Calculating Constant-Reliability Water Supply Unit Costs

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Abstract

Water planners facing a choice between water "supply" options (including conservation) 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 paper presents a method for calculating constant-reliability unit costs that adapts some concepts and mathematics from financial portfolio theory. Comparing on a constant-reliability basis 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 – such as outdoor water conservation -- 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.

Keywords

Reliability, value of reliability, portfolio theory, water supply planning, drought planning, integrated resource planning, water conservation, uncertainty, adjusted unit costs.

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Introduction

Water planners commonly estimate an average unit cost for each water supply option (including conservation measures) by dividing average annual total yield of the option by annual average total cost (the sum of average annual fixed plus variable costs).[2] Lower unit cost options are preferred on a financial basis, although other decision criteria are also used (e.g., see Bureau of Reclamation 1983 or DWR 2005). A time sequence of new facilities is often planned based on anticipated growth of demand, with new facilities brought on line in time to prevent a supply shortfall under appropriate hydrologic (e.g., dry-year rainfall) or other (e.g., average reservoir yield) assumptions. Facilities with lower estimated average unit costs are typically built first.

This procedure is understandable and often appropriate when water supply options do not vary enormously in availability. Two source watersheds with very different rainfall patterns might have similar variation in annual water availability if there are appropriately sized reservoirs in each watershed. Similarly, the variation in availability between a surface water reservoir and a groundwater aquifer might not be that different if the reservoir is large relative to annual demand.

However, annual availability may also vary significantly between options. Consider a run-of-the-river system on an intermittent stream as compared with a deep groundwater aquifer. Furthermore, when demand grows more rapidly than supply, there is an implicit

[2] Since variable costs tend to rise over time, planners often compare "levelized average costs" over the planning horizon (e.g., 30-50 years).

decline in the adequacy or reliability of a variable water source because the frequency with which demand exceeds supply increases. In addition, new sources of supply, such as surface and groundwater from previously unutilized watersheds or aquifers, desalinated seawater, recycled wastewater, and demand management programs often have very different patterns of availability than traditional surface water supplies.

Retirement fund and water managers face a similar challenge. Each must deliver a minimum quantify of something (money or water) every year while the source of that something (e.g., securities markets or nature) varies randomly. Fortunately, random variation can be at least partially characterized with statistics. Of course past investment success is not a prediction of future performance; just as past hydrologic patterns (at least since modern records became available) are not necessarily predictive of future patterns in a world whose climate is changing. Nonetheless, retirement managers who use the statistical tools of portfolio theory are much more successful than those who ignore such considerations.[3] This paper shows water planners how to improve their performance by applying a mathematical adaptation from financial portfolio theory.

What Is Water-Supply Reliability and How Do We Measure It?

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

[3] Markowitz (1952) provided the first mathematically rigorous analysis of the value of diversification in investment portfolios. There have since been thousands of peer-reviewed articles on this subject.

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.

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% implies that supply will meet or exceed demand 19 years out of 20. This approach has the advantage of being simple. However, like most simple approaches, 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 definition because it allows a clear discussion of an important issue. The reliability percentages presented in the numeric illustration are intended 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.

How Do We Measure or Account for the Value of Reliability?

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 20 in any given year, but an investment in a new reservoir can reduce that chance to 1 in 21. 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 dollars per household per year (Griffin and Mjelde 2000, Carson and Mitchell 1987, Howe, et.al. 1994, Barakat and Chamberlin 1994), in year 2003 dollars. 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 (Raucher et al., 2005).

This approach, unfortunately, doesn't help answer our question. Customers don't need to know <u>how</u> 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 how it is achieved – has a value. Consequently, we developed a method for adjusting estimated average unit costs of water supply options, including conservation and end-use efficiency, to obtain "constant-reliability unit costs" that fairly compare supply options with different uncertainty characteristics. Our approach is quite different than that presented in papers that quantify the value of reliability (e.g., Howe, et.al. 1994). We do not quantify the value of reliability, but instead estimate the costs of options when they are sized to provide equal reliability.

Our 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 19 out of 20 years, on average. We call this a reliability level (R) of 95%. In the second step, they create an “apples to apples” comparison of options by adjusting average unit costs ($/unit of water) to get constant-reliability unit costs. The following example illustrates the method. The relevant math is presented in Appendix A.

Constant-Reliability Unit Costs Illustrated

Suppose a community is served by a run-of-the-river water supply. Figure 1 shows the maximum supply available from the river for human extractive purposes[4] each year as having a normal distribution. Although flow data usually follows distributions other than normal,[5] the normal distribution is useful for an illustration. The method presented in this paper can be applied to any statistical distribution.[6]

Insert Figure 1 here

[4] That is, in-stream flows required by law have been subtracted from gross flow before drawing this graph.
[5] The Pearson Type III distribution, for example, is often used for extreme events like floods and droughts.
[6] A reviewer of this paper remarked that a water system he once worked with had a hydrologic probability of annual shortage of only 1 in 3,000. However, it once experienced an ice clog in the main water treatment supply pipeline, and when operators went to activate a bypass valve to bring water from a backup source, the valve broke. At the worst point in time, only hours of treated water remained. Ideally, the probability of supply failure from events like this will be included in the statistical distributions representing supply from each option. But some uncertainty cannot be quantified.

In the normal distribution, the average supply is the most common amount. Low and high supplies are increasingly rare as they get further from the average. The relative "flatness" of the bell is described by the coefficient of variance (V): the standard deviation (SD) divided by the mean (A). The larger the coefficient of variance, the flatter the bell; and the more variable is the annual supply available for human extractive purposes in percentage terms.

The average (S_A) and critical (S_C) year supplies are represented by tick marks on Figure 1. We define critical year supply as the supply that is just large enough to satisfy critical year demand (D_C). Critical year demand is usually higher than average year demand because outdoor water use will increase when rainfall is below average or temperature is above average. Because maximum water available for supply will decrease when weather is drier, critical demand will always equal maximum water available for supply at some quantity. That quantity is the critical supply = critical demand shown in the Figure.

The figure shows critical supply at "Z (R)" standard deviations below average supply. This number is related to the reliability of existing supply, and will vary from system to system. A property of the normal distribution is that in about 5% of the years, flow will be less than the lower tick mark when it is located 1.65 standard deviations below the mean. That is, if Z(R) has value of 1.65, the figure shows a system reliability of 95% (shortage about 1 year in 20).

If the system had another reliability level, say 84%, the critical supply would be 1.00 standard deviation below average supply. The appropriate multiplier (e.g., 1.65, 1.00, etc.) for a chosen reliability level is found from a table (or formula) that is present in most statistics textook:[7] the area under one tail of the standard normal distribution (expressed as a number between 0 and 1) as a function of the standard normal variable. The relevant area under one tail is equal to one minus the reliability level (e.g., 1.00 - 0.95 = 0.05). The multiplier is equal to the value of the standard normal variable that is paired with this area (e.g., a tail area of 0.05 implies 1.65; a tail area of 0.16 implies 1.00).

Assume for our example that average annual maximum supply is 100,000 kilolitres (kL) and the standard deviation of annual maximum supply is 10,000 kL. This implies that the coefficient of variance of the supply is 10% (10,000/100,000). Under these assumptions, the lower tick mark in Figure 1 has value 84,000 kL per year. Suppose critical demand (and therefore the critical supply level) is projected[8] to grow to 90,000 kL over the next decade. As critical demand grows, reliability will decrease. The likelihood of a water shortage will increase from 1 in 20 (95% reliability) to 1 in 6 (84% reliability) as the part of the bell curve left of critical supply grows from 5% to 16%. One of the standard jobs of water managers is to prevent reliability from deteriorating too much. But how they augment supply or manage demand growth in response to their projection of demand growth affects reliability in ways that are often not fully understood or evaluated.

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[7] For example, Table A-3 in Khazanie (1990).

[8] A water demand projection is based on many factors, including projected growth in population and employment in the service area, changes in water distribution or use technologies, etc.

Suppose they want to maintain reliability at 95%. This is the first step in the planning process – chose a design reliability level based on the willingness of customers to pay for reliability. Second, the planner will consider various options for new supply and conservation measures sufficient to satisfy customer needs. The amount of physical water or conservation required to do this in a critical year is the difference between projected critical demand (PD_C) and existing critical demand (D_C). This has been labeled S_N in Figure 1, and in our example is 6,000 kL. If a supply option were to provide exactly this amount in every year, the planner should procure S_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.[9]

But if the yield from a water supply or conservation option is variable from year to year, the planner must procure enough of it to have S_N available 19 out of 20 years or reliability will fall. For example, when the chosen option is a surface water source, the amount available in an average year must be greater than S_N in order to ensure S_N is available in the critical, drier-than-average year.

The amount of water supply greater than S_N that has to be purchased depends on two factors. First, higher standard deviations of annual yield from the new surface water source imply that more water needs to be procured to ensure adequate water in a critical

[9] 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 author believes savings decay can be eliminated or made quite small by carefully specifying water-use efficiency devices.

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 S_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 S_N on average and still get S_N when the existing source is at its critical, drier-than-average level.

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 a low-quality water,[10] a new surface water supply, and outdoor conservation, all have an average unit cost of US$1.00 per kL. Ignoring reliability impacts, there is no financial difference between these sources. But a constant-reliability comparison of unit costs (Figure 2), as described below and mathematically in Appendix A, will show substantial financial differences.

Insert Figure 2 here

For the purpose of this illustration, we've assumed that advanced treatment is neither variable from year to year nor correlated with the existing water source. Consequently, a facility designed to deliver 6,000 kL per year[11] will satisfy the growth in demand in all years: average, critical, or otherwise. The average cost per unit is the same as the cost per unit in the critical and all other years.

[10] This could be seawater desalination, brackish water desalination, wastewater reclamation, or other processes. The average unit cost provided is generic and does not represent any particular technology.
[11] After allowing for normal interruptions in operation such as downtime for maintenance.

However, we've assumed that the new surface water supply is perfectly correlated with the existing surface water supply (has a similar pattern of wet and dry years), but is more variable. Then ensuring the 6,000 kL of new supply that will be needed in a critical year requires that the new source be sized to deliver more than 6,000 kL of water each average year, just as the old source was capable of providing 100,000 kL on average but only 84,000 kL with the desired level of reliability. If the new surface water source has a coefficient of variance of 20%, the water planner will need to procure 8,955 kL in an average year to ensure 6,000 in the 95% reliability design year (8,955 – 1.65 x 0.2 x 8,955 = 6,000). This in turn implies that each unit of water during drought will cost US$1.49 per kL on a constant-reliability benefit basis (US$1.00/ (1 – 1.65 x 0.2)). On a reliability-adjusted basis, this option is 49% more costly than it first appeared.[12]

If an outdoor water conservation measure were to save more water during dry weather, [13] its constant-reliability unit cost would be less than the assumed US$1.00 per kL. 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 $0.86 per acre-foot ($1.00/(1+1.65 x 0.1)). Since the current water source has been assumed to have a coefficient of variance of 10%, this 14% adjustment in unit cost is purely the result of the

[12] Stated differently, the utility could pay 49% more *per average unit* of water from the advanced treatment facility (US$1.49/US$1.00=149%) 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 6,000 kL in the critical year, so a *per unit* premium is justified.

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

counter-correlation. Conventional sensitivity analysis of the financial impact of the variability in yield from the option would miss this adjustment entirely.

Stated in terms of yield, ensuring 6,000 kL of water in the critical year would require outdoor conservation measures sized to deliver only 5,150 kL in an average year. The counter-correlation implies that during a drought where maximum supply from the current surface water source is 1.65 standard deviations below its mean, outdoor conservation would save 1.65 standard deviations above its mean, which equals 6,000 kL when the mean is 5,150 kL and the standard deviation is 515 kL (10% of the mean).

Conclusion

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 method presented in this paper is a powerful starting point for quantitative evaluation of the cost implications of uncertainty in water supply and demand management options. For the first time in the published water literature, it quantitatively evaluates these impacts on a portfolio rather than individual option 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 of options is a new dimension of overall yield and financial 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: Constant-Reliability Unit Cost Adjustment

Finding constant-reliability unit costs involves a two-step process. First, a constant-reliability-benefit standard must be specified. When supply is modeled as normally distributed, the standard normal variable (Z) will be a function of the reliability design standard (R) the planner chooses (e.g., 95%). Mathematically, this means that the annual average of the supply portfolio (P) minus the standard normal variable times the standard deviation of the supply portfolio must be equal to projected future critical demand:

(1) $A(P) - Z(R)SD(P) = PD_C$

The average supply of a portfolio is the sum of the average supplies of its components. If the portfolio has only two components[14] – existing supply (E) and a new supply or demand management program (N), the average supply of the portfolio is:

(2) $A(P) = A(E) + A(N)$

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

$x = A \; or \; N$

$n = the\; number\; of\; years\; of\; annual\; yield\; data\; for\; each\; option$

$Q_{xi} = the\; annual\; yield\; in\; year\; i\; from\; option\; x$

[14] The mathematics for three or more components is a straightforward extension of the equations shown here. However, there will not be a unique answer when three or more components are involved. Instead, one would find numerous pairs of components two and three that would combine with existing supply to satisfy projected demand and the reliability design standard. Choosing between these pairs would require a straightforward but journal-space-consuming third planning step – cost minimization – to select from among the many possible portfolios that satisfy demand with suitable reliability.

The standard deviation of a portfolio depends on the standard deviation and average of each component, the correlation between the components, and the percentage of water from each component. 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 components are involved is:

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

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

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

$$(4)\quad \sqrt{\left(\frac{A(E)}{A(P)}\right)^2 V(E)^2 + \left(\frac{A(N)}{A(P)}\right)^2 V(N)^2 + 2\left(\frac{A(E)}{A(P)}\right)\left(\frac{A(N)}{A(P)}\right) Rho(E,N)V(E)V(N)} = \frac{A(P) - PD_C}{Z(R)A(P)}$$

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

If one specifies a reliability standard (R) and projected critical year demand (PD_C), and knows the average existing supply (A(E)), the coefficients of variance of the existing and new sources of supply (V(E) and V(N)), and the correlation coefficient between supplies (Rho(E,N), equation (4) will contain only one unknown (A(N)). This is the average new supply required to ensure that the chosen reliability standard (e.g., 95%) 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.

For example, in this paper, we have specified R=95% (which implies Z(R) = 1.65) and PD_C=90,000 kL, and assumed A(E)=100,000 kL, V(E)=0.10, and D_C=84,000 kL. Then the A(N) that solves (4) under various assumptions about the supply options is:

Table A-1: Sample Calculations

Option	**V(N)**	**Rho(E,N)**	**A(N)**
New Surface Water	0.2	1.0	8,955 kL
Advanced Technology	0.0	0.0	6,000 kL
Outdoor Water Conservation	0.1	-1.0	5,150 kL

Finally, the constant reliability unit price for each option is found by multiplying the average unit cost for each option by the ratio of A(N)/ S_N. When A(N) equals growth in critical demand (S_N)[15], as with desalination and similar options, the average unit cost for that water supply option is also the constant-reliability unit cost. When A(N) is greater than or less than S_N , as with the surface water and outdoor conservation examples, the constant-reliability unit cost for each option is higher or lower than the average unit cost for that option, respectively.

[15] Recall that S_N = equals PD_C-D_C. In our example, 6,000 kL = 90,000 kL – 84,000 kL.

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Figure 1: Yield Uncertainty For a Run-of-the-River Water Supply

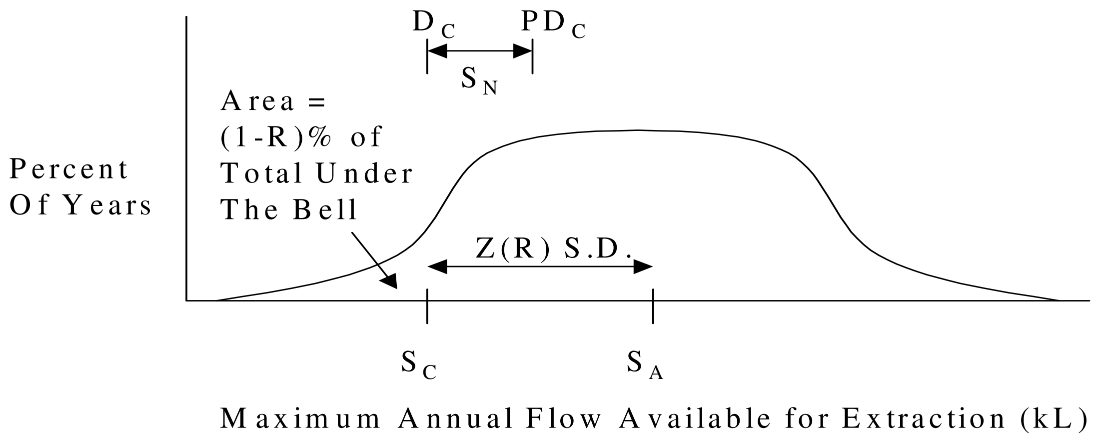

Figure 2: Illustration of Average and Constant-Reliability Unit Costs