

PLAYING THE ODDS: PROBABILISTIC SUPPLY AND DEMAND MODELING

Todd S. Pickton¹ and Darren Thompson²
BBC Research & Consulting
3773 Cherry Creek North Drive
Denver, CO 80210

ABSTRACT

Prior to the passage of the Edwards Aquifer Authority Act in 1993, water resource planning for the San Antonio Water System (SAWS) was a relatively straightforward endeavor. Today, in light of new regulatory restrictions on pumping from the aquifer, required cutbacks during drought and the development of an active water market in the Edwards region, SAWS' planning has become considerably more complex.

SAWS currently faces two different types of uncertainty in making short-term water resource decisions. First there are the conventional risks that confront many water utilities. Weather may impact both the supply of water available to SAWS and the demands of SAWS customers. Unexpected commercial, industrial and residential growth may place added demands on the system. SAWS also faces several more unusual sources of uncertainty. The timing and extent of regulatory pumping limitations has been, until recently, highly uncertain. SAWS does not know for sure when new non-Edwards Aquifer water supply projects will come on line. The new short-term water leasing market for the Edwards Aquifer benefits SAWS, but also complicates its planning.

Faced with these challenges, SAWS seeks to make short-term water resource decisions that will minimize the risk of shortage while placing as little financial burden on SAWS customers as possible. To assist in making these decisions, SAWS asked BBC Research & Consulting to develop a probabilistic short-term supply and demand model. This model uses Monte Carlo modeling techniques to carry out thousands of simulations and determine the probability distributions surrounding monthly supplies and demands. The model captures the interrelationships between supplies and demands; for example, the likelihood that dry weather conditions that limit supply may also increase demand. In the end, the model allows SAWS to look at the odds of a water shortage, and the probable magnitude of that shortage, under any combination of short-term water resource decisions.

SAWS currently uses the model in several ways. The model assists SAWS in evaluating and providing input on rulemaking options under consideration by the Edwards Aquifer Authority. The model also helps SAWS decide how much water to lease each year, and what terms it needs, from the Edwards Aquifer water market. The model will also aid in the system integration of SAWS' new aquifer storage and recovery project and other non-Edwards Aquifer water supplies. Finally, SAWS uses the model to gauge how changes in the timing of new water resource projects will affect its ability to meet customer demands into the future.

¹ Director, BBC Research & Consulting

² Planner, San Antonio Water System.

KEYWORDS

Risk analysis, uncertainty, water resources, planning, Monte Carlo simulation, water supply reserves, level of service reliability.

INTRODUCTION

The uncertainty surrounding SAWS' short-term water resources planning has dramatically increased over the past decade. Before the passage of the Edwards Aquifer Authority Act in 1993, SAWS primarily faced two risks: drought affecting the yield of the Edwards Aquifer, its sole water source at the time; and customer water demands above projected levels due to such events as drought and unexpected population growth.

Following the Edwards Aquifer Authority Act and the Edwards Aquifer Authority (EAA) becoming operational in 1996, SAWS' water supply risk increased in several ways:

- The EAA instituted a permitting process for the aquifer that left SAWS unsure about the amount and timing of long-term pumping reductions (resolved in December, 2003);
- Short-term pumping reductions were required during critical periods, defined by various index well levels on the aquifer and spring flows dependent upon the aquifer; and
- Quarterly aquifer pumping budgets were developed, reducing the ability of SAWS to shift pumping between seasons.

The potential reduction in SAWS' Edwards supplies led SAWS to start developing supplemental supplies. These supplies bring their own types of uncertainty, including timing and success of development, system integration, average yield and susceptibility to drought.

Faced with these challenges, SAWS seeks to make short-term water resource decisions that will minimize the risk of shortage while placing as little financial burden on SAWS customers as possible. Key questions SAWS must address include:

- What is the optimal size and structure of SAWS' water supply reserve?
- How much Edwards water should SAWS attempt to lease from irrigators and what lease term best fits SAWS' needs?
- Which operational scenario best integrates SAWS' Aquifer Storage and Recovery (ASR) project into SAWS' system?

BACKGROUND

SAWS' planning is driven by uncertainty, beginning with water demand and its primary water supply, the Edwards Aquifer.

Water Demand Uncertainty

The amount of water use per customer in SAWS' service area can vary considerably between years depending on weather conditions and addition of new large water users. SAWS' customer growth is also highly variable.

Recent changes in SAWS' water demand projections proved a good illustration of the uncertainties surrounding water demand. The TNRCC develops the water demand projections used by SAWS. Prior to 2003, these population projections were based upon service area population counted in the 1990 Census. New projections based on 2000 Census data show slower growth for the City of San Antonio area. This significantly affected SAWS' planning for future water supplies.

Because SAWS is now using a demand forecast based on slower population growth, there may be a greater risk that SAWS has under-projected future water demand. The history of past projections demonstrates that they will never be completely accurate. One large industry such as a Toyota plant located in the San Antonio area could dramatically change future population and water demand. SAWS' goal is to be prepared to accommodate future growth, even if not all of this growth is anticipated in the most recent State forecasts.

Uncertainty of Supply

SAWS is considering many distinct types of water supply projects across several river basins. Each of these supplies faces uncertainties.

SAWS' primary source of water is the Edwards Aquifer. If the stars were to perfectly align in 2004, SAWS could pump over 220,000 acre-feet per year from the aquifer. However, it is likely that SAWS will face something short of these maximum Edwards supplies:

- SAWS' supplies from the Edwards Aquifer are reduced when aquifer levels drop below specific triggers. SAWS' allowable pumping can be cut by 15 percent or more, with little warning.
- The amount of Edwards pumping rights SAWS has through leases or purchases from local irrigators varies from year to year.
- SAWS' Edwards supplies change with new rules promulgated by the Edwards Aquifer Authority (EAA). Under the new rule issued in 2003, SAWS' permit is split into two parts, with the "junior" rights only available to SAWS when aquifer levels are extremely high. These junior rights comprise about 11 percent of SAWS' total Edwards supplies. As this will probably not be the last rule to change SAWS' available supplies from the Edwards Aquifer, SAWS also faces a risk of supply reductions from future EAA rules.

SAWS also has a portfolio of new water supplies intended to replace lost Edwards supplies, provide some insurance against drought and meet growing water demand. A supply currently online is the Trinity Aquifer project, which produces up to 5,000 acre-feet per year of supply for the northern portions of SAWS' service area.

SAWS' new Aquifer Storage and Recovery (ASR) project will mitigate some of the supply risk concerning the Edwards Aquifer. This project will store up to 22,500 acre-feet of any unused Edwards supplies in the Carrizo Aquifer in a recharge site in southern Bexar County. During times of plenty, SAWS is not able to consume all of its allotted Edwards water rights. The ASR project will allow SAWS to store some unused Edwards water and withdraw it when needed. Because this is a new type of project, there are a number of uncertainties concerning storage and delivery of this water. (SAWS has also acquired up to 6,400 acre-feet per year of Carrizo production with this project.)

The Western Canyon project will use Canyon Lake supplies to serve portions of northern Bexar County. It is being developed by the Guadalupe-Blanco River Authority (GBRA) and various smaller cities located in Bexar, Comal and Kendall counties. This project will deliver up to 8,500 acre-feet of water to SAWS by 2005 and have a longer-term yield of 3,950 acre-feet. SAWS recently benefited from an unexpected opportunity to acquire more of these supplies when a water utility dropped out of this project. Some residents around Canyon Lake are attempting to block project construction.

The Carrizo Aquifer (Gonzales County) project will be a series of wells in Gonzales County producing up to 25,000 acre-feet from the Carrizo Aquifer. Although this project is scheduled to come online in late 2007, it is still only in the concept study phase. Pipeline routes, water quality compatibility tests, pump tests, hydrologic modeling and other issues related to the success of the project are still to be determined. Risks also include concerns over unknown future groundwater regulation. The local groundwater water district is still developing rules and regulations for withdrawal and export of water from Gonzales County.

The Lower Guadalupe Water Supply Project (LGWSP) is a 94,500 acre-foot water supply project being developed in cooperation with SAWS, the San Antonio River Authority (SARA) and the Guadalupe-Blanco River Authority (GBRA). Water will be taken from the Guadalupe River near Tivoli. Groundwater from the Gulf Coast Aquifer will make up for water lost during drought. The LGWSP, scheduled to deliver water to SAWS by 2011, is early in its planning stage. The Conceptual Delivery Study is analyzing potential pipeline routes, treatment plant locations, storage locations, and diversion facility configurations. A number of studies will evaluate any impacts to the bay and estuary. These potential environmental impacts could affect the viability, configuration or yield of the project.

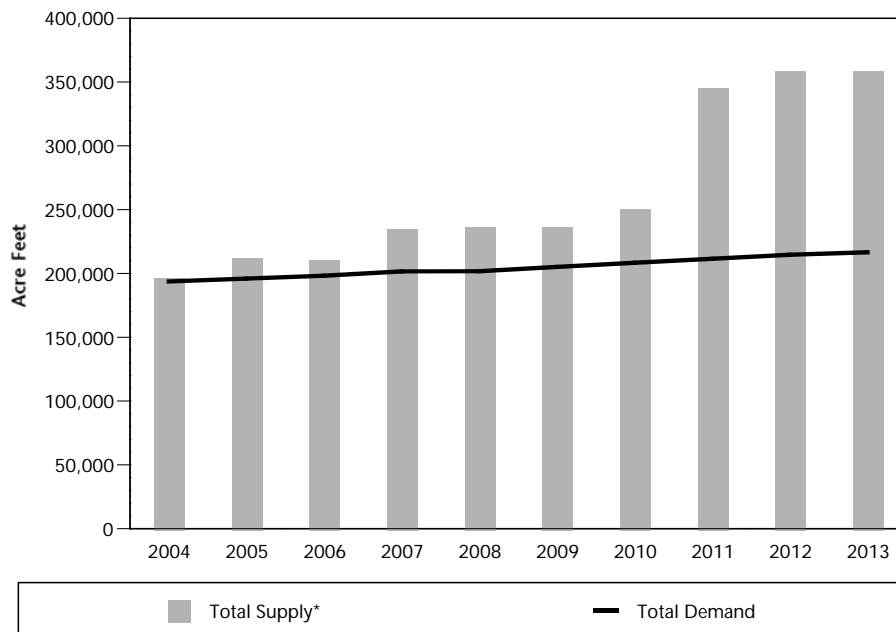
SAWS' Edwards Aquifer Recharge Initiatives project involves water retention structures placed on the recharge zone of the Edwards Aquifer to create additional aquifer recharge during periods of heavy rain. The EAA will grant SAWS water rights for the amount of additional water recharged into the aquifer. These structures may be built by 2012 with a projected yield of 13,451 acre-feet. However, these structures could reduce flow into the Nueces River and might impact supplies in City of Corpus Christi reservoirs. The recharge structures are currently included in a U.S. Army Corps of Engineers feasibility study.

Supply and Demand in the “Close-to-Perfect” World

The following graph shows bars for SAWS’ short-term water supply projects and a line for projected water demand. Demand is shown as a given, with no uncertainties (a perfect world). The bars showing supply assume Edwards pumping with a critical period reduction of 15 percent (a less-than-perfect world, but could be worse). For purposes of this graph, other sources of supply are assumed to come online as planned, with no changes from expected yields and no bumps in the road to development. In other words, the graph portrays a perfect world for these new supplies.

The graph shows enough water to meet demand through 2013 if all of these assumptions hold. The balance of this paper discusses how SAWS plans for a not-so-perfect (real) world.

Figure 1 - SAWS Short-Term Supply and Demand



****Total Supply includes 15% reduction in Edwards Aquifer Supply during Critical Period Management.***

Source: SAWS, 2004.

Figure 2 shows the available sources of supply for SAWS and the projected date that these supplies become available.

Figure 2 -SAWS' Available Supplies through 2013

<i>Supply Project</i>	<i>Projected Delivery Date</i>	<i>Yield</i>
Total Edwards Supply (2004)	Current	228,148
Trinity Project	Current	5,000
ASR Project	2004	22,500
Carrizo (South Bexar County)	2004	6,400
Western Canyon	2005	8,500
Carrizo (Gonzales County)	2007	25,000
Lower Guadalupe Supply Project	2011	94,500
Recharge Initiatives	2012	13,451

Source: SAWS, 2004.

METHODOLOGY

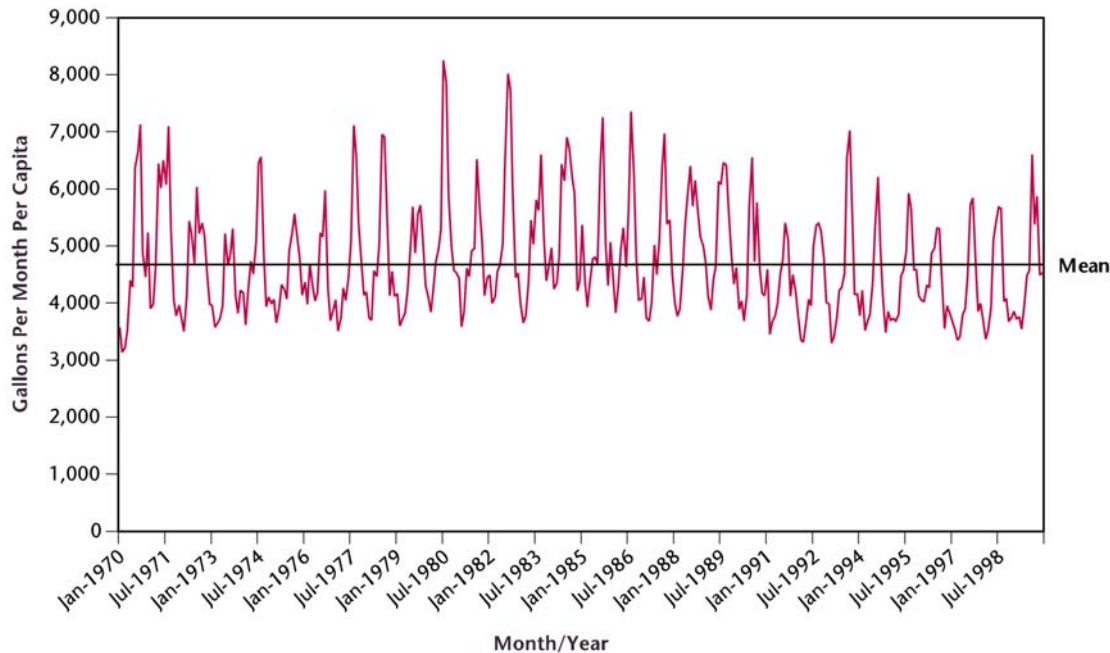
The best way to envision how we modeled many different types of uncertainty in demand and supply to replicate a “less-than-perfect” world is to imagine a large casino with many different roulette wheels. To add glamour, we will place our casino in Monte Carlo, steps away from sunny Mediterranean beaches. We will also compress time, allowing us to give each roulette wheel a million spins and still get to the beach. Instead of casino chips, the product of our roulette wheel spins will be a graph showing the probability of future water shortages for San Antonio. (Although these are all the images necessary for our description of methodology, if you wish to add scenery from James Bond films, you are free to do so).

Modeling Uncertainty in Water Demand

SAWS' model independently considers the two major components of variation in water demand: (1) uncertainty in monthly per capita use and (2) uncertainty in annual population growth (or decline). We have many roulette tables for monthly per capita use and a single roulette wheel for population growth.

Figure 3 shows SAWS' historic monthly water use per capita from January 1970 through December 1999. Although there is a regular pattern of low water use during winter months and high water use in the summer, some summers saw peak monthly use exceeding 8,000 gallons per person while other summers had peak months well short of 6,000 gallons per capita. SAWS seeks to capture this uncertainty in its water planning. There were smaller but still important variations in per capita use in other seasons that are also modeled.

Figure 3 - Historical Monthly Pumping Per Capita

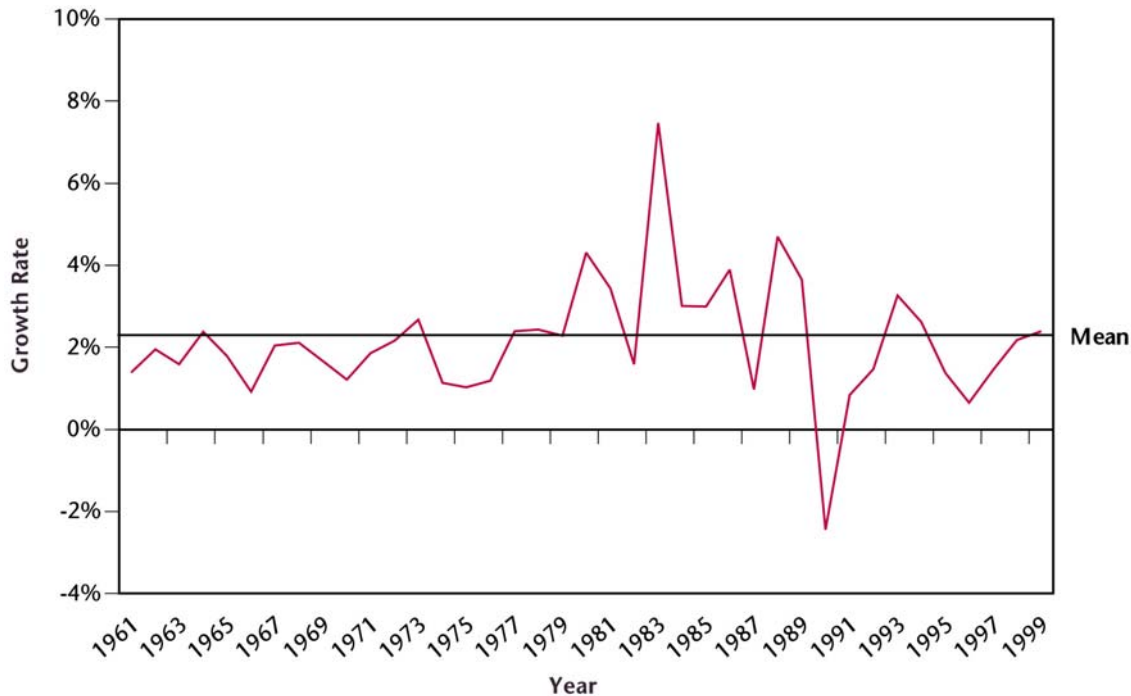


Source: SAWS, 2002.

Six variables help explain variation in monthly per capita water use: the amount of precipitation in that month, precipitation in the prior month, temperature in that month, permanent reductions beginning in the mid-1990s due to conservation, an additional long-term trend toward declining use and the month of the year. We developed a regression equation that related each of these variables to monthly per capita water use. This equation also provided confidence intervals for our estimates of how each factor affects monthly use. Some relationships are very strong, with relatively small confidence intervals. Some are less so, and have relatively larger confidence intervals. These confidence intervals are important in the probability modeling discussed later in this section.

The number of people in SAWS' service area can vary as well. Studying annual change in service area population in the past 40 years shows that population can go down as well as up. The boom years of the early 1980s were followed by slow growth or actual annual declines in population in the late 1980s and early 1990s. Figure 4 illustrates percentage annual change in service area population from 1961 through 1999.

Figure 4 - Service Area Growth Rate, 1961-1999



Source: SAWS, 2002.

The data shown in Figure 4 allow us to develop a probability distribution for average annual growth independent from monthly per capita demand. We have worked out all the values for where the ball can land on our roulette wheel for annual population growth to reflect the past variation - a few spaces for very high growth and a few for population decline, and most with values in between these two extremes.

Modeling Uncertainty in Water Supplies

A wing of our Monte Carlo casino houses the roulette wheels for supply uncertainty. There are two groups of roulette tables depending on type of risk. The first type consider uncertainties in the timing of supplies coming online, the possibility that yields will change because of future regulations, and other impacts. This first group of supply risks also considers the chance that some supplies will simply not be available within the study period because of excessive delays or because project development is terminated.

SAWS assessed the first type of risk without the benefit of any statistical techniques. These risks are simply “educated guesses” about the future of each water supply source made by SAWS staff most familiar with these supplies. Staff held a series of meetings to outline what could go wrong for each project, assess the implications of these events and then place probabilities on these events. These discussions ranged from events that could affect rules governing municipal pumping from the Edwards Aquifer to how confident SAWS was that a new water project would be completed on schedule. This exercise produced a set of alternative futures for each water supply, descriptions of the timing and water yields under each future, and a probability of each future occurring. (SAWS periodically holds additional meetings to update these probabilities and analyze new things that could go wrong.)

Even if the future of each water supply project were known with certainty, and we could eliminate the roulette tables for this first category of supply risk, some water sources face hydrologic risk. For example, yield of SAWS’ Trinity Aquifer project is lower during drought, while the Carrizo Aquifer production portion of SAWS’ ASR project can be increased during drought. Water supplies available from Edwards Aquifer pumping are highly affected by extended drought and low aquifer levels.

Overall Probability of Shortage

In sum, SAWS’ uncertainties group into four categories:

1. Variation in per capita water demand due to weather and other factors.
2. Uncertainties concerning annual population growth within the service area.
3. Alternative futures for each water supply source because of project delays, possible new regulations, and other non-weather risks.
4. Uncertainty about year-to-year yield from a project because of hydrologic risks.

Studying any one of these sources of risk is complex, but how to study them all at once? First consider how to study the combined risks if all of the risks were unrelated. In our casino, we have a roulette wheel for each source of risk. Spin each wheel once, look at the combined outcomes for water demand and water supply, calculate total demand and supply, and you have one data point for the risk of shortage in 2004. Take these results, spin each wheel again, and you have a data point for the risk of shortage in 2005. Repeat the process through 2013 and you have one scenario for the future.

Repeat this process a million times and you have enough combinations of the different risks to form a meaningful probability distribution of supply/demand balance by year. Perhaps 100,000 of the million runs show supplies falling at least 10 percent below demand. SAWS can then plan how to manage this risk.

How realistic is the assumption that all of the risks are independent, that we can spin all the roulette wheels at one time? Not very. This assumption holds true for only the second and third sources of risk described above. For example, it is reasonable to assume that year-to-year

population growth is not affected by the weather. Also, a new regulation affecting a supply source does not depend on whether the SAWS service area population grew by 1 percent or 3 percent last year. However, the variation in per capita water demand and changes in supply yields because of drought are related. This is very important because when it is dry, demand goes up and supply goes down – these interrelated risks increase the chance of severe shortage.

Further complicating the analysis is the fact that weather in one year and the following year are related: dry or wet years tend to be cyclical. Accounting for these interrelationships requires more complex modeling than just operating hundreds of roulette wheels and considering the results before repeating the process.

To examine the odds of seeing particular weather patterns, drought and aquifer levels below certain triggers, we turned to records for the San Antonio area from 1950 through 2002. Each year of data provides information on monthly rainfall, monthly temperatures, whether the aquifer was so low as to trigger mandatory pumping cutbacks (under current rules) and information necessary to determine whether other supply projects would be affected by drought.

Continuing with the casino example, the model, in effect, spins the wheel to get a starting year for a model run and then uses all of the weather, drought and aquifer level information for that year and the following nine years to complete the run. Other roulette wheels take these inputs and consider how the temperature or rainfall in a given month affect per capita water demand. Some of the calculations are more fixed: once the roulette wheel gives a starting year, we simply look up what pumping restrictions SAWS would face given the monthly aquifer levels in that year.

In statistics, this technique is called “Monte Carlo simulation³,” the reason for the Monte Carlo locale for our imaginary casino. The computer model spins the roulette wheels for us if we provide the correct probability distributions for each event, describe their consequences and identify which events are linked and which are independent.

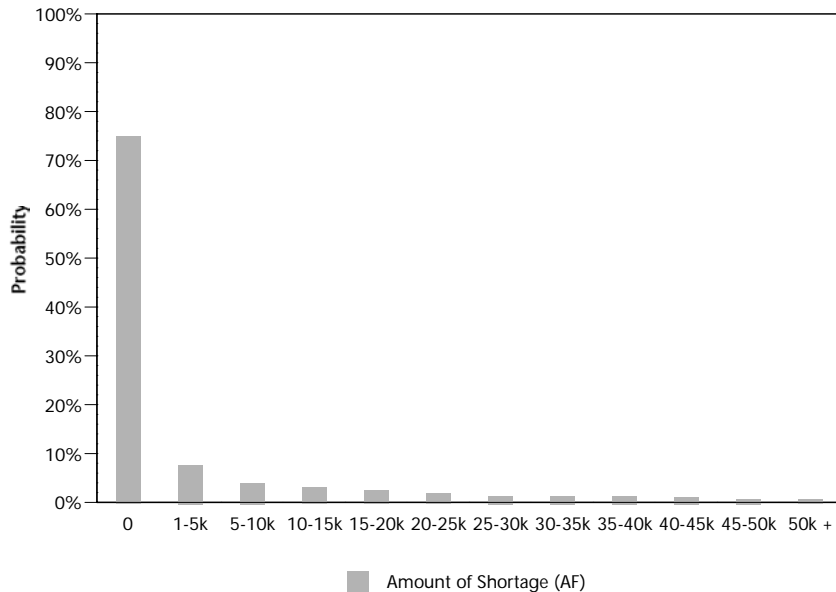
Now, what do all these spinning roulette wheels tell us about the risks of water shortage for San Antonio?

³ See Harberg (1997) for a more detailed discussion and applications in water system reliability.

RESULTS

Analysis of the not so perfect world shows more reliability risk than the simple planning model indicated. The Monte Carlo simulation results show that SAWS faces a 13 percent chance of a shortage greater than 10,000 AF in 2007. Figure 5 provides the estimated probability of various size shortages for the year 2007.

Figure 5 - Shortage Probability in 2007



Source: BBC Research & Consulting, 2004.

A look at the detailed monthly data produced by the simulation model provide some insight into the star-crossed events that could lead to a shortage:

- Adverse weather in 2006 would cause SAWS to enter 2007 with no water stored in the ASR project.
- Adverse weather in 2007 would:
 - Increase customer demands;
 - Curtail Edwards aquifer pumping beyond 15 percent; and
 - Reduce of Trinity project yields by about 50 percent.
- Above-projected population growth would increase water demands.
- Delay of the Carrizo (Gonzales County) project by one or more years could reduce supplies.

IMPLICATIONS

Now that our roulette wheels have stopped spinning, quickly glance back at the year 2007 in Figure 1. SAWS appears to have a cushion of about 33,000 AF if demands are exactly as projected, pumping on the Edwards is curtailed 15 percent and all remaining supplies work as advertised. Weather and aquifer levels similar to those experienced in 1996 might produce this situation on the supply-side. The Monte Carlo simulation provides information about the probability of encountering a worse situation and allows SAWS to examine its supply planning from another perspective.

Another way to state the results shown in Figure 5 is that SAWS can be 87 percent confident of supplying 95 percent of its customers' demands⁴ in 2007. If we examined the results for the year 2012, we would see that SAWS can be 99 percent confident of supplying 100 percent of its customers' demands. This way of thinking offers an alternative approach to setting the appropriate level of supply reserves. Several other water utilities and districts, including the Metropolitan Water District of Southern California (Metropolitan, 2003), use similar confidence goals to establish the level of supply reserves.

Cost and Reserve Level

Why might SAWS not want to take action now to secure enough water to be 100 percent confident of supplying 100 percent of its customers' demands in 2007 (or any other future year)? The primary reason is that level of service reliability comes at a high price. For example, if SAWS purchases an additional 10,000 AF of supplies, there is only a 13 percent chance that they will use all of this water in 2007 and less than a 1 percent chance that they will use any of this water in 2012. This would be expensive water to leave in inventory.

Additionally, SAWS has several things in its favor:

- More information about water supplies and demands will become available prior to 2007;
- SAWS' water leasing program provides it the flexibility to make short-term adjustments to its supplies; and
- Operational changes might improve the service reliability at a lower cost.

Also, SAWS could also examine changes to their operations or try other innovative approaches to meet such requirements. Several of these options are discussed below.

⁴ Unconstrained except for EAA mandated watering restrictions at low Edwards aquifer levels.

Operational Strategies

EAA rules and SAWS' currently minimal storage capacity constrains SAWS from effectively moving the timing of water production between months. It is possible that SAWS' annual supply volume could exceed its annual demands yet production in a given month would fail to meet that month's demands. The simulation results show that this constraint contributes to the lack of service reliability in the short-term.

This result demonstrates the importance of the Aquifer Storage and Recovery project in SAWS' mix of production assets. Further expansion of this project or the development of additional ASR projects may be a cost effective way for SAWS to increase service reliability. Refinements to the storage and recovery schedule for the current ASR project may also yield some benefits.

Another option is to re-examine the quarterly pumping schedule that SAWS submits to the EAA each December. This schedule limits the amount of water that SAWS can produce from the Edwards aquifer if the aquifer level or spring flows drop below certain thresholds. Simulation model results show a risk of shortage during the summer months of 2007 much greater than the risk of shortage during the first quarter of the year. Rebalancing the budget schedule might improve the overall service reliability by transferring some of the summer risk to the first quarter.

Alternative Reserve Strategies

SAWS and BBC Research & Consulting recently examined the feasibility of instituting a dry year option program that would increase SAWS' service reliability in hot, dry years. This program would transfer the rights to pump water from participating farmers to SAWS if the Edwards aquifer dipped below a certain threshold prior to the planting season. There would be an annual payment for participation in the program and an additional payment during years when a transfer took place.

We examined a program that would provide about 11,000 AF during exactly those years that SAWS needs the water. Initial estimates indicate a cost savings of \$6 to \$8 million per year over other alternatives supplying similar amounts of water.

REFERENCES

Edwards Aquifer Authority. (2003) Edwards Aquifer Authority Rules.

Harberg, Robert J. (1997) *Planning and Managing Reliable Urban Water Systems*.

Metropolitan Water District of Southern California. (2003) Report on Metropolitan's Water Supplies, pp.24-25.