Conjunctive Use of Florida's Ground & Surface Waters Solves Source Water Cost Issues

John C. Haapala and Gregory L. Tate

Projected population growth in the coastal plain of Florida's Gulf Coast is driving the need for additional sources of raw water. New source water opportunities are constrained in Southwest Florida by a low-yield shallow aquifer, a regulatory-restricted deep but more prolific aquifer, and surface water sources with small tributary areas that have high minimum flow level requirements.

Surface water flows in the region typically exhibit both large seasonal variations and highly variable average annual flows, with wet years having flows of up to 15 times the flow in dry years. Long-term flow records show periods of essentially no flow available for diversion to a new water supply for several months at a time.

The Peace River/Manasota Regional Water Supply Authority commissioned a source water study in the Upper Myakka River and the Shell and Prairie Creek watersheds. Study outputs included the location and size of off-stream reservoirs needed to harvest water from these watersheds. A reservoir operation study model calculated the required reservoir storage sizes to provide a range of system yields based on stream flow records, required minimum instream flows, and pumping capacity assumptions. The need for 100-percent reliability of water supply delivery was assumed. This article will focus on one potential reservoir site and diversion point on Prairie Creek in Southwest Florida.

With only small amounts of groundwater inputs used conjunctively with the surface water, reservoir sizes were reduced by over half with resultant cost savings. Pumping and transmission sizes were similarly reduced. The groundwater contribution proved to be critical because of a combination of highly variable natural flows, with the majority of flow reserved for instream uses, and the capture of high surface water flows necessarily limited by pumping of diversions to an off-stream reservoir.

A stochastic hydrologic analysis was performed to generate 1,000 traces of equally probable long-term surface water time-series flow data. The reservoir yield analysis of the stochastic hydrology further indicated the water supply yield reliability benefits of conjunctive use.

This finding provided for the first time a basis for placing a dollar value on conjunctive use in Southwest Florida and can provide the impetus for proceeding with these watersheds for source water. This article should be of interest to those involved with developing new water supply yields or firming up existing yields where conjunctive use of groundwater is possible.

Alternatives and costs for potential raw water reservoir storage sites were evaluated within the study watersheds. During this first phase, a step-wise screening process was used to evaluate and rank 19 potential reservoir sites. The result was a list of six potential reservoir sites that were evaluated further in Phase 2.

Reservoir Operation Model

The flows available for diversion are the remainder in excess of the required minimum flows. The flow available for diversion was further adjusted to subtract the full authorized downstream city of Punta Gorda withdrawals.

The flow available for diversion to the new off-stream reservoir represents about 48 percent of the total long-term average streamflow and can be zero for several months at a time because the flows available for diversion are first allocated to the Punta Gorda water supply. Streamflows available for diversion to the potential new reservoir are zero at least 50 percent of the time. In this situation a reservoir is needed to re-regulate the available diversions into a constant, reliable water supply yield.

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A reservoir operation study model was developed to determine the reservoir storage capacities required to develop a range of water supply yields. Direct rainfall on the reservoir and evaporation from the reservoir were included.

The reservoir operation study model determined diversions, reservoir storage, and water supply on a daily basis for 30 water years from 1978 through 2007. Because above-ground, off-stream reservoirs are planned so that flow must be pumped from the intake on the river to the reservoir, all the flows potentially available for diversion can not be utilized for water supply yield because of economic pump capacity limitations.

The diversions to reservoir storage were limited by a given intake/pumping capacity, which was varied to determine the sensitivity to this parameter. The results represent the reservoir storage required to develop the indicated water supply without any shortages over the 30-year period. The water supply demand is assumed to be constant all year.

Water Supply Yield without Groundwater

This section presents results for a potential surface water supply intake on Prairie Creek located downstream from SR 31, without the addition of supplemental groundwater. The drainage area at this site is 239 square miles. The results represent the reservoir storage required to develop the indicated water supply without any shortages over the 30-year period. The water supply demand is assumed to be constant all year.

Results of the study for an intake/pumping capacity of 100 cubic feet per second (cfs)—which translates to 38.8 million gallons

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Table 1: Reservoir Storage Capacity Required to Develop Water Supply Yield – 100 cfs Pumping on Prairie Creek at Potential Intake Site below SR 31

100 cfs Intake/Pumping Diversion Capacity			
Water Supply Yield		Required Reservior Storage	
(mgd)	(cfs)	(ac-ft)	(billion gallons)
2.0	3.09	2,447	0.80
4.0	6.19	4,082	1.33
6.0	9.28	6,769	2.21
8.0	12.38	10,376	3.38
10.0	15.47	13,988	4.56
12.0	18.57	18,871	6.15
14.0	21.66	24,732	8.06
16.0	24.76	32,886	10.72
18.0	27.85	47,885	15.60

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per day (mgd) or 26,930 gallons per minute (gpm)—are presented in Table 1. For example, if a 10-mgd water supply yield is required, a reservoir capacity of 4.56 billion gallons (13,988 acre-feet) is required.

The storage-yield functions presented on Figure 1 show the variation of water supply yield with intake/pumping capacities of 25, 35, 50, 75, 100, 150, and 200 cfs. At the higher water supply yields, it is clear that the intake/pumping capacity must be increased along with storage capacity to provide an effective combination.

An example scenario was selected that would reasonably maximize the yield available from the Prairie Creek watershed at the potential intake site. The reservoir area was assumed to be 1,000 acres with a maximum depth of 19 feet, for a total reservoir capacity of 19,000 acre-feet. With a river intake/pumping capacity of 100 cfs, the reservoir could supply a constant water supply yield of 12 mgd. The simulated reservoir storage variation over time for this scenario is depicted on Figure 2.

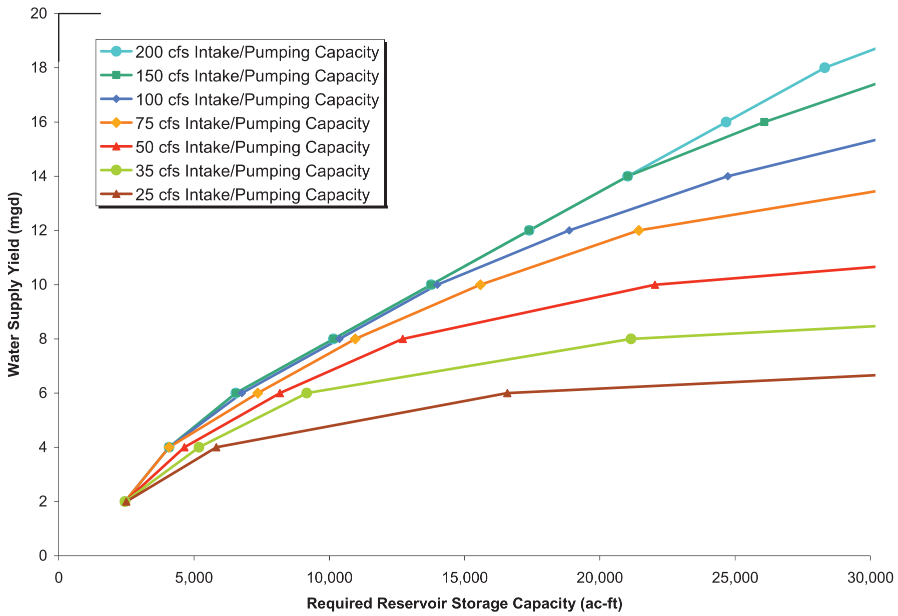

Figure 1: Required Reservoir Storage for Water Supply Yields on Prairie Creek at Potential Intake Site below SR 31

Water Supply Yield with Groundwater

Results in the previous section show that for the Prairie Creek intake site with 100 cfs pumping capacity from the creek, a reservoir with at least 18,871 acre-feet of storage would be needed to deliver a 12 mgd water supply with 100-percent reliability using the surface water source only. Table 2 shows the effects of adding 10 mgd of groundwater pumping capacity, when needed, to a 100-cfs (64.4-mgd) surface water intake pumping capacity, with variations in water supply yield, reservoir size, and the initiation point for groundwater use. The desired operating concept is to maximize

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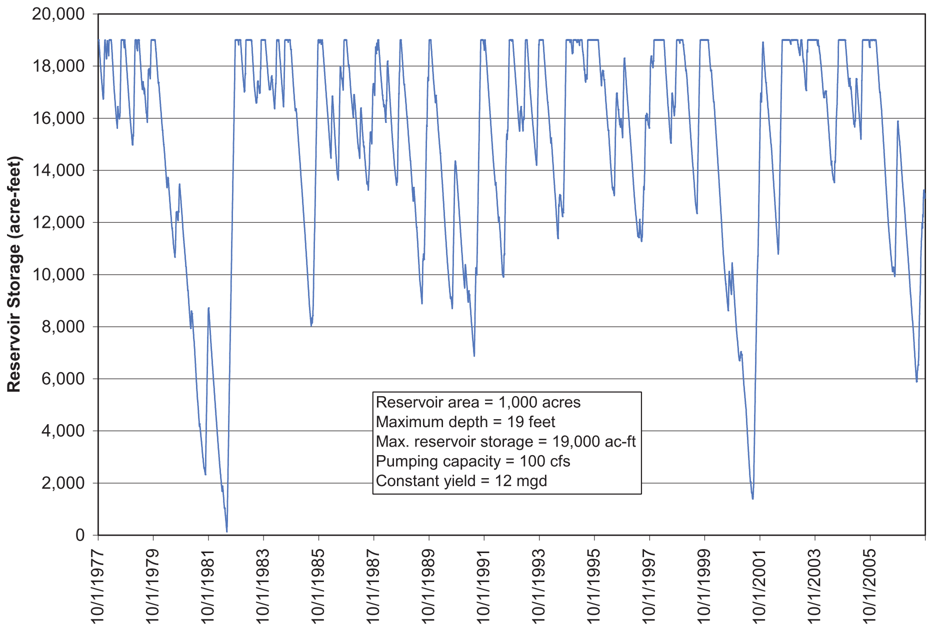

Figure 2: Reservoir Storage over Time for 12-mgd Yield and 19,000 acre-feet Storage on Prairie Creek at Potential Intake Site below SR 31

100 cfs Intake/Pumping Diversion Capacity - 10 mgd Maximum Groundwater Pumping Capacity									
Water Supply Yield		No GW Use		8,000 ac-ft reservoir		10,000 ac-ft reservoir		12,000 ac-ft reservoir	
		Required Reservoir Storage	Average GW Use	Start GW Use at Storage	Average GW Use	Start GW Use at Storage	Average GW Use	Start GW Use at Storage	Average GW Use
(mgd)	(cfs)	(ac-ft)	(mgd)	(ac-ft)	(mgd)	(ac-ft)	(mgd)	(ac-ft)	(mgd)
12.0	18.57	18,871	0.00	1,400	1.36	1,400	0.89	1,400	0.55
14.0	21.66	24,732	0.00	2,800	2.67	2,300	1.79	2,200	1.26
16.0	24.76	32,886	0.00	6,400	5.59	5,100	3.51	4,500	2.62
18.0	27.85	47,885	0.00	-----	-----	-----	-----	9,500	5.63
20.0	30.94	74,870	0.00	-----	-----	-----	-----	-----	-----

Table 2: Prairie Creek at Potential Intake Site below SR 31

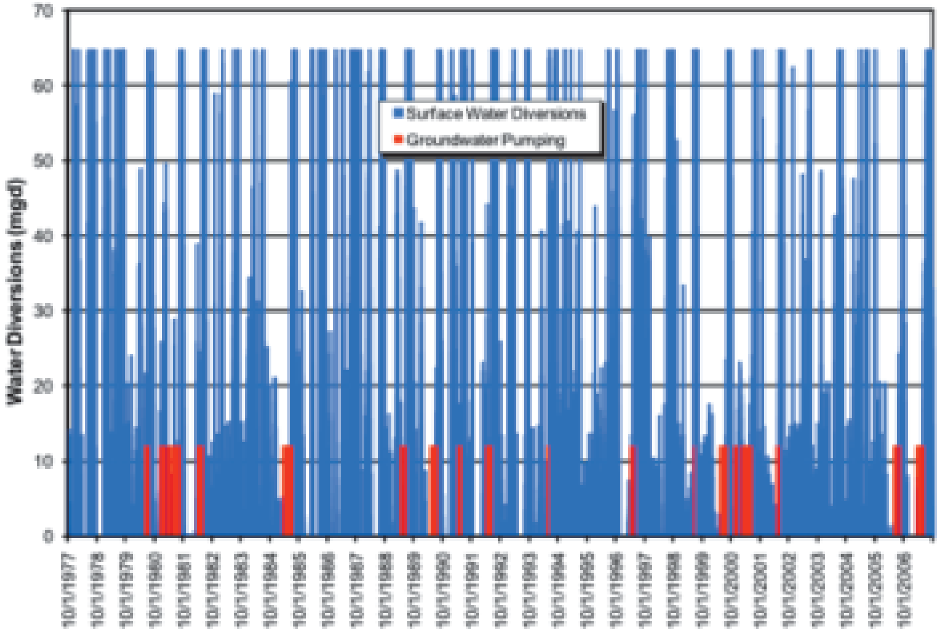

Figure 3: Prairie Creek Reservoir Surface and Groundwater Diversions

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surface water use and minimize groundwater use so that groundwater is used only when reservoir storage is substantially depleted.

Where no values are shown in Table 2, the combination of parameters can not deliver a 100-percent reliable water supply yield. For example, an 8,000-acre-foot reservoir can not deliver an 18-mgd yield with 100-cfs intake pumping and with a maximum of 10-mgd groundwater pumping.

Table 2 shows that by adding a 10-mgd supplemental groundwater pumping capacity, an 8,000-acre-foot reservoir would deliver a 12-mgd water supply with 100-percent reliability. Groundwater pumping would be initiated when reservoir storage dropped below 1,400 acre-feet.

The resulting long-term average groundwater usage would be 1.36 mgd, or only 12 percent of the average water supply yield. The significant benefit would be a 58-percent reduction in the required storage capacity to produce the same 12-mgd water supply yield.

Figure 3 and Figure 4 present results for the same case: an 8,000-acre-foot reservoir with a 100-cfs (64.6-mgd) intake/pumping capacity, a constant 12-mgd water supply yield, and a 10-mgd groundwater pumping capacity that is used to capacity whenever the reservoir storage is 1,400 acre-feet or less.

Figure 3 highlights the frequency and magnitude of the surface and groundwater diversions. Several years may pass between periods of groundwater use, but the 10-mgd groundwater pumping can be constant for a period of a few months. There are some periods when neither surface water nor groundwater diversions are made. These occur during periods when surface water is not available for diversion, but the reservoir storage is above 1,400 acre-feet.

A comparison of Figure 2 with Figure 4 shows that the reservoir storage is at low levels much more frequently for the case with groundwater. Figure 4 shows that the 1,400-acre-foot level (17.5 percent of maximum storage) at which groundwater use begins is reached in at least 50 percent of the years.

A similar level of low storage is reached in only 10 percent of the years for the condition with only surface water diversions. The groundwater supply is an effective buffer to reservoir storage.

Figure 5 shows the monthly distribution of average surface water and groundwater diversions, with groundwater use peaking toward the end of the dry season, as would be expected.

Stochastic Hydrology

Although historic recorded hydrology commonly is used to determine the reservoir storage required to develop a reliable water supply yield, it is known that the historic sequence of recorded flows will not be repeated in the future. The main philosophy behind synthetic streamflow generation is that synthetic data sets are generated that preserve certain statistical properties that exist in the natural hydrologic process (Lane and Frevert, 1990).

Stochastic hydrology is used in design or for operational decision-making. Stochastic hydrology methods were first introduced as a solution to the problem of reservoir sizing. A stochastic analysis using many input sequences of flow yields a probability distribution of reservoir system response (Linsley, et al, 1982). Stochastic hydrology is representative of a prescriptive modeling approach, as opposed to a descriptive approach.

Stochastic hydrology methods are used to generate critical periods of high and low runoff that may not be included in historical records, but which, from the viewpoint of probability theory, could be expected to occur in an actual record of sufficient length. A mathematical model of streamflow is used for generation of stochastic streamflow sequences that are as equally probable as the historic sequence and with essentially the same statistical properties as the historic sequence.

Potential long-term climatic changes are <u>not</u> accounted for in stochastic generation. The long-term average and variability of the stochastic flows will be essentially the same as those statistical properties of the historic flows.

A recently updated computer program called Stochastic Analysis Modeling and Simulation (SAMS) was used to develop the stochastic streamflow values (Sveinsson, et al, 2007). Stochastically generated streamflow values were generated in sets called traces, each having 30 years of monthly values.

It has been found empirically that approximately 1,000 stochastically generated traces are required to define accurately the distribution of storage required to ensure that the water demand will be supplied fully (Burges and Linsley 1971). With 1,000 traces of 30 years each, 30,000 years of synthetic streamflow was used to define the range of possible storage requirements and the position that the storage requirement would have within the range, as determined from the historic hydrology.

Stochastic Yield Analysis

A daily reservoir operations model was necessary to determine the water supply yield and storage requirements accurately at the Prairie Creek reservoir site for several reasons. These include diversions to off-stream reservoir storage with a limited pumping capacity and to determine the required minimum flow levels in the creek.

The monthly stochastic flows were disaggregated to daily flows, based on historic dis-

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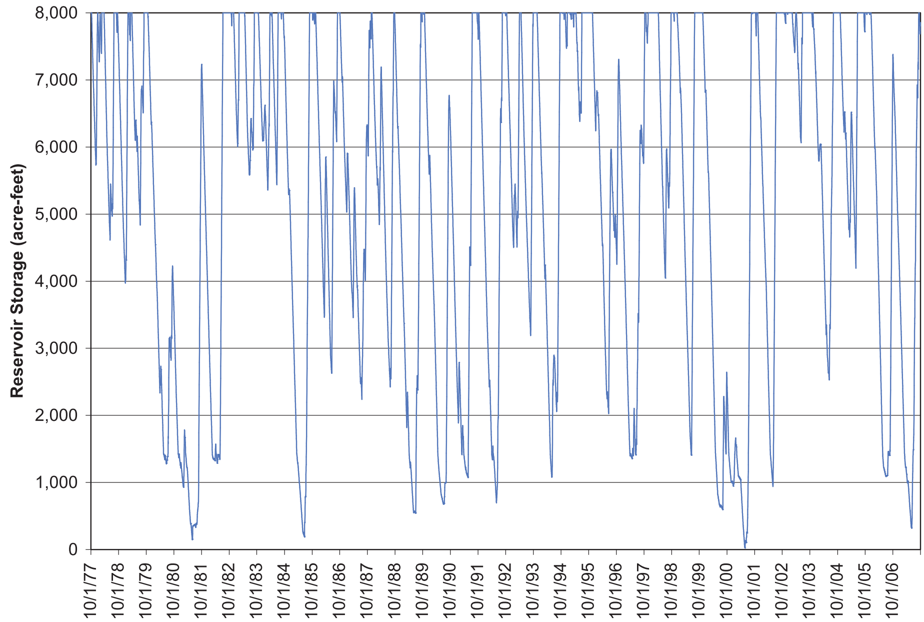

Figure 4: Reservoir Storage over Time for 12-mgd Yield, Conjunctive Groundwater Use and 8,000 acre-feet Storage on Prairie Creek at Potential Intake Site below SR 31

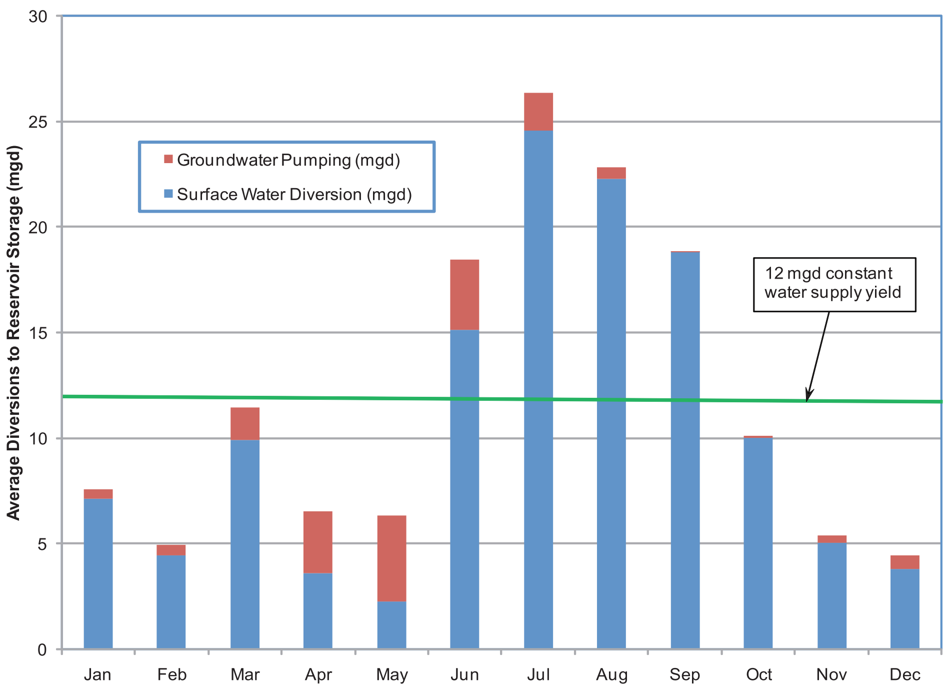

Figure 5: Prairie Creek Reservoir Average Monthly Surface and Groundwater Diversions

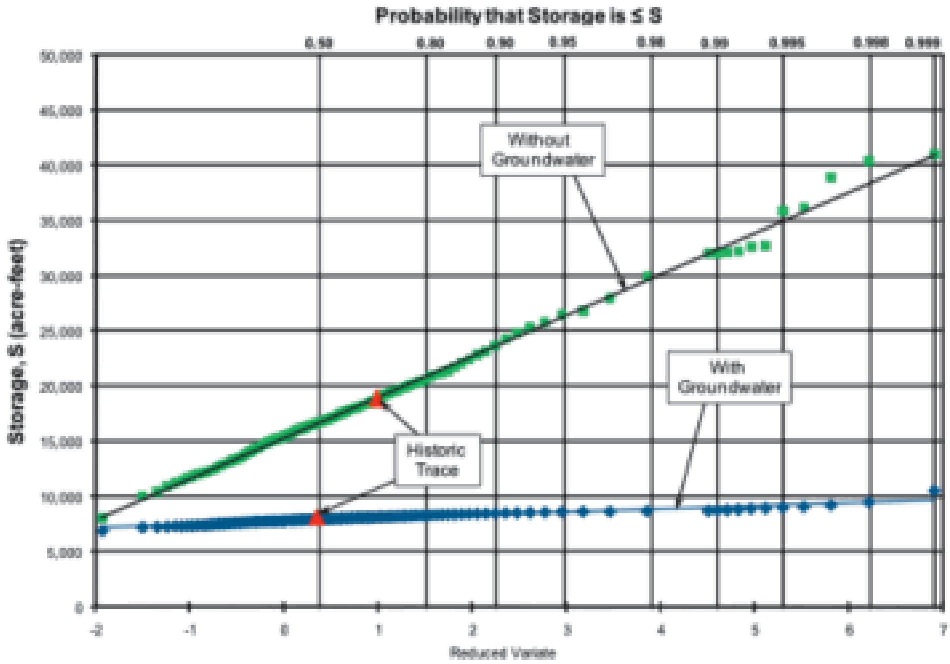

Figure 6: Stochastic Traces Ranked by Storage Capacity on Gumbel Probability Plot

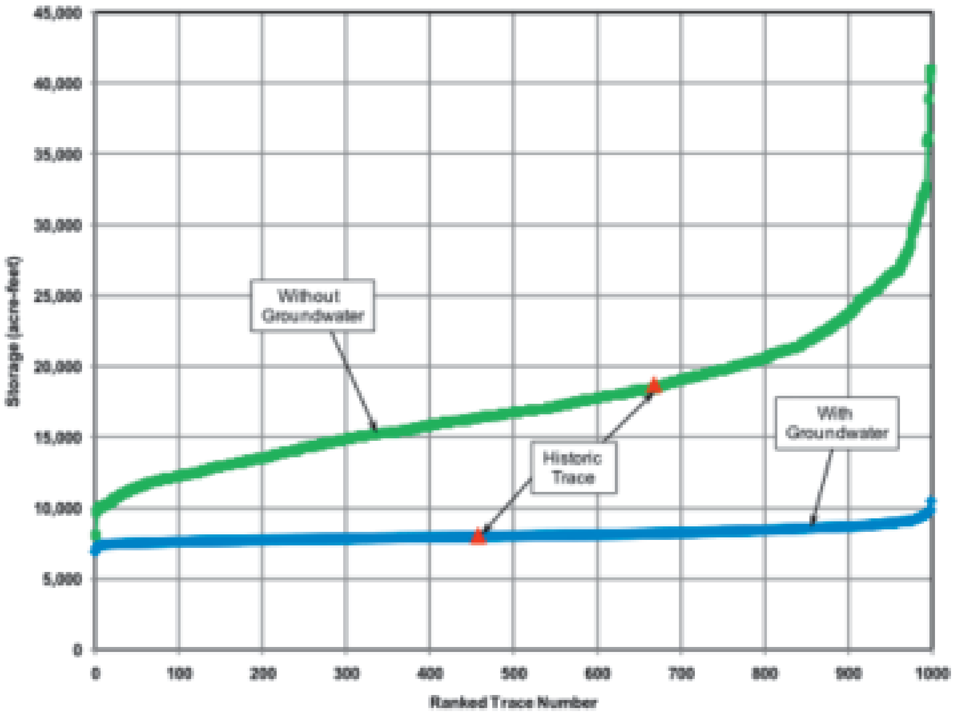

Figure 7: Stochastic Traces Ranked by Storage Requirements

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tributions of daily flows for the same month and similar monthly flow rate. With 10,950,000 days (30,000 years) of data to be processed, a FORTRAN program was developed to process all the stochastic flow data efficiently in the same detail in which the historic daily flow data was analyzed.

The daily reservoir operation model provides summary output for each trace. The run time for the entire 30,000 years with a daily time increment was only about 10 seconds on a standard laptop computer.

The 1,000 stochastic traces were rank-stratified, based on storage requirements determined in the same manner as for the historic hydrology. The numerical rank of a trace refers to the number of traces that require a storage volume less than or equal to that of the trace being considered. For example, the 400th ranking trace requires more storage than 399 traces, but less storage than 600 traces at the given fixed demand level. The entire set of 1,000 storage requirements is considered to represent the probability distribution of storage to deliver a given demand.

It has been suggested (Burges and Linsley 1971) that stochastic hydrology will show that the distribution of required reservoir storage will conform to the extreme value type 1 (Gumbel) distribution. Figure 6 presents a Gumbel probability plot of the distribution of required storage to satisfy the 12-mgd demand without shortage in each of the 1,000 stochastic traces.

Separate distributions are plotted for the surface water supply only and the combined surface water and groundwater supply (every 10th point plotted at the appropriate probability point below 0.99 probability). Based on Figure 6, several observations can be made, including:

- The storages required for the surface water-only case are not only greater than for the conjunctive use case, but the range of potentially needed storages is greater.
- For the surface water supply-only case, required storages for the stochastic traces ranged from 8,079 acre-feet to 41,024 acre-feet, which is a range of 43 percent to 217 percent of the 18,871 acre-feet based on the historic hydrology trace.
- For the combined surface and groundwater supply case, required storages 6,890 acre-feet to 10,519 acre-feet, a range of 86 percent to 132 percent of the 7,977 acre-feet based on the historic hydrology.
- Both of the storage distributions with and without the groundwater supply plot as a nearly straight line on Gumbel probability paper, as expected. This means that the storage distribution satisfies the requirements of the Gumbel distribution.
- Perhaps the most important conclusion from Figure 6 would be that a reservoir designed with both surface water and groundwater supplies would be more reliable in delivering future water supplies from a given reservoir size for the potential range of hydrologic conditions.

A review of groundwater use in the 1,000 stochastic traces showed that the average groundwater use would actually be lower than for the historic trace. In the 1,000 stochastic traces, the average groundwater use was 1.08 mgd (compared to 1.36 mgd in the historic trace), with a range of 2.41 mgd maximum in the 1,000 traces to a minimum of 0.15 mgd.

It is probably easier to understand the relationship of the reservoir storage as designed from the historic recorded hydrology (historic trace) by plotting both the storage requirements and ranks or storage required for each trace on a linear scale (all 1,000 points plotted), as shown on Figure 7. From Figure 7 it can be observed that:

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- With groundwater, the required storage is 7,977 acre-feet, which ranks at trace 460.
- Without groundwater, the required storage is 18,871 acre-feet, which ranks at trace 680.

Although it is a matter of judgment, the reservoirs based on the historic hydrology appear to be reasonably sized with regard to reliability. It would probably be unreasonably conservative to size a reservoir for a drought with a probability of occurrence of 0.0033 percent per year (one in 30,000 years). Conversely, if the goal is to meet the water supply demand fully in every year, then using the minimum storage from the 1,000 stochastic traces would ensure that the goal is never met over a 30-year period.

Measuring the Benefit of a Conjunctive Source Water System

There are at least two ways to measure the benefit of implementing a source water supply based on the findings noted above. The conclusion drawn from this analysis is that the benefits of conjunctive use can be measured in dollars when examined in the way shown above; however, it is also important to mention that there are some obvious environmental benefits to a conjunctive source water system. These environmental benefits have been acknowledged but generally have been understood only on an intuitive level.

Because reservoirs may be disruptive to the environment, any reduction in footprint provides direct environmental benefits. These benefits can be in the form of reduced impacts to wetlands, less disruption of natural surface water flow patterns and surficial groundwater—and, of course, the reduction in the visual impact of a small mountain of reservoir embankment.

Usually, predicting the cost savings resulting from a conjunctive source water system has been more difficult. Engineers, planners, and economists intuitively understand that supplementing groundwater with surface water and vice versa on a seasonal basis results in system-wide savings and greater reliability in the supply, but measuring and predicting that effect has not been easy.

In the analysis above using reservoir operation modeling to size facilities for groundwater and surface-water systems, measurable reductions in facility costs that are created by conjunctive use can be calculated and used in water resource planning and decision making. Using the results of Table 2, a new table can be developed with the costs associated with the reservoir sizes noted and the costs of the needed groundwater system to supplement surface water. Also, using the results from Table 2 and estimated facility costs from the source water study, we can calculate with planning-level accuracy the reservoir costs saved with conjunctive use of groundwater:

For the base case, assume that the needed water supply is 12.0 mgd (average annual basis) and assume also that no groundwater is available. The required reservoir size per Table 2 is 18,871 acre-feet, or approximately 6 billion gallons.

From the source water study we have the total estimated cost of $110 million, including a 30-percent contingency and an allowance for certain development costs. Not included are land acquisition, embankment construction, pipeline construction, wetland mitigation, threatened and endangered (T&E) species mitigation, floodplain mitigation, and indirect costs.

Now assume that a new groundwater source will be constructed and dedicated to providing supplemental water during defined reservoir drawdown conditions. Again from Table 2, for an 8,000-acre-foot or 2.6-billion-gallon reservoir, a groundwater system capable of a maximum rate of 10 mgd would be required, but on a long-term basis, the needed groundwater input would be far less at only 1.36 mgd.

From the source water study, the cost of the 2.6-billion-gallon reservoir is estimated to be $47 million. The cost of a new 10-mgd groundwater supply with manifolded transmission networked to the reservoir system has been estimated by others at $14 million, with the same contingency and allowances.

Considering only the cost of the reservoir and the supplemental groundwater supply, the net savings would therefore be $49 million out of an otherwise $110 million reservoir-only construction project. Similar cost savings can be calculated for the related facilities, such as intake pumping, raw water transmission lines, power costs, operation and maintenance, and utility easements.

Using data from Table 2, similar calculations can be made for various reservoir and supplemental groundwater combinations, which then can be used to optimize system size for the lowest cost.

Note also that while further investigation should be done, several key points became clear following the development of this method:

1. The need for a short-term maximum groundwater pumping rate of 10 mgd does present complications in facility planning, but the long-term average annual rate of groundwater needed is only 1.36 mgd, and it can be argued that this is the real impact to the aquifer on a decade-by-decade basis. Given the large cost savings at stake, it may be easier to justify a higher multi-month or even multi-year cumulative groundwater withdrawal from one or multiple sources when the savings are so large. In other words, with that much money at stake, it is easier to become more creative in how the short-term maximum flow would be provided.
2. The required groundwater input, 10 mgd for the case above, need not be from a new system or new water otherwise introduced into the system. Since the need is much shorter in duration, there may be opportunities to use excess groundwater capacity from one or more existing systems. Options such as re-equipping wells with two-speed motors and use of capacity assigned to peak or maximum-day capacities could be considered.
3. The location of the groundwater input need not be even near the reservoir. In fact, the

groundwater need only be available somewhere within the transmission system, either as raw water to the raw water supply or as treated water to the distribution system.

4. Aquifer storage and recovery could provide a means to further reduce the cost of the groundwater component, provided that the regulatory issues with ASR are ultimately resolved.

Conclusions

The following conclusions can be drawn from this study:

1. Because of highly variable seasonal and annual streamflow, the reservation of a majority of flow for instream uses, and the priority of senior diversions, significant reservoir storage is required to develop constant, reliable new water supply yields in Southwest Florida.
2. Although the possible combinations of surface water diversion rate, groundwater pumping rate, and reservoir storage capacity are virtually unlimited, a likely design case showed a 58-percent reduction in required reservoir capacity when the water supply yield was composed of 88 percent surface water and 12 percent groundwater, rather than 100 percent surface water.
3. Because surface water reservoirs in Florida can be environmentally disruptive, require long time periods for permitting, and carry a high first cost (albeit with a high economy of scale), it is important to consider ways to mitigate these disadvantages. Hybrid systems with various levels of groundwater used conjunctively can help.
4. There are significant quantifiable cost savings that can be associated with the conjunctive use of groundwater and surface water. These savings can help water resources planners make better decisions with respect to water supply facility investments.
5. In addition, large conjunctive use potential savings should help utility planners become more creative with ways of providing the groundwater supplement needed to reduce reservoir sizes.
6. Stochastic hydrology has shown that for the future range of potential streamflow, which will not exactly replicate the historic sequence of flows, the range of reservoir storage necessary to meet the water supply demand fully is much smaller for the combined groundwater and surface water supply case than for the surface water supply-alone case; therefore, the combined groundwater and surface water case provides a more reliable water supply for a given reservoir size.
7. Because the distribution of storages required to meet a given water supply demand conforms to the extreme value type 1 (Gumbel) distribution, reservoir sizes can be selected for any given reliability.
8. The stochastic hydrology indicates that for the reservoir site that was studied, the historic hydrology appeared to result in reservoir sizing that would provide reasonable water supply reliability.

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