# Improving Water Supply Reliability through Portfolio Management: Case Study from Southern California

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*Abstract:* - This paper applies Portfolio Theory to water resource management, presenting an independent analysis of the reliability of Southern California's water supply. Historically, Southern California has been heavily reliant on imported water supplies from the San Francisco Bay-Delta and the Colorado River Aqueduct. However, yields from these sources are hydrologically variable and constrained by complex water entitlements. The principle water resource agency, Metropolitan Water District (MWD), has embarked on an ambitious plan to reduce Southern California's reliance on these hydrological sources from 56% to 25% of the water supply portfolio by 2020 through developing alternative supply sources such as recycling, desalination and conjunctive groundwater use, as well as demand management programs. This study applies Monte Carlo stochastic inflow generation and a deterministic sequential approach to capture MWD's harvesting and storage dynamics. Long-run reliability of MWD's Year 2020 target portfolio is estimated, accounting for hydrological correlation between source regions and entitlement constraints. The results indicate that the target portfolio delivers high reliability (>98%), but that reliability was sensitive to portfolio composition. As the proportion of the hydrological sources increases within the portfolio, reliability declines markedly given 2020 parameters. This outcome implies that it is essential for Southern California to implement MWD's diversification plan (and continue the development of alternative supplies over the next 10 years) in order to maintain future water source reliability.

*Key-Words:* - portfolio theory, diversification, water supply, reliability, volatility, hydrological correlation

## 1 Introduction

The water supply manager's *raison d'être* is to provide a steady water supply given the variability of source inflows. In several respects this challenge is very similar to that of the company director seeking to deliver a steady dividend stream despite volatile earnings, or a financial manager aiming to deliver smooth returns on a share portfolio despite fluctuation in the stock market. As Kasower *et al.* (in review) [1] highlight, Portfolio Theory (from the Economics and Finance discipline) offers an approach (and a suite of tools) that can assist the water supply manager, not only in strategic tasks (such as the decision to procure additional supply) but also in operational tasks (e.g. active intra-system transfers to optimize reliability within the existing suite of infrastructure). Kasower *et al.* (in review) discuss the application of Portfolio Theory to water resource management from an economist's viewpoint: the objective of this paper is to present the portfolio approach to managing water supply systems from a hydrologist's perspective.

The case for portfolio management has never been more compelling in the water sector. In an era of seemingly rolling droughts, population growth and the spectre of climate change all applying negative pressures on the available water resource, the task of managing shrinking supplies against increasing and competing demands is acute in many parts of the world. Moreover, many water agencies have responded to these water source pressures by diversifying their supplies away from traditional, hydrologically-dependent sources, embracing 'alternative' supplies such as recycling and desalination. Whereas a water supply manager in the past was typically confronted with the coordinated management of a network of surface water reservoirs, the modern water supply manager in California and Australia (to name two regional examples) must now contend with an array of water assets: recycled water schemes, desalination plants, conjunctive groundwater use, surface water reservoirs and demand management programs. The modern water supply manager must therefore be well-versed in thoroughly economic (as opposed to hydrological) management strategies including water trading, negotiated settlements on water rights, purchases of water shortfalls on the spot market, and hedging using water market futures and options instruments. In short: to meet expectations of supply reliability, the modern water supply manager must be a sophisticated portfolio manager, as well as a competent hydrologist.

## 1.1 Case Study: Southern California's Water Supply

Southern California's water supply system is a particularly challenging exercise in portfolio management, well-suited to case study analysis. The greater Los Angeles region is home to over 18 million people, with a powerhouse regional economy. Due to its semi-arid climate and geography, LA lacks abundant local surface water supplies, and has for many decades been heavily dependent on imported water [2], conveyed large distances *via* two main sources:

- Colorado River Aqueduct (CRA) – constructed in the 1930s, and conveying water 242 miles interstate from Arizona to LA;
- State Water Project (SWP) – constructed in the 1960s and conveying water 444 miles from the San Francisco 'Bay-Delta' of the Sacramento and San Joaquin river systems.

The primary agency tasked with maintaining supply-demand balance in Southern California is the Metropolitan Water District (MWD). MWD is a consortium of 26 cities and water districts that provides drinking water to parts of Los Angeles, Orange, San Diego, Riverside, San Bernardino and Venture counties [3].

### 1.11 Planning for Reliable Future Supply

Under California's complex water rights, MWD has a variable allocation up to a maximum of 2,011,500 AF *per annum* from the SWP. MWD also has a fixed annual allocation of 550,000 AF from the CRA, plus a variable component up to 662,000 AF, contingent upon a surplus being declared by the Federal Secretary of the Interior. Both of these surface water sources are inherently risky: in the last 8 years, the SWP has been able to meet 100% of MWD's entitlement in only one year (2006), and in two years (2001 & 2008), the allocation has been less than 40% of the full entitlement. To immunize itself against the risk of a supply shortfall, MWD has embarked on an ambitious *Integrated Resource Plan* (IRP) [4] to diversify its water source portfolio, in particular by reducing overall exposure to these risky surface water sources from 56% in the 1990s to 25% by 2020. This portfolio composition is being achieved through strong investments in conservation (demand management), 'local sources' including recycling, desalination and groundwater conjunctive use, and significantly expanded local storage for surplus flows. As MWD's 2020 demand is forecasted at 6,793,793 AF, the target volumetric contribution in 2020 of the combined SWP/CRA surface water source is 1,698,448 AF.

MWD's past practice involved harvesting the maximum allowable allocations from the SWP and CRA, and *consuming* these volumes each year; there was no 'surplus' to save. The commissioning in 1999 of Diamond Valley Lake (DVL - the largest reservoir in Southern California at 800,000 AF) increased MWD's storage capacity for SWP and CRA flows from 285,000 AF to a substantial 1,085,000 AF. MWD's IRP strategy involves continuing to harvest the full allowable allocation each year from SWP and CRA; but by reducing the maximum annual volume consumed from these sources to 1,698,448 AF, any surplus flows harvested can be stored locally to offset years where harvested volume is less than 1,698,448 AF. MWD's corporate intent as stated in the IRP is to deliver 100% reliability by 2020. The purpose of this study was to independently examine the reliability consequences of this surplus storage strategy from a Portfolio Theory perspective, taking account of hydrological correlation between the SWP and CRA, as well as existing entitlement constraints.

## 1.2 Portfolio Theory Fundamentals

Equation (1) captures a fundamental principle of Portfolio Theory: any two sources (assets) with a positive correlation will produce a combined source with higher variance than either of the two sources individually. In short: the volatility of two positively correlated sources amplifies when combined.

$$\sigma^2(X+Y) = \sigma^2(X) + \sigma^2(Y) + 2\rho\sigma(X)\sigma(Y) \qquad (1)$$

where $\sigma^2$ is variance and $\rho$ is the correlation coefficient (Table 1).

**Case 1: $0 < \rho < 1$ Synchroneity**

While undesirable from the viewpoint of the water supply manager, for supply systems with a strong reliance on traditional surface water supplies, volatility amplification can be difficult to avoid when drawing water from regional river systems that exhibit a degree of hydrological correlation. For example, the two major river systems that feed the San Francisco Bay-Delta (the Sacramento and the San Joaquin) exhibit a correlation coefficient of 0.915 (based on the 103-year record of total annual 'natural'[1] flows, logarithmically transformed). A water supply strategy that aimed to improve reliability through combining proportions drawn from these two sources would be limited in its effectiveness due to this high correlation.

**Case 2: $\rho = 0$ Independent**

If two sources are statistically independent (i.e. exhibit a correlation coefficient of or close to zero), the variance of their combination will be the straight sum of the two individual variances. Combining independent sources gives a neutral outcome in terms of reliability.

**Case 3: $-1 < \rho < 0$ Reverse Synchroneity**

Of most interest to the water supply manager is the case of assets that are *negatively* correlated. Over time, inflows from these assets tend to move in opposite directions – i.e. when flows from one source are high, flows from the other source are low, and *vice versa*. From a reliability viewpoint, this is the ideal diversification scenario, as the timing of flux in the two sources provides a mutual buffer, resulting in a comparatively stable supply that minimises extremes of either surplus or deficit.

How does the water supply manager achieve this elusive negative correlation in managing the sources of a supply system portfolio? The keys are: (1) recognizing the risk properties of each source and (2) recognizing the degrees of freedom (if any) available to the operator of a given source. The Southern California water portfolio (see below) can be divided into two risk types, shown in Table 2.

**Table 2: Water portfolio analogues for risky and riskless assets.**

| Source Type: | Volume supplied is: | Example: |
|---|---|---|
| Risky | hydrologically dependent | surface water reservoir inflows |
| Riskless | hydrologically independent | recycled water; desalination |

Here, risk is explicitly defined as hydrological uncertainty. Finance literature uses the term 'market risk' to refer to overall flux in a given stock market, which is beyond the control of an individual investor. The correlation of each individual stock with an appropriate general market index is calculated and used as the basis to select stock combinations that buffer against market flux. Returning to the water portfolio scenario, if the hydrological condition of the dominant surface water source is defined as the benchmark, water supply managers seeking to diversify their portfolio should select sources that are as negatively correlated with this hydrological condition as possible. There are at least two means to accomplish this:

- **Actively manage** a riskless source to directly offset hydrological condition. For example, operating a desalination plant when reservoir inflows are low, and *not* operating the plant when inflows are high will produce a negative correlation that optimizes reliability for a given yield target, *ceteris paribus*. By comparison, operating a desalination plant continuously, regardless of hydrological condition (i.e. independently), will at best give a neutral correlation of zero, implying a suboptimal reliability outcome for a given yield target.
- **Passively manage** storage infrastructure to achieve the same effect. For example, if storage capacity is sufficient, surplus hydrological inflows can be stored, and calls on this storage made when hydrological inflows are low. The portfolio decision here concerns the scaling of the storage capacity in order to deliver a target level of reliability (expressed as % of years demand can be met). MWD's investment in DVL is an example of this latter approach.

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[1] 'Natural' flows (i.e. prior to anthropogenic impoundment and extraction) are here determined through retrospective modelling undertaken by the California State Department of Water Resources.

For the Southern California case study, 'market risk' is here defined as the hydrological variance of inflows to the Bay-Delta system (as the largest surface water component of the portfolio). Relating the concept of reliability to market risk, a key comparative metric can be derived. A well-performing water supply portfolio is one that *yields robust reliability results in the face of market fluctuation.* This is assessed using model simulation.

## 2 Modelling the Reliability of MWD's Portfolio

A sequential Monte Carlo model was constructed to specifically examine the risky surface water sources comprising MWD's portfolio (Table 3). The model combined a Monte Carlo approach to generate surface water inflows, and a deterministic sequential approach to capture MWD's harvesting and storage dynamics in response to the given inflows in continuous time. In order to test the robustness of MWD's strategy for managing its risky surface water sources, the simulation was conducted over 1,000 years, exposing MWD's operations to the full range of hydrological variation observed in the historical record. Reliability is calculated at the completion of the simulation, and is defined as the percentage of years that the combined SWA/CRA surface water source (supported by the surplus storage strategy of Diamond Valley Lake) can meet its 1,698,448 AF target (i.e. a 25% contribution to the 2020 portfolio supply of 6, 793,793 AF). A 103-year historical record of natural inflows to the Bay-Delta is available from the California State Department of Water Resources. These total annual flow data were first tested for independent random sampling. A simple plot of $x_{i-1}$ *versus* $x_i$ revealed no systematic serial correlation between successive values in the time series (i.e. the scatter plot was random, without a significant regression gradient supporting the hypothesis of serial correlation). Hence it was concluded that each year's sampling from the underlying distribution was random and independent of previous years' values (i.e. the time series of total annual flow was assumed to exhibit no inter-annual persistence). Having established independence, it was found that the Bay-Delta inflows satisfied a Log-Normal (LN) distribution – the logarithmically-transformed series passed the Shapiro-Wilk normality test. LN distributions are common in hydrology, and as Portfolio Theory relies on the assumption of Normally-distributed returns [5], the logarithmically-transformed Bay-Delta data are consistent with a portfolio framework. The mean of the logarithmically-transformed series is 3.075 (corresponding to 21.65 AF), and standard deviation is 0.466. Having determined these parameters, it was then possible to generate a stochastic series of 1,000 years by random sampling from a LN distribution with these parameters. The next step was to model the correlation structure of CRA water against Bay-Delta inflows. The desired outcome is a conditional distribution of CRA hydrological year types, given the hydrological year type of Bay-Delta inflows. To facilitate this, the stochastically generated Bay-Delta inflows were classified into hydrological year types according to Table 4. Next, an *a priori* conditional distribution of CRA hydrological year types given Bay-Delta hydrological year type was developed (Table 5), assuming a moderate degree of regional hydrological correlation. For example, given a Bay-Delta hydrological year type of 'Below Normal', there is a 60% chance that hydrological conditions in CRA dependent regions would also be 'Below Normal'; a 15% chance that CRA regions would be 'Normal' in that same year; a 7.5% chance that CRA regions would be 'Above Normal', etc. This conditional distribution was then used to determine the corresponding CRA hydrological year type for each year in the given 1,000 Bay-Delta inflow sequence. A further step is to translate CRA hydrological year type into a probability of surplus from this source (of which MWD is eligible to extract up to 662,000 AF p.a.). It was assumed that at full development (under *ceteris paribus* conditions, including crop type and area under irrigation), the remaining California CRA water right holders (irrigation consortia) would generate a surplus of 40% of 662,000 AF in 'Above Normal' hydrological years, 662,000 AF in 'Wet' hydrological years, and zero surplus in all other year types (i.e. it is assumed the other water right holders would claim their full allocation in 'Dry', 'Below Normal' and 'Normal' hydrological years). Having determined the source availability in each year of the model, the respective extraction rules were applied to determine MWD's harvest volume each year. Finally, this harvested volume sequence is routed through a simple model of sequential reservoir storage (assuming 1,085,000 AF capacity incorporating DVL). In each year of the simulation, the annual harvested volume is compared to the fixed demand of 1,698,448 AF to be serviced from the combined SWP/CRA source. Where harvested volume is greater than demand, the residual volume can be stored in the reservoir as a surplus, up to the maximum storage capacity. Where annual harvested volume is less than demand, the model attempts to call the deficit from the reservoir. In years where reservoir storage is insufficient to meet this call, a residual deficit is recorded. The number of years with this residual deficit is used to calculate reliability.

## 3 Results

Assuming MWD's 25% target for the portfolio contribution from the SWP/CRA sources, the model yielded a reliability of 98.3% (i.e. in only 17 of 1,000 years was there a residual deficit that could not be serviced from storage).

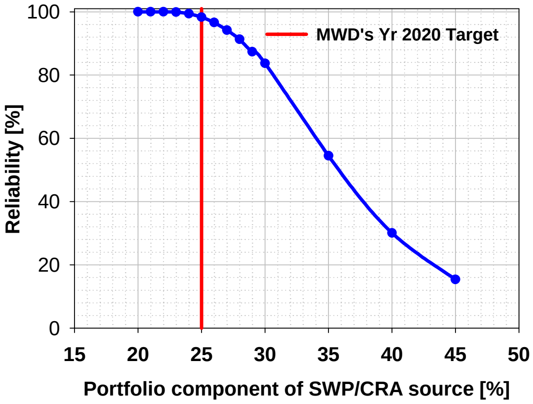

**Fig. 1: Reliability of MWD's Yr 2020 supply with increasing portfolio exposure to SWP/CRA surface water sources.**

However, if the 25% assumption is relaxed, and MWD's portfolio relies on larger percentage contributions by the SWP/CRA source, reliability rapidly declines (Fig. 1). Reducing dependence on this source to only 30% results in reliability dropping to 83.7%. This result clearly reinforces the need to concentrate efforts over the next 10 years to develop alternative sources such that MWD can reduce the SWP/CRA surface water component of its portfolio down to 25%.

## 4 Conclusion

In Portfolio Theory terms, Metropolitan Water District's water supply portfolio for Southern California can be divided into two components:

- Risky - hydrologically dependent surface water sources, and;
- Riskless - hydrologically independent sources such as recycling and desalination.

MWD possesses harvestable rights from two key surface water sources: the State Water Project, which diverts flows from the Sacramento/San Joaquin Bay-Delta in Northern California, and the Colorado River Aqueduct, which diverts flow from interstate. The long run reliability of MWD's portfolio is determined by the extent of exposure to the risky component, and the degree of correlation between the individual surface water sources comprising the risky component. Overlaid on these fundamentals are specific entitlement rules that constrain the maximum harvestable volume from the SWP and the CRA. To ensure reliability in 2020, MWD has a broad strategy to reduce the risky proportion of its portfolio (by developing alternative supplies) from 56% to 25%. The specific strategy for managing the risky component is to consume a fixed quantity from the surface water harvested each year, and (through the construction of a large additional storage asset, the Diamond Valley Lake), store surpluses to draw upon during years when harvested volume is less than the fixed quantity consumed from this source. This study modelled the reliability of MWD's projected 2020 water supply profile, based on: (i) the observed distribution of Bay-Delta inflows; (ii) the assumption of a moderate degree of regional hydrological correlation between these inflows and regions dependent on the CRA, and (iii) the constraints imposed by MWD's current water entitlements. The modelled results indicate that MWD's projected 2020 portfolio delivers a high degree of reliability (>98%). Reliability, however, was sensitive to the fixed quantity of annual consumption from the risky component – reliability drops dramatically as this fixed quantity increases from the targeted 25%. If the risky component of MWD's portfolio is 30%, reliability drops to ~84%. The implication of this portfolio analysis is that it is imperative for MWD to achieve the targeted reduction in exposure to the risky surface water sources in order to meet its reliability objectives.

*References:*

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**Table 1: Correlation of water sources: water supply portfolio consequences.**

| | **Correlation** | | **Combined Source Standard Deviation:** | **Reliability Effect for Water Supply Portfolio:** |
|---|---|---|---|---|
| | **Type** | **Coefficient ($p$)** | | |
| **Case 1** | positive | $0 < p < 1$ | portfolio SD <= SD of individual assets | not ideal |
| **Case 2** | zero (independent) | $p = 0$ | portfolio SD << SD of individual assets | neutral |
| **Case 3** | negative | $-1 < p < 0$ | portfolio SD <<< SD of individual assets | desirable |

**Table 1: Comparison of attributes-MWD's IRP2004 modelling results and this study's model.**

| **Factor:** | **MWD Modelling Results presented in IRP(2004)** | **This Study's Model** |
|---|---|---|
| Inflow sequence | deterministically sampled | stochastically sampled |
| Simulation period | 11 years | 1000 years |
| Demand & supply | **Variable** (i.e. evolve over the course of the simulation to reflect rising aggregate demand with population growth, and progressive development of planned schemes to achieve preferred resource mix of IRP 2003) | **Fixed** at 2020 demand and final asset configuration of IRP 2003 |
| **Assumptions:** | | |
| ***Water Quality*** constraint SWP:CRA = 1:3 | captured at operational level | captured in aggregate |
| complex intra-system operational transfers | captured | not captured |
| ***System Losses*** through seepage, evaporation | captured | not captured |
| ***Surplus Storage Capacity*** | • MWD Assets: Diamond Valley Lake + Lake Matthews + Lake Skinner = 866,000 AF<br>• Partner Assets: SWP terminal reservoirs = 219,000 AF<br>• TOTAL = 1,085,000 AF | |
| ***Water Rights: SWP*** [1994 Bay-Delta Accord] | Exact: Specific pumping constraints captured at operational level | Approximate: SWP entitlement =80% of Sacramento-San Joaquin unimpeded inflows |
| ***Water Rights: CRA***<br>[1922 Colorado River Compact] | *Quantification Settlement Agreement* assumed (i.e. 5th property right converted from variable to fixed entitlement) | Existing property right conditions (ie. fixed base allocation [4th property right] with variable surplus [5th property right]) |

**Table 2: Definition of hydrological year type, based on percentiles of total annual natural flow.**

| | **Hydrological Year Type:** | | **Percentile Range:** |
|---|---|---|---|
| 1 | D | Dry | 0th-20th |
| 2 | BN | Below Normal | 21st-40th |
| 3 | N | Normal | 41st-60th |
| 4 | AN | Above Normal | 61st-80th |
| 5 | W | Wet | 81st-100th |

**Table 3: *A priori* conditional distribution of CRA hydrological year type given Bay-Delta year type.**

| | **San Francisco Bay-Delta Hydrological Year Type** | | | | | |
|---|---|---|---|---|---|---|
| | | **D** | **BN** | **N** | **AN** | **W** |
| **Colorado Hydrological Year Type** | **D** | 60.0% | 15.0% | 5.0% | 2.5% | 1.0% |
| | **BN** | 20.0% | 60.0% | 15.0% | 7.5% | 4.0% |
| | **N** | 15.0% | 15.0% | 60.0% | 15.0% | 15.0% |
| | **AN** | 4.0% | 7.5% | 15.0% | 60.0% | 20.0% |
| | **W** | 1.0% | 2.5% | 5.0% | 15.0% | 60.0% |
| | **TOTAL** | 100% | 100% | 100% | 100% | 100% |