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Water resources planning and management at the Salt River Project, Arizona, USA

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Abstract The Salt River Project (SRP) was created in the early 1900s to assure an adequate water supply for its shareholders in the Salt River Valley, Arizona, USA. The straight forward job of storing inflows and meeting demand from a single reservoir system soon became more complex. As the population of the Salt River Valley swelled, additional reservoirs were added to the system, alternative supplies of water were developed, and hydro-power generation became a financial consideration in reservoir operations. Nevertheless, the primary operational objective continues to be the conjunctive management of multiple sources of water to ensure an adequate carry-over supply of water for SRP's shareholders in the Salt River Valley. This objective has traditionally been accomplished by managing the reservoir system as if each time the reservoirs fill to capacity is the beginning of an extended drought comparable to the worst historical drought in recorded history. Over the past 20 years, several subtle yet significant events have taken place which raise concerns regarding SRP's traditional method of water planning and management. Changes in demand patterns as land is converted from mainly agricultural use to urban use, an ongoing drought rivaling the historical drought of record, tree-ring studies suggesting even more severe droughts having occurred in pre-historic times and, the specter of a changing climate due to global warming all suggest that a business as usual approach to water management and planning may no longer be appropriate.

Keywords Conjunctive management · Carry-over water supply · Drought planning · Tree-ring record · Urbanization · Water supply

Abbreviations

CAP	Central Arizona Project
LTDPM	Long-Term Drought Planning Model
PROP	Project Reservoir Operations Plan
SPD	Storage Planning Diagram
SRP	Salt River Project

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Introduction and background

SRP (Salt River Project) is a water provider and an electrical utility in the Salt River Valley, Phoenix Metropolitan Area, Arizona, USA. SRP is a collective name used to refer to two separate entities: the Salt River Valley Water Users' Association, a private company, and the Salt River Project Agricultural Improvement and Power District, a political subdivision of the State of Arizona. The Salt River Water Users' Association was created in the early 1900s to assure an adequate water supply for its, at that time mainly agricultural, shareholders in the Salt River Valley. SRP is one of the primary public utility companies in Arizona. (For a history of the SRP and the two entities it comprises, please refer to http://www.srpnet.com/about/history/timeline.aspx.)

SRP operates seven dams, 248 groundwater wells and, 1,300 miles (2,092 km) of canals and laterals. SRP delivers annually on the average 950,000 acre–feet (1,172 million cubic meters) of combined surface and groundwater to its shareholders and contracts holders. As the Salt River Valley has urbanized (its urbanized form is referred to as the Phoenix Metropolitan Area), SRP has transitioned from providing water to agricultural customers to providing water to primarily municipal customers and urban turf irrigators.

Water service area

SRP's water service area in the Phoenix Metropolitan Area (Salt River Valley), Maricopa County, Arizona, is about 250,000 acres (100,000 ha). Lands within the service area have been converted from agriculture to urban use rapidly since the 1970s. By 2008, nearly 90% of the service area was urbanized. (A demonstration of the rate of urbanization in Maricopa County for the last 100 years can be found at the following link: http://www.maricopa.gov/assessor/gis/growthslides.asp .) As the land urbanized, cities in the Phoenix Metropolitan Area built their water treatment plants right along the by SRP operated canals. SRP now delivers most of its water to the municipal water treatment plants.

Most cities have grown beyond the boundaries of the SRP service area. Those cities have access to other sources than SRP water to satisfy the water demand of the developments outside SRP's service area. Those sources include among others Colorado River water, reclaimed water, and groundwater. In a recent paper, Gooch et al. (2007) discuss how SRP changed from being a mainly agricultural water supplier to a mainly municipal water supplier.

Water supply

SRP operates four dams on the Salt River (Roosevelt, Horse Mesa, Mormon Flat and Stewart Mountain) and two dams on the Verde River (Horseshoe and Bartlett). Roosevelt Reservoir, the most upstream reservoir on the Salt River, stores runoff from the Salt River and Tonto Creek. A number of years ago, SRP bought Blue Ridge Reservoir (renamed C.C. Cragin) from Phelps Dodge Corporation. The reservoir is on the Little Colorado River watershed, but water stored in the reservoir is pumped into the East Verde River, which discharges into the Verde River.

All dams were constructed to create reservoirs for water conservation. Total storage capacity (all seven dams) is 2.3 million acre–feet (2,872 million cubic meters) with 0.3 million acre–feet (373 million cubic meters) of storage in two reservoirs on the Verde River. (See Fig. 1.) The dams on the Verde and Salt rivers' are referred to in this paper as the SRP reservoir system. The combined average annual historic inflow is about 1.2 million acre–feet

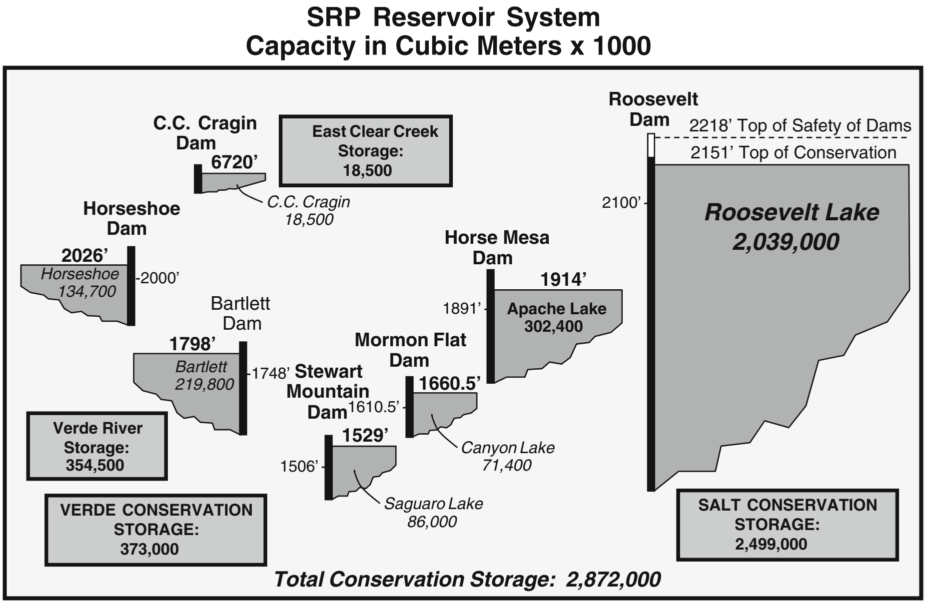

Fig. 1 SRP reservoir system

(1,482 million cubic meters) and the combined median annual inflow is about 0.9 million acre–feet (1,104 million cubic meters). It would take 2 years of average runoff to fill the reservoir system, if no water were released.

Most of the water stored in the by SRP-operated reservoirs comes from snowmelt from the Salt and Verde rivers' watershed. The Verde and Salt watershed is about 13,000 square miles (33,670 square kilometers), and is located in Central Arizona. The Salt River watershed is slightly larger than the Verde River watershed (see Fig. 2). Precipitation on the watersheds is both seasonal and variable from year to year, creating the need for reservoir storage to even out this variability.

In addition to the reservoirs, SRP operates 248 groundwater wells in its water service area. (See Fig. 3.) For water resources planning purposes, groundwater is considered as just another 'reservoir' with an annual maximum capacity of about 325,000 acre–feet (401 million cubic meters). This annual maximum pumping capacity is just over one-third of the annual water demand. A minimum amount must be pumped to reach parts of the canal and lateral system that cannot be served by gravity flow (about 50,000 to 75,000 acre–feet/year, 61–93 million cubic meters).

SRP has a water exchange agreement with the Central Arizona Project (CAP) through which it can receive Colorado River water at the head of its canal and lateral system. This arrangement gives SRP an additional source of surface water. The exchange agreement allows for SRP to receive Colorado River water if the resource is available (certain legal conditions need to be satisfied). SRP can pay CAP back by delivering its shareholders' water to CAP customers on SRP canals (cities with a CAP allocation). Or SRP can buy CAP water under certain conditions with no obligation of delivering shareholders' water to CAP customers.

In the further discussion, the water supply (maximum of 15,000 acre–feet, 18.5 million cubic meters) from C.C. Cragin Reservoir has not been taken into account in the analysis. It is uncertain how much of Cragin's water actually reaches the Verde River reservoirs.

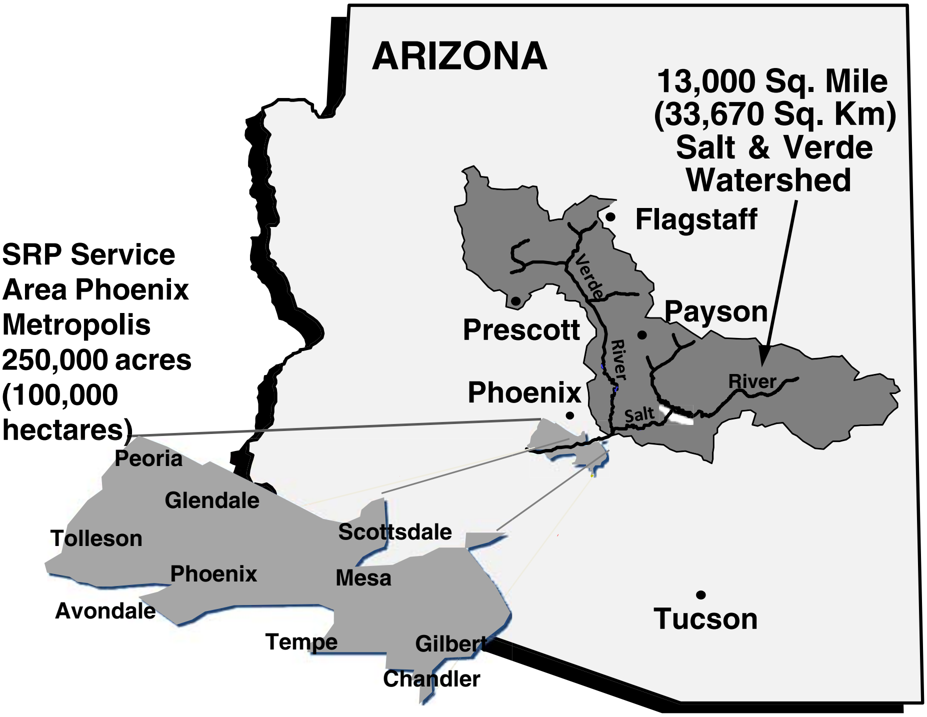

Fig. 2 Salt & Verde Rivers' watershed and SRP water service area

Over the past 20 years, several subtle yet significant events have taken place which raise concerns regarding SRP's traditional method of water planning and management. Changes in demand patterns as land is converted from mainly agricultural use to urban use, an ongoing drought rivaling the historical drought of record, tree-ring studies suggesting even more severe droughts having occurred in pre-historic times and, the specter of a changing climate due to global warming all suggest that a business as usual approach to water management and planning may no longer be appropriate. To address these issues, SRP's Water Resource Operations staff has evaluated the water resource planning process and based on that evaluation changed its storage planning diagram and planning guidelines in January 2008.

In this paper, the authors describe the water resource planning process used by SRP through time from the 1980s through the early 2000s and the analysis performed requiring the water resources planning process to change to deal with the prolonged drought from the tree-ring record. Further analyses were performed to validate the recommended changes in planning guidelines using the prolonged droughts from 800 years tree-ring record and 100+ years of historic record.

Water resource planning process

The primary operational objective of SRP's water resources management is the conjunctive management of multiple sources of water to ensure an adequate carry-over supply of water for SRP's shareholders in the Salt River Valley. This objective has traditionally been

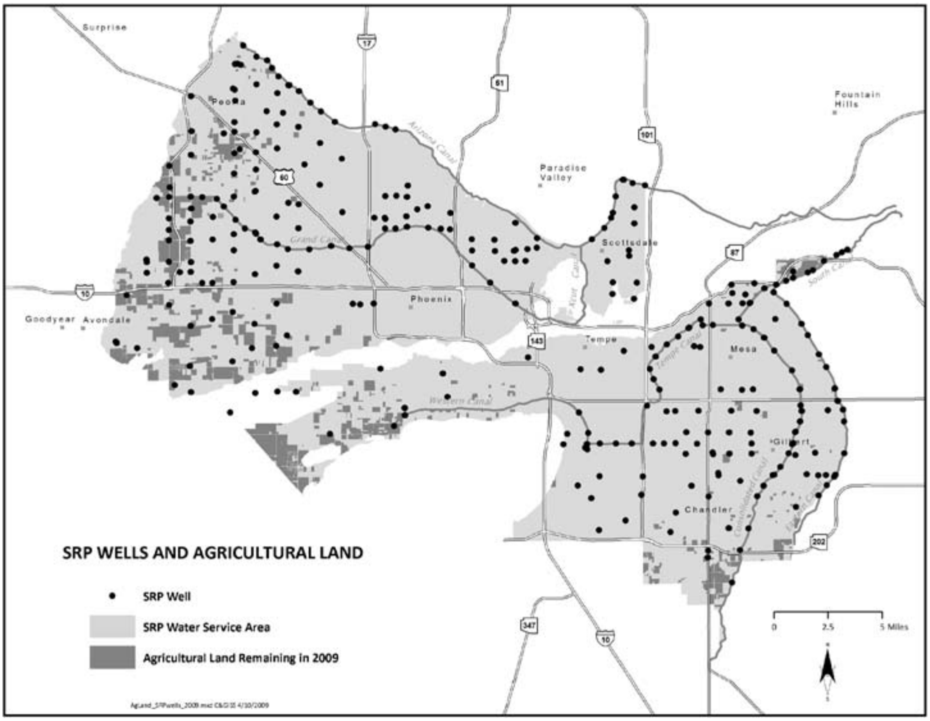

Fig. 3 Wells in SRP water service area

accomplished by managing the reservoir system as if each time the reservoirs fill to capacity is the beginning of an extended drought comparable to the worst historical drought in recorded history. This translates in optimizing water storage in the reservoirs and minimizing the use of groundwater.

SRP annually sets water allocations for its shareholders. The *normal* allocation is 3 acre–feet/acre (9,140 cubic meters/ha). Water allocations consist of part surface water and part groundwater. A reduction or increase in allocation is used in the management of SRP's water supply to affect demand.

Water allocations are conservatively set such that farmers can plan for their cropping pattern and cities can determine what other resources they need to use or buy to meet their customers demand. After the allocation is set, the mix of surface water may be changed, depending on the runoff stored in the reservoirs at the end of the runoff season. Generally, water allocations are not reduced once set, although they can be increased.

The water allocation is set so as to assure an adequate carry-over supply of stored surface water in the reservoir system. This process is accomplished through a relatively simple process utilizing a Storage Planning Diagram (SPD). The original SPD was developed in the 1980s (Fig. 4). The diagram gives the relation between total reservoir storage, inflow, groundwater pumping production as a percentage of demand, and water allocation. The SPD and the critical process it guides had remained unchanged for more than 30 years until recently.

Given current reservoir conditions and projected runoff and demand, SRP makes a Project Reservoir Operations Plan (PROP) with short-to-medium term planning horizon

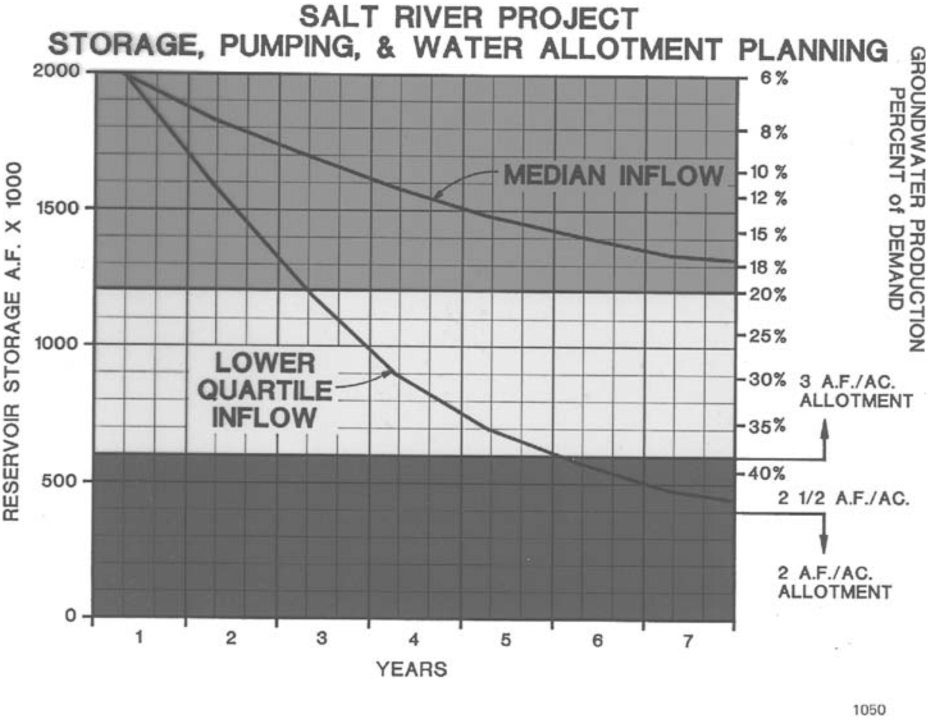

Fig. 4 Storage planning diagram (SPD) 1980s

(6 months to one and a half years). The PROP provides the monthly quantities of surface water releases (Salt and Verde), groundwater pumping, and CAP water (if needed and available and used for the plan to achieve water management goals). Given the quantities of surface water moved through the reservoir system to satisfy the water demand, power operation groups determine the amount of hydrogeneration available. Sometimes, changes in timing of the water releases are requested to optimize hydrogeneration. Since the PROP gives monthly quantities, changes within the month can be accommodated as long as total quantities of water moved or pumped remain the same during that month.

The PROP is regularly updated (up to two times per year if reservoir conditions change) in coordination with five other SRP groups (power and water) involved in the operation of the dams.

Water resource planning in the 1980s

In the beginning 1980s, the following procedure was used to arrive at a PROP. The first step in the process was determining the groundwater pumping goal given reservoir storage at the end of the runoff season, May 1, and assuming median or lower quartile inflows by consulting the SPD (Fig. 4). Monthly quantities of pumping were estimated from 10-year mean monthly pumping. The water order was estimated by looking at the following variables: mean 10-year demand, agriculture irrigation constraints, cropping patterns, conservation programs, cities' use, and canal operational constraints. Once the total demand was estimated, the surface water demand could be calculated by subtracting the groundwater pumping amount. By releasing the majority of the surface water demand from the Salt River Reservoir System during the warmer months (May–September), when both water and power demands are highest, hydrogeneration is maximized. During the winter months (October–April), Salt releases are minimal and the bulk of the surface water demand is met from the Verde River Reservoir System. Because the two reservoirs on the Verde River only have about 13% of the combined SRP reservoir system storage capacity, the planning process must ensure that sufficient water is used from the Verde River reservoirs each year to prevent spilling water the next spring. Hence, the following criteria were used to achieve those goals: a) the Verde system should have at least 100,000 acre–feet (123 million cubic meters) of storage on May 1st each year to adequately supplement Salt releases during the summer; b) there should be 100,000 acre–feet of *available* space in the Verde River reservoirs by December 1st, so as to contain the upper quartile Verde River runoff during the winter and spring; and, c) the probabilities of filling and spilling each system during the runoff period should be as near as equal as reasonable possible on December 1st each year. To meet the latter criterion, it may be necessary to adjust and shift the release amounts from one system to the other. All these operational goals were achieved by doing a number of iterations.

Reservoir operations planning in the mid 1990s

In the mid 1990s, the reservoir planning process started to incorporate more probabilistic factors, such as winter weather forecasts, La Nina or El Nino predictions and other factors deemed important. In Fig. 5, the factors taken into consideration to prepare a PROP are shown.

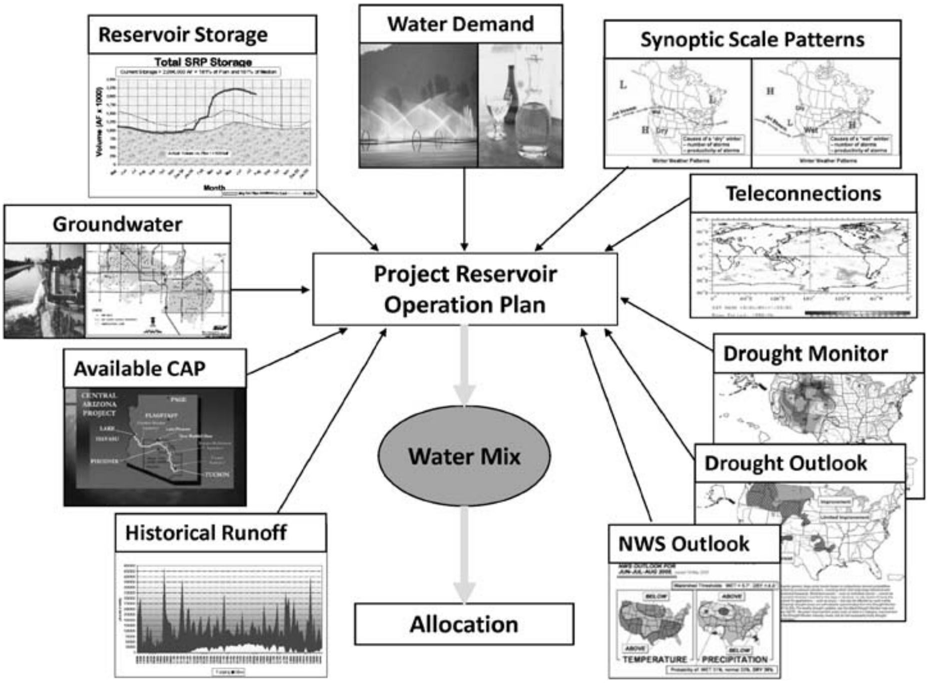

Fig. 5 Project reservoir operations planning (PROP) process 1990s

The PROP planning process was programmed into a spreadsheet. The SPD was changed to reflect reservoir storage fluctuations throughout the year and to include the flow record of the then longest known drought record in the historic record (1898–1904), see Fig. 6. Reservoir storage, while operating in accordance with the SPD guidelines, is shown for median inflows and for the drought of record. The diagram was developed by assuming that each time the reservoirs fill to capacity is the onset of a new drought comparable to the 1898–1904 drought of record. Note that on this diagram, groundwater pumping is shown as a level of pumping in thousands of acre–feet instead of a percentage of demand as in Fig. 4. As reservoir storage declines during the 7-year period, groundwater pumping is gradually increased to maximum capacity and water allocations are reduced. For any given year, total stored water relates to a recommended water allocation and groundwater pumping goal. By adhering to the SPD guidelines, SRP would be guaranteed to weather the worst drought in the historical record without running out of surface water. This planning process was used satisfactorily during the 1990s and early 2000s.

What made SRP review its water supply planning process?

In 2008, Arizona began its 13th year of drought, the longest in SRP history. Until this drought, which started in 1996, the longest drought affecting the Salt-Verde watersheds had been the seven years, mentioned previously, from 1898–1904. In Fig. 7, the total annual inflow into the SRP reservoir system for the period 1889–2007 is shown. The droughts in the beginning and at the end of the 20th century can easily be distinguished from the record.

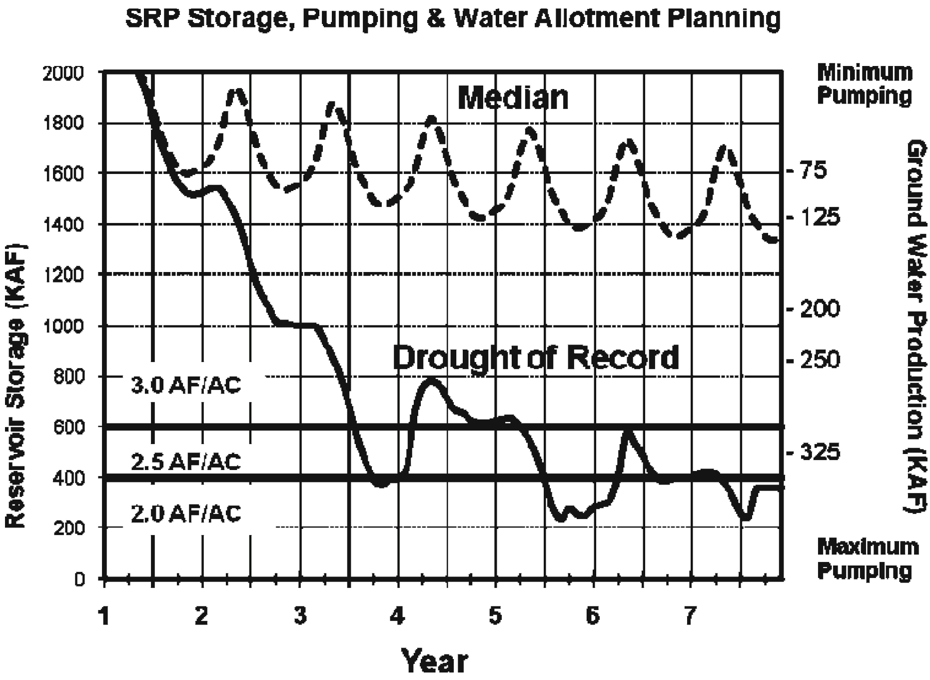

Fig. 6 Storage planning diagram—Mid 1990s

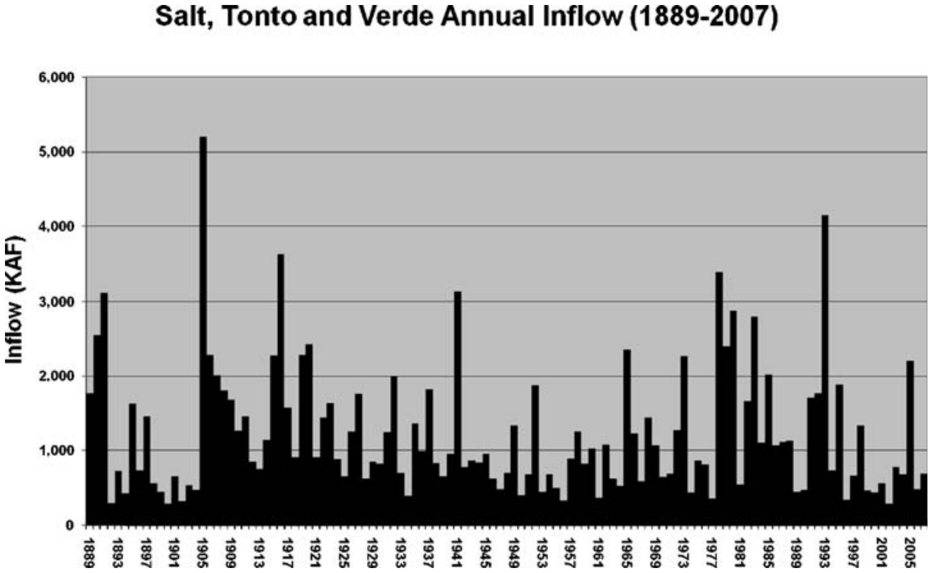

Fig. 7 Total annual inflow for 1889–2007

Actions which SRP has taken to manage the current drought include increasing groundwater pumping to its maximum level, buying or exchanging CAP (Colorado River) water and, a reduction of allocation, along with a water conservation advertising campaign.

If a drought persists, with groundwater pumping at maximum levels and reservoir storage continuing to decrease, the only remaining option is to reduce allocations. Since 1925, annual allocations have been less than the full allocation of 3 acre–feet/acre for two consecutive years five times. Since 1920, allocations have been reduced to 2 acre–feet/acre for two consecutive years only twice: 1947–48 and 2003–04.

SRP has borrowed or purchased, from 1998–2008, 515,000 acre–feet (635 million cubic meters) of water from CAP to keep more carry-over storage in the reservoirs. SRP has no annual CAP allocation but excess Colorado River water was available for purchase during those years.

If not for the excess Colorado River water purchased or borrowed from the CAP, Roosevelt Reservoir would have been close to empty in 2002. Since the mid-1990s, the availability of Colorado River water (via CAP) has made it possible for SRP to maintain full allocations, until 2003–04.

The reduction in allocation did not result in the decrease in demand as one would have expected when the service area was mainly agricultural. On the other hand, after the two years with reduced allocation, it took several years for the demand to come back to the level before the reduction. Several explanations have been theorized, but none of them have been fully analyzed. Following is a list of those possible explanations:

- The water conservation campaign started in the beginning of the 21st century is working;
- Cities having bought and scheduled CAP water deliveries, could not make use of the full allocation in 2005 (after the reservoirs filled);
- Most cities' water use is generally less than the full allocation; or,
- The water users kept on conserving water because the message to the public still was that 'one wet year does not end the drought.

To understand the reason for the decrease in demand, it will be necessary to conduct a separate study analyzing the trends in demands in the Phoenix Valley. From a water supplier view point though, it became important to look how SRP could change the water supply planning principles to maintain carry-over storage for the longest sustained drought over the watershed and maintain its goal of managing shareholders' water resources in an environmentally prudent manner to sustain life and economic growth in the Phoenix Metropolitan area.

Eleven year tree-ring drought

Historical data and statistics

Mean daily flow data of good quality are available for the Salt and Verde rivers and Tonto Creek for the period 1913–present. Monthly mean flow data for the Salt and Verde rivers of lesser quality are available from about 1889–1913 with some gaps in the record. An analysis of historical data from 1914–2006 yields a combined (from Salt plus Verde rivers plus Tonto Creek which discharges in Salt River reservoirs) average annual flow of 1,660 cfs (47 cubic meter/sec) and an annual median flow of 1,236 cfs (35 cubic meter/sec). The earlier data indicates that the 7-year period from 1898–1904 was the most severe drought in recorded history with an approximate average annual flow of 61% of the historical median. The "historical" record is the record of inflows which was actually recorded and published. "Pre-historic" refers to the period before the historical record began.

Tree-ring research

In 2005, the Laboratory of Tree-Ring Research at the University of Arizona issued the final report for an SRP sponsored research project with the primary purpose to assess the likelihood of simultaneous drought on both the Upper Colorado and Salt/Verde watersheds (Hirschboeck and Meko 2005). The study also provided an extended reconstruction of river flows on the Salt and Verde rivers, dating back to around 1200 A.D. The major conclusion of the study was that severe drought on the Colorado River watershed was likely to coincide with severe drought Salt and Verde rivers' watershed (flow values in two basins were significantly correlated in 444-year record; simple correlation was r =0.599). In addition, the tree-ring record for the Salt and Verde watersheds showed extended periods of drought more severe than anything observed in the historical record.

SRP vulnerability to droughts in the tree-ring record

To more fully assess SRP's vulnerability to a prolonged drought, a new application was developed for long-term drought analysis. The PROP spreadsheet, developed in the 1990s, was modified in 2006 to model the system water balance for an eleven year period to assess the impact of the eleven year tree-ring drought. This was not enough for the long-term analysis (over 20 years) of the system. The spreadsheet was extended to allow for analysis of projected monthly data for a period up to 50 years. Methods for inputting inflow series, demand and pumping curves were enhanced. The method for inputting an inflow series was modified to allow for multiple inflow series to be analyzed within the same spreadsheet. The new spreadsheet is the Long-Term Drought Planning Model (LTDPM).

The LTDPM provides a tool to analyze the effect of long-term droughts on the SRP Reservoir System using current operational guidelines. The severity of any drought simulated in the inflow series can be seen graphically using the model. The historical medians based on the 1914–2006 inflow record were the basis for the analysis.

In 2006, SRP evaluated its vulnerability to extended drought periods in the pre-historic tree-ring record. A severe 11-year drought period identified in the tree-ring record was selected for the drought vulnerability analysis. This drought, dating from 1575–1585, had an average annual flow of 70% of the historic median, based on reconstructed river flows from the tree-ring record. Longer droughts were identified from the reconstructed flows; however these extended periods contained at least one wet year sufficient to refill the reservoirs to capacity. Similarly, more severe droughts were apparent for shorter durations, but not long enough to threaten the reservoirs going dry. In analyzing the 11-year drought, it was assumed that coincident drought was occurring on the Colorado River and that Colorado River water would not be available to supplement SRP's usual sources of supply. It was also assumed that demand would follow recent historical trends for a given annual water allocation and that maximum groundwater pumping would remain unchanged from recent levels of about 325,000 acre–feet/year (401 million cubic meters). A preliminary analysis indicated that SRP would be unable to manage the 11-year tree-ring drought without drawing the reservoirs down to an unacceptable level by the end of the period. The drought became more manageable when the timing (based on total reservoir storage) and the size of the allocation reduction in the SPD were changed. Urbanized land, which comprises about 90% of SRP's service area, rarely uses more that 2.5 acre–feet per acre. A reduction in allocation, which affects both agricultural and urban water users, of a half acre–foot (from 3 to 2.5 acre feet) did not result anymore in the desired effect on the water demand. As a result, more drastic reductions in allocation are required to affect water use. So, instead of reducing the allocation from 3 acre–feet/acre to 2.5 acre–feet/acre, the 2.5 acre–feet/acre allocation was eliminated. If an allocation reduction is warranted, the allocation will be reduced to 2 acre–feet/acre. Groundwater pumping guidelines on the SPD were adjusted to initiate pumping sooner in the extended drawdown period. Through iterations on the allocation and pumping guidelines, the SPD was modified to the point at which SRP could now manage the 11-year drought contained in the tree-ring record. The modified SPD is shown below, Fig. 8.

The decisions to reduce allocation and to determine the amount of pumping were automated in the new spreadsheet based on the end-of-year total system storage, incorporating the guidelines developed for the new SPD. Total system storage was generated by using a simple water balance method of inflow and release from the Salt and Verde reservoirs systems calculated month-to-month. The LTDPM allows the user to efficiently compare the effect multiple inflow scenarios have on the water supply by saving the results to a summary page. Results are graphed automatically. A table (see example Table 1) showing the end-of-year storage, allocation, and pumping volume is also automatically generated.

Vulnerability to long-term drought

The science and understanding of climate change processes is constantly evolving and the projected implications for any given region are subject to change. Therefore, rather than trying to assess a moving target, a more general analysis of SRP's vulnerability to sustained drought is appropriate.

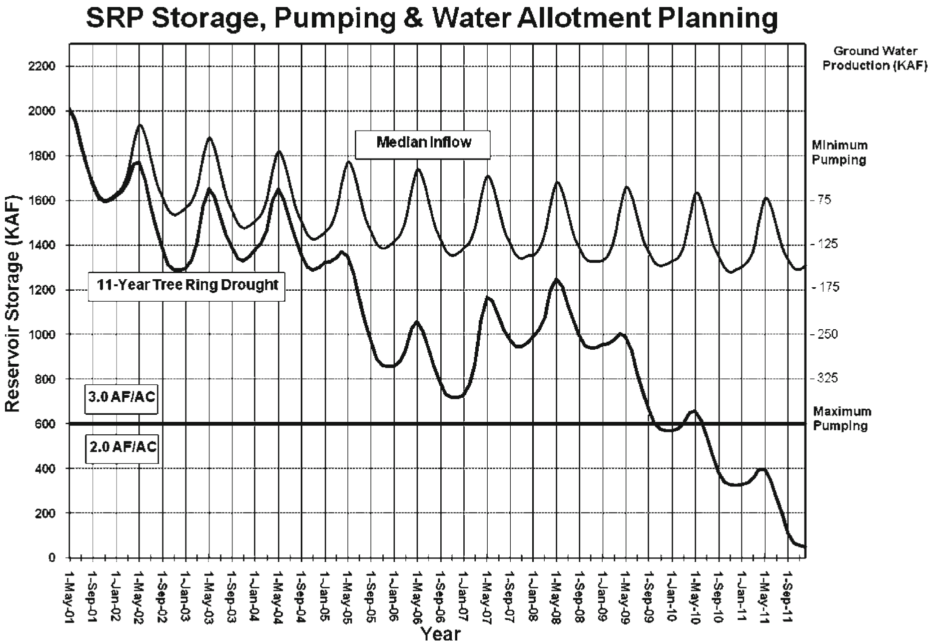

Fig. 8 SRP's new storage planning diagram

To accomplish this analysis, a broad range of drought scenarios were created. It was assumed that annual reservoir inflows are reduced to a constant percentage of historical annual median inflows for a period of 50 consecutive years. While this approach fails to simulate natural variability in stream flow, it represents a systematic and objective way of assessing the effects of long-term drought on reservoir storage.

In addition to the assumed persistent annual inflows at a fixed percentage of historical median, it was assumed that no additional source of water would be available to supplement SRP's water resources and SRP continued to operate, throughout the drought in accordance with the newly developed SPD.

Table 1 Example summary output from LTDPM

		Beginning Storage (af)	
May	1665	1721.0	
Inflow Year	Allocation	Pumping	End of Year Storage (af)
1665	3.0	Min	1,600.8
1666	3.0	Min	1,071.6
1667	3.0	200.0	626.4
1668	2.0	325.0	592.0
1669	2.0	325.0	535.3
1670	2.0	325.0	208.4
1671	2.0	325.0	635.4

Increasingly severe droughts, based on simulated perpetual inflows at a fixed percentage of the historical median, were analyzed to determine how much reduction of inflow would be required to eventually empty the reservoirs. An example of the model's graphical output is shown in Fig. 9 for a scenario of median inflows over a 50-year period. The analysis shows that SRP could perpetually operate, under new SPD guidelines, without experiencing a significant drawdown in reservoir storage. (The right axis in the figure shows the required level of groundwater pumping in 1,000s of acre–feet.)

In Fig. 10, the historical median inflow and the various percentages of the median inflow used in the analysis are presented.

A key finding of this analysis is that a prolonged period of average annual inflows at 64% of the historical median inflow can be managed indefinitely using current management procedures without the reservoirs going completely dry. However, a further slight reduction in inflow to a prolonged period of average annual inflows at 63% of median will result in the eventual depletion of all stored surface water in slightly more than 50 years. As annual inflows are further reduced below the 63% of median threshold, the time required for the reservoir system to go dry is reduced as well. Figure 9 shows total reservoir system storage over time for a range of sustained reduced inflow scenarios.

The relationship between sustained below median annual inflow, as a percent of historical median, and the time required emptying the reservoir system is shown in Table 2 below.

Effects of reduced runoff

To assess the effects of a potential reduction in future runoff into the reservoir system, a range of fixed percentage of historical average or median flows were evaluated. While there

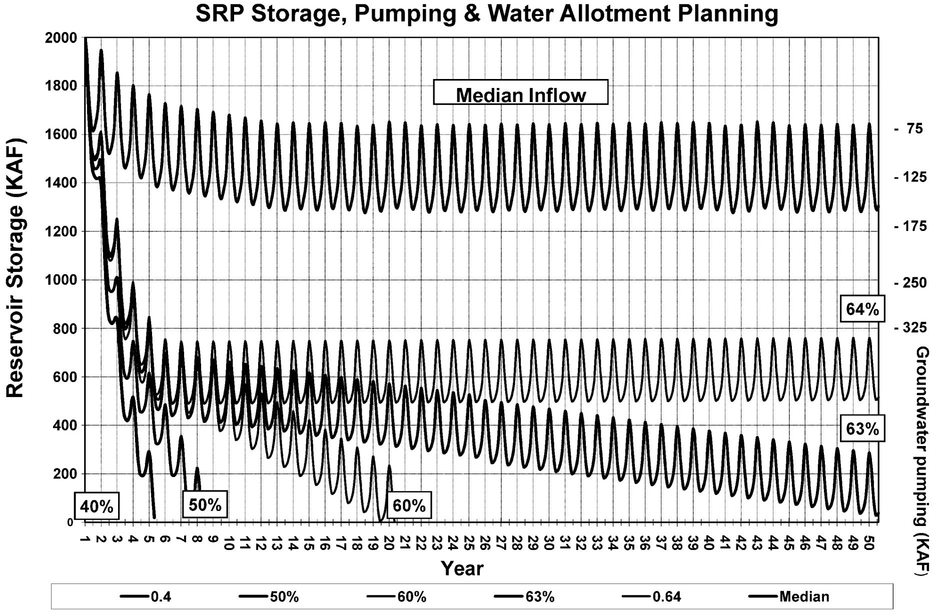

Fig. 9 Simulated reservoir storage for a range of perpetually reduced inflows (as a percent of historical median)

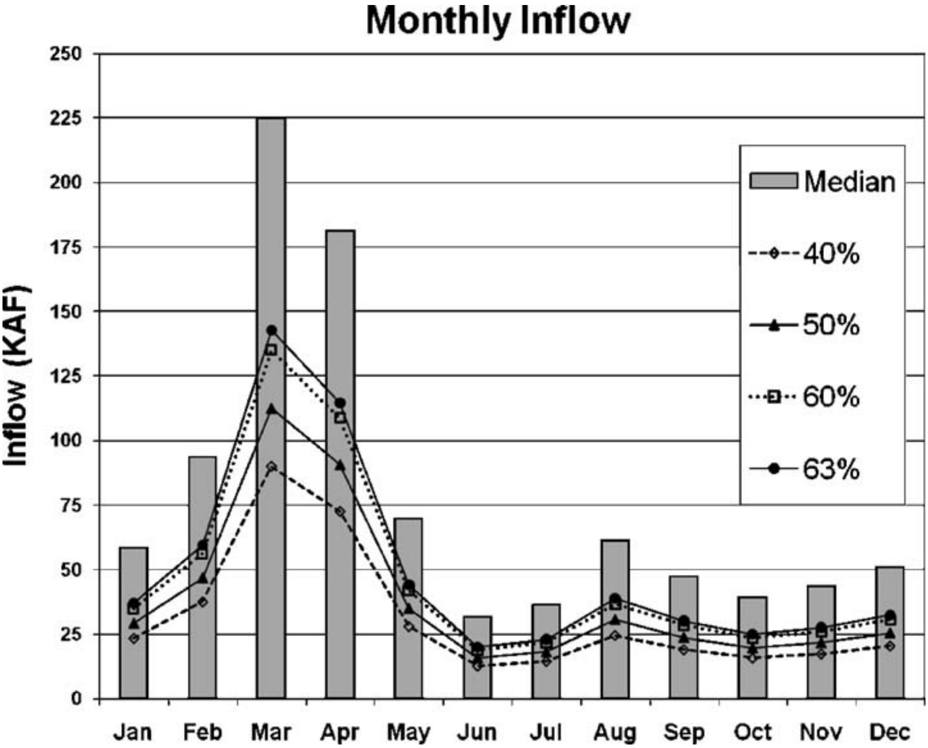

Fig. 10 Historical monthly median inflow and the various percentages of the median inflow used in the analysis

are an infinite number of ways to achieve, for example, a 10% reduction in long-term median flow, the most straight forward approach is to simply apply the 10% reduction to each year. This has the added advantage of achieving both a 10% reduction in the long-term median as well as a 10% reduction in the long-term average flow, while still maintaining the natural variability of the runoff record. What this method does not simulate is a change in variability which might accompany the reduction in flow.

Table 2 Percent of median inflow vs. years to reservoir dry up

Percent of Median Inflow	Years to Reservoir Dry Up
64	INDEFINITE
63	50+
60	19.5
55	9.3
50	7.3
48	6.4
45	5.4
40	4.4

Historical record

Published estimates of annual flow dating back to 1890 were used to extend the high-quality historical record beginning in 1913. Theses estimates were used to include the 1898–1904 drought in the analysis. Annual flows for each river system were reduced by 10, 15, 20, and 30%.

In no case would a 10% reduction in flow result in a drought period severe enough to deplete the surface water supply.

Likewise, a 15% reduction in flow did not produce any periods which would completely empty the reservoirs, however, two periods in the historical record came very close to depleting the surface water supply: A four-year period from 1999–2002 was reduced to an average annual flow of 43% of median, and the seven-year drought of record from 1898–1904 was reduced to an average annual flow of 51% of median.

A 20% reduction in flow resulted in two periods which met or exceeded the thresholds required to deplete the surface water supply. The seven-year 1898–1904 drought would have been reduced to an average annual flow of 48% of historical median, depleting the surface water supply by the end of the drought. The nine-year 1996–2004 drought would have been reduced to an average annual flow of 55% of historical median, also depleting the surface water supply.

A 30% reduction in flow did not produce any additional historical periods resulting in a depletion of the surface water supply. The two drought periods identified above, however, were significantly more severe and the surface water supply was depleted much earlier in the drought period.

Tree-ring record

A similar analysis was applied to the 800+ year reconstructed flow record derived from the tree-ring analysis. The results were remarkably similar to those found using the historical record, lending some confidence to the results.

A 10% reduction in flow did not produce any drought periods capable of depleting the surface water supply.

A 15% reduction in flow resulted in one critical period. The seven-year period from 1579–1585 had an average annual flow of 50% of median. In addition, three additional periods came very close to meeting the criteria: 1214–1217 at 43% of median, 1666–1670 at 48% of median, and 1818–1823 at 51% of median.

A 20% reduction in flow identified the same drought periods found with the 15% reduction, but the drought periods were more severe.

Table 3 Severe droughts capable of depleting surface water supply with the noted reduction in flow

Period	Source	Duration (yrs)	Flow Reduction	Average Annual % of Historical Median
1214–1217	Tree-ring	4	20%	40%
1579–1585	Tree-ring	7	15%	50%
1666–1670	Tree-ring	5	20%	45%
1817–1823	Tree-ring	6	20%	48%
1898–1904	Historical	7	20%	48%
1999–2002	Historical	4	20%	40%

In combining the historical and reconstructed flow records from tree-ring research, several severe drought periods have been identified (see Table 3). For example, given the 1214–1217 inflow series, reduced by 20%, it will take 4 years to deplete the surface water supply. The reduced inflow series is 40% of the median inflow. As can be concluded from the data presented in the table, even a modest long-term reduction in flow would result in reservoir depleting conditions.

Conclusions

Analysis of historical and tree-ring reconstructed inflow records has shown that a 10% reduction in long-term flows would not produce a drought severe enough to deplete SRP's surface water supply, using the newly developed operating guidelines in the SPD. A 15% reduction in flows, however, would have resulted in at least one period capable of emptying the reservoirs and precluding SRP from meeting its minimum water delivery obligations. A 20% reduction in flow would result in six historic or pre-historic periods of critical severity over an 800-year period with durations ranging from 4–7 years.

A review of the most recent climate-change assessments and projections suggests that runoff from the Salt and Verde Watersheds could be reduced by 20–50% within the next 50 years.

If the climate-change projections have the slightest chance of occurrence then SRP could be faced with an unprecedented water management crisis in the not too distant future.

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