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Performance evaluation of a water resources system under varying climatic conditions: Reliability, Resilience, Vulnerability and beyond

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SUMMARY

As introduced by Hashimoto et al. (1982), Reliability, Resilience, and Vulnerability (RRV) metrics measure different aspects of a water resources system performance. Together, RRV metrics provide one of the most comprehensive approaches for analyzing the probability of success or failure of a system, the rate of recovery (or rebound) of a system from unsatisfactory states, as well as quantifying the expected consequence of being in unsatisfactory states for extended periods. Assessing these comprehensive metrics at current (baseline) and future scenarios provide insight into system performance in changing or varying climatic conditions. Such an approach makes it possible to analyze different scenarios that could include specific mitigation or adaptation strategies to accommodate a varying climate. The method requires a subjective decision defining what constitutes an "unsatisfactory state" depending on acceptable risks.

The application of this methodology is demonstrated using Tampa Bay Water's Enhanced Surface Water System. In this case, for each scenario, a thousand ensembles of 300-years of monthly stream flow traces were first generated by a multi-site rainfall/runoff model. Second, a novel nonlinear disaggregation algorithm was developed to translate monthly outputs into daily values. The daily stream flow traces and their derivatives are then used to drive complex operational models that produce several system variables (e.g., permitted river withdrawals, reservoir storage volumes, and treatment plant production rates) at different locations. Outputs from the operational model were then used to define criteria over which the RRV and other metrics were evaluated. Several mitigation scenarios such as treatment and reservoir capacity expansion, as well as adaptation through operational changes were considered to evaluate system performance under varying climatic conditions. The approach highlights the benefits of comprehensive system performance metrics that are easy to understand by decision makers and stake holders and demonstrates the implementation of seemingly intractable ensemble size and simulation length in a distributed computing environment.

1. Introduction

As water resources systems become increasingly complex, one of the challenges is how to assess and quantify performance using an approach that will capture a variety of system uncertainties. Most complex water supply systems do not have baseline performance analysis conducted in a comprehensive fashion. Thus, the value of incremental systems expansion, significant operational changes, or "no-regret" options (i.e., low or no capital cost improvements) is difficult to quantify. In addition to hydrologic process and/or input uncertainties, and climate variability adds another set of challenges to water supply systems. Some major utilities have some mix of supply sources such as direct surface water diversions, ground water extractions, aquifer storage and recovery systems, on site or offsite reservoirs, or desalinated sea/brackish water sources. Each source has its own set of uncertainties that are difficult to analyze within the entire system. The issue is quantifying risk associated with water shortages for these complex systems. If left unchecked, examples of the consequence of risks are: frequency and duration of supply sources depletion (e.g., empty reservoir) while demand is still high and, hence, exceeding regulatory limits on wellfield pumpage to compensate for loss in surface water; actual operational costs exceeding budgeted costs as more expensive but "drought proof" sources such as desalinated sea water are used but not planned for, and hence, water rates rising faster than planned.

Cost increase to provide equivalent service confronts resistance from the utility customers who shoulder costs of additional expansions/adaptations that are needed to adapt to changing

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climatic conditions. Water utility managers face the delicate task of preparing for changing and/or varying climatic conditions versus capital improvement programs (CIPs) needed to bridge gaps between future demand and supplies. In order to manage these risks, performance evaluations of current systems using a variety of metrics are needed to determine baseline conditions as well as future scenarios. Some of the factors that influence these water management decisions include regulatory (i.e., water use permit change), growth in demand, or changing/varying climatic conditions. Such methodological approach lets one understand the value of an incremental adaptation technique that would be needed in future.

One of the most widely used water resources system performance measures are those introduced by Hashimoto et al. (1982) (Maier et al., 2001; Fowler et al., 2003; Sandoval-Solis et al., 2011). It consists of the use of Reliability, Resilience, and Vulnerability (RRV) metrics. Each criterion assesses different aspects of water resources systems and as such these criteria complement each other. It is important to note that these criteria, as defined in literature, may not be applicable as-is to all practical cases and may need to be modified on case by case basis. At the heart of applying these metrics is the identification and quantifications of what constitute an undesirable situation based on associated level of risk posed to the water resources system as a whole. In the past, establishing RRV metrics using a Monte-Carlo based framework like the one reported here have been limited because of the huge computational burden if one were to solve it for realistic size of problem (Maier et al., 2001). Hence, many authors were forced to use approximate solutions or simplify its application significantly. It will be shown how these computational limitations are circumvented using a cluster of computers in a distributed computing system. A review of applications of RRVs in water resources is given in Blackmore and Plant (2008) and Wang and Blackmore (2009).

2. Performance criteria

Let X_t, $t = 1\ldots,T$, be a simulated time series of a parameter of interest, such as supply sources or reservoir level, used as an indicator of a system's performance when compared with a criterion, C. The comparison would then indicate the system being in either satisfactory, S, or unsatisfactory, U, states. Defining a state variable Z, where,

$$If\ x_t \in S, Z_t = 1\ else\ X_t \in U\ and\ Z_t = 0 \tag{1}$$

Let W_t be an indicator for the transition from unsatisfactory to satisfactory state such that

$$W_t = \begin{cases} 1 & if\ X_t \in U\ and\ X_{t+1} \in S \\ 0, & otherwise \end{cases} \tag{2}$$

Reliability, Resiliency, and Vulnerability are defined as follows (Hashimoto et al., 1982 and Fowler et al., 2003):

$$\text{Reliability} \quad C_R = \frac{\sum_{t=1}^{T} Z_t}{T} \tag{3}$$

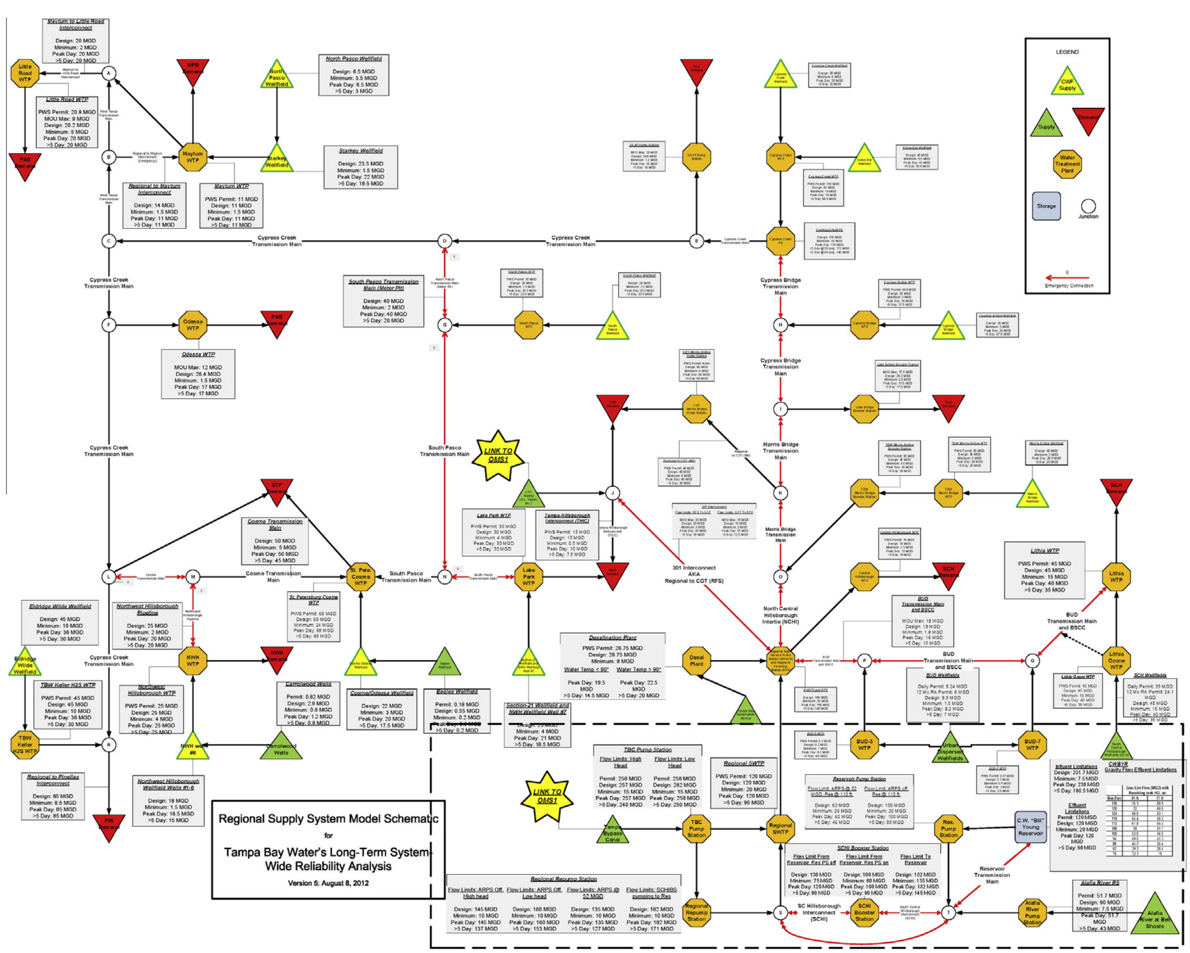

Fig. 1. Study area schematic. Rectangular section is the subject of this study presented in Fig. 2.