Performance criteria for multi-sourced urban water systems

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ABSTRACT
Urban water management is now constrained by rapid population growth, climate change and variability and their prediction uncertainty and above all by resource limitations. The ability of water systems to operate satisfactorily under these constraints is an important system characteristic. Performance criteria described in terms of mean yield and variance are not sufficient. Therefore risk-based performance criteria for urban water systems are proposed. These criteria are risk and reliability, resiliency and vulnerability. The quantitative estimation of these criteria and their implications for water resources planning are expected to improve the long term sustainability of water systems. The relatively new concept of integrated urban water management encourages water source diversification. This includes the use of rainwater, stormwater and treated wastewater. In this paper, multi-sourced urban water systems and their risk-based performance criteria have been proposed.

KEYWORDS
Climate change, performance, resilience, reliability, risk, water systems

INTRODUCTION
A water system's operational status can be stated as being either satisfactory (supply > target demand) or unsatisfactory (supply < target demand). These status levels are also known as the operational and failure status, respectively. One way in which a water system can fail is through structural damage of system components (dams, supply mains, etc.) from catastrophic floods, earthquakes or even from deficient design. The second way is through operational failure due to long sustaining droughts, increased water demand or climate variabilities and uncertainties. This paper focuses on operational failure of water systems. Simple annual, seasonal or monthly mean yield and variance are widely used performance criteria. But these criteria are unable to define the frequency, duration and severity of poor performance. Hashimoto *et al.* (1982) illustrated this, as shown in Figure 1. In presence of climate variabilities and their prediction uncertainties, it is expected that extreme climate events will be increased (Chowdhury and Beecham, 2010; Beecham and Chowdhury, 2010). Risk-related performance criteria mentioned in this paper are:

- Risk and reliability
- Resilience
- Vulnerability

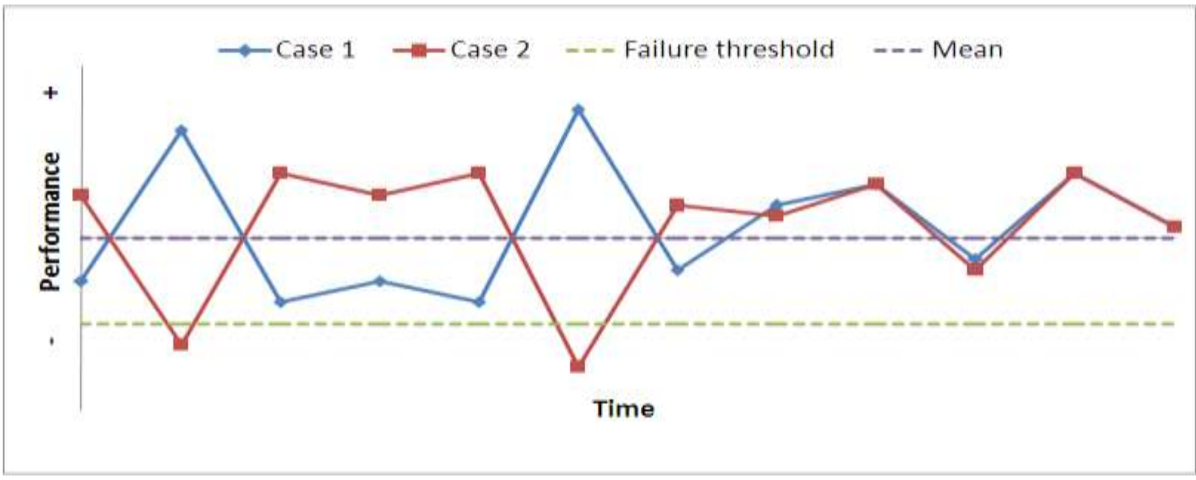

Figure 1: Illustration of simple performance indicators: mean annual yield and variance. In the performance scale, "+" indicates high or desirable conditions and "–" indicates poor or undesirable conditions. For both Cases 1 and 2, mean and variance are similar but for Case 2, the system fails twice by exceeding the failure threshold (adapted from Hashimoto *et al.*, 1982).

Risk and Reliability

Reliability can be expressed in terms of the expected number of failures in a specified period of time. The probability of failure or expected number of failures is the system's risk (Moy *et al.*, 1986). At any time (t), a water system's operational output can be either in a satisfactory state (S) or in a failure state (F). If sequences of these operational states are recorded as a random variable (X_t), then the reliability (α) of the system can be defined as the probability that the system is in a satisfactory (S) state. Risk and reliability are opposite in sense. Risk is the probability that the system is in a failure state. Therefore both reliability and risk indicate a probability (in percentage) of whether a system is likely to be in a satisfactory or failure state. Neither state provides any information about failure severity and their consequences (Hashimoto *et al.*, 1982). For example, the risk for a water supply reservoir is the total number of deficits (number of times a reservoir's supply is less than a target demand) divided by the total period of analysis. The magnitudes of deficits are not considered. For historical yields (Y_t) and target demand (D_t) of a water system, reliability (α) and risk (r) can be expressed as follows:

$$S_t = 1|Y_i > D_i \quad (1)$$
$$F_t = 0|Y_i < D_i \quad (2)$$
$$X_t = [S_t, F_t] \quad (3)$$
$$\alpha = P[X_t \in S_t] \quad (4)$$
$$\alpha = \lim_{N\to\infty} \frac{1}{N}\sum_{t=1}^{N} S_t \quad (5)$$
$$r = P[X_t \in F_t] = 1 - \alpha \quad (6)$$

where N is the total number of states and P is the probability.

Resilience

The concept of resilience was first introduced for ecological systems. Resilience can be defined as the rate of change of a system's condition from a failure state to a satisfactory state, which indicates how quickly a system recovers once a failure state has occurred. A resilient system is one that can recover from a deficit (supply < demand) condition to an operational state in a short time. Moy *et al.*, (1986) have defined the resilience of a water reservoir system in terms of the maximum number of consecutive deficits prior to recovery; the larger the number, the lower the resilience. For a consecutive failure period (T_F), Hashimoto *et al.*, (1982) have defined resilience as the inverse of the expected value of T_F. From X_t (Equation 3), the transitional probability (ρ) from a satisfactory state (S) to a failure state (F) can be estimated as:

$$Z_t = 1 | X_t \in S, X_{t+1} \in F \quad (7)$$
$$Z_t = 0 | X_t \in F, X_{t+1} \in S \quad (8)$$
$$\rho = P[X_t \in S \, | X_{t+1} \in F] = \lim_{N\to\infty} \frac{1}{N} \sum_{t=1}^{N} Z_t \quad (9)$$

The average failure duration (also known as the sojourn time in failure states) during N periods can be estimated as:

$$\overline{T_F} = \frac{A}{B} \quad (10)$$

where A is the total failure time and B is the number of transitions to a failure state.

$$\overline{T_F} = \lim_{N\to 0} \frac{\frac{1}{N}\sum_{t=1}^{N}(F_t)}{\frac{1}{N}\sum_{t=1}^{N} Z_t} = \frac{r}{\rho} = \frac{1-\alpha}{\rho} \quad (11)$$

The inverse of $\overline{T_F}$ is the system's average recovery rate or the measure of resiliency (γ).

$$\gamma = \frac{1}{\overline{T_F}} = \frac{\rho}{r} = \frac{\rho}{1-\alpha} \quad (12)$$

An illustrative example of resilience is shown in Figure 2. Resilience can be shown as the recovery rate from a failure state to a satisfactory state. As the rate increases, the system's resilience is also increased.

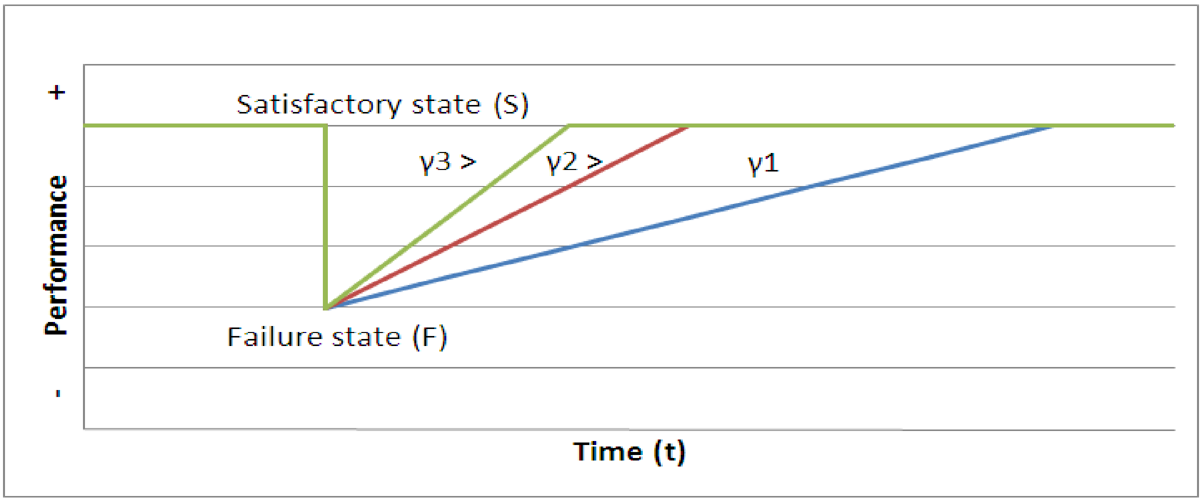

Figure 2: A conceptual example of a system's resilience. System performance falls into a failure state and then the recovery rate or slope of recovery to a satisfactory state is the measure of resilience (γ). The higher the recovery rate, the higher the resilience.

Vulnerability

When a system falls into a failure state, the vulnerability is the performance criterion that measures the severity of that failure state. How long a failure state persists (T_F) is not a measure of vulnerability but rather how bad or severe is the impact. For reservoir operation, vulnerability can be defined as the magnitude of the largest deficit (the difference between demand and supply) during the operation period. According to Hashimoto *et al.*, (1982) vulnerability can be estimated as:

$$x_t \in F \quad (13)$$

$$v = \sum_{t=1}^{X_t \in F} s_t e_t \quad (14)$$

where v is vulnerability, s_t is a numerical indicator of severity for failure state F_t and e_t is the probability of the most unsatisfactory failure state.

MULTI-SOURCED URBAN WATER SYSTEMS

In the presence of rapid population growth in urban areas, reduction of physical water resources and climate change and variabilities and their prediction uncertainties, it is acknowledged that urban water sources need diversification. This includes incorporation of rainwater, stormwater and treated wastewater to supplement the mains (potable) water supply through a second or third reticulation system. In Australia, several major cities have already implemented rainwater harvesting and wastewater reuse schemes in order to reduce mains water demand. In south east Queensland, it is mandatory to achieve 70 kL/year of mains water savings through use of alternative water sources (DIP, 2008). Therefore it is expected that urban water systems will be more multi-sourced in the future. A conceptual diagram of a multi-sourced urban water system is shown in Figure 3.

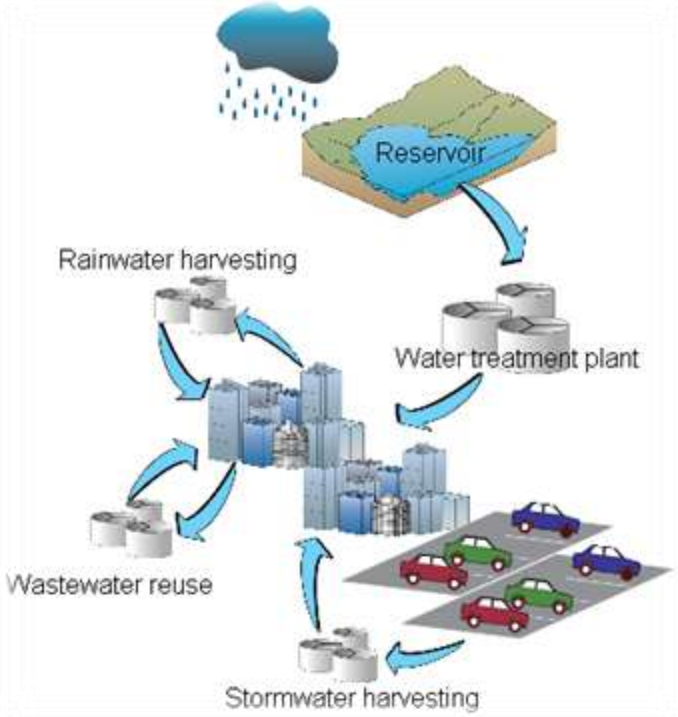

Figure 3: A schematic view of a multi-sourced urban water system. Three alternative water sources are used to supplement the mains water supply system.

AN EXAMPLE ANALYSIS

A conceptual case study of rainwater harvesting is developed in this paper as an example analysis of risk-related performance criteria and the results are compared to conventional criteria. Figure 4 shows the rainwater harvesting scheme in a household. The system is located in Queensland in Australia. The mean annual rainfall during the period 1985 to 1999 was 1589 mm. A variable size rainwater tank (2000 L to 6000 L) is connected to the roof area of 200 m^2. Harvested rainwater pumped from the tank are used for toilet flushing and gardening purposes. It is assumed that the household has four occupants. The total water consumption is assumed to be 1316 L/household/day, garden irrigation and toilet flush water requirements are 50% and 12% of total consumption, respectively (Young, 2005). The US EPA Stormwater Management Model (SWMM) has been used to estimate roof runoff to the rainwater tank through a circular downpipe of diameter 0.1 m. The tank height is considered to be 2 m for all tank volume sizes. The SWMM model was calibrated for some catchments in south east Queensland in Australia (Chowdhury et al., 2010) and similar model parameters are used in this example analysis. A pump is connected to the tank where the pump rate (816 L/day) is equivalent to the gardening and toilet flush water demand. A circular orifice (0.1 m diameter, with a discharge coefficient of 0.65) is connected to the top of tank to convey overflow from the tank to the stormwater drain. Continuous 6 minute rainfall data from 1985-1999 (collected by the Australian Bureau of Meteorology) have been used. The pump commences operation when the water depth exceeds 0.1 m in the tank. Figure 5 shows the simulated rainwater tank water depth time series for the year 1990, as an example.

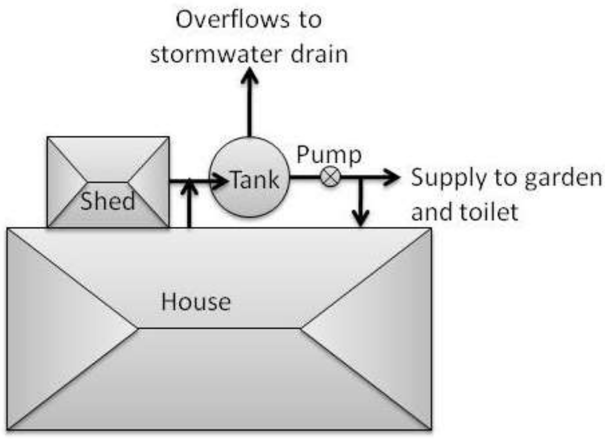

Figure 4: Schematic view of the rainwater harvesting system at a household level

The mean annual yield, variance (ratio of standard deviation to the mean annual yield) and average volumetric reliability (ratio of yield to demand) are conventional performance criteria. Both conventional and risk-based performance criteria (except for vulnerability) have been estimated for various tank sizes. The results are reported in Table 1. Mean annual water demands for gardening and toilet flushing have been assumed to be 240 kL/year and 58 kL/year respectively (Young, 2005). Table 1 shows that for a single sourced water supply system (rainwater harvesting as an example in this study), an increase in tank size is not effective in terms of increasing the resilience of the scheme. From Figure 5, it is observed that both water level and the average sojourn time in the tank generally follow the rainfall pattern. Therefore in order to increase the resilience of the scheme, it is necessary to incorporate other supply sources into the scheme. Alternatively, it can be said that incorporation of alternative water sources (such as rainwater, stormwater and greywater harvesting) to supplement the mains water supply system can increase the system's resilience.

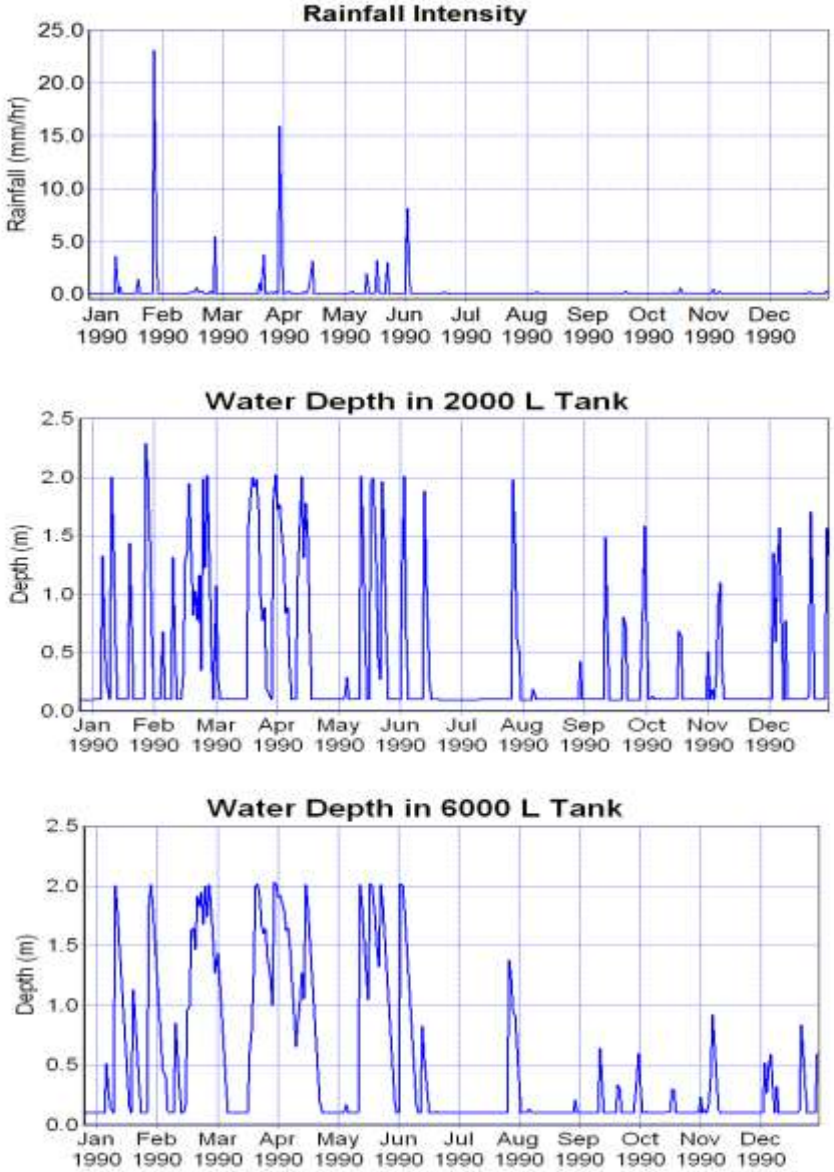

Figure 5: Simulation of water depth time series for the year 1990 at rainwater tank of sizes of 2000 L (2 m x 1 m^2) and 6000 L (2 m x 3 m^2) for a 200 m^2 roof area.

Table 1: Estimated performance criteria for an example rainwater harvesting scheme.

Tank size (L)	Conventional criteria			Risk-based criteria			
	Mean yield (kL/yr)	Variance (kL)	Average volumetric reliability (%)	Reliability, α (%)	Risk, r (%)	Average sojourn time, T_f (day)	Resilience, γ (day^{-1})
2000	96	0.13	32	32	68	7.05	0.142
3000	113	0.15	38	38	62	7.08	0.141
4000	125	0.15	42	42	58	7.17	0.139
5000	134	0.16	45	45	55	7.07	0.141
6000	141	0.16	47	47	53	6.98	0.143

CONCLUSION

Supply reliability is the fundamental design concept for any water supply scheme. Conventionally this is accomplished by storage-yield-reliability analysis. This conventional approach does not include an assessment of risk-related measures of the scheme such as the frequency, duration and severity of failures. Therefore several risk-related performance criteria have been proposed in this paper. These criteria are risk and reliability, resilience and vulnerability. These criteria are particularly important in the presence of climate change and variabilities and their prediction uncertainties. It is important to understand how incorporation of different alternative water sources augments the resilience of urban water schemes. For a defined water demand, resilience of a single-sourced scheme is influenced by rainfall distribution patterns. Therefore incorporation of alternative water sources (rainwater, stormwater and treated wastewater) improves the scheme's resilience by ensuring water savings and supply reliability. Risk-based performance criteria are more appropriate than conventional criteria for multi-sourced urban water systems, particularly in the presence of climate change and variabilities and their prediction uncertainties.

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