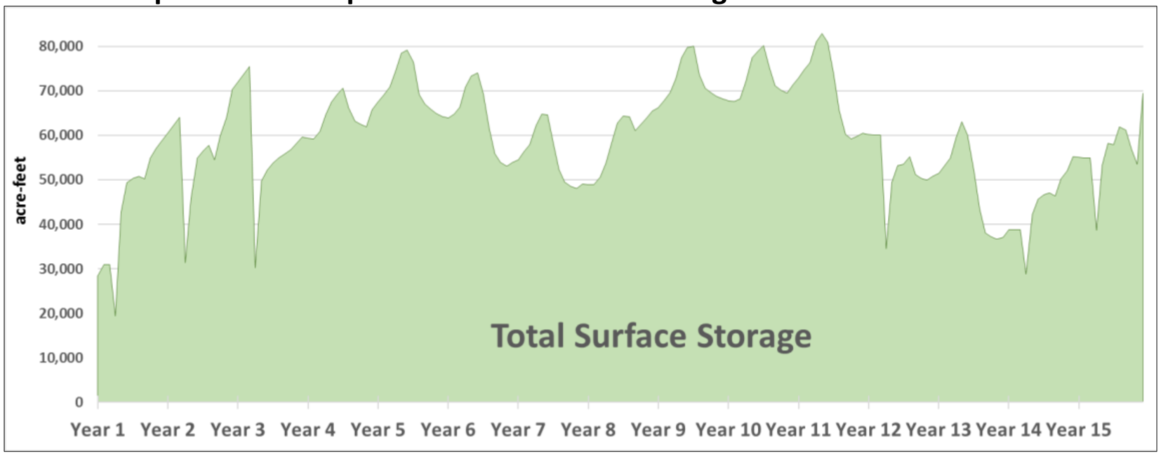


Figure 2.4: Example of surface storage output from a model run at current system parameters and demands (drought scenario 1A). Note the dramatic drops in storage during Years 2,3,12, and 15 which is due to TROA specifications requiring a transfer of available supplies to fish water in non-drought years.

DSS can be viewed as graphs or tables, on a monthly or yearly timescale. The outputs are derived from the NFP database table, which following a successful solve of the model, is populated by values for the quantity of water moving through any modeled arc. Since each arc represents a physical system for transportation, delivery, or storage of water for each month modeled, these values can be easily translated into a summary of operational actions.

While outputs from a single model run are generally considered "optimal" operations, the DSS does have some discrepancies with actual real-world operations. One such discrepancy is with water supply timing, and the way the NFP specifies which water supplies to use. A water supply with greater associated pseudo-cost will never be used unless all cheaper water supplies are exhausted or unavailable. However, once a water supply of greater cost is needed during a particular year, the objective function value will remain the same regardless of when that water supply is used (if timing doesn't affect the quantity of other supplies). As a result, the exact timing of some operations may vary between runs with the same defined conditions, and supply use can be modeled differently than what would occur based on real life operations. Timing is also affected by the model having future knowledge of what hydrologic conditions will be experienced in any year of the run. In the real world, accurate hydrologic predictions can never exceed more than a few months. This factor must be considered when analyzing individual run outputs. Regardless of timing, these outputs are ultimately valuable because they show which water supplies are required to meet demands.

As a result of the above considerations, DSS runs were typically evaluated in a comparative fashion, rather than on an individual basis. Runs with similar conditions were compared at different demand levels, and slightly adjusted parameters (varying based on desired factors to be tested). In this way, the model was effectively used to determine what demand levels require which additional water supplies, and how changing system parameters affect those limits. The additional analyses required to compare model outputs was performed using both Excel and Python.

e). Final Version (V4.2)

The DSS went through several different forms before a final version was settled upon. In its infancy, the model was created from scratch using Stoddard's (2006) DSS as a guide. These early versions were overly complex, and so model versions V1.1 through V1.9 worked to simplify, debug, and complete the initial model. These versions each only solved for a one year period, which was substantially easier to modify than a full 15 years. Model version V2.0 was a major milestone for simplification of the DSS. V2.0 excluded a large outlying system, which was solely dependent upon a small amount of independent surface water, and did not offer any benefit to the operational questions being addressed. This version of the model was also upgraded to solve for two years. Further iterations in the V2 series models included modified evaporative loss calculations, and a thorough amount of debugging. Finally, V3.0 was the first model edition to solve for the whole 15 years as desired. Although this version was thought to be complete, extensive debugging and a few small modifications were still needed. V3.1 through V3.9 featured adjustments to groundwater storage and supply rules, and a factor was added to address issues with reservoir storage timing. The model's user interface was reorganized for the V4 series, and with further debugging and adjustments to groundwater supply, V4.2 was determined to be an adequate final edition. This version is a clean and operable model, including system parameters which default to current operation conditions.

A network flow diagram for month one (time period 01) of V4.2 can be seen in Figure 2.4. With a few exceptions, the NFP is essentially repeated for each following time period (180 months total). There are 13 nodes in each time period, representing water sources, storage decisions, system infrastructure, and customer demands. Most months have 31 arcs which link these nodes, except for the following three. Each January (month one), annual groundwater rights enter the system, and for timer period 01 (first January) the model is assigned its starting values (Figure 2.4). In month four (April), the model requires two extra arcs for a possible water type transfer, as specified in the Truckee River Operating Agreement (TROA, 2008). At the end of the year (month 12, December), flow paths are also slightly different to account for excess groundwater either

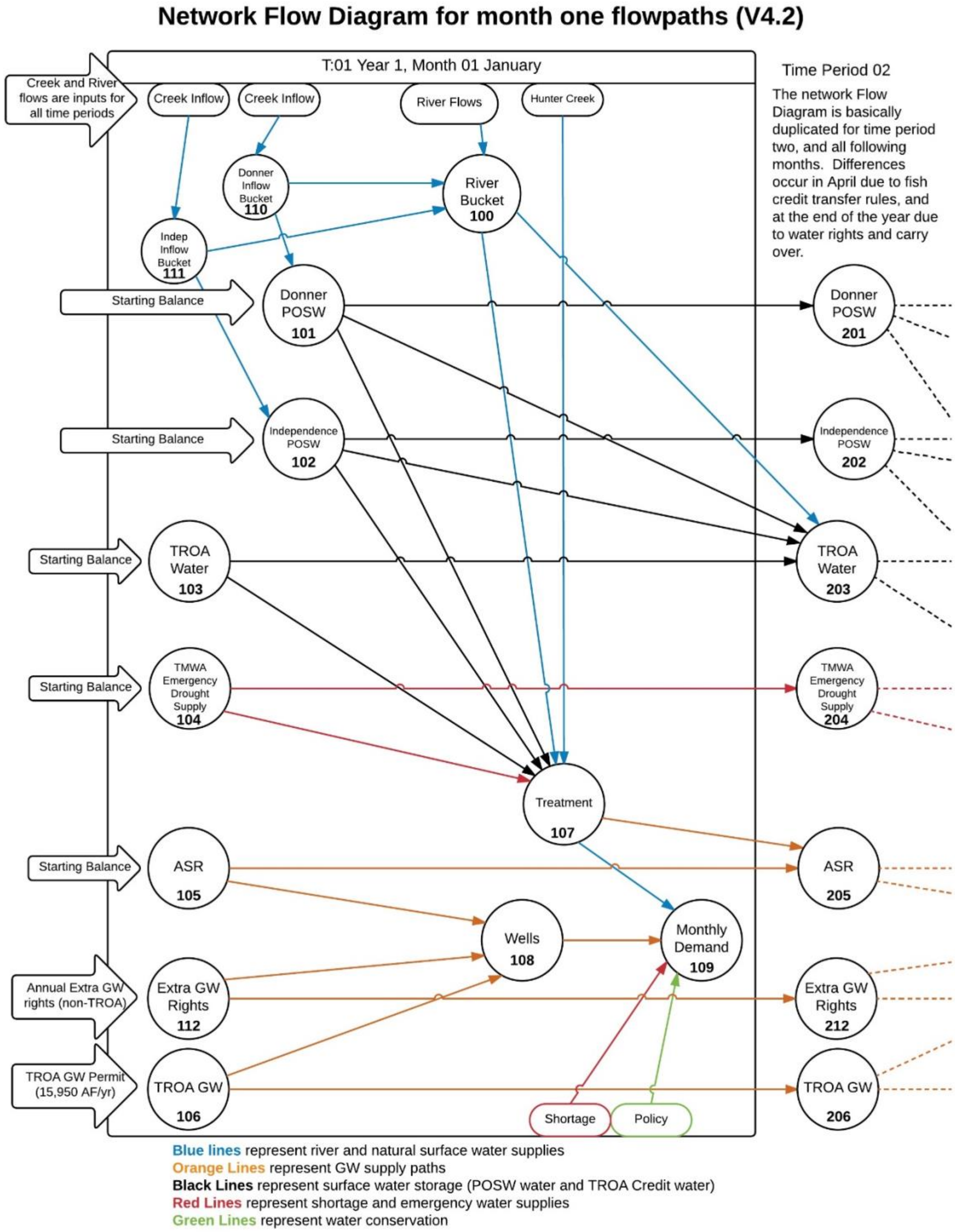


Figure 2.5: Abbreviated network flow diagram for the final model version (V4.2), showing nodes and arcs for month one, and the arcs which connect to month two.

being banked (Turnipseed, 2000), or lost to the aquifer. In total, V4.2 has 5660 arcs, which translates to the same number of decision variables in the mathematical LP setup.

Each arc has an upper and lower bound, creating 11,320 constraints in the LP. In addition, there are 2,340 mass balance constraints, or one for each node (detailed in equations of section 2.1a). Starting balances, monthly water sources (river/creek flow, conservation, shortage), and annual groundwater allowances do not originate from a node. Rather, these come from "supply arcs", in which the upper bounds are the specified monthly flows (hydrologic inputs). Water quantities which are not used from these inputs, simply never enter the LP, and are not held by the mass balance constraints which affect all nodes. As such, water source inputs are only constrained by upper and lower arc bounds. In addition to arc and node constraints, the final version of the model has 1,166 system specific constraints which affect multiple arcs or nodes. The result is a total of 14,826 constraints within the mathematical LP setup, which limit the 5,660-variable objective function.

2.2 Stakeholder Involvement

Since the model and its results are highly relevant for the utility and local community, additional stakeholders were involved in the process of its creation. Stakeholder input came in two forms: from utility professionals familiar with the water system, and via a group of community representatives through meetings in an open discussion style format. The former helped shape individual model parameters and specifics, while the latter (i.e. the Drought Planning Task Force, or DPTF) ultimately drove the direction of the project and questions addressed. Further details about these involvements can be found below.

a). Utility Professionals

To fine-tune and accurately model the local water system, water resource experts from TMWA were involved in this project throughout construction of the DSS. Those consulted were from a wide array of utility departments, including: economics, hydrology, hydrogeology, and engineering. These professionals helped to provide utility specific information and records, and were instrumental in recommending the proper documents which describe system rules (such as water rights, groundwater extraction, reservoir capacity constraints, etc.). Multiple system parameters were estimated and evaluated by TMWA employees, and the network flow program was ultimately diagrammed based off their guidance. These experts verified both the underlying structure of the model, as well as its inputs and parameters.

Following early completion of the DSS, it underwent a rigorous calibration and testing phase. This was performed using historic USGS stream flows and other hydrologic data, matched to utility operation records. The results were shown to several individuals at TMWA, who made recommendations about the performance of the model. Through this continual feedback structure with utility professionals, calibration and correction of the model continued until V4.2 was finalized.

b). Drought Planning Task Force

TMWA serves a wide variety of customers including residential, commercial, industrial, agricultural, and wholesale consumers. The goal of the DPTF was to represent the interests of these various customer classes through feedback on the DSS project, and to offer an open forum for discussion of management strategies under climate change. The DPTF is also a way for the implications and results of this project to be more easily communicated to the involved stakeholder groups. Individuals from numerous groups around the region were selected to join the DPTF, with a full list of the originally selected participants seen in Table 2.3. These individuals were initially engaged through an online survey, regarding climate change and drought issues which concerned them or the customer class they represented. Following the survey, three semi-annual meetings were held to discuss the modeling and direction that it should take, and ultimately to share results from the DSS.

DROUGHT PLANNING TASK FORCE MEMBER LIST

Participant Name	Affiliation	Position
Lynne Barker	City of Reno	Sustainability Manager
Neil Krutz	City of Sparks	Deputy City Manager
Jim Smitherman	Northern Nevada Water Planning Commission	Program Manager
Seth Williams	Reno Fire Dept.	Fire Protection Services Representative
Karl Katt	TMWA's Standing Action Committee	Senior Citizen Stakeholder Representative
Colin Hayes	TMWA's Standing Action Committee	Multi-family / Commercial Stakeholders Representative
Jerry Wager	TMWA's Standing Action Committee	Residential Stakeholder Representative
Bruce Gescheider	TMWA's Standing Action Committee	Chamber Representative
Neil McGuire	TMWA's Standing Action Committee	Irrigation Stakeholder Representative
Jeremy Smith	Truckee Meadows Regional Planning Authority	GIS Coordinator
Laine Christman	Truckee Meadows Water Authority	Resource Economist / USBR Project Manager
Shawn Stoddard	Truckee Meadows Water Authority	Senior Resource Economist
Robert Charpentier	Truckee Meadows Water Authority	Communications Specialist
Sonia Folsom	Truckee Meadows Water Authority	Meeting Facilitator
Beth Christman	Truckee River Watershed Council	Director of Restoration Programs
William Boyer	University of Nevada, Reno	Drought Planning Task Force Graduate Research Assistant
Maureen McCarthy	University of Nevada, Reno / Tahoe Science Consortium	Water for the Seasons Project Director
Vahid Behmaram	Washoe County	Water Management Planner Coordinator

Table 2.3: List of DPTF participants and affiliations

Through the survey and meetings, DPTF members identified six different categories of water supply concerns related to climate change. Each category featured multiple risks, except for the "watershed degradation" category, which was recognized as a concern but with no specifics. The identified categories and risks were:

1. Inadequate water supply
    - Inadequate snowpack
    - Inability to fill reservoirs
    - Inability to capture runoff at proper time
    - Quality of snowpack runoff
    - Increased evaporation losses
    - Over withdrawal of groundwater supplies
    - Loss of groundwater quality
    - Impacts to groundwater return flow
2. Inability to meet future demands
    - Extended growing season
    - Increase in demands due to higher temperature
3. Overreaction by agencies
    - Demand hardening
    - Decreased revenue from conservation
4. Economic turmoil
    - Energy for operations/energy costs
    - Inability to raise rates

- Risk to utility credit rating
- Loss of service connections
- Public perception of rate changes
- Prioritization of capital improvement projects

5. Higher costs
    - Increasing water rates due to conservation
    - Decreasing utility revenue
6. Watershed degradation
    - No specific concerns were listed in this category.

An approach was taken with the DSS which would help address a majority of the concerns presented by DPTF, without making the modeling process unreasonable or excessively complicated. Simply put, not all the issues brought forward could be examined by one model. Since most of the DPTF concerns focused on an inadequate water supply and inability to meet future demands, addressing these became the focus of work. As such, the DSS structure was designed to be well adapted for optimizing operations related to water supply and demand, goals which are also facilitated by the climate change data available. The model runs which were subsequently performed with the DSS, were selected in a fashion that would also most effectively address DPTF concerns. Thus, the DPTF helped to shape both the model, and the questions being analyzed by it. Full details regarding results from the model runs performed, can be found in section IV: Results and Discussion.

III. Data

The DSS has been created for a case study on the Truckee River, to approximate operations for the Truckee Meadows Water Authority (TMWA). This chapter gives a full discussion of model inputs and parameters, which relate to TMWA and Truckee River hydrologic conditions. These are specific to the studied system, and can be broken into three categories: physical, institutional, and theoretical (Figure 3.1). Physical parameters define real world limits such as reservoir capacities, surface water treatment, and maximum discharge. Institutional parameters are based on existing water rights, permits, and regulations. Theoretical inputs are conditions which have been estimated to answer the desired questions, consisting of factors such as future customer demand, river flows, and evaporation rates. They are the main inputs for the model. Further details about all this data can be found in the following sections.

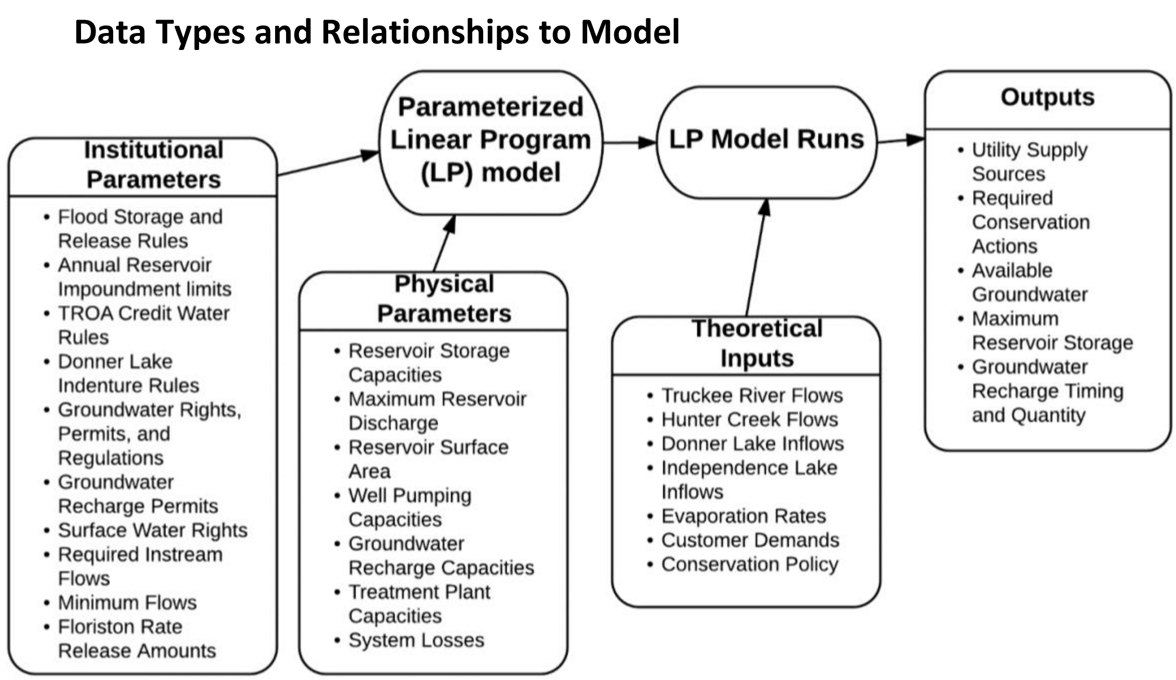


Figure 3.1: Diagram showing data categories and their relation to model and outputs. The majority are utility specific

3.1 Climate Change Scenarios

Two drought scenarios have been used for this research. These scenarios were developed by the Water for the Seasons (WftS) project team, through a collaborative effort amongst team members and regional stakeholders. The scenarios, titled Scenario 1A and Scenario 1B, have been both been constructed based off the same historical water years. They represent design drought or nearly worst-case conditions for the region, and are discussed in greater detail below. The hydrologic modeling done by WftS to create the resulting river flows of these scenarios, is documented in the section immediately following (3.2).

a). Scenario 1A

The hydrologic conditions for Scenario 1A have been modelled using a combination of two of the worst historical droughts on record: the 1987-1995 drought, and the 2012-2015 drought. For this scenario, hydro-climatic conditions from 1987-1995 have been concatenated to the end of 2012-2015 conditions. Temperatures for the ending years

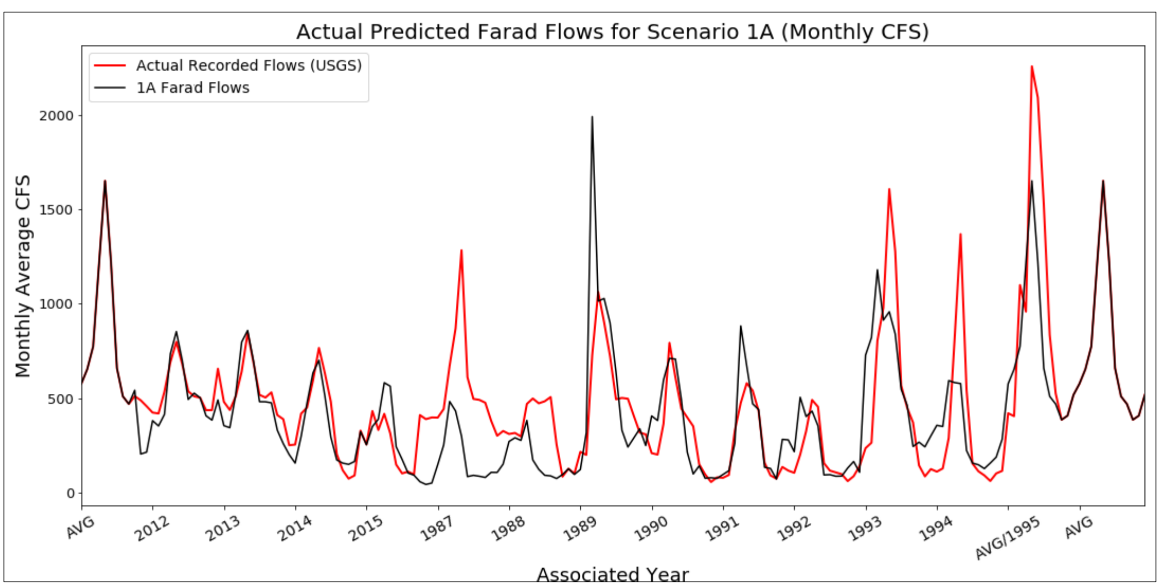


Figure 3.2: Scenario 1A constructed Truckee River flows at Farad, compared to historical USGS data

(1987-1995) have also been calibrated to modern temperature profiles, which correlates to about a 1.1ºC daily increase on average, for the 1987-1995 years. The result is a 13-year drought for modern times, with plausible hydrologic conditions. As seen in Figure 3.2, there is some discrepancy between modeled flows and historic flows, due to the change in temperatures and slightly different reservoir states. If the resulting conditions were to occur, it would technically constitute the longest drought in recorded history. However, paleoclimate data suggests that a drought of this length is not out of the question, and that substantially longer drought periods have occurred in the past (Hatchett et al., 2015).

The 1987-1994 drought is often considered the regional design drought, or most severe, lasting eight years and posing significant challenges for all water users. During this time, multiple water years experienced substantially below average precipitation. 1987 and 1988 started the drought as two of the driest years, but the reservoirs were mostly full and able to accommodate the lack of precipitation. 1989 was an improvement, just above average, but ultimately providing insufficient water to recover from what had been lost. The following three years ('90, '91, '92) were very dry, representing the worst part of the drought. In 1993 the region received above average precipitation and was able to recover somewhat, but not fully. 1994 proved to be another exceptionally dry year, again taxing what limited water supplies which were available. Finally, the drought was broken by the massive water year of 1995.

Although not as long lasted, the 2012-2015 drought is considered to have produced conditions about as severe as 1987-1994, and is absolutely the worst four-year drought on record. The drought consisted of four years with substantially below average precipitation, and was exacerbated by abnormally high temperatures (Hatchett et al., 2015; Griffin and Anchukaitis, 2014). Mainly due to record high temperatures, 2015 was the worst water year on record. In that year, the reservoirs were substantially depleted, Tahoe was below the rim, and natural Truckee River flows were nearly too low to be useable by the utility. The drought was broken by two successive above average years, with 2017 ending as the largest water year on record.

Scenario 1A has been created by WftS as a 13-year scenario. The flows used for this study begin at a time period that correlates to October 2011 (the start of water year 2012), and end at a time that correlates to December 1994 (month three of water year 1995). The DSS has been created to model a 15-year scenario, with time beginning in January and not at the start of the water year. This allows the DSS to correlate better with yearly utility operations. To accommodate the difference in scenario length, nine months of average flows have been added to the beginning of Scenario 1A, and two years of average flows have been tacked on to the end (Figure 3.2). These average flows were calculated using available USGS streamflow data. For practical purposes, the elongated scenario will still be referred to as Scenario 1A.

b). Scenario 1B

Scenario 1B has been constructed from the same series of drought years as Scenario 1A. Again, the scenario consists of hydro-climatic conditions from the 2012-2015 drought, with conditions from 1987-1995 appended to the end. The difference is that Scenario 1B has been adjusted to represent projected temperatures for the time period 2051-2070

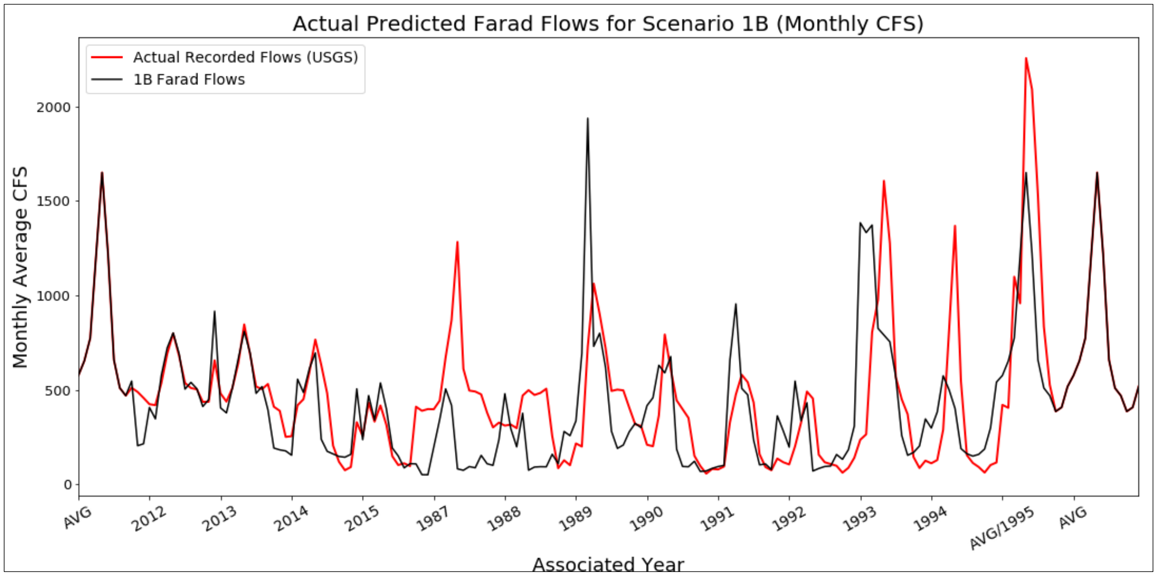


Figure 3.3: Scenario 1B constructed Truckee River flows at Farad, compared to historical USGS data

(under moderate emission scenario), correlating to an average daily temperature increase of around 2.5 Celsius. It is assumed that weather patterns will not be dramatically different by that time, and so these historical droughts can still plausibly represent hydro-climatic conditions. The resulting 13-year future drought scenario has also had average flows tacked on to the beginning and end (Figure 3.3), as detailed in the previous section for Scenario 1A.

3.2 Hydrology and Water Supply

This section includes information on how river flows and other hydrologic inputs were created, utilizing a suite of hydrologic models. For Scenarios 1A and 1B, this process began by utilizing PRISM datasets for temperature and precipitation. Those inputs were used in several coupled surface-groundwater models (GSFLOW), and ultimately output hydrologic data into an operations model (RiverWare) which accounts for system rules and regulated operations (Sterle et al., 2016). Truckee River flows are the main output from this RiverWare model, and were further translated into inputs which could be used by the DSS. All this hydrologic modeling is discussed in greater detail below.

a). GSFLOW Hydrologic Modeling

The Truckee River system relies on snowmelt and runoff as its main source of water, which mostly originates within the Upper Truckee Watershed (upstream of the Farad

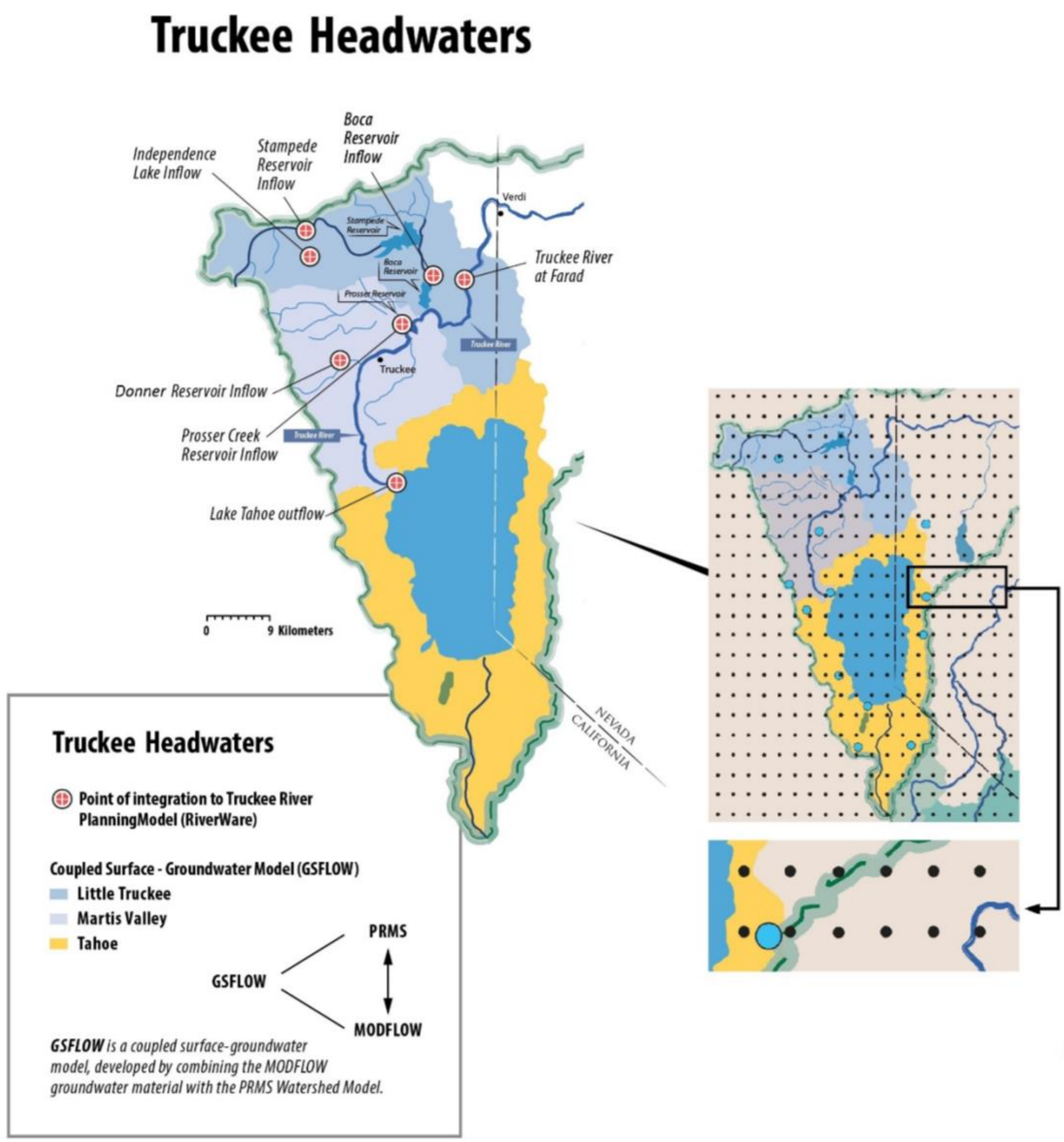


Figure 3.4: Extent of Upper Truckee Watershed models, points of integration, and PRISM gridding
Source: Sterle, Singletary, and Pohll, 2017

gauging station). As a comparatively small amount of water enters the system within the Lower Truckee Watershed, and the DSS requires Farad flows as an input (not to mention the various other accounting and modeling functions which relate to Farad/Floriston flows), properly modeling the Upper Truckee Watershed is highly important. The Watershed is composed of three major sub-basin: The Little Truckee, Martis Valley, and Lake Tahoe. Each has its own coupled surface-groundwater model (GSFLOW), which interact along boundaries and at points of integration, and can be seen in Figure 3.4 (Sterle et al., 2017).

Scenarios 1A and 1B were constructed by piecing together gridded PRISM data (4km grids), which feature daily precipitation, minimum, and maximum temperatures for the selected water years (Dettinger et al., 2017). The temperatures were adjusted to reflect the climate change scenarios discussed above, and the resulting temperature and precipitation data was then input into the GSFLOW model for each of the Upper Truckee Watershed sub-basins. GSFLOW is a surface-groundwater model which combines the MODFLOW (Modular Groundwater Flow) model with the PRMS (Precipitation Runoff Modeling System) model to improve simulations of surface-groundwater interactions. These surface-groundwater interactions are particularly notable in shallow alluvial aquifers such as those found in the Upper Truckee Watershed, hence why this model is appropriate (Sterle et al., 2017).

GSFLOW simulates flow in three regions. The top region is bounded by the plant canopy on top, and the lower limit of the soil zone on bottom. PRMS is used to simulate runoff and surface flow within this region. The second and third regions are modeled by

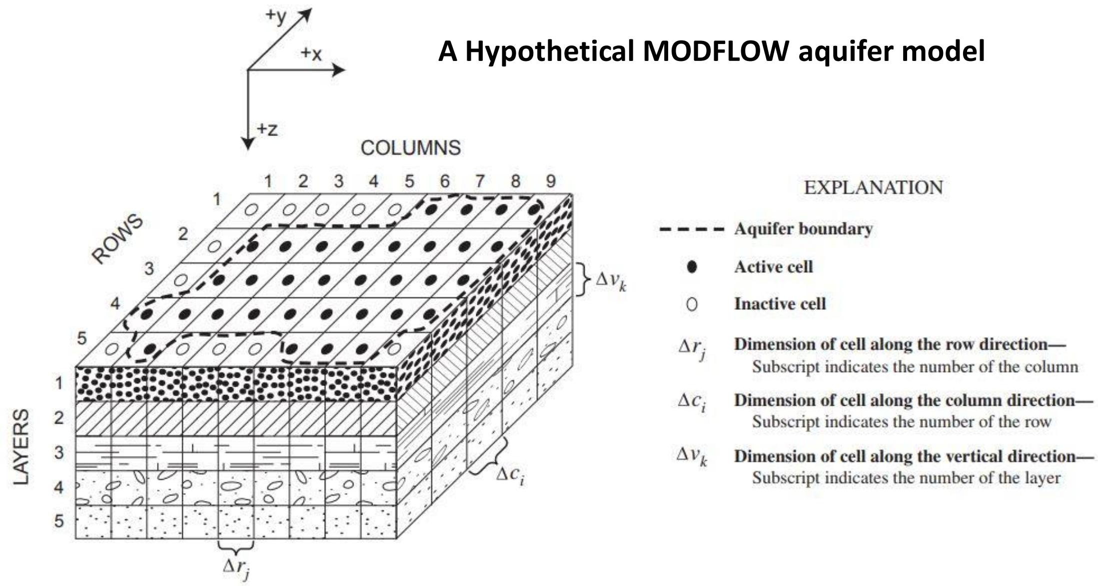


Figure 3.5: A discretized hypothetical aquifer system; source: USGS, 2008 (modified from Harbaugh, 2005)

MODFLOW and consist of one region containing all streams and lakes, and a subsurface region beneath the soil zone. All three of these regions are split into a set of discrete finite-difference cells. Within PRMS, these are called hydrologic response units (HRUs), and each has its own hydrologic and physical characteristics such as slope and aspect, plant type and cover, land use, geology, flow direction, etc. These characteristics specify how water is exchanged or stored (in snowpack) between the HRUs over time, and how water enters the other two regions from each individual cell. A similar modeling approach is used through MODFLOW for the subsurface and stream/lake regions. A grid of computational cells is created for the extent of each aquifer, with cells determined by their discrete characteristics and assumed to be homogenous. In this way, different geologic layers, or units with different flow and storage characteristics can be represented within an aquifer. Flow is then modelled between the cells, and especially along boundary conditions and at interactions with the other regions. For streams and lakes, only the boundary conditions are used, as it can be assumed that the bodies of water are homogenous. Head is modeled along these boundaries, and used to simulate interactions with groundwater (USGS, 2008). For all regions in the model, a timestep is required to simulate processes. For the creation of flows in Scenario 1A and 1B, a daily timestep was used (Rajagopal et al., 2015).

The resulting outputs from the whole GSFLOW model depict simulated changes in runoff, streamflow, groundwater levels, and groundwater flow to and from streams. For the three Upper Truckee Basin models, these outputs link to the Truckee Planning Model (RiverWare) at seven locations (Figure 3.4), and are the inputs for that model (Sterle et al., 2017).

b). RiverWare Operations Model

RiverWare © is a river system modeling software which can be used in a variety of hydrologic applications including decision making, water accounting, water rights administration, and flow forecasting (CADSWES, 2017). The program features a variety of different functions, which are solved mathematically depending on the desired outputs and hydrologic product. In general, the mathematical format of RiverWare is as either an optimization model or a simulation model (both can be used for the same system). RiverWare's optimization methods share a similar linear programming structure to this DSS, solving an objective function to determine the best solution. For simulation, the model utilizes governing equations for each object in the system, and propagates values via links as water is available. In simulation, the operating policies contain logic for operating the system based on hydrologic conditions, time of year, demands, water rights, and other considerations (CADSWES, 2017). RiverWare has mostly been used as a simulation model within this project, acting as the operations model for WftS.

The Truckee Planning Model is a RiverWare model which has been created for the Truckee River System. It considers water rights, Truckee River Operating Agreement (TROA) operating rules and regulations, system capacities, and most likely actions for all users on the system. As a simulation model, it utilizes these governing constraints to determine how water would most likely move through the system under the hydrologic conditions of Scenarios 1A and 1B. This includes reservoir levels in all the Truckee River reservoirs, natural river flows and specified releases, diversions, and exchange with groundwater in the Truckee Meadows. This model is also able to specify the amount of water available to any user, at any point in time for each Scenario. Thus, it is a useful tool for determining the quantities of water which TMWA could utilize under the drought conditions of these scenarios.

Outputs at seven locations from the GSFLOW hydrologic models, are inputs for the Truckee Planning Model. These locations are primarily hydrologic inflows into the Truckee River Reservoirs, but also include natural inputs to the Truckee River above the Farad gauging station (Figure 3.4). The Truckee Planning Model then approximates user and reservoir operations for the entire system, outputting a time series of Truckee River flows at Farad. These flows are made up of different water types or "colors", which refer to the origin and water right associated with each quantity. In this way RiverWare accounts for which party can use what water, at what time. For the DSS, this flow series was ultimately broken down further to determine the quantity of water that TMWA could use (more details in following section).

Stream flows for Hunter Creek, a major tributary which enters the river below Farad, were also approximated using RiverWare. Since dedicated hydrologic models for the Hunter Creek watershed do not exist, these flows were calculated using a regression based on other modelled stream flows within the study area. As those other stream flows change based on temperature adjustments (from 1A to 1B), the regression reflects that, and thus Hunter Creek flows also consider modeled climate change. Hunter Creek is a valuable water source for the utility, as TMWA has exclusive rights to its use. Thus, the calculated Hunter Creek Flows have been used as another input for the DSS.

c). Final Conversion to DSS Inputs

RiverWare outputs were received in the form of daily flows at Farad for the duration of both scenarios. These outputs had to be further analyzed to determine which portion of the modeled flows TMWA was entitled to. In general, the utility has high priority or senior water rights on the river system, which makes this determination easier. In Nevada, the prior appropriation doctrine (first in time, first in right) controls which users get access to available water first, with the oldest (or most senior) water rights given priority. For the Truckee River, the most senior rights were originally granted to agricultural users, and the Pyramid Lake Paiute Tribe (PLPT). However, the utility has worked to obtain enough of the original agricultural water rights, to be considered a senior water right holder. Thus, any time Floriston Rate release water (FRW) is moving down the Truckee River, it is assumed that TMWA can maximize its use of that water

(TROA, 2008). The exception to this is the last 40cfs in the river, which must be split with the system's other most senior water rights holder, the PLPT. The tribe uses its water rights to benefit the Lahontan cutthroat trout and other native fish species, and so their 20cfs is left in the river as fish flows (Wilds, 2014).

The provided RiverWare outputs included reservoir releases by water type for each time period, giving details on how much of each water type made up the river flow. This split the water into 118 categories, necessitating an analysis to determine the water TMWA was eligible to use. To further complicate matters, some categories do not actually enter the river and are instead impounded in another reservoir. This is due to the chain of dams that exist on the Little Truckee River, and the way water is stored and transferred within the system. The Truckee Planning Model also estimates TMWA decision-making, so

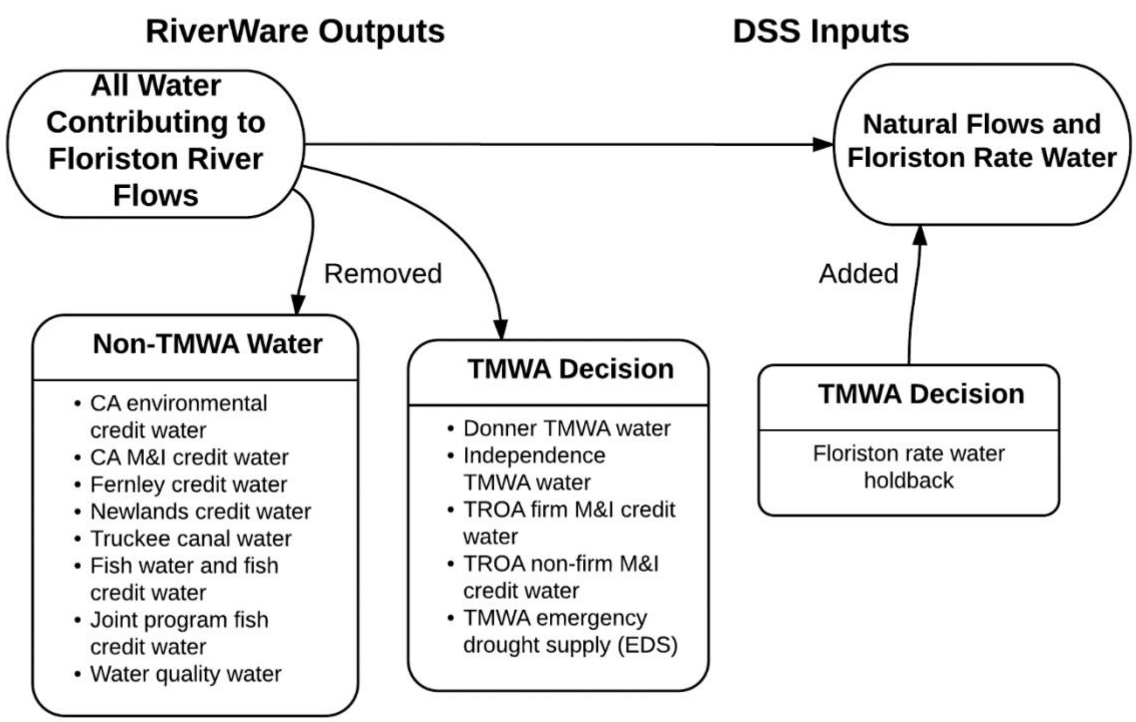


Figure 3.6: Detail of conversion from RiverWare outputs to DSS inputs, showing added and removed water types

care had to be taken to remove water that TMWA has access to, but the DSS would be modeling. This included water inputs and outputs from the two reservoirs that TMWA controls, Donner and Independence Lakes.

To determine TMWA available water, the first step was to determine which reservoir releases were contributing to Farad Flows in the RiverWare model. This included Lake Tahoe and all Truckee River Reservoirs, except Stampede and Independence. Stampede and Independence were detailed to release water, but that water gets recategorized as it either passes through or is impounded in Boca. The second step was to take Farad flows and remove all contributing water accounts which TMWA does not ever have rights to. This includes fish credit water, agricultural water, state of California water, and a few other categories. Next, water that TMWA decides to store and manage was also removed. This includes POSW in Donner and Independence Lakes, as well as M&I credit water (a TROA designated supply which the utility can accumulate through water rights holdback, rather than release), and TROA emergency drought supply water (EDS).

Water Type	Details	Reservoir
Natural Flows	Ground and surface water inflows	none
Boca Stored Water, Above Boca Stored Water, Carry Over Stored Water	Floriston Rate Water (FRW) stored in the Little Truckee Reservoirs	Boca
Floriston Rate Pass Through	Instream accounting for FRW releases.	
Boca Tahoe Floriston Rate Water	Tahoe FRW stored in Boca	
Martis Temporary Floriston Rate Water	FRW stored in Martis	Martis
Prosser Temporary Floriston Rate Water	FRW stored in Prosser	Prosser
Tahoe Prosser Exchange Water	Tahoe FRW exchanged to Prosser	Tahoe
Tahoe Floriston Rate Water	Tahoe FRW	
M&I Credit holdback water	FRW which RiverWare decided to hold back for TMWA operations	Any/All

Table 3.1: TROA designated water types that TMWA can utilize if part of Farad flows

Inflows to Donner and Independence are inputs to the DSS, and the DSS models how much of these water types should be stored or released. The DSS also models accumulation and release of M&I credit water and EDS. Including these categories in the Farad flows would essentially create extra water, which would be counted twice. Because RiverWare approximates M&I credit operations for the utility, a final category of water was added to the Farad flows. This category was Floriston Rate water which RiverWare had simulated being held back in the reservoirs, to accumulate M&I credit water. The holdback water would have been Farad flows, if the utility had made no action. Again, we want the DSS to determine the timing and necessity of such holdback. Thus, that water was added to the flows at the time when RiverWare specified it being held back in the reservoirs rather than being released (Figure 3.6). Details about which water types were included as being TMWA-available can be found in table 3.1.

In addition to Truckee River flows, the DSS has three other hydrologic inputs: Hunter Creek streamflow, Donner Lake hydrologic inflow, and Independence Lake hydrologic

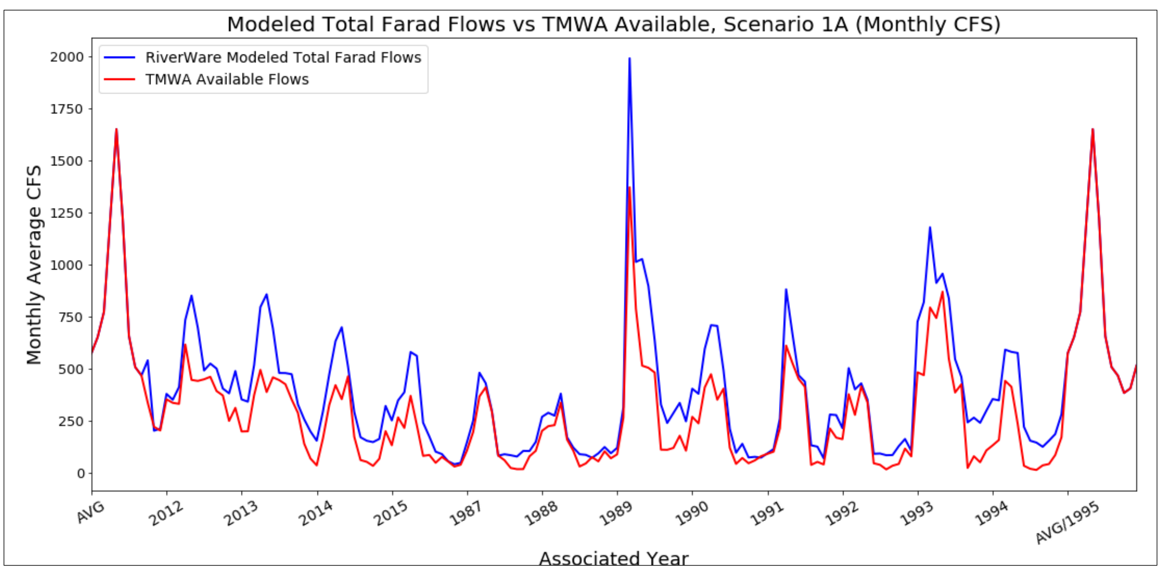


Figure 3.7: RiverWare modeled Farad flows vs TMWA available Farad flows for scenario 1A

inflow. As previously mentioned, Hunter Creek stream flows were also provided by RiverWare. For Donner and Independence Lakes, hydrologic inflows for each were also inputs to the Truckee River Planning model, which have been calculated and provided by the GSFLOW models. Water rights and water sources are much less complicated for these three systems, and so the DSS inputs simply consist of all the available water.

The final step was to convert all the hydrologic inputs (including Truckee River Flows) from daily to monthly values. This was simply accomplished by combining and averaging the daily discharge values for each month.

3.3 Customer Demands

The following two sections detail TMWA customer demands, which were used as model inputs on both a monthly and annual level. A third section includes information about water conservation, which ultimately impacts customer demands by requesting cutbacks in use. Further details can be found below.

a). Annual Demands

Each run of the DSS requires 15 years of annual customer demands to be input. For accuracy and plausibility, these annual demands should increase slightly for each successive year, mimicking projected growth for the region. TMWA's 2016 water resource plan contains customer demand projections from present to the year 2060, which were split into 15-year intervals, and used for multiple different model runs with unique starting demands (for model year 1). These projections were calculated based on

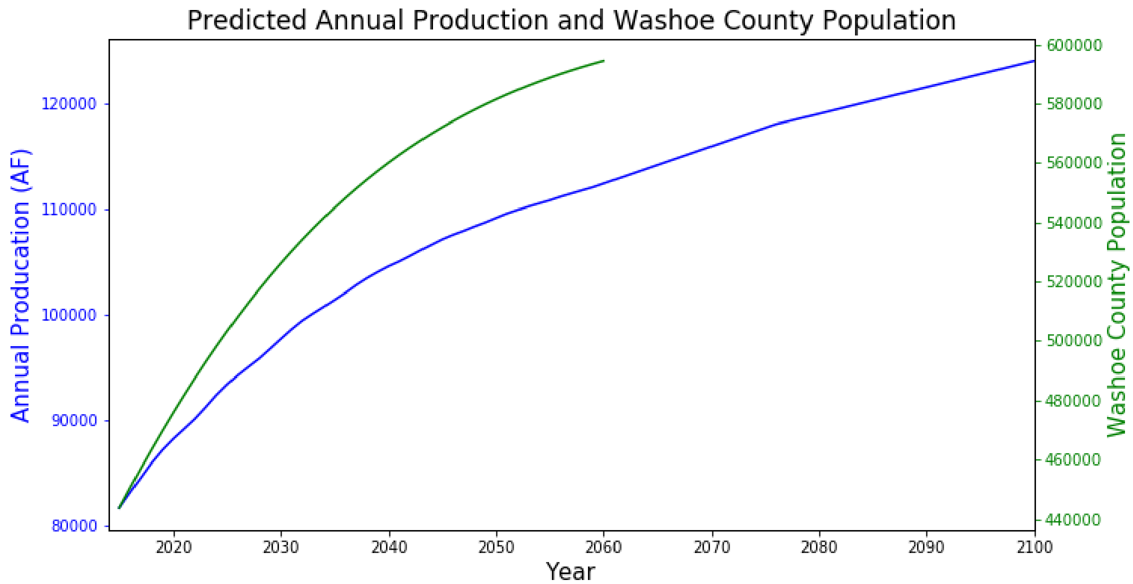


Figure 3.8: Logistic curve population projections, and estimated customer demands (TMWA production). Note that population predictions end at 2060, so customer demands were estimated linearly after that

population predictions, and with demand determined by the respective portions of residential demand, commercial demand, irrigation demand, and system losses. The population projections were calculated using a logistic curve model (Keyfitz curve), with a population ceiling estimated to be slightly above 600,000 for Washoe County (TMWA, 2016). TMWA's modeled future population is in line with the Nevada State Demographer's projection through about 2025, but then the logistic curve approach shows the increase in population beginning to level off (Figure 3.8).

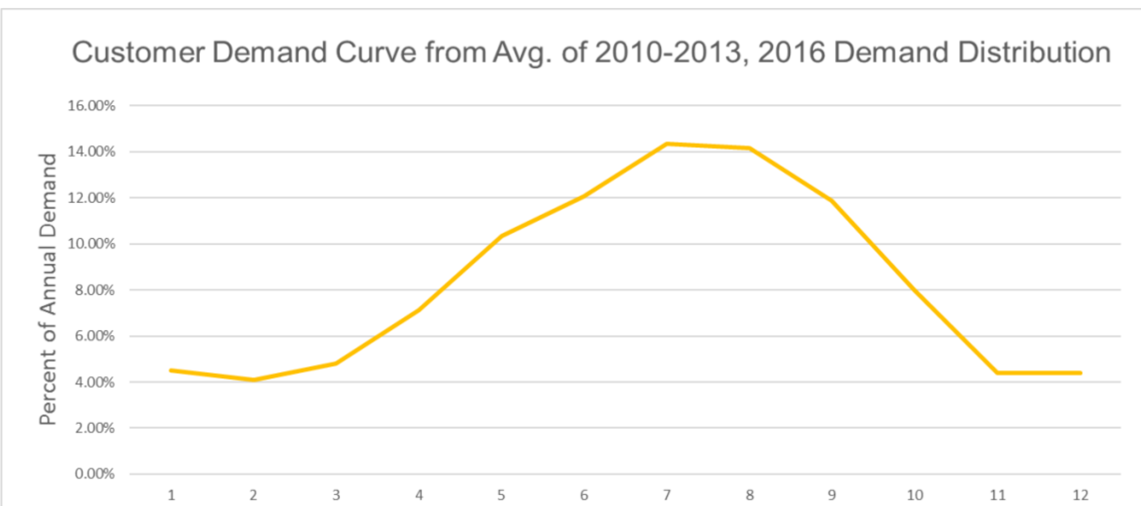
The TMWA produced population and demand projections end at 2060, when total customer demand is estimated to be 112,400 AF. For the purposes of plausibility, demand levels beyond the year 2060 were simply estimated in a linearly increasing fashion. From demands of 112,400 AF to 118,000 AF, demands increased annually by 350 AF (difference between 2059 and 2060). Above 118,000 AF, demands were estimated to increase by 250 AF annually (Table 3.2).

***Table 3.2**: Population and demand predictions for 2015 to 2100*

Year	Washoe County Population	Total Production	Year	Washoe Country Population	Total Production
2015	443729	81735	2061	Not Predicted	112750
2016	450488	83190	2062	Not Predicted	113100
2017	457072	84589	2063	Not Predicted	113450
2018	463476	85999	2064	Not Predicted	113800
2019	469699	87213	2065	Not Predicted	114150
2020	475740	88254	2066	Not Predicted	114500
2021	481596	89184	2067	Not Predicted	114850
2022	487267	90129	2068	Not Predicted	115200
2023	492754	91221	2069	Not Predicted	115550
2024	498058	92379	2070	Not Predicted	115900
2025	503178	93383	2071	Not Predicted	116250
2026	508118	94283	2072	Not Predicted	116600
2027	512879	95083	2073	Not Predicted	116950
2028	517463	95866	2074	Not Predicted	117300
2029	521874	96774	2075	Not Predicted	117650
2030	526115	97703	2076	Not Predicted	118000
2031	530188	98608	2077	Not Predicted	118250
2032	534099	99431	2078	Not Predicted	118500
2033	537850	100105	2079	Not Predicted	118750
2034	541445	100745	2080	Not Predicted	119000
2035	544890	101398	2081	Not Predicted	119250
2036	548187	102072	2082	Not Predicted	119500
2037	551342	102806	2083	Not Predicted	119750
2038	554358	103459	2084	Not Predicted	120000
2039	557241	104036	2085	Not Predicted	120250
2040	559995	104571	2086	Not Predicted	120500
2041	562624	105031	2087	Not Predicted	120750
2042	565133	105550	2088	Not Predicted	121000
2043	567526	106097	2089	Not Predicted	121250
2044	569807	106608	2090	Not Predicted	121500
2045	571981	107122	2091	Not Predicted	121750
2046	574052	107549	2092	Not Predicted	122000
2047	576024	107924	2093	Not Predicted	122250
2048	577901	108337	2094	Not Predicted	122500
2049	579688	108714	2095	Not Predicted	122750
2050	581387	109135	2096	Not Predicted	123000
2051	583003	109547	2097	Not Predicted	123250
2052	584539	109891	2098	Not Predicted	123500
2053	585999	110232	2099	Not Predicted	123750
2054	587387	110531	2100	Not Predicted	124000
2055	588705	110825			
2056	589956	111162			
2057	591145	111463			
2058	592273	111759			
2059	593344	112050			
2060	594359	112400			

b). Monthly Demand Profile

Since climate change has the potential to shift the timing of runoff for the Truckee River, it was especially important to accurately portray the monthly timing of customer demands. To accomplish this, records of TMWA's total monthly production values were used (monthly production is the total amount of water produced, or customer demands plus distribution losses). From these data, production was averaged by month for the years 2010- 2016, excluding 2014 and 2015. 2014 and 2015 were drought years in which TMWA asked for a reduction in water use, so the production values do not represent a typical water year. The resulting customer demand profile is the average of the five most recent non-drought influenced years (Figure 3.9). It depicts water use peaking in the summer months, with July and August having the highest customer demands. Conversely, water use is substantially less during the cold winter months, with February generally seeing the least demand for water.



Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Percent	4.5%	4.1%	4.8%	7.1%	10.3%	12.0%	14.3%	14.1%	11.9%	8.0%	4.4%	4.4%

Figure 3.9: Monthly customer demand profile, by percent of total annual production

c). Water Conservation Policy

During a normal water year, TMWA has a number of conservation policies and programs in place, aimed at reducing overall customer water use. These fall into two categories: supply-side management programs, and demand-side management programs. Supply-side programs involve actions directly taken by the utility, such as detecting leaks and repairing infrastructure. Demand-side programs involve helping the customer to use water efficiently and reduce waste, including things such as customer education and conservation advertising (TMWA, 2016). The impact that both types of programs have on customer demands is assumed to have been incorporated into the utility's demand projections (see section 3.3a).

During a drought, TMWA enhances its conservation policy, to limit the amount of actual drought supplies needed to meet demands. Drought conservation is above and beyond normal policy, with actions specified according to TMWA's drought response plan. These actions depend on the severity of the drought and the available quantity of drought supplies. They are referred to as *enhanced* demand-side management programs (*e*DMPs), with the focus being on customer cutbacks in water use. Historically, the target reduction in customer demand has been 10%, facilitated through the use of *e*DMPs. The timing of this cutback (i.e. the month in which TMWA requests conservation to begin) depends on the severity of the drought.

TMWA uses a three-stage drought situation classification system to determine the severity of drought conditions for a water year. This creates three different categories of drought classification: non-drought situation, drought situation with no action needed,

Table 3.3: TMWA's Enhanced Demand Management Programs by Drought Situation. Source: TMWA, 2016

			Month					
			May	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**
Non-Drought Situation			DMP	DMP	DMP	DMP	DMP	DMP
Drought Situation Reserve supplies **not** needed before Labor Day	→	Level 1	DMP	DMP	DMP	DMP	DMP	DMP
Reserve supplies needed *Before* Labor Day	in month → August:	Level 2	DMP	DMP	EMC	*e*DMP	*e*DMP	DMP
	July:	Level 3	DMP	EMC	*e*DMP	*e*DMP	*e*DMP	DMP
	June:	Level 4	EMC	*e*DMP	*e*DMP	*e*DMP	*e*DMP	DMP

DMP - standard demand-side management program
*e*DMP - *enhanced* demand-side management program
EMC - enhanced message campaign begins at least a month prior to *e*DMP deployment

and drought situation with action needed. In a non-drought situation, no drought has been identified, and Lake Tahoe supplies are adequate to maintain Floriston Rates until October 31st. If a drought has been identified (i.e. Floriston Rates cannot be maintained until October 31st), but drought reserves are not needed until after Labor Day, then no *e*DMPs are necessary. This is called a Level 1 drought. If a drought situation is identified and drought reserves are needed before Labor Day, then the situation is

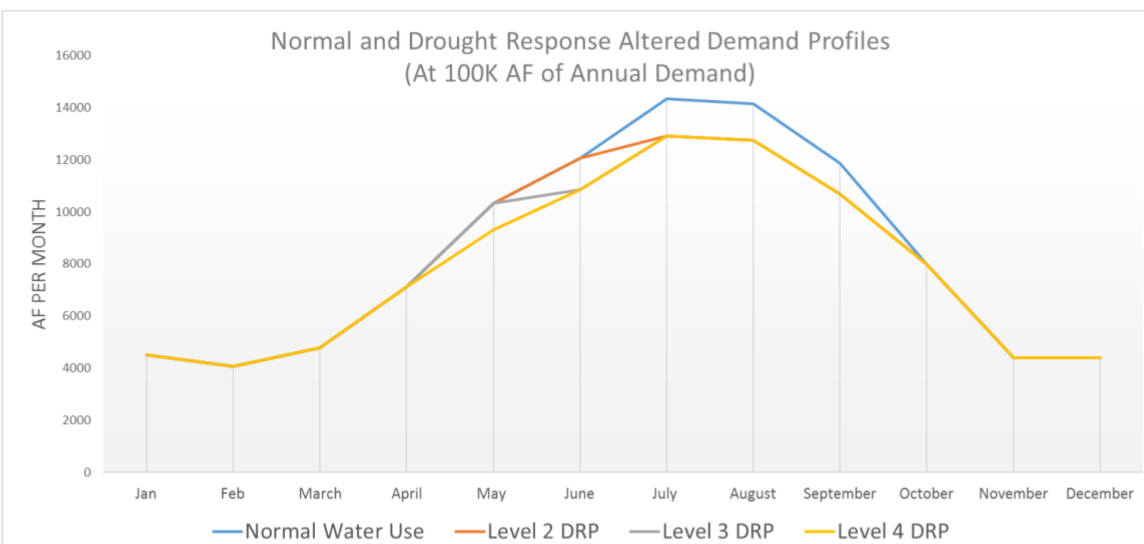


Figure 3.10: Monthly customer demand profile, and drought response demand profiles, for an annual demand of 100,000 AF

categorized as a level 2, 3, or 4 drought depending on when reserves are needed (Table 3.3). In level 2, 3, or 4 drought situations, *e*DMPs are put into place, with the goal being a reduction in customer demands starting the month before reserve use would be necessary (TMWA, 2016).

Conservation rules have been written into the DSS, matching those detailed above as specified in TMWA's drought response plan. The default amount of conservation requested is 10%, the historical request by TMWA. The model evaluates the drought situation for each year of the given scenario, and allows cutbacks beginning in the month relating to the drought level as specified above. Cutbacks have been modeled to end after September (Figure 3.10). In the model, these conservation actions can be forced, or simply allowed. Forced conservation means that the model automatically assigns water cutbacks, simulating the utility asking for conservation in drought years, and its customers responding exactly as desired (per the above conservation plan). If conservation is not forced, the DSS will utilize conservation up to an amount equal that which is specified based on the above policies. If not forced, conservation will be available but not necessarily occur, unless the model determines it beneficial to the overall optimization

3.4 System Parameters

This section includes further details about TMWA specific infrastructure. The parameters discussed include those related to both surface water and groundwater supplies, falling into the categories of both physical institutional parameters.

a). Surface Water

Surface water parameters are those related to any surface water operations for the utility. Physical parameters include treatment plant capacities, distribution losses, and typical amount of consumptive use. Institutional parameters include water rights, Floriston rates, and required in-stream flows. Full details about these parameters and the values can be found in table 3.4.

Table 3.4: Model Parameters – Surface Water

Institutional Parameters	Acre Feet	CFS/MGD	Comments
Hunter Creek Water Rights (annual)	9847	3209 MG	Actual TMWA water rights according to TMWA hydrologists
Avg. Summer Floriston Rate Cutoff (AF/day)	1041	525.0 CFS	500 CFS technically (TROA), but often more due to spikes/variance
Avg. Winter Floriston Rate Cutoff (AF/day)	843	425.0 CFS	400 CFS technically (TROA), October through February (but see above)
Reno required In-stream Flows (AF/day)	40	20.0 CFS	20 CFS for tribe, who also have senior water rights
Physical Parameters			
Chalk Bluff Treatment Capacity (AF/day)	276	90.0 MGD	Actual cap is 90 MGD a day with build-out to designed to 120 MGD
Glendale Treatment Capacity (AF/day)	101	33.0 MGD	actual cap is 33 MGD with up to 45 MGD designed
Glendale Comes Online (month)	4	April	Typical operations, no set date
Glendale Goes Offline (month)	11	Nov.	Typical operations, no set date
Distribution Loss (%)	0		5.6% from TMWA WRP, but demands used in model factor in distribution loss, so set to 0
Consumptive Use Percent (%)	62%		On average, 36% of water used is returned to river.

b). Groundwater

These parameters relate to TMWA's groundwater operations, including aquifer storage recharge (ASR) parameters. Values have been determined from TROA and other legal documents such as NV State Engineer order 1161 (Turnipseed, 2000). Again, parameters such as well and recharge capacities are physical system quantities, whereas groundwater

Table 3.5: Model Parameters - Groundwater

Source Type	Acre Feet	Million Gallons	Comments
Well capacity (AF/day)	163	53 MGD	Approximated as sustainable based on pumping Avg. from 2015 WY, when well use was maxed. Confirmed by TMWA Hydrogeologists. All wells
Annual TROA Groundwater Permit (AF/year)	15950	5197 MG	TROA specified, and confirmed in NV Engineer order 1161
Annual GW rights outside of TROA	11000	3584 MG	Very conservative value, based on how much was pumped in 2015. Mostly constrained by distribution, actual rights plentiful
Max total TROA Well extraction (one year)	22000	7169 MG	NV Engineer order 1161 specified
Allowed number of years at max well extraction	3		See above comment
Max GW bank transfer from year 1 to year 2	1000000	325851 MG	Limits the max transfer of GW to bank at years end. Extra GW rights (above and beyond TROA) can't be banked. Should basically be unlimited
TRA ASR Capacity (AF/day)	20	7 MG	Based off anticipated recharge volumes for wells
ASR Permit (AF/year)	11939	3890	Same as above, no real permitted max, not limiting constraint
ASR loss rate (%/yr.)	0.10		This varies based on GW basin, but 10% is the average

rights, permits, and allowed years of maximum extraction are institutional parameters. Since definite values do not exist for all the listed parameters, a few have been estimated based on all their constraining parts. An example of this is the capacity of piping and infrastructure for groundwater distribution, for which an exact number is slightly uncertain, but constrains well use in the system. Thus, the parameters for extra groundwater rights have taken this factor into consideration. Table 3.5 gives an entire list of groundwater parameters and their sources.

3.5 Reservoirs

TMWA has privately owned stored water (POSW) in both Donner and Independence Lakes, and is able to store M&I credit water in the other Truckee River reservoirs per TROA rules. As a result, Donner and Independence are fully modeled in the DSS, and their associated parameters fully cover the range of possible institutional and physical constraints. The other Truckee River reservoirs have been modeled with less individual detail, and can be considered as one lumped "bucket". TMWA's use of water in them is limited only by institutional constraints. A fundamental assumption of this work, is that there would always be adequate infrastructure and storage space for TMWA to move and store M&I credit water as desired, under the rules of TROA.

Table 3.6 lists parameters which are relevant to all reservoirs on the system. The sections which follow detail parameters for the each of the other reservoirs specifically.

Table 3.6: Model Parameters – All Reservoirs

Parameter			**Comments**
Reservoir Flood Release (month)	10	October	Estimates typical Current Conditions
Reservoir Storage Begin (month)	4	April	Current flood requirements for Donner (Indep. on its own). Based off ACOE safety requirements
	AF	MG	
Max Shortage Supply (AF)	1000000	325851.00	This is a hypothetical bucket that represents shortage, so the model can solve when all other supplies have been exhausted. Should not really have a limit, so set to a million

a). Donner

Parameters for Donner include flood release specifications, annual water rights/impoundment, and physical characteristics like the surface area and maximum amount of water that can be released (Table 3.7). One interesting characteristic is that the full amount of POSW in Donner Lake cannot currently be utilized, as it is impossible to fully draw down the lake. This results in an useable capacity of approximately 9000 AF. Donner Lake is also limited by the rules of the Donner Lake Indenture. This agreement states that the lake level will not be lowered to an elevation less than 5932 feet above sea level, during the months of June, July, and August. That level corresponds to a storage amount of approximately 6,315 AF, close to 2/3 of the Lakes total storage. The rules of this indenture can be modified and turned on or off within the DSS.

Table 3.7: Model Parameters – Donner

Parameter	Acre Feet	Million Gallons	Comments
Donner Lake Capacity (AF)	9500	3095.58	Actual capacity
Donner Transfer to TROA Max (AF)	9000	2932.66	Donner can't be fully drawn down due to facility/head specifications
Donner Flood Release (AF)	6000	1955.11	Typical flood release (if full), from USGS data
Donner Annual Impoundment Limit (AF/yr.)	9500	3095.58	TROA specified. Donner can be fully filled from empty according to water rights.
Donner Max Discharge (AF/month)	9000	2932.66	See comment for Donner Transfer to TROA Max
Donner Evap Surface Area (Acres)	870		870 is full, assume no change as lake level drops.

b). Independence

The parameters used for Independence Lake are roughly the same as for Donner, and can be found in Table 3.8. Independence has a slightly smaller surface area, but more overall storage (17500 AF). That storage is broken apart into two different priority levels, with the threshold being at 7500 AF of storage. That priority level has to do with TROA credit water, as TROA states that M&I water cannot be used as a drought supply until Independence is drawn below that level. For simplicities sake in the model, the full storage amount is considered to be one homogenous priority level. Other operating rules specify that Independence water levels may be pumped to a level below its natural rim, in times of extreme drought. Since infrastructure does not currently exist to do so, and the extra quantity of water would be relatively small, this practice has also been excluded from the DSS.

Table 3.8: Model Parameters – Independence

Parameter	Acre Feet	Million Gallons	Comments
Indep. Lake Upper Level Capacity (AF)	17500	3258.51	Max amount allowable, doesn't consider release level priorities
Indep. Lower Release Level (AF)	0	0.00	Last 7500AF are lower priority, but set to zero to avoid complications with that. (treats all 17500 AF of POSW the same)
Indep. To TROA Max (AF)	10000	3258.51	Amount of Upper level category of water in Independence. Could probably do more.
Indep. Typical Release (AF)	3000	977.55	Generally drawn down for exchange/flood (from USGS data)
Indep. Max Discharge (AF/month)	10000	3258.51	Not 100% on actual value, so estimated 10000 AF with help of TMWA hydrologists
Indep. Annual Impoundment Limit (AF/yr.)	3000	977.55	Complicated, but 3000 always allowed. More if other water rights satisfied
Indep. Evap Surface Area (Acres)	700		700 is SA if lake is full. Assume no change as lake level drops. Change would likely be minimal anyway, as storage is just top few feet of lake

c). TROA Credit Water

The utility can accumulate TROA credit water in two ways. POSW in Donner or Independence can be converted to credit water through an exchange, or Floriston Rate water that is scheduled for release can be held back. The limits which TROA specifies for those processes, are included in the list of TROA Water parameters (Table 3.9). TROA credit water falls into two categories: firm M&I water, and non-firm M&I water. In general, firm M&I water is less easily released or traded for other (non-TMWA) water types. Non-firm M&I water can be replaced by other water types, and is more easily discharged from the reservoirs in many storage situations. Another type of TROA water,

Table 3.9: Model Parameters – TROA Water

Parameter	Acre Feet	Million Gallons	Comments
Max. TROA M&I Water Supply (AF/yr.)	119000	38776.27	No apparent actual limit, but many constraints on accumulation. Set at the maximum demand that TROA has been designed to accommodate.
Max TROA Water Holdback (AF/day)	95	47.90 (cfs)	According to TROA
California Water Use Factor (AF)	9500	3096	Arbitrary value, exact condition unknown, but 9500 is middle of range
Min Firm M&I Base Amount (AF)	2000	652	Specified in TROA
Max Firm M&I Base Amount (AF)	12000	3910	Specified in TROA
Min non-Firm M&I Base Amount (AF)	4000	1303	Specified in TROA
Max non-Firm M&I Base Amount (AF)	20000	6517	Specified in TROA
Max Emergency Drought Supply (AF)	7500	2443.88	Specified in TROA

referred to as Emergency Drought Supply water (EDS) in the document, can also be accumulated over time from M&I water supplies. The maximum amount of EDS that can be accumulated and stored is 7500 AF, but that water is never discharged unless it gets used by the utility. Both types of M&I water and EDS water are generally slated to be stored in Stampede Reservoir, although TROA allows for trading amongst the other Truckee River reservoirs. Stampede is the largest reservoir in the system (apart from Tahoe), and rarely fills to it’s maximum. As a result, these water types have been modeled simply as one water storage “bucket”, which is assumed to always have storage space if the rules of TROA are followed. Given the large amount of space available in

Stampede, and since M&I water and EDS have priority over many of the other water types designated in TROA, this is a valid assumption.

d). Evaporation Rates

To accurately represent the storage and loss of reservoir water, the DSS model requires reservoir evaporation rates as an input. Evaporation rates are needed for Donner and Independence Lakes, as well as some representation of evaporation losses for other categories of water which are stored via reservoir (M&I credit water and EDS). Current estimates of open water evaporation exist for these reservoirs, and estimates of future evaporation rates corresponding to Scenario 1B are provided for this model.

These evaporation rates have been calculated by Huntington and McEvoy (2011), using the Complementary Relationship Lake Evaporation (CRLE) model. The CRLE model works for open water evaporation, and accounts for water temperature, albedo, emissivity, and heat storage effects. The results are realistic operational estimates of monthly evaporation, which have been based off actual climate data from 2000 to 2009 for each water body. For scenario 1A, these current evaporation rates have been used. For scenario 1B, the calculations were repeated, but with temperature increased to match 2051-2070 predictions (about 2.5^{o}C increase), while other parameters which affect reservoir evaporation remained the same. As might be expected, the resulting evaporation rates are somewhat higher for Scenario 1B than 1A (Table 3.10).

The calculated evaporation rates for Donner and Independence Lakes, are in inches per month. That value is then multiplied by the surface area of each lake. Conversely, the evaporation rates which have been used in the DSS for M&I credit water and EDS, are as a percentage of total water (Table 3.10). This is because M&I credit water only constitutes a portion of the water in the reservoir it is stored in (most likely Stampede or sometimes Boca). As M&I credit water supplies are increased, and the proportion of M&I credit water to other water types increases, and M&I credit water incurs a greater portion of the reservoir's evaporative losses. The calculated percentages are a rough estimate of what that loss might be. This number is difficult to determine, as the water could potentially be stored in several different reservoirs (each with different evaporative losses), and the proportion of M&I credit water to other stored water would be unknown (varies depending on lake level, operations of other water users, etc.). These evaporation percentages have been calculated with it assumed that the water would most likely be stored in Stampede Reservoir. Since they are just estimates, the values have been left the same for both 1A and 1B. Per TROA, emergency drought supply (EDS) water never incurs evaporative losses, and so the model inputs reflect that (TROA, 2008).

Table 3.10: Evaporation Losses for Both Scenarios

Month	Donner (in/Mo)		Independence (in/Mo)		M&I Water (%/Mo)		EDS (%/Mo)	
	1A	1B	1A	1B	1A	1B	1A	1B
1 (Jan)	1.78	1.84	0.25	0.26	0.24%	0.24%	0.00%	0.00%
2 (Feb)	0.75	0.78	0.00	0.00	0.03%	0.03%	0.00%	0.00%
3 (March)	0.91	0.94	0.17	0.17	0.12%	0.12%	0.00%	0.00%
4 (April)	1.28	1.33	0.48	0.50	0.27%	0.27%	0.00%	0.00%
5 (May)	2.29	2.37	2.12	2.20	0.47%	0.47%	0.00%	0.00%
6 (June)	3.39	3.52	3.72	3.87	0.69%	0.69%	0.00%	0.00%
7 (July)	4.84	5.03	5.25	5.46	0.95%	0.95%	0.00%	0.00%
8 (Aug)	5.52	5.73	5.85	6.07	1.05%	1.05%	0.00%	0.00%
9 (Sep)	5.38	5.59	5.47	5.67	0.96%	0.96%	0.00%	0.00%
10 (Oct)	4.73	4.91	4.65	4.83	0.84%	0.84%	0.00%	0.00%
11 (Nov)	3.70	3.84	3.45	3.59	0.62%	0.62%	0.00%	0.00%
12 (Dec)	2.80	2.91	2.39	2.48	0.46%	0.46%	0.00%	0.00%

3.7 Cost Coefficients and Flow Paths

For the DSS to optimize operations, water supply flow paths are assigned a pseudo-cost or weight value (non-monetary). The weighting is based both on the priority of use for the utility, and TROA specified operational order for the water supplies. The exact value of each pseudo-cost is not necessarily important, but the values must decrease in sequential order, corresponding to priority of use (most desirable = least cost). In the model, each water supply follows a flow path made up of arcs, with each arc representing some flow of water through space or time. These arcs have their own associated pseudo-cost value, and the total pseudo-cost of a water source, is therefore the sum of all pseudo-costs for the arcs which create the water source flow path.

In a model run, each arc's pseudo-cost value is multiplied by the amount of water flowing through it. The model's objective function is equal to the sum of all these values (Section II, equation 1), and the overall mathematical goal is to minimize the objective function. Thus, utilizing arcs and flow paths which have a greater associated pseudo-cost will increase the objective function value, and be less desirable. Arcs with a smaller pseudo-cost are more desirable, as their use has less impact on increasing the objective function value. Arcs can also have negative pseudo-cost values, and so their use is beneficial to minimizing the objective function. Negative pseudo-cost values have been assigned to arcs that represent operations which are desired to be maximized, such as groundwater recharge or reservoir storage. Each time these arcs are used, the objective function value decreases, and so the model will use them as much as possible. Although water storage is considered an optimal operation, use of those stored supplies is not necessarily a priority water source. Thus, the total flow path pseudo-cost associated with those sources is still greater than zero. To ensure that priority operations are simulated despite storage goals, it was necessary to have the pseudo-costs for some priority flow paths be negative.

The general idea of these flow paths, is to avoid using drought reserves if possible, and so those sources have the highest cost. Conversely, normal utility operations have the lowest cost, and it is most desirable to simply use treated river water to meet demands. Subject to applicable constraints written in the model, water supplies will be utilized to their full extent before to using the next priority of water supply. The water supply source paths are listed in Table 3.11, in order of priority as specified.

Table 3.11: Supply flow paths and associated pseudo-costs

Source priority	Total path pseudo-cost	Source description
1.	-10	Use treated Truckee River or Hunter Creek water to meet customer demand
2.	15	Use groundwater rights to meet demand
3.	20	Use ASR to wells to meet demand
4.	24	Store creek inflows in Donner as POSW, then move to treatment plants to meet demand (slightly preferable to Independence per TROA)
5.	29	Store creek inflows in Independence as POSW, then move to treatment plants to meet demand
6.	34	Use TROA M&I water accumulated from either Floriston Rate holdback or POSW conversion, move to treatment to meet demand
7.	55	Use a policy option (conservation/water use cutbacks), to decrease overall demand. The model looks at this like a supply source, ultimately providing the cutback water to meet demands rather than reducing demands.
8.	119	Utilize Emergency Drought Supply water, move to treatment to meet demand.
9.	150	Shortage supply is used to meet demand, enabling the model to solve when all actual sources have been depleted.

IV. Results and Discussion

Runs of the model were initially performed with current system parameters, at customer demands matching those beginning in 2017 and annually increasing over the 15 year modelling period, as detailed in TMWA's 2016 Water Resource Plan (TMWA, 2016). Scenarios 1A and 1B were both used, to determine how the current system could reliably supply water under the drought conditions specified, and how the two scenarios stressed the system differently. For both scenarios, the model showed TMWA being able to provide water to its customers, with no shortage incurred. For the conditions of Scenario 1A, TMWA was shown to have operational flexibility, with TROA providing adequate drought supplies. Under Scenario 1B, operations were more stressed, and all available water supplies nearly exhausted.

To further test the limitations of TMWA's current water supply system, model runs were performed for both scenarios, at increasingly higher demand levels. The goal was to determine a breaking point, at which the utility could no longer meet the demands specified. Following this work, a few selected parameters of the model were adjusted, and tested to see how much they affect overall operations and reliability. Incrementally increasing customer demand runs were performed with these adjusted parameters, and compared to the original runs (at current parameters). In this way, the model was used to help specify which parameters most affect and limit operations, ultimately determining ways in which the utility could improve its drought operations.

A full documentation of the results from these model runs, and a discussion of the accompanying implications, can be found in the following sections.

4.1 Current Operating Conditions, Scenarios 1A and 1B

The following sections detail results for model runs, which were performed using system parameters and demands for 2017 conditions.

a). Scenario 1A

Under current (2017) operating conditions and demands, the model shows that TMWA can supply water for all years, using the available modeled water supplies (figure 4.1). When conservation actions are not forced (i.e. water use cutbacks are automatically assigned by the model, occurring as specified in the drought response plan, regardless of modeled need for conservation), the model does not even show a need for cutbacks in

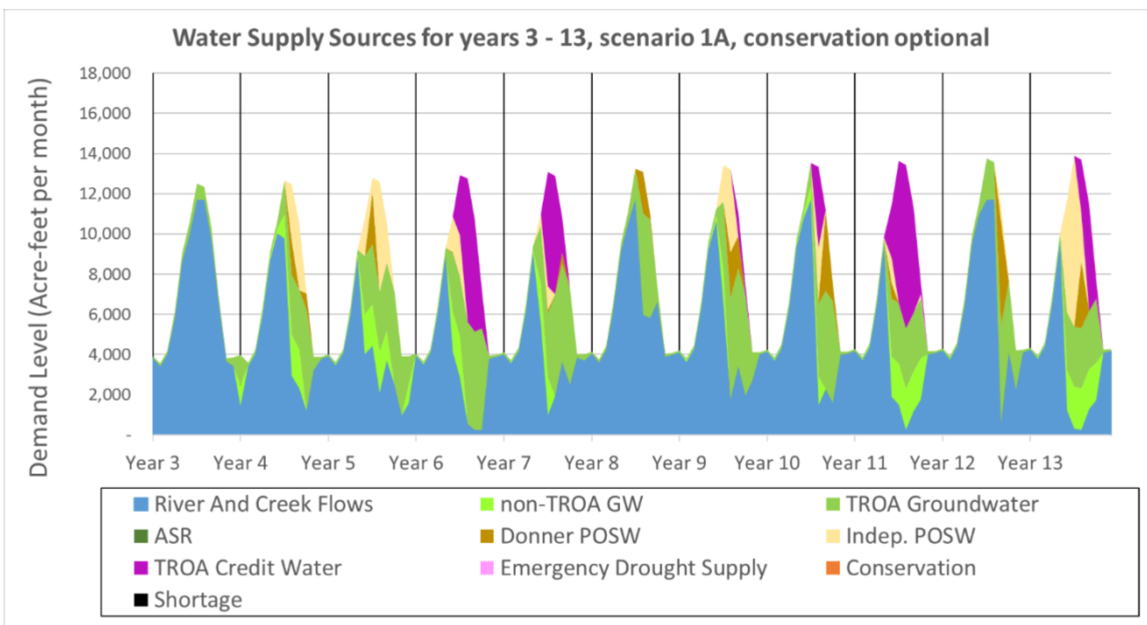


Figure 4.1: Modelled water supplies for Scenario 1A, years 3-13, conservation optional. Note that the years specified are calendar years and NOT water years

Scenario 1A - Supply Output - 85-99k Demand Profile - Conservation Forced										
Scenario Year	Drought Designation	Total Demand*	River Supply	TROA GW	Other GW Rights	Drought Reserves	Demand Management Policy	Total Production	Recharge	Shortage
1	None	84,589	86,996	2,753	1,377	-	-	91,126	6,537	-
2	None	85,999	88,004	2,784	1,392	-	-	92,180	6,181	-
3	None	87,213	87,931	3,149	1,574	-	-	92,653	5,440	-
4	Level 3	88,254	59,426	14,391	7,195	6,259	(4,624)	87,270	3,640	-
5	Level 4	89,184	47,656	20,689	10,344	7,920	(5,595)	86,609	3,020	-
6	Level 4	90,129	45,179	17,579	8,790	16,725	(5,654)	88,273	3,798	-
7	Level 4	91,221	51,741	17,197	8,599	11,583	(5,722)	89,119	3,620	-
8	Level 2	92,379	80,637	8,337	4,169	733	(3,727)	93,876	5,224	-
9	Level 3	93,383	61,234	15,532	7,766	7,647	(4,893)	92,179	3,688	-
10	Level 2	94,283	68,541	11,751	5,875	9,223	(3,804)	95,390	4,910	-
11	Level 4	95,083	45,479	17,579	8,790	20,906	(5,965)	92,754	3,636	-
12	None	95,866	77,749	10,806	5,403	5,930	-	99,887	4,021	-
13	Level 4	96,774	44,611	17,579	8,790	23,603	(6,071)	94,583	3,879	-
14	None	97,703	95,638	4,926	2,463	-	-	103,027	5,324	-
15	None	98,608	96,069	5,098	2,549	-	-	103,715	5,108	-

* Includes system loss.

Table 4.1: Modelled annual water supplies for Scenario 1A, conservation forced (all units in Acre-Feet)

water use. Instead, the main sources of additional supply are groundwater and drought reserves in the form of TMWA POSW and TROA M&I credit water. Use of Donner and Independence POSW is maximized under both conservation situations. Without specified demand cutbacks, the model is more reliant on M&I credit water, using about as much M&I credit water as POSW from Donner and Independence Lakes. With conservation forced, that quantity is nearly halved (from 69,190 AF to 36,989 AF over the entire 15 years). In both instances, TMWA would not be able to provide water through the duration of scenario 1A without the flexibility of extra storage provided by TROA. The model also shows less groundwater use when conservation is forced, and more groundwater recharge can occur. Thus, even though demand cutbacks are not necessary, they do help improve operational flexibility and aquifer health.

Under the hydrologic conditions of scenario 1A, there are ample river flows to sustain normal operations (only river water and groundwater) until the end of year three. This would be due to the operation of Tahoe and other reservoirs under TROA, which provide a storage buffer of approximately two years before being severely affected by drought. At the end of our scenario, river flows return to average conditions for years 14 and 15. With this hydrology, normal operations can quickly be resumed at the start of year 14. As such, years 1, 2, 14, and 15 have been omitted from the accompanying graphs since they merely show standard operations. The toughest and most interesting drought conditions happen during the middle of our scenario, as shown above.

These runs also reveal some of the limiting factors in our supply system. One of these is the timing of POSW releases from Donner Lake. The Donner Lake Indenture specifies that if the lake is below an elevation of 5,932 ft. (about 66% of maximum storage) during the months of June, July, and August, then water shall not be released from the reservoir. In drier scenario years, Donner Lake does not fill entirely when storage accumulation begins in April, and thus is limited in its ability to release water during those summer months (which correspond to the highest customer demands). Instead, model runs show TMWA being forced to use POSW from Independence Lake during those months (Figure 4.1), and Donner Lake is use less as a drought supply. Relaxing the conditions of the Donner Lake Indenture, or allowing the reservoir to begin storing water supplies earlier in the year, would make Donner POSW a more readily available source of drought supply water.

b). Scenario 1B

Under the hydrologic conditions of scenario 1B, modelled results are drastically different than those for scenario 1A. At current demands and operating conditions, the model shows TMWA just barely being able to supply water throughout the duration of the

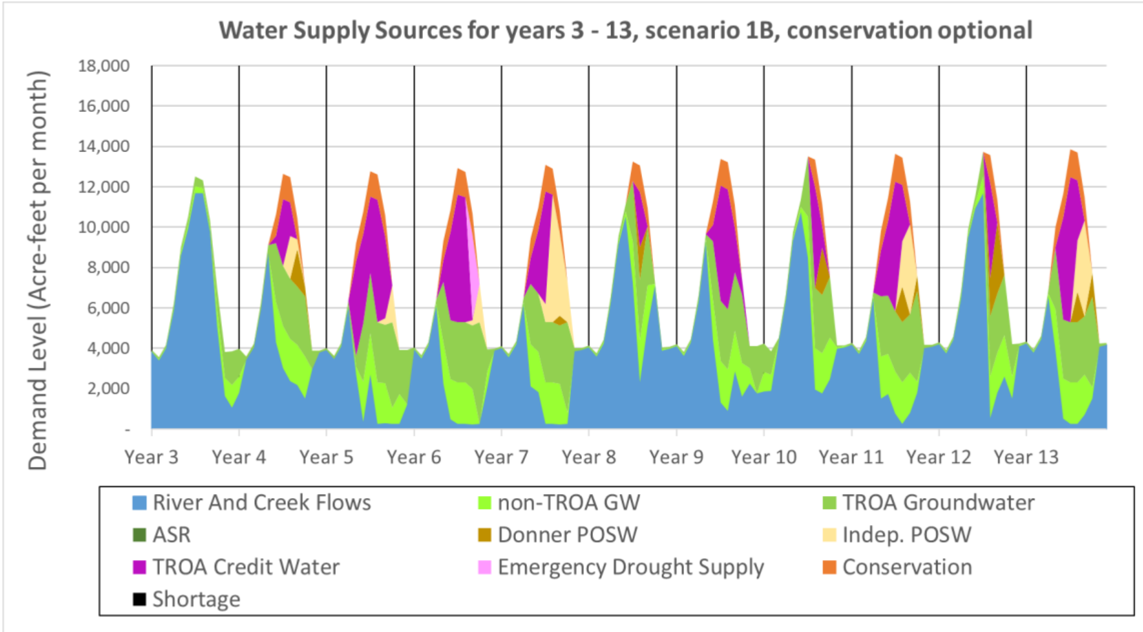


Figure 4.2: Modelled water supplies for Scenario 1B, years 3-13, current demands, conservation optional

scenario (Figure 4.2). The model even shows a need for TROA emergency drought supply water (EDS), which should be the last category of water to ever be used in a drought situation. In addition, use of POSW in Donner and Independence Lakes is maximized, use of TROA M&I credit water is maximized, and water conservation is necessary for every month possible (Table 4.2). TMWA can survive this scenario thanks

Scenario 1B - Annual Supply Output - 85-99k Demand Profile - Conservation Optional										
Scenario Year	**Drought Designation**	**Total Demand***	**River Supply**	**TROA GW**	**Other GW Rights**	**Drought Reserves**	**Demand Management Policy**	**Total Production**	**Recharge**	**Shortage**
1	None	84,589	86,996	2,444	1,686	-	-	91,126	6,537	-
2	None	85,999	88,004	2,471	1,704	-	-	92,180	6,181	-
3	None	87,213	80,769	6,312	4,353	-	-	91,433	4,220	-
4	Level 4	88,254	47,190	18,195	11,000	10,285	(4,624)	86,670	3,040	-
5	Level 4	89,184	27,909	22,000	11,000	25,081	(5,595)	85,989	2,400	-
6	Level 4	90,129	30,389	21,733	11,000	24,374	(5,654)	87,495	3,020	-
7	Level 4	91,221	34,252	20,022	11,000	23,845	(5,722)	89,119	3,620	-
8	Level 3	92,379	70,878	11,128	7,674	4,387	(3,171)	94,068	4,860	-
9	Level 4	93,383	45,697	19,375	11,000	15,439	(4,893)	91,511	3,020	-
10	Level 3	94,283	60,911	15,465	10,665	8,402	(2,452)	95,443	3,612	-
11	Level 4	95,083	37,254	20,022	11,000	24,411	(5,965)	92,687	3,569	-
12	Level 2	95,866	65,627	12,794	8,824	10,149	(2,493)	97,394	4,021	-
13	Level 4	96,774	37,431	20,022	11,000	25,250	(6,071)	93,703	3,000	-
14	None	97,703	95,638	7,389	-	-	-	103,027	5,324	-
15	None	98,608	96,069	7,647	-	-	-	103,715	5,108	-

* Includes system loss.

Table 4.2: Modelled annual water supplies for Scenario 1B, conservation optional (but use maxed)

to the flexibility and extra supplies provided by TROA, but the utility comes very close to incurring a shortage. Full results detailing the suggested water supply under these conditions can be found in Figure 4.2 and Table 4.2.

Similar to scenario 1A, there are ample river flows to sustain normal operations (only river water and groundwater used to meet demands) until the end of year three. After that, drought conditions become more severe due to a loss of Tahoe outflows. Even under the climate change conditions of scenario 1B, Tahoe and the other large Truckee River Reservoirs provide an approximately 2-year drought buffer of stored water. However, the projected increase in evaporation rates combined with earlier runoff, renders the smaller reservoirs such as Donner and Independence less efficient for storage. Little water is available to be stored, and again, the Donner Lake Indenture further limits POSW release from Donner Lake.

4.2 Current Operating Conditions, Increasing Demands (1A and 1B)

Two series of further model runs were performed using both Scenarios 1A and 1B, with operating parameters specified to match current conditions. For these series, annual customer demands were sequentially increased (listed in table 4.3) until the model experienced a water supply shortage. The results from these runs are detailed below.

a). Scenario 1A

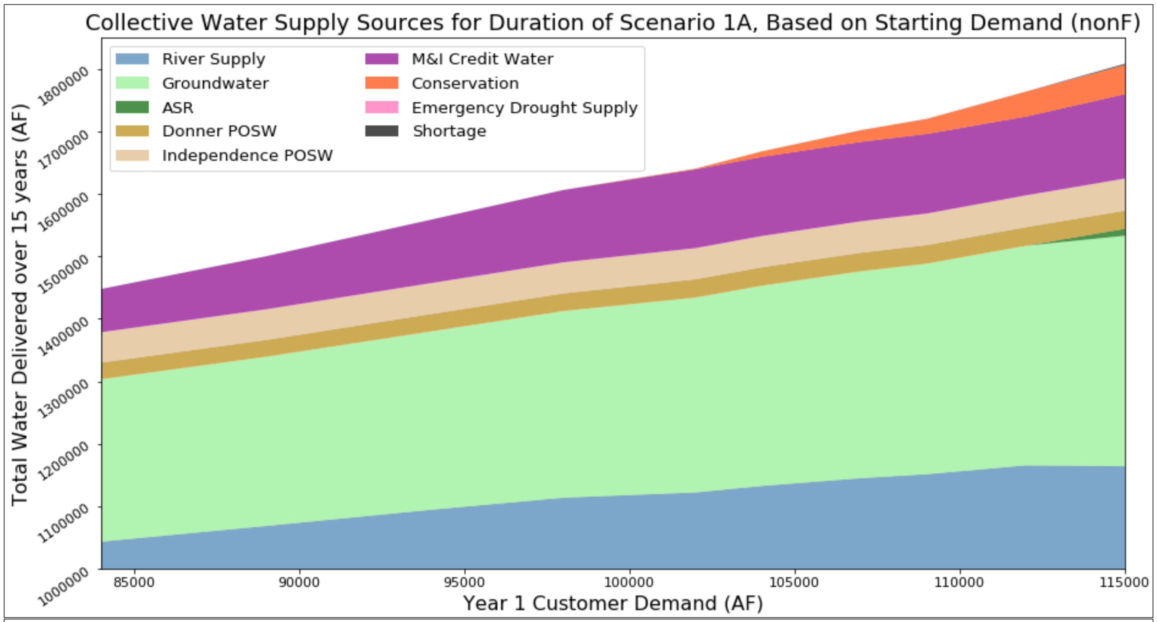
For scenario 1A, model runs up to a starting demand of 109,000 annual AF did not experience a shortage, with both conservation forced and optional runs. At a starting

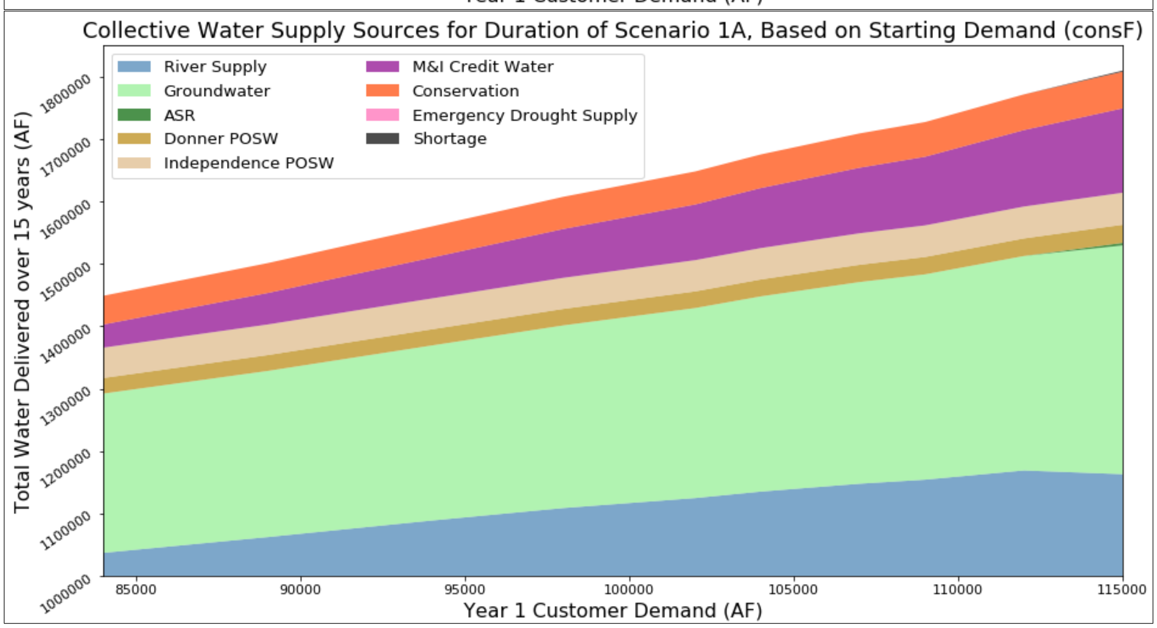
Year 1 Demand Level	Conservation Optional	Conservation Forced
84K	Groundwater, POSW and TROA M&I water reliant, more POSW than TROA.	Less than half as much TROA M&I water than POSW used. Reliant on both as well as Groundwater
89K	Same as above, but more TROA M&I water than POSW use	
94K		
98K		
102K	Conservation (very small amount)	More TROA M&I water than POSW use now
104K		
107K		
109K	6 years conservation use	
112K	Shortage without SW treatment capacity upped.	Shortage without SW treatment capacity upped.

Table 4.3: Starting demands at which water supplies are used during Scenario 1A

demand of 112,000 AF, the model was unable to solve without a shortage being incurred. Interestingly, this shortage can be attributed to a lack of surface water treatment capacity, and not due to drought conditions. Further model runs with surface water treatment capacities increased (meeting specified upgrade capacities), allowed the model to solve up to a starting demand level of 118,000 annual AF without experiencing a shortage. This is in line with the 119,000 AF annual maximum demand level that TROA has been designed to support for the region (TROA, 2008). Details about which water supplies were used during these runs can be found in table 4.3. In that table, for starting demands which do not have any details listed, it is implied that the supplies used are essentially the same as lower demand level runs.

Although the model does not specify conservation policy being necessary at current demand levels, the results of these incremental demand runs were similar for both





Figures 4.3 & 4.4: Water sources for duration of Scenario 1A, over increasing demand level runs

conservation forced and optional runs (figures 4.3 and 4.4). Even in the drought conditions of scenario 1A, river water is the primary supply source for the utility, with groundwater the second most used. POSW and TROA M&I water were also used at all demand levels, although runs with forced conservation used about half as much TROA M&I water as otherwise (figure 4.4). This is one benefit of having a conservation policy

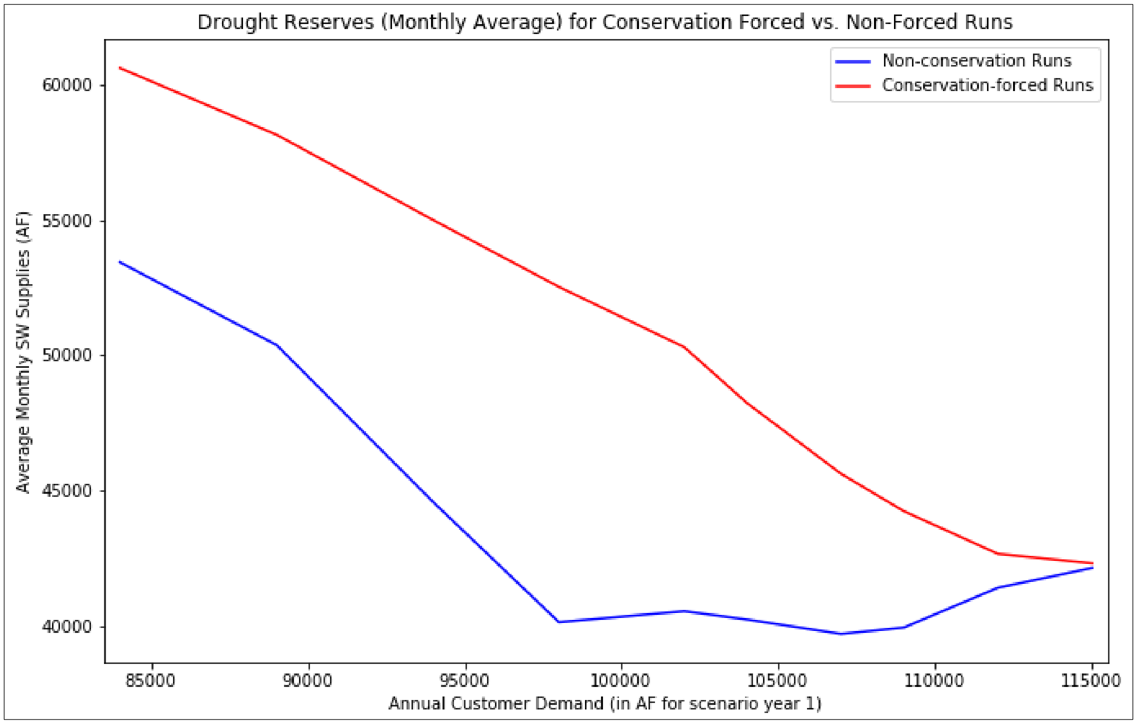


Figure 4.5: Average monthly surface water supplies, based on starting demand level, Scenario 1A

in place. Asking for cutbacks in water use allows more surface water to be available throughout the course of the drought (figure 4.5), and increases the flexibility of utility operations. Runs with conservation forced also allowed for more groundwater recharge (figure 4.6). Thus, although current water conservation programs have not been modelled as necessary until demand levels approach 102,000 annual AF, they help increase operational flexibility and improve aquifer health.

These runs reveal two more limiting factors in the water supply system: surface water treatment capacities, and monthly well capacities. Together, these two parameters constrain the model from solving at a higher demand level without shortage. All water being provided to customers must come from wells or be treated, and the current capacities are not enough to meet peak summer demands around an annual demand of 112,000 AF, regardless of available water. Upping surface water treatment allows the

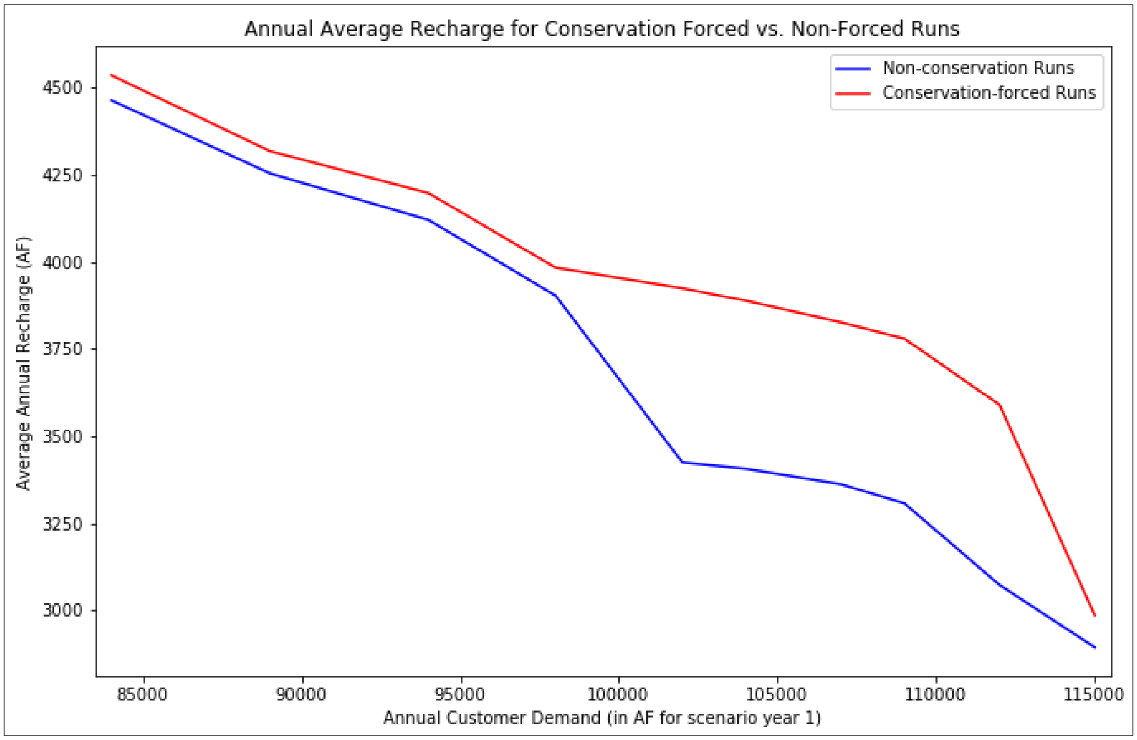


Figure 4.6: Average annual recharge, based on starting demand level, Scenario 1A

model to solve further. Increasing monthly well pumping capacities would also allow the model to solver further, and would make ASR water a viable source. ASR was not seen as a supply during these runs, because current well capacities limit its usefulness. ASR is only extracted after all groundwater rights have been used, and with current well capacities, that was never the case for any year in scenario 1A. The wells were never able to pump enough groundwater for ASR to be a utilized source.

b). Scenario 1B

For scenario 1B, results of the incremental demand runs were not very encouraging. At current demand levels (84,000 annual AF), the model was just barely able to solve without incurring a shortage (figure 4.2 and table 4.2). With starting demands increased to 89,000 annual AF, a shortage was incurred (figure 4.7). Running the model with

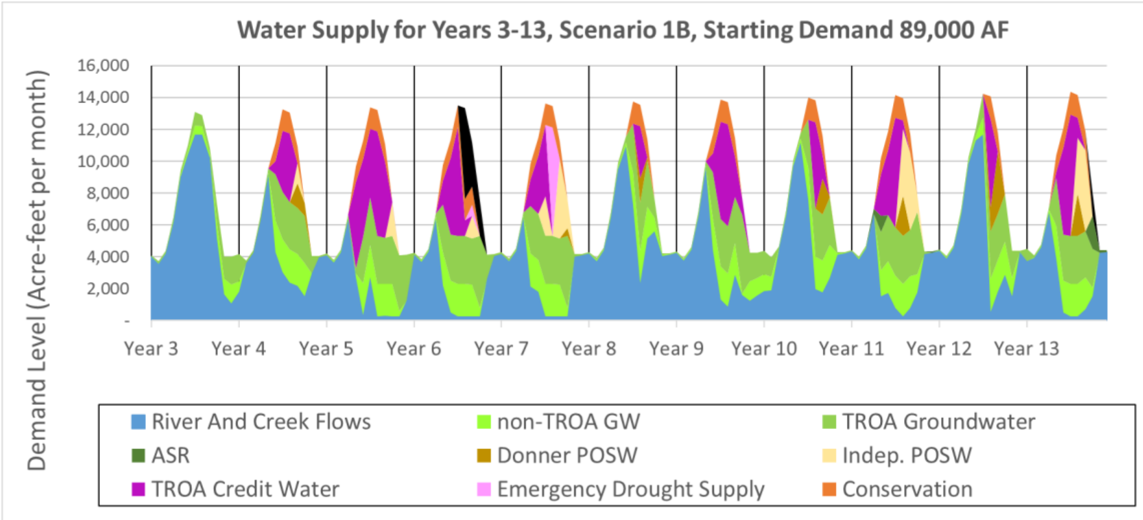


Figure 4.7: Water Supply for 89,000 AF Starting Demand, Scenario 1B

conservation policy optional or forced made little difference, as maximum cutbacks were necessary to avoid a shortage either way.

Scenario 1B is much tougher on the utility than scenario 1A. There is slightly less water available in the river, especially later in the year and during peak summer months. This is partially because more precipitation is modelled to fall as rain rather than snow, and partially because the current reservoir operating rules don't allow for early enough water storage. As a result, much of the modelled precipitation immediately flushes through the system during the winter months. The water that gets stored is susceptible to increased evaporation rates, further limiting the system. This ultimately results in less reservoir water available, which could release Floriston Rate water or POSW later in the year. TMWA is also less able to accumulate TROA M&I credit water from Floriston Rate holdback, because Floriston Rate water is released for a shorter period of time. Adjusting the time of reservoir storage does benefit the system immensely, and will be discussed in greater detail below.

4.3 Scenario 1A, Adjusted Operations

Incremental demand model runs were again performed using scenario 1A, but with TMWA infrastructure upgraded. For the first series of improved model runs, surface water treatment was increased to meet build out specifications (120MGD at Chalk Bluff and 45MGD at Glendale). For the second series of improved model runs, daily well pumping capacities were increased, and tested at both 64MGD and 70MGD. These improved runs again began at current demand levels, and ended once the model experienced a shortage. The full results are detailed below.

a). Increased SW treatment

With surface water treatment increased, the model produced similar results for lower demand level runs. The model is most limited by low river flows during the months with greatest customer demand, so increasing treatment capacity does little to help the utility manage through those time periods. However, major differences begin to be seen at starting demand levels of 100,000-110,000 AF. Around these levels, the increased treatment capacity allows for more flexibility in well operations, leaving more groundwater available for very dry months and years. With treatment capacities upgraded (as detailed above), the model is also able to solve at higher starting demands without incurring a shortage. The limit on this comes around 118,000 AF, when water supplies become the limiting factor for the system. Even with upgraded treatment capacities, the model cannot solve beyond this demand level without experiencing a

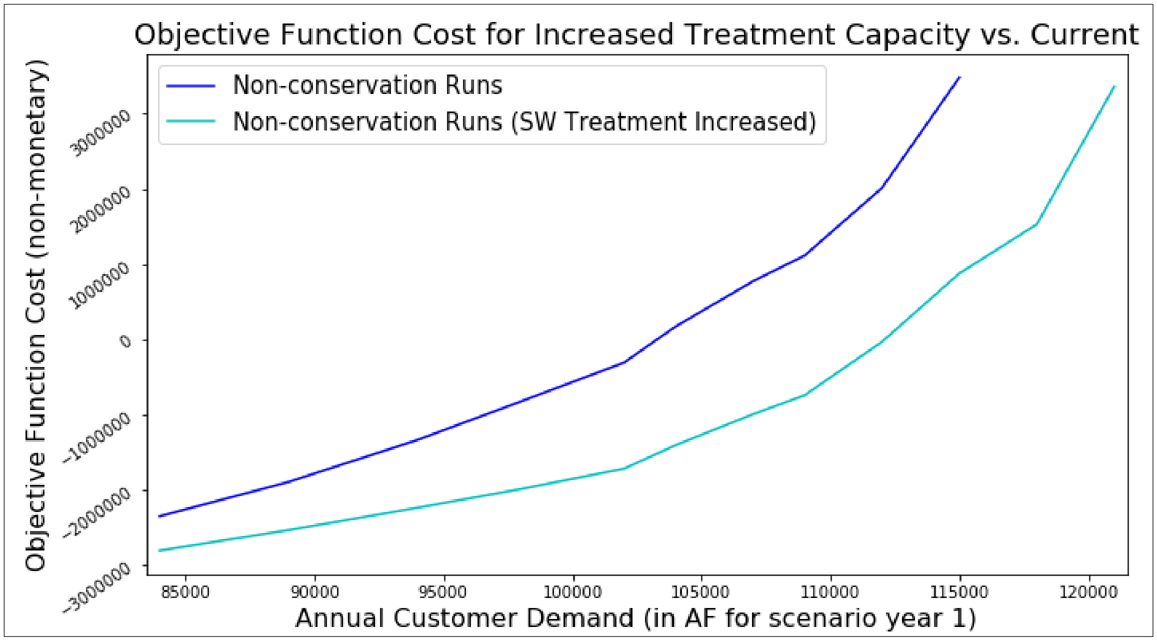


Figure 4.8: Objective function comparison for treatment capacity increase vs current, Scenario 1A

shortage. This result is in line with what TROA has been designed to accommodate, which is a customer demand of 119,000 AF annually.

These results can be visualized in figure 4.8, which compares overall objective function values for the runs with treatment increased vs not. Objective function values are not actual monetary values, instead they are essentially a measure of difficulty for operations. When the objective function value is lower, the utility is closer to normal operations (river water and wells), and conversely the value gets higher as the utility is closer to a shortage. In figure 4.8, the two objective function curves are initially close at current demands. Since operations are initially similar for both sets of parameters, they follow a similar trajectory. Around demands of 102,000 AF, the objective function really starts to increase for the non-upgraded runs. This is the demand level where operations really improve by having increased surface water treatment capacities. Beyond a starting demand of 112,000 AF, only the upgraded treatment capacity runs can continue to solve without shortage, and the objective function curves split dramatically. Thus, the model suggests that a surface water treatment upgrade would be useful around 102,000 AF of demand, and is necessary beyond demands of 112,000 AF annually.

b). Increase in daily well capacities (64MGD and 70MGD)

As might be expected, the model runs with increased daily well capacities were more resilient to the drought conditions of scenario 1A. The use of drought reserves was substantially diminished with well capacity increased to 64MGD, and even more so at 70MGD. For current demand levels, all runs were still reliant on TROA M&I water as a supply. However, with daily well capacities set to 70MGD, the amount of M&I water needed was reduced by more than half. The runs with increased well capacities were also able to serve a higher customer demand level without a shortage being incurred. With daily well capacity set to 64MGD, the model experienced a shortage around a starting demand of 125,000 AF. That same shortage limit was found to be 127,000 AF with daily well capacity set to 70MGD (table 4.4). It is worth noting that to reach these limits, it was assumed that surface water treatment would also be increased to build out conditions.

The most severe parts of scenario 1A are a few summer months, when the river supply is essentially non-existent. Being able to extract more groundwater during those months dramatically improves utility operations, and reduces the need for surficial drought supplies (POSW and TROA M&I water) during those time periods. Increasing the daily pumping capacity also allows for ASR water to become a useful source of water. With a pumping capacity of 53MGD, the well capacities and timing of limited water supplies

Starting Demand Level	Daily well Cap = 53MGD	Daily well Cap = 64MGD	Daily well Cap = 70MGD
84K	Groundwater, POSW and TROA M&I water reliant, (69,190 AF M&I use)	Groundwater, POSW and TROA M&I water reliant, (42,304 AF M&I use)	Groundwater, POSW and TROA M&I water reliant, (30,286 AF M&I use)
89K			
94K			ASR used
98K			
102K	Conservation Use necessary	ASR used (2,794 AF)	9,212AF ASR
104K			
107K			
109K		10,526 AF ASR	16,474 AF ASR
112K	Shortage without SW treatment upgrade (used in higher demand runs)	Conservation use (13,440 AF)	Conservation use (9,387 AF)
115K			
Build Out (118K)	Very slight bit of EDS		
121K	EDS maxed and absolute shortage occurs	Shortage without SW treatment upgrade (used in higher demand runs)	Shortage without SW treatment upgrade (used in higher demand runs)
123K		EDS use	
125K		Absolute shortage (3,611 AF)	EDS use specified
127K			Absolute Shortage (6,371 AF)

Table 4.4: Starting demands at which water supplies are used during scenario 1A, increased well capacities. Where water supplies are not specified, they are assumed to be the same sources as lower demand level runs.

never make ASR a useful water source. With increased well capacities, the model shows ASR becoming a supply of water which can be utilized, with a maximum of 16,474 AF being used when well capacity is 70MGD and starting demands are 112,000 (table 4.4). For ASR to be used, yearly groundwater rights must first be maximized for that particular year. Thus, the model is showing that groundwater rights can become a limiting factor for the system. However, increasing the daily well capacity much further would soon lead to a point at which this does not benefit the system, as the sum of total groundwater and ASR extraction is ultimately most constrained by the rules of order 1161. Order 1161 supersedes the limits provided by annual groundwater rights.

Increasing the daily well capacities makes a greater difference at lower demand level runs, and is less pronounced at higher demands. This is likely due to the pattern of the drought in scenario 1A, in which river water is almost always adequate during the winter, but shortages occur for a few extremely dry summer months. At lower demand levels, the increased well capacity is adequate for closing the gap between supply and demand during these dry months. At higher demand levels, the monthly demand is substantially greater than the available water. Increasing well capacities helps to close this gap, but is not sufficient at completely providing water during these tough months. The utility must still rely heavily on drought reserves.

4.4 Scenario 1B, Adjusted Operations

Initial testing of scenario 1B was not overly promising. At current demand levels, the model showed TMWA relying on emergency drought supply water and conservation to meet demands. With just a slight increase in annual demands, a shortage was incurred.

Thus, it was determined that alternative supply solutions or improvements to the system must to be found for drought resiliency. Four potential factors were selected, which are easily modifiable parameters of the model. The selected factors are: reservoir storage timing, daily well capacities, recharge capacity, and conservation policy. Each of these has the potential to be upgraded, or for its associated policies to be modified in the future.

To examine the effects of these potential changes, incremental demand runs were again performed with scenario 1B, with system parameters changed as appropriate. Starting demands began at the current level, and ended when a shortage was incurred. Details about these runs and the observed benefits can be found in the following sections.

a). Adjustment to Reservoir Storage Timing

Traditional system rules specify that the reservoirs can begin storing water in April. With that timing adjusted to begin storage in March, substantially more water can be stored during scenario 1B. That quantity is further increased by allowing storage to begin in February, dramatically improving system resiliency for drought management. With reservoir storage beginning in February, the model shows that TMWA can provide water for around 10,000 AF of annual demand more than with April storage (table 4.5); a difference in starting demands from 84,000 AF to 94,000 AF. This is especially

Starting demand level	April Reservoir Storage (Mo 4)	March Reservoir Storage (Mo 3)	February Reservoir Storage (Mo 2)
84K	Conservation maxed (46,639 AF), Emergency Drought Supply Used	M&I water reliant, conservation use specified (8 years, 32,291 AF total)	M&I water reliant, conservation use specified (4 years, 19,880 AF total)
89K	Shortage (12, 149 AF)	Emergency Drought supply used.	Same, but 9 years conservation (41,438 AF total)
94K		Shortage (7,156 AF)	Emergency Drought supply used.
98K			Shortage (11,816 AF)

Table 4.5: Water supplies used for Scenario 1B, different reservoir storage timing

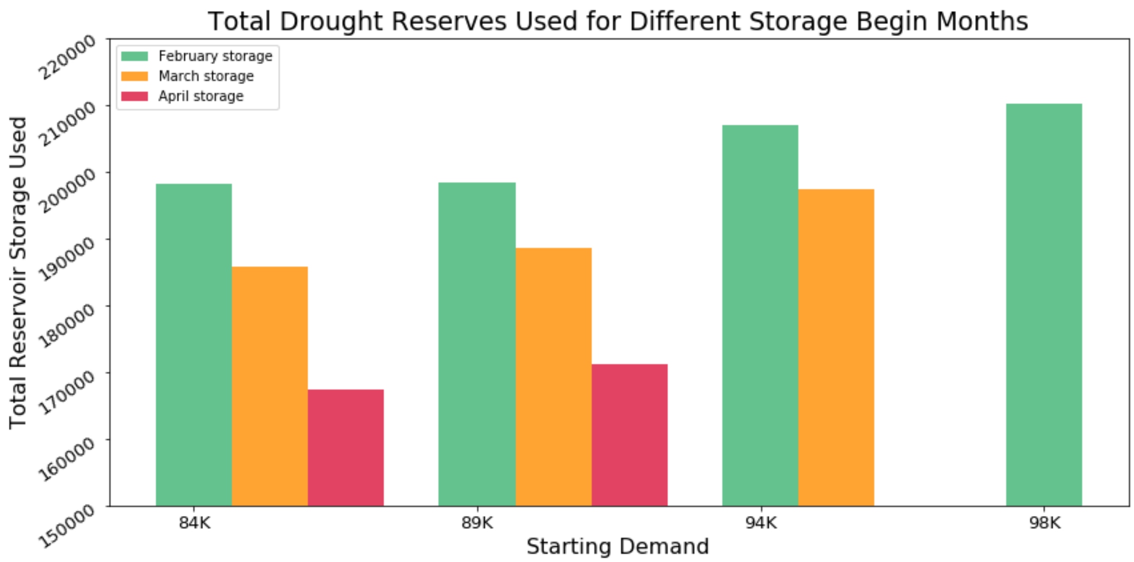


Figure 4.9: Difference in used reservoir water for Scenario 1B, by storage begin month

important, as those starting demands are the difference between modern demands, and a few years into the future. Over the course of the entire 15-year scenario, the total difference is about 30,000 AF of drought reserves which are made available (figure 4.9).

The difference in modeled operations is greatest when reservoir storage changes from month 4 (April) to month 3 (March). Essentially, TMWA gets the most benefit from the extra storage in March, and less (although still substantial) increase in benefit from the extra storage in February. This is due to two causes. In scenario 1B, March is often the last month of high flows and runoff, with April generally drier. Thus, being able to store that March runoff is a dramatic difference for the system. In addition, the reservoirs modelled are relatively small, and can fill quickly. With the reservoirs able to fill in March rather than April, this change alone is often enough for them to reach capacity. Thus, the greatest improvement is achieved by allowing March reservoir storage, but filling the reservoirs in February is also very beneficial for drought resiliency. Although outside the scope of this model, it is likely that a similar adjustment in storage timing would also benefit operations of the other larger reservoirs on the Truckee River.

b). Increase in Daily Well Capacities (64MGD and 70MGD)

The increase in daily well capacities was seen to benefit the system, but has substantially less impact than the results for scenario 1A. This is likely due to the severity of scenario 1B, which hinges around a shorter period of runoff. In 1B, the river provides adequate flows for a shorter period, and so wells must be used to supplement river water more often. As such, the increased number of months in which well use is maximized, often leads towards yearly water rights and annual groundwater permitting being the binding constraint. Thus, improving pumping capacities over a shorter time period (daily) does not improve the situation as much, since yearly limits are already often being met.

Starting demand level	53MGD well capacity (April res storage)	64MGD well capacity (April res storage)	70MGD well capacity (April res storage)
84K	Conservation maxed, Emergency Drought Supply Used (4,167 AF total)	Conservation, Some ASR use (5,638 AF), Emergency Drought Supply Used (3,068 AF total)	Conservation, Some ASR use (7,205 AF), Emergency Drought Supply Used (2,963 AF total)
89K	Shortage (12, 149 AF)	Shortage (5, 072 AF)	Shortage (4,984 AF)

Starting demand level	53MGD well capacity (March res storage)	64MGD well capacity (March res storage)	70MGD well capacity (March res storage)
84K	32,291 AF of conservation specified, no EDS	16,378 AF of conservation specified, no EDS	15,463 AF of conservation specified, no EDS
89K	No ASR use, 3,247 AF EDS	7,658 AF of ASR, 2,292 AF EDS	9,546 AF of ASR, 2,198 AF EDS
94K	Shortage (7,156 AF)	Shortage (4,804 AF)	Shortage (4,730 AF)

Tables 4.6 & 4.7: Difference in modelled water supplies for Scenario 1B by daily well capacity, for both April and March reservoir storage timing

However, improving daily well capacities does help the system some. Increasing well capacities to 64 MGD cuts the amount of conservation required and shortages imposed by around half (Table 4.6 & 4.7). Upping well capacities also allows ASR to be utilized as a water supply, something which is not seen at 53MGD.

Interestingly, the system improves substantially less when increasing daily pumping capacities to 70MGD from 64MGD, and the benefits are barely seen. This suggests that beyond a daily pumping capacity of 64MGD, the max daily pumping rate is hardly a binding constraint for scenario 1B; yearly limits are much more in play. Thus, it would likely be more useful to try and increase groundwater rights and permit amounts, than to increase the daily well capacity past 64MGD.

c). Recharge Capacity Increase

ASR use helps the system more in scenario 1B runs than in 1A. If the model could utilize ASR water more efficiently, then perhaps it would show TMWA operating more reliably under these tougher drought conditions. To test this theory, runs were performed with the daily recharge capacity doubled from 20AF/day to 40AF/day (6.5MGD to 13MGD).

Even with well daily capacities at 70MGD, this change has little effect on drought reliability. Sources of supply are virtually the same as model runs performed with the normal recharge capacity, and the system does not gain any extra resiliency. Daily well capacities, combined with annual groundwater rights and permits, are the real limiting factors on ASR use within the system. Currently, recharge capacities are more than ample for recharging substantially more GW than could ever be extracted. Even with 70MGD well capacities, the model still shows an excess of water being recharged, compared to what could be withdrawn. The only benefit to increased ASR capacities, is that the model shows nearly twice the total recharge occurring. Thus, this upgrade would be useful for improving aquifer health, and increasing groundwater quality. Even in tough drought conditions, enough water comes down the river during winter months for an increase in recharge to occur.

d). Conservation modifications

The goal of these runs was to determine what changes in conservation policy might be the most useful, and to what extent. First, incremental demand runs were performed with conservation forced at 15% rather than the usual 10% (with water cutbacks requested at the same time). To further examine conservation actions and benefits, runs were also done with the timing of requested cutbacks modified. This involved one series with conservation policy beginning a month earlier, and another lasting a month later. Full results from these policy tests are discussed further below.

d1. 15% conservation request

For conservation forced with 15% cutback requested, TMWA can supply water under scenario 1B conditions at greater demands. With this change in conservation policy, all model runs show the utility effectively providing water at the next higher tier of starting demand level. In addition, when a shortage occurs, the modelled amount of shortage is

Starting - Ending Demand Level	April reservoir storage		March reservoir storage	
	10% conservation	15% conservation	10% conservation	15% conservation
84K – 98K	Emergency Drought Supply Used (4,167 AF total)	98,247 AF TROA M&I water used	114,186 AF TROA M&I water	79,002 AF TROA M&I water used
89K - 101K	Shortage (12,149 AF)	Emergency Drought Supply used (2,890 AF)	No ASR use, 3,247 AF EDS	96,591 AF M&I water used
94K – 104K		Shortage (7,467 AF)	Shortage (7,156 AF)	Emergency Drought Supply used (2,890 AF)
98K – 107K				Shortage (2,161 AF)

Table 4.8: Water supplies for Scenario 1B with 10% conservation compared to 15% conservation

less than what would have been previously seen (Table 4.8). This policy action is about as useful as adjusting the allowed timing of reservoir storage (see previous results).

Conservation use is an effective tool for the utility, because it strategically reduces demands during months when river supplies are low and demands are high. This is especially useful for scenario 1B, where there is virtually no water for many of the summer months. Thus, further reducing demands during these dry periods is very effective, and its benefit is obvious. It is likely that adjusting conservation amounts to 20% would show similar positive results, and that any modelled increase in requested conservation would do the same. However, the feasibility of these requests must be taken into consideration. There will be a point at which the utility can no longer increase the requested conservation amount, and expect to get that amount from its customers. The customers will simply not be able to reduce use any further. This is likely above the modelled 15%, but is something that must be considered. Ultimately though, determining that threshold is outside the scope of this model.

d2. Adjustment to conservation timing

Despite snowmelt and runoff occurring earlier in the year for scenario 1B, having conservation start one month earlier made no difference in drought resiliency for the utility. The only impact on results was that river flows used to meet demand, were lessened. However, having conservation last a month longer did increase TMWA's ability to supply water through scenario 1B. When shortages occurred, the amount of shortage was generally reduced by at least 50% with this change (table 4.9). This is a substantial benefit for a minor policy change.

In drought years, and especially for scenario 1B, the fall months are often the driest. River water supplies are virtually nonexistent, but demands can continue to be substantial even into October. It is also likely that the growing season could become longer with the warmer conditions of Scenario 1B, however these potential effects to customer demands were not analyzed. Regardless, adjusting this timing helps TMWA to manage its resources better during those months. Conversely, even in the tough drought conditions of scenario 1B, there is enough river water to meet demands in the spring.

Starting Demand	Reservoir Storage = March		
	Original Conservation	One month earlier	One month later
84K	No EDS	No EDS	No EDS
89K	EDS (3,247 AF)	EDS (3,247 AF)	EDS (402 AF)
94K	Shortage (7,156 AF)	Shortage (7,156 AF)	Shortage (2,607 AF)

Starting Demand	Reservoir Storage = April		
	Original Conservation	One month earlier	One month later
84K	Emergency Drought Supply (4,167 AF)	Emergency Drought Supply (4,167 AF)	Emergency Drought Supply (1,506 AF)
89K	Shortage (12,149 AF)	Shortage (12,149 AF)	Shortage (6,150 AF)

Tables 4.9 & 4.10: Difference in modelled water supplies for Scenario 1B with adjusted conservation timing, April and March reservoir storage timing

It's not exactly clear when the effects of summer conservation policy begin to fade. For example, if TMWA works to reduce water use early in the summer by advertising for a 10% cutback, do its customers think that conserving water is still necessary in September, October, or November? It's difficult to quantify the exact effects of these conservation programs, and it may be the case that the effects of conservation are in fact still seen in October. Regardless, if TMWA were to put effort into extending the time of conservation, the model shows that policy would be most effective for the fall.

e). Best Case Operations

A final series of runs was performed for Scenario 1B, with daily well capacities at 70MGD, reservoir storage beginning in February, conservation at 15%, and conservation lasting through October. Since increasing ASR capacities was not shown to improve system resiliency, those parameters were left the same. The goal was to determine the maximum demand which might be served under these hydrologic conditions, with the most beneficial system upgrades implemented and combined.

Starting Demand	TMWA Water sources
84K	Reservoir POSW maxed, 6.2K AF ASR, 7K AF of conservation (2 years)
89K	8.6K AF ASR, 21K AF of conservation (3 years)
94K	11.8K AF ASR, 43K AF of conservation (5 years)
98K	15.1K AF ASR, 63K AF of conservation (7 years)
102K	20K AF ASR, 73K AF conservation, 2K AF of Emergency Drought Supply
104K	Conservation and ASR Maxed, 6K AF of Emergency Drought Supply
107K	Shortage Incurred (2,953 AF)

Table 4.11, water supplies for 1B runs with system optimized

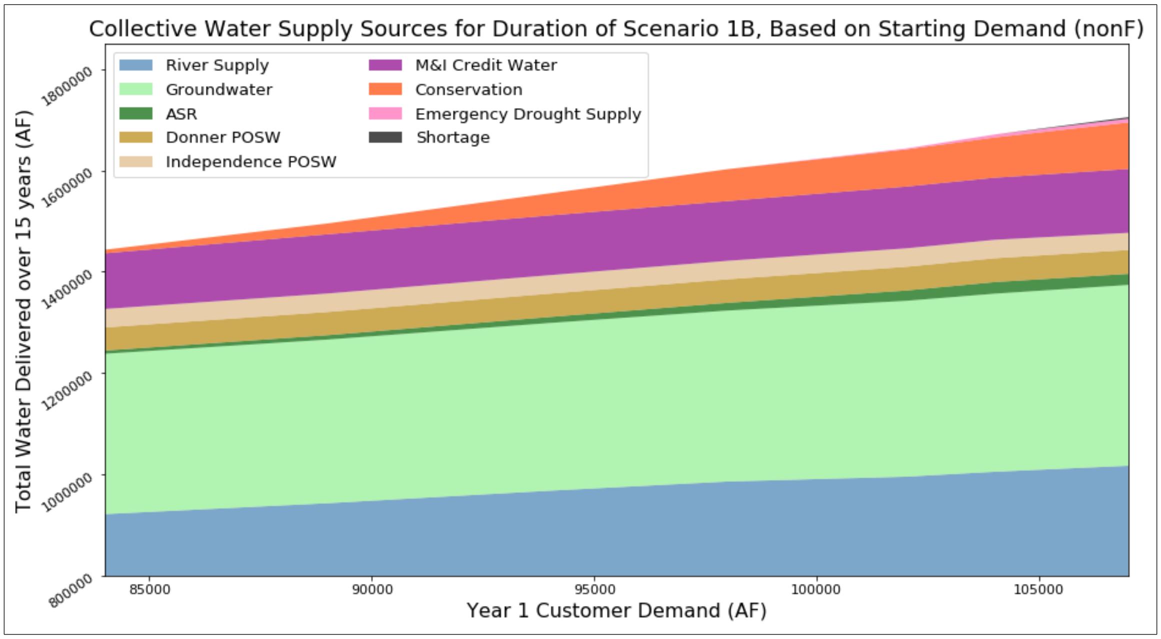


Figure 4.10: Water supplies for 1B runs with system optimized, increasing customer demands

Results show TMWA being able to supply water up to a starting demand of 104,000 annual AF (table 4.11). At this level, the utility is completely reliant on TROA credit water supplies and drought supplies as specified in the operating agreement. Having conservation be 15% also helps offset a substantial portion of total demand, and is critical towards the model being able to solve without shortage. While these results don't show the utility being able to supply water up to 119,000 AF of demand as specified in TROA, they are certainly an improvement over other 1B runs.

4.5 Implications for planning and improvements

a). Climate Change Impacts

Results of the model suggest that at current demand levels, TMWA can adequately manage its water supplies for a near "worst case" drought and climate change scenario (1B), and provide water to its customers. With increased demands however, management becomes substantially more difficult, and the utility is less resilient to climate change. Further actions will be needed if TMWA expects to reliably supply water under future customer demands and hydrologic conditions.

The difficulties in management are predominantly due to a modelled shift in the timing of runoff, and not because of any change in the overall quantity of water available. For both scenarios 1A and 1B, the total amount of water flowing downriver is similar. The main difference is that for scenario 1B, more water becomes runoff during the winter, and the period of higher flows ends about a month earlier. Summer flows are also lower, for a longer period of time (one to two months more). It is these very dry months that stress the system the most, as peak customer demands also occur in the summer. This difference between available river supply and customer demand is what ultimately dictates the amount of drought reserves needed. As that difference increases, which is expected with climate change and seen in scenario 1B, it becomes more difficult to provide an adequate amount of water to customers.

To further compound these difficulties, the earlier runoff times seen in Scenario 1B make reservoir storage less efficient. Due to flood storage requirements, traditional operations specify keeping space in the reservoirs until late in the spring. As a result, by the time reservoir storage can begin under climate change conditions, much of the available water has already moved downstream. The reservoirs are not able to store the limited precipitation that falls, and drought conditions are worsened as a result. For a system like the Truckee River, where reservoirs are linked to almost all the river flow and TROA regulations revolve around available water (Floriston rates, credit water, etc.), efficient

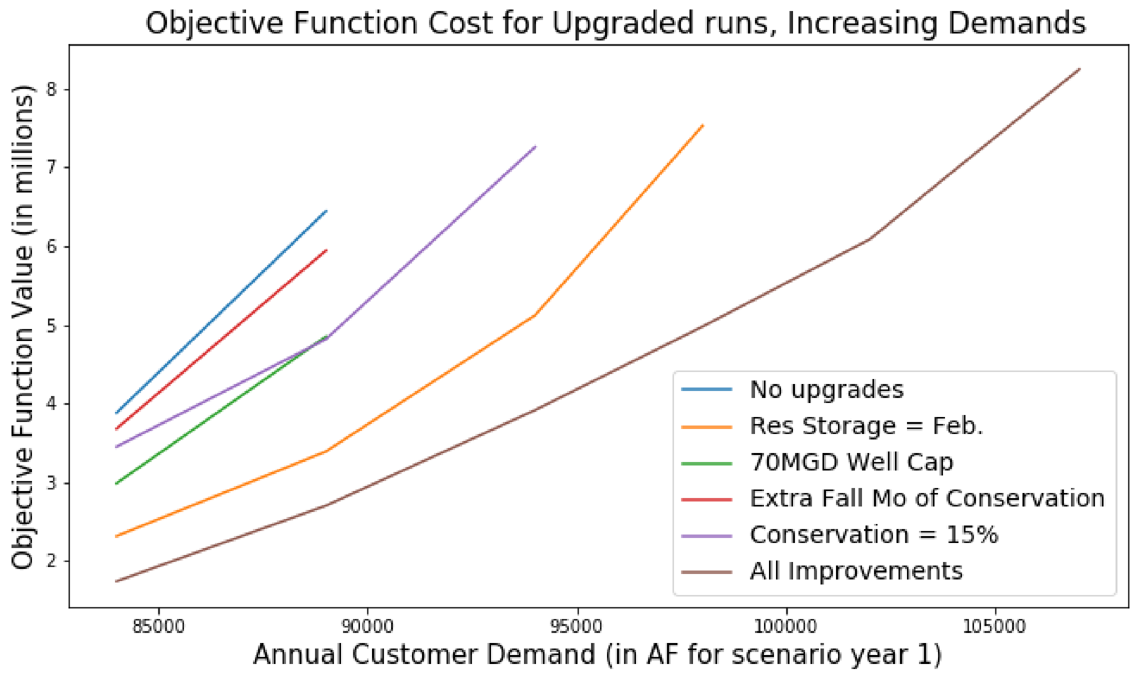


Figure 4.11: Objective function values for different upgraded runs, Scenario 1B, increasing demands

reservoir operations are a necessity. Adjusting the reservoir storage time to begin earlier in the year, was the biggest single factor shown to help operational resiliency under these scenarios (figure 4.11).

Increased reservoir evaporation rates are another potential impact from climate change, although this increase is not as detrimental to water resource management as the shift in snowmelt timing. To further understand the impact of the modeled increase in reservoir evaporation, two model runs were performed with scenario 1B river flows but scenario 1A evaporation rates. These runs were performed under current customer demand conditions (84k AF annual starting demand), and near future customer demand conditions (89k AF annual starting demand). The difference in results was minimal, with both runs showing a total increase in available drought supplies of around 1,000 AF, for the entire 15-year period. Thus, the projected increase in evaporation does influence available water supplies, but that effect is relatively small. Rather, the change in runoff timing due to increased temperatures is a much larger and more severe impact on the system.

b). Suggested System Upgrades and Policy Changes

The DSS proved to be an effective tool for drought planning, easily accepting different inputs, and outputting management strategies for each scenario and given conditions. Through this work, it has become apparent what capital improvement projects (CIPs), policy changes, and system upgrades might be most useful for drought resiliency. Some of these changes can be seen in figure 4.11, which shows the associated objective function value (non-monetary) for model runs of scenario 1B with different system improvements. The objective function value essentially correlates to difficulty of operation for the utility, with lower values representing greater ease of management and vice versa. Thus, the model runs which have lower objective function values, are those with modifications that are the most beneficial to the utility.

As discussed above, the most beneficial single change to operations is an adjustment of reservoir storage timing. Allowing the reservoirs to store water earlier in the year, dramatically helps with drought resiliency. Increasing the daily well pumping capacities also helps substantially with drought resiliency, allowing more groundwater to be extracted during the few extremely dry summer months. In addition, an increase in well capacities makes ASR extraction a viable water source, whereas it currently is not. As it stands now, limited well capacities do not make it practical to ever exceed yearly groundwater rights and extract water that has been recharged by the utility. With daily well capacities increased to 70MGD, annual water rights and permitting begin to become the limiting factor, and ASR can be used. However, the regulations of Order 1161 begin to limit total groundwater and ASR extraction as well. As such, increasing pumping capacities beyond 70MGD is less beneficial to the system.

Conservation policy is another resource the utility could possibly explore for greater drought resiliency. Under some conditions, such as those seen in Scenario 1B, a water use cutback of 15% was shown to be highly beneficial. Even greater cutbacks could potentially be used to lessen demand in extreme drought conditions. Asking for cutbacks to remain in place until later in the year, is also beneficial to the system. This increase in conservation duration could be especially useful if warming temperatures extend the growing season. Currently, TMWA's drought response plan is more than adequate for introducing conservation measures and reducing water demands. However, under future demands and drought conditions, asking for an increase in water conservation might be the simplest solution to avoid a water shortage.

V. Conclusions

Overall, the DSS is a useful tool for drought resiliency planning. It can highlight limiting infrastructure and policies, recognize optimal operations under difficult drought conditions, and determine some hindrances and impacts from climate change. For long term planning, this is an excellent tool which can be used to evaluate any number of potential factors. The model can also be easily modified for further testing, future analysis, or potentially for other water systems. Given a reasonable means to estimate hydrologic conditions and system parameters, the same modelling method could be applied for any utility or resource management agency. Through the mathematical LP setup, the DSS is quick to solve and mathematically efficient. It can be easily understood through the graphical user interface, and is relatively simple to rewrite and modify. The potential applications of this method are nearly limitless.

5.1 Suggested Improvements and Other Potential Water Sources

For the TWMA system in particular, the model identified what CIPs, policy changes, and system upgrades might be the most useful for drought resiliency. This was accomplished through stress testing under very extreme drought conditions (Scenario 1B), in which the system was “broken” for the purpose of performing a sensitivity analyses. Given the very severe hydrologic conditions modeled in Scenario 1B, the DSS shows that TMWA is challenged to provide adequate water for customer use. To accommodate this, the most beneficial single change to operations is an adjustment to the allowed timing of reservoir storage. Allowing drought reserves to begin accumulation in March or

February, rather than April, is extremely helpful for drought resiliency. Increasing the capacity of TMWA's production wells also helps substantially, allowing for increased use of available groundwater supplies during the extremely dry summer months which accompany a drought. An increase in pumping capacities would also allow TMWA to utilize its recharge water (ASR) in a more efficient fashion. With the current well capacities, ASR operations are more useful for maintaining aquifer health, and that water is never extracted for the purpose of drought resiliency. Although increasing well pumping capacities would be a useful upgrade, the DSS suggests that this upgrade would become substantially less useful above a daily capacity of 70 MGD. Beyond that point, annual water rights and permitting begin to become the limiting factor. TMWA could potentially upgrade its ASR capacities to recharge more water into the aquifer, but annual pumping quantities specified by Order 1161, limit the total extraction of many (but not all) TMWA wells. Thus, the model shows that it would be most beneficial to upgrade those wells which are not limited by Order 1161. TMWA does in fact have unused groundwater rights for many of these wells (Table 5.1), and could potentially use those groundwater systems to a greater extent.

Water conservation is another avenue which was identified to help with drought resiliency. As would be expected, increasing the requested customer cutback amount is seen to be beneficial under scenario 1B. If greater cutbacks could be achieved, this policy would always help the utility manage through very dry conditions (and could be used as a last-minute resort). Asking for cutbacks to remain in place until later in the year, is also beneficial to the system, and could be even more useful if warming temperatures extend the growing season. While asking for an increase in water conservation might be the simplest solution for avoiding a water shortage, it does incur a cost to the utility. Increased cutbacks could also potentially lead to a phenomenon known as demand hardening, in which customers are unable to conserve more water because they have already cut back substantially. As such, it would likely be more prudent to focus on CIPs and system changes (as mentioned above), than to rely on an idea of increased conservation for drought resiliency. Given the projected timeframe of Scenario 1B (years 2050-2070), it does seem likely that system improvements could occur before then. Thus, it is more interesting to look at water conservation in the context of Scenario 1A. Results suggest that a 10% cutback, as currently specified in TMWA's drought response plan, is more than sufficient to deal with the drought conditions presented in that scenario. In fact, water conservation actions are not even needed, and drought reserves alone are sufficient to meet monthly demands. However, asking for water conservation allows for increased recharge activities, more available reservoir storage, and generally more flexibility in operations. In short, TMWA's drought response plan is shown to be more than adequate under current and near future conditions.

In addition to the suggested improvements and upgrades listed above, there are several other water supplies which could potentially be used in extreme drought conditions, but have not been included in the model (Table 5.1). These water supplies include both annual resources such as additional creek water and groundwater, as well as "last resort" supplies which are stored in some of the regional lakes and reservoirs. As mentioned above, groundwater supplies which are not limited by TROA and Order 1161 might be

Table 5.1: Additional Water Supplies

Water Source	Amount	Comment
Independence Lake (drawdown from below rim)	5,000 AF	Specified drought supply water source in TROA
Thomas and Whites Creeks	~3,200 AF/yr (estimated typical conditions)	Obviously less in drought years
Non-TROA constrained GW rights	~10,000 AF/yr	Currently not utilized due to well pumping/other constraints
Sparks Marina	3,000 AF	TROA specified drought supply if necessary
Lake Tahoe (drawdown from below the rim)	121 million AF in total	Last resort water supply if necessary (TROA specifies conditions under which this would be allowed)

the most useful for improving drought resiliency. The utility owns over 10,000 AF of additional ground water rights, which are not being utilized to their maximum potential. Thomas and Whites Creeks are another annual source of water, which have not been included in the model. TMWA owns up to 4,852 AF of water rights on these creeks, which could potentially meet some customer demands if necessary. However, hydrologic conditions on these creeks have not been modeled for the drought scenarios given, and it is likely that they would produce a minimal amount of water under very dry conditions. “Last resort” water supplies mostly consist of standing bodies of water, which could be pumped as a resource if necessary. In the case of an anomalously severe drought (such as Scenario 1B), these could possibly offset a shortage for one or two years as needed. Although unlikely, TROA also specifies that Lake Tahoe water can be pumped from below the rim if all other supplies have been exhausted. If this were to occur (in a worst-case scenario), there is an ample amount of water to meet all customer demands. This would be a dire situation, and is not likely to ever happen, but it is nice to have that water as a security net just in case.

5.2 Climate Change Impacts and Scenarios

Results of the model suggest that at current customer demand levels, TMWA can adequately manage and supply water under the climate change conditions imposed in both scenarios. However, the hydro-climatic conditions of Scenario 1B stress the system substantially more. This becomes an issue with greater customer demands, and further action will be needed if TMWA expects to reliably supply water under similar conditions.

The major difference between the scenarios, is a modeled shift in the timing of runoff due to warmer temperatures in Scenario 1B. In that scenario, more water becomes runoff during the winter, and the period of higher spring flows ends about a month earlier. This results in summer flows which are less, and last for one to two months more. These very dry months stress the system the most, as peak customer demands also occur in the summer. Thus, having more summer months with a lack of river water increases the amount of drought supplies needed, and makes it more difficult to reliably supply water for the whole year.

Increased evaporation rates also have a role on reducing water supplies, although secondary to the effects of a shift in runoff timing. Scenario 1B features slightly less available water (due to reservoir evaporation), and Tahoe falls to its natural rim about a month earlier. For TMWA reservoirs, an increase in evaporation does affect the system slightly, although the impacts are negligible compared to those of earlier runoff. Instead, the most detrimental effects of climate change are related to an inability to capture that runoff efficiently. Due to flood safety requirements, traditional operations specify keeping space in the reservoirs until late in the spring. As a result, by the time reservoir storage can begin under climate change conditions, much of the available water has already moved downstream. As previously discussed, adjusting the reservoir storage time to begin earlier in the year, was the biggest single factor shown to help operational resiliency under these scenarios.

Both scenarios are extremely dry, academic in nature, and have been created to test the limits of our current system. While they both feature plausible drought conditions, the region has not seen a drought of this severity in recorded history. What makes these scenarios so tough is their first six years, which both feature extremely dry years and no break. Historically, we have never seen a drought with six years in a row as dry as those modeled. In recorded droughts, after a couple years the region typically receives a water year that is close to average conditions (although still below), which maintains the drought classification, but does not worsen the situation. With these scenarios, the drought situation continues to worsen for each of the first six years with no let up, creating a very harsh scenario. It is this same concept that dramatically reduced water supplies during the 2012-2015 drought, making that four-year period as severe as the eight-year drought of 1987-1995. By the time these scenarios encounter a less-dry water year (year 7), the modeled conditions are already stuck in a more severe state of drought.

It is therefore important to ponder the implications of these results, and recognize the non-likelihood of such conditions occurring. While these scenarios are excellent for testing the limits of a water system, it may not be ideal to plan standard operations from them. However, it is important to recognize that a drought of the magnitude presented is plausible, and to have a contingency plan in place which could deal with a dry period as such. Associated with the many impacts of climate change, an increase in weather variability is also expected. This may manifest itself in the form of an increase in very wet winters (such as that seen in WY 2017), and also longer and more frequent droughts. Thus, although we have not historically seen a drought of the severity modeled in these scenarios, we may be experiencing an increase in the likelihood of one occurring. Unfortunately, such factors are difficult if not impossible to quantify.

One upside to an increase in weather variability, would be an increase in very wet winters. In the record year of 2017, controlled storage in Lake Tahoe filled completely, and over 1 million AF of water traveled down the Truckee River (enough to fill the controlled storage in Tahoe an additional 1.5 times). In the last 50 years, we have seen five water years of similar (although lesser) magnitude. These years sometimes occur together (such as 1982 and 1983) but often stand alone, and generally happen every 12-15 years. In section 5.1, "last resort" water supplies are discussed, which would be utilized on a small-scale basis if absolutely necessary. Were the region to experience a drought as severe and debilitating as Scenario 1B, one very wet year could easily bring enough precipitation to refill the reservoirs, and make up for any "last resort" supplies which had to be extracted.

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