FINAL DRAFT[1]
The Portfolio Approach to Water Supply: Some Examples and Guidance For Planners

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Executive Summary

Water planners facing a choice between water "supply" options (including conservation and other water management strategies such as operational changes, and conjunctive ground and surface water management) customarily use the average unit cost of each option as a decision criterion. This approach is misleading and potentially costly when comparing options with very different reliability characteristics. For example, surface water, desalinated seawater or recycled wastewater, and some outdoor demand management programs have very different yield patterns. This guidance document introduces planners to some methods adapted from financial portfolio theory. These methods allow planners to explicitly account for uncertainty in yield or water quality by calculating "constant-reliability-benefit unit costs" or blending requirements to reliably achieve water quality objectives (e.g., 500 ppm of TDS 99.5% of the time). Explicitly accounting for these uncertainties via adjusted unit costs can significantly change the relative attractiveness of options. In particular, surface water, usually a low cost option, is more expensive after its variability has been accounted for. Further, options that are uncorrelated or inversely correlated with existing supply sources will be more attractive than they initially appear. This insight, which implies options should be evaluated and chosen as packages rather than individually, opens up a new dimension of yield and financial analysis for water planners.

Some Emerging Water Supply and Demand Challenges

Water managers have historically responded to projected average year (baseline) or dry year (drought) water shortages by procuring additional supply or storage. But new sources of water are increasingly difficult to find and a wide range of other problems affect the supply/ demand balance. Existing supplies can decrease as environmental water needs, competing water rights, climate change, or other events cause allocations to change. Water quality degradation can also effectively reduce historic supplies, creating a supply/demand imbalance. And subsurface storage, increasingly attractive as suitable surface storage sites have been used up, can involve water quality degradation if the

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[1] A final guidance manual for public distribution will be prepared in a later work effort if funding is available. This final draft presents enough detail to evaluate the potential benefits from further work.

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storage location already contains brackish water or water with undesirable substances (e.g., minerals or radon). Bureau of Reclamation (2005) presents numerous other examples.

The challenge for water planners and decision makers is to accurately identify the risks and uncertainties associated with each water supply or water management alternative. Moreover, quantifying and thus evaluating those risks becomes critical to making good water supply/management decisions. This guidance document provides tools with which to address some types of risk and uncertainty in these challenges. It does not address the challenges overall or even all types of risk and uncertainty. However, this guidance document will introduce you to concepts that clarify the risks and uncertainties embodied by water supply and management planning. Additionally, this guidance document will present detailed methods that you can use to integrate risk and uncertainty into your water supply and management plans and illuminate these concepts in a quantified manner for decision makers.

Actions to match supply with demand – including water use efficiency programs -- face at least three types of uncertainty.

<u>Yield</u>

Natural variations in weather create variability over time and space in surface and some ground water supplies. Planners have accounted for this variability by designing projects to provide adequate supply often enough to satisfy their customers. System reliability standards are not uniform, and in many cases aren't numeric, but they amount more or less to an acceptable fraction of the time that water will be available without curtailment (e.g., 19 out of every 20 years). Climate change may be increasing the variability of supplies; effectively increasing the percentage of time that supply is inadequate. But even if not, climate change increases the uncertainty associated with relying on historical records of yield as the basis for future projections of yield.

Other supplies and demand management programs also have uncertain yields. Advanced treatment technologies like thermal desalination, reverse osmosis, electrodialysis, micro and nanofiltration, don't always work. Like any technology, they have scheduled and unscheduled downtime. Even if small in comparison with the weather, some amount of yield uncertainty exists. A data set from a thermal seawater desalination plant is used later in this guidance document to show how one might quantify the uncertainty in yield from advanced technologies.

Yields from water use efficiency programs vary both as a result of human behavior and because some types of programs yield more or less depending on other conditions. Leak detection and repair yields increase during drought because people pay more attention. Improved irrigation efficiency that saves 10% of applied water will save a larger absolute amount of water when use is high (e.g., hot summers) than when it is low (e.g., cool summers, or other seasons). Even simple techniques like auto-rain shutoff for sprinklers have variable yields because they save more water in wet years than in dry ones. These uncertainties are layered on top of demand variation driven by demographic or economic change.

Cost

The cost of water supply is more variable than is typically realized. Many people think water supply has relatively invariant costs since the water sector is much more capital intensive than any other utility sector (NRC 2002). When fixed costs account for 2/3 or even ¾ of total costs, large changes are required in variable costs to cause small changes in total costs. So it is true that total or annual costs of a traditional water system do not vary greatly.

But because yield varies, unit costs vary. For example, consider a gravity system that provides water so pure it does not require treatment. Then nearly all the cost is amortization of capital. If yield is 10% lower in year 2 than in year 1, the unit cost of water delivered is 10% higher in year 2 than in year 1. The example shows that yield variation and cost variation are inversely related. However, they are not simple inverses since other causes of variation in unit cost exist, such as chemical and energy costs.

Net income (revenue less costs) is also subject to uncertainty both overall and on a per unit of service basis. Rate structures greatly affect the variability of net income. Some rate structures create patterns that do not mimic variations in unit cost. For example, suppliers that do not meter water use experience much less revenue volatility due to changes in water use than suppliers who recover all costs through a volumetric, per unit rates. Because rate setting is both complex and contentious, this manual focuses on variability in costs rather than net income.

Environmental and Social

Finally, many of the examples in the Data Collection booklet involve environmental and social changes that were not foreseen when projects were initially developed and that are difficult to project into the future. Reductions in water available for delivery to people due to endangered species limitations depend on science that is developing and uncertain. Changes in availability due to legal decisions or settlements of water rights or contract disputes are similarly hard to predict, and often take decades to play out. Some water quality concerns are the result of changes in social conditions, such as salt-water intrusion or groundwater pollution that result from growth or land use.

The Planning Context

Most water planning efforts are based on either least-cost or cost-benefit approaches. See for example, Bureau of Reclamation (1983), California Department of Water Resources (2005), and Chesnutt and Pekelney (forthcoming), for thorough discussions of the relevant planning issues and challenges.

Least cost planning compares sources of water based on estimates of their unit cost. Source X with unit cost of $400 per acre-foot is considered more desirable than source Y with unit cost of $500 per acre-foot. This approach is incomplete in that it implicitly assumes that waters from two sources have the same environmental profile, for example, or the same level of reliability. Also, average or "expected value" estimates are usually used. If uncertainty is addressed at all, it is usually through sensitivity analysis that evaluates how unit costs vary with changes in assumptions or conditions (e.g., weather). Finally, it does not ask whether a source of water brings advantages to a portfolio of sources that another, same-cost source of water would not. Cost-benefit analysis also has some of these disadvantages, although it does allow one to list or quantify reliability, environmental, and other benefits and costs. But summary measures like "net benefit" or "benefit/cost ratio" do not necessarily allow "apples to apples" comparisons between options whose yield or water quality reliability characteristics have been equalized.

Regardless of planning approach, voluntary water transfers from rural to urban users are an increasingly common planning solution in the western US. This is a natural economic and political response – as alternatives become increasingly costly, economically and politically powerful communities look to agricultural water supplies to "purchase" and transfer. Because there are social concerns and costs associated with these transfers, however, demand management and advanced technologies are also being implemented. These solutions are also economically desirable so long as their costs are less than the marginal value to customers of additional water or water-based services.

Advanced technologies have two primary advantages: high reliability and high water quality. They also have a minimal possibility of infringing on contested water rights, suffering from seasonal and periodic climatological impacts, and highly impacting habitats or environmental quality. They do have at least the following potential disadvantages: relatively high cost, increased reliance on energy, and environmental impacts such as from brine disposal or air pollution caused by increased energy use.

This document does not evaluate advanced technologies. It is a first effort to show how at least some of the uncertainty involved with these technologies and others in supply portfolios might be quantified and valued. There has been a great deal of talk about "diversification" in water circles in recent years, but little analysis of how much or what type of diversification would be most beneficial. Kasower, et al. (forthcoming) and Buehler (undated), provide broad discussions of potential applications of portfolio theory and other advanced economic tools to water supply planning.

A Simplified Portfolio Approach

This guidance manual uses a modification of the least-cost approach because it is the simplest way to apply the portfolio approach. One can specify a total quantity of water or water-based services that must be delivered with a specified level of reliability (e.g., demand is satisfied 19 out of 20 years), then compare the cost of alternative portfolios of water "sources"[4] that meet those specifications. The least-cost portfolio among those that satisfy the specifications is probably the most desirable. This differs from the usual least-cost approach in only two ways. First, one is comparing portfolios rather than individual sources. Second, the portfolios include a reliability specification along with the usual total quantity specification.

Similarly, one could specify a quantity and quality of water that must be achieved (e.g., TDS of 500 ppm or less) and compare portfolios that are capable of meeting those specifications (perhaps ignoring reliability at first to simplify the analysis). Again, the lowest cost portfolio is probably the most desirable.

Finally, one can ask whether the least cost portfolio in either of these cases has higher uncertainty with respect to cost[5] than other, apparently more costly portfolios. But rather than use sensitivity analysis as in the conventional approach, one could estimate the unit cost variability as a separate decision variable. That is, create a table showing portfolio unit costs and the standard deviation of unit costs as a decision tool. A decision rule probably cannot be constructed in general because the trade-off between the desirability of lower cost and the undesirability of uncertain cost depends on circumstances such as community sentiment concerning water shortages and public expenditure. Nonetheless, at least some water districts some of the time would probably choose portfolios that are not the lowest cost if provided such information.

This approach has limited application, but high value, as the examples later will show. It is limited in three ways:

- It does not address all sources of uncertainty discussed above.
- It does not make use of all of the theoretical concepts put forward in the papers cited above.
- It does not replace conventional water planning, but merely adds to the toolbox.

Although this way of using portfolio theory focuses less on unit prices for sources than the conventional approach, unit prices for each source will be involved in the analysis or can be calculated once the portfolios are developed. Doing so will show that at least some advanced technologies and demand management techniques are worth substantial unit price premiums because they achieve reliability or water quality objectives with smaller facilities or programs than new surface water or conventional supplies. This result shows decision-makers and the public why paying a higher unit cost is sometimes justified.

[4] We include demand management among sources of water as is becoming typical in least cost planning.
[5] One can also ask this question with respect to net income, but that is beyond the scope of this manual.

A Financial Example

An illustration of the portfolio approach is both useful and necessary before diving into water. The following illustration is purely financial. It shows how and why a financial manager might diversify investments, and the type of thinking that is involved.

Suppose the finance director of a municipality needs to provide \$5 million (M) per year of revenue from \$100 million (M) of reserves as a contribution to the City's general fund, under the following conditions:

- He has only three investment choices
- The first is a money market fund that pays 3% every year
- The second is an advertising business that pays 20% return in "growth years" and negative 10% return in "recession years,"
- The third is a bankruptcy law firm that pays 20% return in "recession years" and negative 10% return in "growth years"
- Every year is either a growth year or a recession year
- Growth and recession years are equally likely
- The City can borrow money at 5% per year, but only to make payments to the general fund, not to purchase investments

The manager can't meet his target of \$5M every year by investing all \$100 million in any one investment (Table 1). He would earn only \$3M per year in the money market fund, although he would earn that amount every year. Consider the advertising agency, which will yield \$20M in half the years but lose \$10M in the other half. Its annual average yield will be \$5M [0.5 x \$100M x 20% + 0.5 x \$100M x (–10%)]. The same math shows a \$5M annual average yield for the bankruptcy law firm. Although the average annual earnings look like enough for two of the three investments, they are not because the manager needs to earn \$5M every year.

Table 1: Annual Earnings From Investing \$100 Million Entirely in Each Option

Investment Options	**Growth Years (50% of Years)**	**Recession Years (50% of Years)**	**Average Annual Earnings**
Money Market	\$3M	\$3M	\$3M
Advertising Agency	\$20M	- \$10M	\$5M
Bankruptcy Law Firm	- \$10M	\$20M	\$5M

To get \$5M every year the manager must save money in good years to be spent in bad ones. Since he'll earn 3% on the saved money, it seems as if he would have enough. But that is not the case because in a random world he will eventually suffer a string of bad years that depletes his savings and forces him to borrow at 5% to make payments to the general fund for one or more years. Even though he will also experience strings of good years that allow him to build up his savings, it turns out that on average his borrowing expense will more than offset his earnings in the money fund, over time, because the rate he borrows at is more than the rate he earns on savings. (The water supply parallel is that losses from storage are inevitable due to evaporation or percolation. One can't save 100% of the inflow that is not needed in a given year for later years.)

Does this mean the manager's goal is unattainable? No, because he can diversify. If the manager invests $50M in each of the advertising and law firms, he'll earn exactly $5M per year every year (Table 2). He won't need to borrow or save. Diversification alone makes his cash flows reliable and allows him to avoid the net expense of "storing money" ensure reliability.

Table 2: Annual Revenue From Investing $50 Million In Each Business Option

Investment Allocation:	**Growth Years**	**Recession Years**
Advertising Agency ($50M)	$10M	- $ 5M
Bankruptcy Law Firm ($50M)	- $ 5M	$10M
Annual Revenue In Each Type of Year	$ 5M	$ 5M

Water Supply Reliability

Water-supply reliability is an important characteristic of all municipal systems. For example, California's water utilities invest substantial amounts of money to reduce the risk of supply interruptions due to earthquakes. They understand that the cost to their customers of supply disruptions is often far greater than the cost of improved system reliability. Similarly, dams and reservoirs are widely used to reduce the risk of supply interruption due to dry weather. Other threats to water supply reliability include climate change, changes in runoff patterns as more impermeable surfaces are created by land development, changes in water quality or environmental regulations, variation in important cost factors (e.g., interest rates, labor, or energy), legal issues related to water rights or contracts for water deliveries, and cultural and political factors.

The parallels to water supply planning are intriguing. Demand is like the cash flow requirement, supply is like the annual earnings from the investments, and reliability is a high probability that supply will equal or exceed demand (annual earnings will equal or exceed required cash flow). Storage is like savings. Storage losses are like the difference between the borrowing and savings rates.

But the parallel is not perfect. Investors can usually buy as much or as little of an asset as they like. In contrast, most water investments are "lumpy." Financial investors can also sell when they like. Water assets are much harder to sell both because there are fewer buyers and numerous institutional barriers to sale. Financial investments do not have irreversible consequences, while some water investments do (e.g., loss of habitat). Also, financial data on yield are reasonably characterized by a mean and standard deviation, assuming a normal distribution. Assuming normal distributions for water-related data is not necessarily correct. Other distributions are much more commonly used, for example, to characterize extreme events like floods and droughts. The following example has been constructed to avoid these differences.

Measuring Reliability and Its Value

There is no widely accepted method for measuring water-supply reliability. The simplest method is to measure the risk of projected supply falling below projected demand, on average. For example, a system with a reliability level of 95 percent implies that supply will meet or exceed demand 19 times out of 20. This approach has the advantage of being very simple. Like most simple approaches, however, it has drawbacks. The most notable one is that it does not measure the severity of the water shortfalls. One can imagine a system with reliability of 90% that is more desirable than another system with reliability of 95% because the shortfalls in water supply in the first system are very small while the less frequent shortfalls in the second system are very large.

Nonetheless, for the discussion below we use this simple definition because it allows a clear discussion of an important issue. The reliability percentages presented in the numeric illustration can be thought of as a summary statistic for all of the uncertain issues mentioned above, although in practice many of these factors are very difficult to quantify accurately.

Proponents of advanced technologies correctly point out that more reliable water is worth more. They argue that the relatively high cost per unit of desalinated water is justified by its higher reliability. How can one evaluate this very important claim?

Economists typically address this question by assessing customer willingness to pay for a slightly reduced chance of water shortages. For example, suppose the chance of a water shortage that would require rationing is 1 in 40 in any given year, but an investment in a new reservoir can reduce that chance to 1 in 41. If additional water isn't needed (except in severe drought), then customer willingness to pay for the reservoir is a measure of the value customers place on increased reliability. Numerous economic studies have found high willingness to pay to avoid drought-related or other restrictions on water use; ranging from $32 to $421 year 2003 dollars per household per year (see Raucher et.al., 2005, for a summary of these studies). When the estimated quantity of water use foregone due to a drought restriction is multiplied by the probability (frequency) of the drought scenario investigated, these annual household WTP estimates imply a reliability value to residential customers as high as about $4,000 per acre-foot.

This approach, unfortunately, doesn't help answer our question. Customers don't need to know how reliability will increase in order to value it. Customers aren't saying anything about the relative value of different options for increasing reliability. They're just saying that more reliability – regardless of source – has a value.

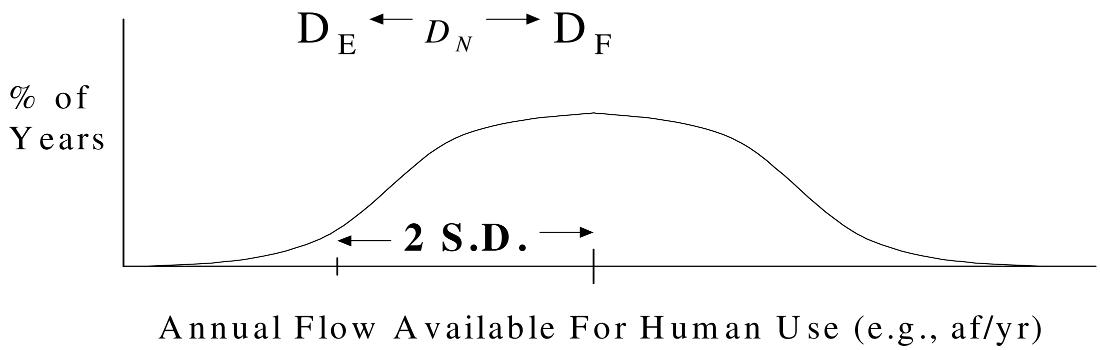
Constant-Reliability-Benefit Unit Costs

Consequently, we developed a method for adjusting estimated unit costs of water "supply" options (including conservation and end-use efficiency). The method borrows and adapts tools from financial portfolio theory. It leads to "constant-reliability-benefit unit costs" that provide a fair comparison between supply options with different uncertainty characteristics.

The method involves a two-step process. In the first step, water managers define the level of reliability benefit they want to maintain or achieve. For example, they might want to ensure that enough water is available to meet demand in 39 out of 40 years, on average. In the second step, they create an "apples to apples" comparison of options by adjusting average unit costs ($/acre-feet) to get constant-reliability benefit unit costs. The following example illustrates the method. The relevant mathematics are presented in Appendix A.

Suppose a community is served by a run-of-the-river water supply. Figure 1 shows water available from the river for human extractive purposes each year as having a normal distribution. The average flow is the most common level of flow. Our example assumes the extractable yield in average years is 10,000 acre-feet and the standard deviation of annual flow is 1,000 acre-feet. Low and high flows are increasingly rare as they get further from the average. The relative "flatness" of the bell is described by the standard deviation (S.D.) of the normal distribution. The larger the standard deviation as a percentage of the mean, the flatter the bell; and the more variable is the annual flow available for human extractive purposes.

Figure 1: Reliability in a Run-of-the-River Water Supply System



The average flow and the flow two standard deviations below the average are marked in Figure 1. A property of the normal distribution is that in 2.5% of the years, flow will be less than the lower of these two marks. In our illustration, the flow two standard deviations below the mean is 8,000 acre-feet per year (i.e., the 10,000 acre-feet per year mean minus 2 times the 1,000 acre-feet per year standard deviation). Flow available for human use will be lower than the lower mark (8,000 acre-feet per year) in only 1 out of every 40 years over a long period of time.

Now let's consider demand. The demand numbers in our illustration are conveniently chosen to match some of the numbers in the description of supply, above. Any other numbers could be assumed, but they would make the illustration harder to follow. Assume that current drought year demand (labeled D_E in the Figure)[6] is at the lower tick mark. Then the community served by this water system will experience a water shortage only one year out of 40. As defined above, this is a reliability level of 97.5%.

Suppose drought year demand is projected[7] to grow by 2,000 acre-feet over the next decade. As drought year demand grows, reliability will decrease in the sense that the likelihood of a water shortage will increase from 1 in 40 to 1 in 2, because half of the bell curve is below the middle tick mark (which conveniently has been assumed for the purposes of this paper, to represent both the average supply yield of 10,000 acre-feet and the future drought year demand of 10,000 acre-feet). That is, the reliability level would fall from 97.5% to 50%, because enough water would be extractable in only half the years. One of the standard jobs of water managers is to ensure that this doesn't happen. But how they satisfy new demand may affect reliability.

Suppose they want to maintain the current level of reliability at 97.5%. This is the first step in the planning process – chose a design reliability level and the benefit level associated with it. This is held constant in the analysis that follows.

The amount of physical water (or water-use efficiency) required to satisfy growth in drought year demand is the difference between future drought year demand (D_F) and existing drought year demand (D_E). This has been labeled D_N in Figure 1, and in our example is 2000 acre-feet. If a supply option were to provide exactly this amount in every year, the planner should procure D_N of new supply. Water from advanced treatment processes (e.g., desalinated seawater or recycled wastewater) has this characteristic if treatment facilities are designed with enough redundancy to prevent downtime other than for regularly scheduled maintenance.[8]

But if the water supply option is variable from year to year, the planner must procure enough of it to have D_N available 39 out of 40 years, or reliability will decline. For example, when the chosen option is a surface water source, the amount available in an average year must be greater than D_N in order to ensure D_N is available in a dry year.

The amount of water supply greater than D_N that has to be purchased depends on two factors. First, higher standard deviations of annual yield from the new surface water

[6] We define drought year demand as the demand that would exist when flow is at a point chosen by the planner on the horizontal axis of Figure 1 – in this case, demand when flow is at the lower tick mark. Note that drought year demand will often be higher than average year demand because outdoor water use will increase when rainfall is below average or temperature is above average.
[7] A water demand projection is based on many factors, such as projected growth in population and employment in the service area.
[8] Some indoor water conservation measures may also have this characteristic of supplying exactly D_N every year if they are designed carefully. While the issue of "savings decay" in water conservation has been hotly debated, the authors believe savings decay can be eliminated or made quite small by carefully specifying water-use efficiency devices.

source imply that more water needs to be procured to ensure adequate water in a low-flow year. Second, lower correlations of annual yield between the new source and the existing source imply that less of the new source will be required, on average, to ensure D_N is available when water from the existing source is at or below the lower tick mark in Figure 1. That is, if the new source is wet when the existing source is dry, one can procure less than D_N on average and still get D_N when the existing source is dry.

What this means is that comparing unit costs for options based on the average amount of water each option will deliver leaves out an important piece of the economic picture. Suppose for illustration purposes that advanced treatment of impaired water, a new surface water supply, and outdoor conservation, all have an average unit cost of $600/acre-foot. Ignoring reliability impacts, there is no financial difference between these sources.

But suppose further that the new surface water supply has a similar pattern of wet and dry years to the old surface water supply but is more variable. Then ensuring the 2,000 acre-feet of new supply that will be needed in a drought year requires that the new source be sized to deliver more than 2,000 acre-feet of water each average year, just as the old source was capable of providing 10,000 acre-feet on average but only 8,000 acre-feet with the desired level of reliability. If the new surface water source has a coefficient of variance (the standard deviation over the mean) of 20%, the water planner will need to procure 3,333 acre-feet in an average year to ensure 2,000 in the constant-reliability-benefit design year (3,333 – 2 x 0.2 x 3,333 = 2,000). This in turn implies that each unit of water during drought will cost $1000/acre-foot on a constant-reliability benefit basis ($600/(1 - 2 x 0.2)).[9]

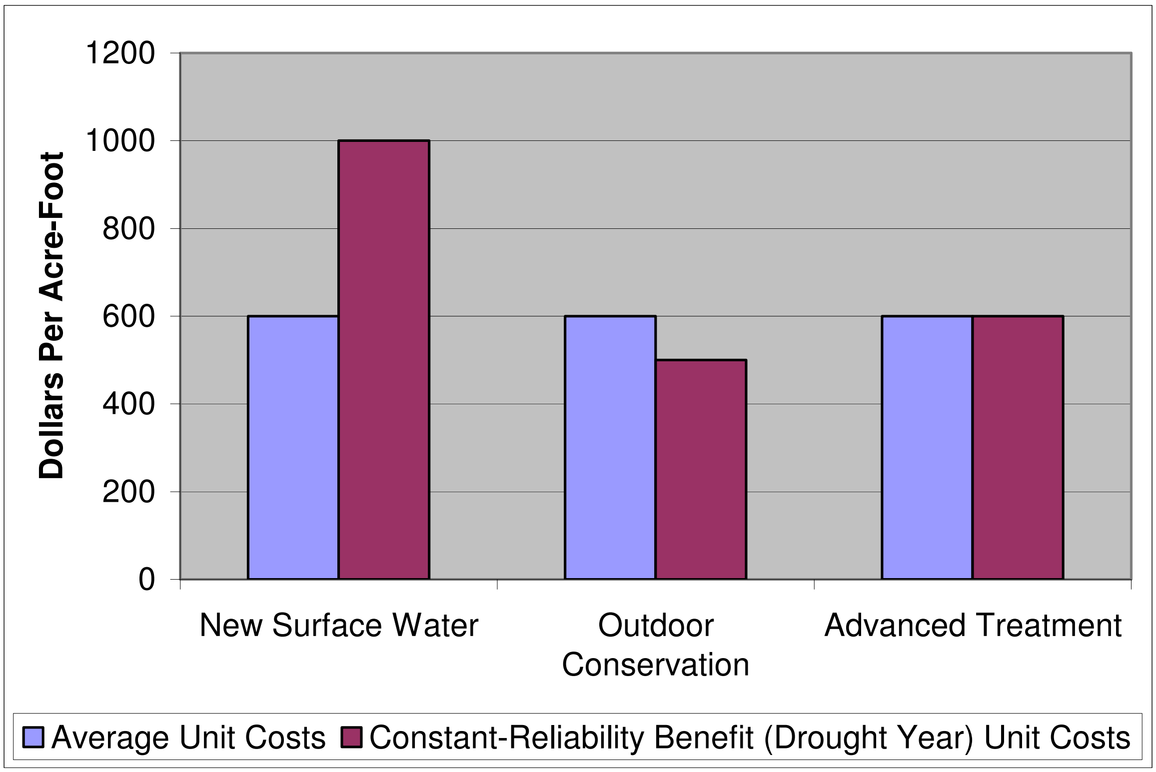
If an outdoor water conservation measure were to save more water during dry weather, [10] its constant-reliability benefit unit cost would be less than the assumed $600 per acre-foot. If it were perfectly counter-correlated with the current surface water source, and had a coefficient of variation of 10%, its constant-reliability unit cost would be $500 per acre-foot ($600/(1+2 x 0.1)). That is, ensuring 2,000 acre-feet of water in a drought year would require outdoor conservation measures sized to deliver only 1,667 acre-feet in an average year. The counter-correlation implies that during a drought where flows in the current supply source are two standard deviations below its mean, outdoor conservation would save two standard deviations above its mean, which equals 2.0 when the mean is 1.667 and the standard deviation is 0.1667 (10% of the mean).

[9] Stated differently, the utility could pay 67% more *per average unit* of water from the advanced treatment facility (1000/600 = 1.67) compared to each average unit in the new surface water alternative -- and provide the same economic benefit at the same cost to customers. Note that the premium is not in total, but per unit. The smaller advanced treatment facility is just as good as the larger surface water facility at reliably providing two thousand acre-feet, so a *per unit* premium is justified.

[10] For example, laser leveling, drip or micro-spray irrigation, scheduling improvements (e.g., ET controllers), and adjustments in sprinkler heads to improve distribution uniformity, all reduce the percent of applied water that percolates or evaporates. Since applied water must go up during drought, these measures will save more water during drought than during average or wet weather. Auto-rain shut-off devices, by contrast, save more water when it rains than when it is dry.

Figure 2 summarizes the average unit costs and constant-reliability benefit (drought year) unit costs under these assumptions. Accounting for variance and correlation between water supply sources – as is done for securities when managing a portfolio of financial assets – is clearly important. Water supply planners who do not consider these factors might think options are similar in cost when they are in fact quite different once reliability benefits of the options are equalized. Worse yet, an apparently inexpensive source might turn out to be very expensive on a constant-reliability benefit basis, or an apparently expensive source might turn out to have the lowest cost per acre-foot once reliability is considered.

Figure2: Illustration of Average and Constant-Reliability Benefit Unit Costs



A Water Quality Example

One of the advantages of desalination is the high quality of product water. Customers are willing to pay more for better quality water, especially when hardness in the source water creates water softening expenses for the customer or when taste is noticeably affected by high total dissolved solids (TDS).

However, the willingness of customers to pay for higher quality water is not directly relevant to the value of higher quality water from desalination, just as willingness to pay for higher reliability was not directly relevant to the reliability value of desalination.

Planners need to compare supply options (including conservation[11]) on a constant-water-quality basis. This involves, first, choosing a quality standard based on the willingness of customers to pay for quality. Second, it involves finding the lowest cost option of combination of options for attaining that standard.

Again, a simplified example is useful. Suppose the following:

- A community needs 100 afy of water that satisfies the secondary drinking water standard of 500 ppm of TDS 99.5% of the time. The 99.5% percent requirement can be thought of as an "internal" water quality standard.

- The purchased quantities will be delivered exactly every year. That is, water quantity reliability is not a problem.

- There are three sources of water available. The planner can purchase any two of them in any quantities desired that add up to 100 afy.

- Source One is the lowest low cost source but unfortunately has average annual TDS content of 650 ppm. Its annual TDS is normally distributed with standard deviation of 65 ppm (10% of its average). Colorado River water delivered to Southern California has approximately these characteristics (Redlinger 2005). Water from Source One costs $100 per af.

- Source Two is a higher cost surface water and has normally distributed TDS with mean of 350 ppm and standard deviation of 70 ppm (20% of its average). Water from Source Two costs $500 per af.

- Source Three is from seawater desalination, also has normally distributed TDS but with a mean of 50 and a standard deviation of 5 ppm (10% of its average). Water from Source 3 costs $800 per af.

- The water quality of the three sources is completely uncorrelated.

Under these assumptions there are two possible lowest-cost portfolios with TDS of 500 ppm or lower 99.5% of the time. Both involve using as much of the low cost Source One as possible. Source Two is less expensive than Source 3, but also has higher TDS. So it is possible that paying for the higher quality Source Three will allow more of the lowest quality Source One to be used; reducing the average cost of suitable water. Table 3 shows the mix of sources and the unit cost of produced water with TDS 500 at least 99.5% of the time. The relevant math is presented in Appendix A.

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[11] Water conservation may help, harm, or be neutral with respect to blended water quality. Unlike physical water supplies, conserved water does not have a water quality "of its own." Conserved water will help to improve blended water quality when conservation allows less water from a poor quality source to be used, but in contrast it will worsen blended water quality if it leads to less water from a high quality source.

Table 3: Portfolios Providing 500 ppm TDS 99.5% of Years.

Portfolio	Source One	Source Two or Three	Average Unit Cost
Sources One and Two	5 afy	95 afy of Source Two	$484 per af
Sources One and Three	51 afy	49 afy of Source Three	$443 per af

Table 3 shows that only 5% from Source One may be used when Source 2 is the only other water available for blending, under the assumptions made. In contrast, 51% of blended water can come from Source One when Source Three is available for blending. Although Source Three is 60% more expensive per unit than Source Two ($800/$500 = 1.6), its high quality and low variance in quality make it more than worth the premium. In fact, one could pay about 75% more for it (i.e., about $875 per af) and have an average unit cost for blended water that is equal to the average unit cost of water obtained by blending Sources One and Two. So any unit cost premium up to 75% is justifiable for desalinated water, under the given assumptions, based on the water quality benefit alone.

Conclusions and Next Steps

Accounting for variance and correlation between water supply sources – as is done for securities when managing a portfolio of financial assets – is clearly important. Water supply planners who do not consider these factors might think options are similar in cost when they are in fact quite different once reliability benefits of the options are equalized. Worse yet, an apparently inexpensive source might turn out to be very expensive on a constant-reliability basis, or an apparently expensive source might turn out to have the lowest unit cost once reliability is considered.

The methods presented in this document are powerful starting points for quantitative evaluation of the cost implications of uncertainty in water supply, demand management, and water quality blending options. These methods not only quantify the uncertainty involved but also evaluate options costs as part of a portfolio rather than on an individual basis. An option that is attractive when combined with an existing water supply in one setting might be unattractive if combined with a different existing water supply in a different setting. The correlation between the yields or quality of options is a new dimension of analysis for water planners. For water supply portfolios with numerous sources, as is the case in some regional systems, quantifying the impacts of these correlations may lead to surprising outcomes and changes in water supply plans.

Application of the method may be hindered, however, by data limitations or patterns that are difficult to describe via normal or other statistical distributions. As many a financial planner has found, the mathematics of portfolio theory do not guarantee superior investment results. One must struggle with the data and other decision criteria every time an investment decision is made. Nonetheless, better or additional tools have value.

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Appendix A: Mathematics

Constant-Reliability-Benefit Unit Costs
Finding constant-reliability-benefit unit costs involves a two-step process. First, a constant-reliability-benefit standard must be specified. For example, the water planner might say that water supply (including conservation measures) must just equal drought year demand 97.5% of the time. Mathematically, this means that the annual average of the supply portfolio minus two times[12] the standard deviation of the supply portfolio must be equal to future (planned for) drought year demand:

$$(A-1) \quad A(P) - 2SD(P) = D_F$$

Other reliability standards can be chosen using a table present in any statistics textbook that shows the percentage of time a random variable will be more than a chosen multiple of the standard deviation from the average. For example, a reliability standard of about 84% requires specifying a "1" in equation (A-1) rather than a "2." Stated differently, a normally distributed random variable will be lower than the average minus one standard deviation about 16% of the time. In our application, if our reliability standard allows supply to fall below demand about 1 year in 6, on average, we would specify a "1" in equation (A-1) rather than a "2."

The average supply of a portfolio is the sum of the average supplies of each of its parts. In our example, one compares combinations of the existing supply with a new supply:

$$(A-2) \quad A(P) = A(E) + A(N)$$

$$Where \quad A(X) = \frac{1}{n}\sum_{i=1}^{n} Q_{xi}$$

$$n = the\ number\ of\ years\ of\ annual\ flow\ data$$

$$Q_{xi} = the\ annual\ flow\ in\ year\ i\ from\ source\ x$$

The standard deviation of a portfolio of sources depends on the standard deviation and average of each source, the correlation between the sources, and the percentage of water from each source. The standard deviation of a portfolio is the square root of the variance of the portfolio. The appropriate formula (modified by the author from Tucker, et.al. 1994) when two sources are involved is:

[12] Or if expressed with an additional significant figure, as is common in statistics textbooks, 1.96.

$$(A-3)\quad S(P)=\sqrt{W(E)^2 S(E)^2+W(N)^2 S(N)^2+2W(E)W(N)Rho(E,N)S(E)S(N)}$$

$$\begin{aligned}
&Where\quad W(E)+W(N)=1\\
&\qquad W(x)\equiv\frac{A(X)}{A(P)}\\
&\qquad S(X)\equiv\frac{SD(X)}{A(X)}\\
&\qquad Rho(E,N)\,is\,the\,correlation\,coefficient\,between\,E\,and\,N
\end{aligned}$$

Formulas for the standard deviation (SD) and correlation coefficient (Rho) are provided in any statistics textbook. One can calculate these summary statistics using any spreadsheet program. Combining Equations (A-1), (A-2) and (A-3) yields:

$$(A-4)\quad \sqrt{\left(\frac{A(E)}{A(P)}\right)^2 S(E)^2+\left(\frac{A(N)}{A(P)}\right)^2 S(N)^2+2\left(\frac{A(E)}{A(P)}\right)\left(\frac{A(N)}{A(P)}\right)Rho(E,N)S(E)S(N)}=\frac{A(P)-D_F}{2A(P)}$$

$$Where\quad A(P)=A(E)+A(N),as\,above$$

If one knows the average existing supply, the standard deviations of the existing and new sources of supply, and the correlation coefficient between supplies, equation (A-4) will contain only one unknown (A(N)). This is the average new supply required to ensure that the chosen reliability standard (97.5% in this case)[13] will be achieved. A(N) can be found by assuming a value for A(N), seeing how close or far apart the left and right hand sides of the equation are, and iteratively adjusting the assumed value until the value of A(N) that solves the equation is found. Table A-1 presents the solutions in the body of this report (new surface water supply, desalination, and outdoor water conservation).

Table A-1: Unit Cost Reliability Premiums Under Various Assumptions

Water Supply Options	**Coefficient of Variance (SD/A)**	**Correlation of Supply Options (Rho(E,N))**	**A(N)**
Surface Water	20%	1.0	3,333 afy
Desalination	0%	0.0	2,000 afy
Outdoor Water Conservation	10%	-1.0	1,667 afy
Assumes Coefficient of Variance of the Existing Source of 10%; A(E)=10,000 afy; D_F=10,000 afy; Reliability Level of about 97.5%			

Finally, the constant reliability unit price for each option differs from the average unit price for each option by the ratio of A(N)/ D_N. When A(N) equals growth in drought demand (D_N)[14], as with desalination and similar options, the average unit price for that

[13] Replacing the "2" in the denominator on the right hand side with the appropriate value, as discussed above, yields the appropriate equation for other reliability standards.
[14] Recall that D_N = equals D_F-D_E.

water supply option is also the constant-reliability-benefit unit price. When A(N) is greater than or less than D_N , as with the surface water and outdoor conservation examples in Table A-1, the constant-reliability-benefit unit price for each option is higher or lower than the average unit price for that option, respectively.

Mathematics of Blending When Water Quality Is Uncertain

As in the reliability mathematics, a two-step process is involved. First, a water quality standard and probability of achieving the standard must be specified. For example, the planner might specify that water quality must be 500 ppm of TDS at least 99.5% of the time. Mathematically, this means that the average quality of the supply portfolio (A(QP)) less three times the standard deviation of the portfolio's quality (SD(QP)) must equal the water quality target (500 ppm):

$$(A-5) \quad A(QP)-3SD(QP)=500$$

Other probabilities of achieving the target standard can be chosen using a table present in any statistics textbook that shows the percentage of time a random variable will be more than a chosen multiple of the standard deviation from the average. For example, a reliability standard of about 84% requires specifying a "1" in equation (A-5) rather than a "3." Specifying a "0" rather than "3" would mean water quality will be worse than 500 ppm 50% of the time. In this case, blended quality is simply the arithmetic average of the quality of the water sources.

The average quality of a portfolio is the weighted sum of the average qualities of the water sources that are blended. In our example, only two sources are blended at a time:

$$(A-6) \quad A(QP)=W(1)A(Q1)+W(X)A(QX)$$

$$Where \quad X = Source\,2\,or\,3$$

$$y = Source\,1,2\,or\,3$$

$$W(y) = Percent\,of\,\,the\,\,Portfolio\,\,From\,Option\,\,y$$

$$W(1)+W(X)=1$$

$$A(Qy)\frac{1}{n}\sum_{i=1}^{n} q_{yi}$$

$$n = the\,number\,of\,\,years\,of\,\,annual\,average\,quality\,data$$

$$Q_{yi} = the\,annual\,average\,quality\,in\,year\,i\,\,from\,source\,\,y$$

The standard deviation of the quality of a portfolio of sources depends on the standard deviation and average quality of each source, the correlation between the source qualities, and the percentage of water from each source. The standard deviation of a portfolio is the square root of the variance of the portfolio. The appropriate formula (modified by the author from Tucker, et.al., 1994) when two sources are involved is:

$$(A-7) \quad S(QP)=\sqrt{W(1)^2 S(1)^2 + W(X)^2 S(X)^2 + 2W(1)W(X)Rho(1,X)S(1)S(X)}$$

$$Where \quad S(y) \equiv \frac{SD(Qy)}{A(Qy)}$$

$$And\ Rho(1,X)\ is\ the\ correlation\ coefficient\ between\ Q1\ and\ QX$$

Formulas for the standard deviation (SD) of and correlation coefficient (Rho) are provided in any statistics textbook. One can calculate these summary statistics using any spreadsheet program. Combining Equations (A-5), (A-6) and (A-7) yields:

$$(A-8) \quad \sqrt{(1-W(X))^2 S(1)^2 + W(X)^2 S(X)^2 + 2(1-W(X))W(X)Rho(1,X)S(1)S(X)} = \frac{A(QP)-500}{3A(QP)}$$

$$Where \quad A(QP) = (1-W(X))A(Q1) + W(X)A(QX)$$

$$And \quad S(y) \equiv \frac{SD(Qy)}{A(Qy)}, as\ above$$

As with the reliability example, there is only one unknown in equation (A-8) if one knows the summary statistics related to water quality for the water supply options (average quality, standard deviation of quality, and correlation coefficient between quality measures). The unknown is W(X): the fraction of the blend with Source 1 that must come from Source X in order to maintain 500 ppm or better 99.5% of the time. As before, one must solve for W(X) by iteration. One then finds the fraction of the blend from source 1 by subtracting W(X) from 1. The cost of each blend that satisfies the quality specification is the weighted average cost using these fractions.

Appendix B: Data and statistics for the water quality example

Table B-1: Flow Weighted TDS in Colorado River Water Below Parker Dam

Calendar Year	Total Dissolved Solids (TDS) in mg/L
1970	760
1971	758
1972	734
1973	709
1974	702
1975	702
1976	690
1977	687
1978	688
1979	701
1980	712
1981	716
1982	713
1983	678
1984	611
1985	561
1986	535
1987	538
1988	540
1989	559
1990	600
1991	624
1992	651
1993	631
1994	673
1995	671
1996	648
1997	612
1998	559
1999	591
2000	580
Mean	**648**
Standard Deviation	**68**
Source: Redlinger, 2005	