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LOAD AND MANAGEMENT UNCERTAINTY NEEDED IN CAPACITY PLANNING: SINGAPORE WATER EXAMPLE

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Planning for the development of new system capacity routinely considers the uncertainties in the forecasts of requirements. However, capacity planning generally fails to account for the uncertainties in the way managers will operate the system once the capacity is built. This omission results in errors in calculating both the performance of the capacity provided, and the specification of the capacity required. We demonstrate this situation through a case study of an urban water supply system inspired by Singapore. Our analysis simulated the performance of 3,000 cases, consisting of 60 possible operating rules under 50 synthetic possible evolutions of loads on the system (i.e., climate-driven water availability). The results demonstrate that (1) uncertainty in management's operating rules can significantly impact the assessed system performance; (2) the effect of operational uncertainty can be both comparable in size to the effect of uncertainty in the hydrologic loads on performance, and moreover additive to it; and (3) the consideration of uncertainty in management operating rules can lead to a two-fold range for the assessment of system capacity needed to meet projected requirements. The overall implication is that planning for capacity expansion should consider both load and management uncertainty.

Keywords: Uncertainty, Operating rules, Capacity planning, urban water resources.

1 The Capacity Planning Problem

The capacity planning problem is a generic issue in systems planning and design. It refers to the process of defining the amount, the size, and kind of capacity to develop to meet future needs. Two main factors complicate this problem. One complicating factor is that good system design should consider the multi-dimensional performance of the system: can the capacity provided provide adequate performance? Can the new highway, for example, not only handle the traffic, but do so sufficiently safely and without excessive delay? The other factor is that future needs or loads on the system are uncertain. This is because predictions of future social demands are inevitably fallible, and natural processes routinely vary (such as the amount of rainfall).

1.1 *Neglect of management uncertainty*

It is obvious that system performance depends both on what we have – the capacity of the system – and how we use it. It is thus reasonable to assume that we should consider both factors when we assess prospective performance of any capacity addition. However, the fact is that while designers of system capacity routinely consider uncertainty in the loads on their systems, they commonly neglect consideration of uncertainty in how managers will operate the system (Herman et al., 2014; Beh et al., 2015).

This neglect understandably occurs both for institutional and analytic reasons. Institutionally, the planning of new capacity occurs well before the facility is built and then managed. Moreover, the professionals in charge of long-term planning of infrastructure differ from those who are responsible for day-to-day management. There are thus time, skill, and motivational gaps between the planning and management processes.

Considerable analytic gaps between planning and management further accentuate the gap, and thus the neglect of operational considerations in planning. Indeed, planning for the size of capacity has to consider major elements over long periods (the plant to be built in three to five years, for example). Management issues basically consider adjustments to existing facilities over much shorter periods (such as days or months). It is difficult to combine such scales and differences in time.

The neglect of operating uncertainties leads to systematic sub-optimization of the system. The neglect of operational uncertainty imposes a constraint on how managers may operate the system, and limits the solution space. Elementary optimization informs us that such constraints impose a shadow price on the solution, that is, reduce the possible optimal performance (Bradley et al., 1977).

1.2 *To what extent is this neglect a significant issue?*

Previous research has indicated that the neglect of management rules in capacity planning may lead to significant system sub-optimization. See for example Yang, 2009. Inspired by such studies, we examined two questions in the context of capacity planning of urban water supply systems:

- What is the impact of different management approaches on long-term system performance?
- How does operational flexibility affect long-term plans for capacity expansion?

2 Analytic Approach

We analyzed the combined effect of recognizing both load and management uncertainty in capacity planning using simulation. Two factors justify this approach over the optimization techniques commonly used in capacity planning studies.

Most obviously perhaps, it is simply very difficult to set up operationally effective sets of equations that span the range of scale and time differences between long-term planning and short-term operational management. Furthermore, the stochastic programming appropriate for optimization under uncertainty is acutely sensitive to the number and of constraints and uncertain parameters (Shapiro et al., 2009). The problem rapidly becomes operationally intractable.

More subtly, any optimization that truly expects to find the best solution has to impose judgments about the relative value of the several measures of system performance, such as cost, reliability, delays, and so on. These measures are not on the same scale, their relative value depends on the stakeholders in the system, and their relative values are not likely to be linear. Given this reality, it seems reasonable to explore the solution space using a simulation that can follow and display multiple measures of performance simultaneously.

3. Case Study: Singapore Urban Water Supply

We explored the effect of including management uncertainty on capacity planning through the lens of a case study. This was inspired by, but not directly representative of the existing situation in Singapore. That is, we used representative hydrologic data to represent the hydrologic uncertainty in the loads, and applied this to a situation representing the overall characteristics of Singapore water supply system, for a specific hypothetical level of long-term demand.

3.1 *Operating rules for case study*

An important characteristic of the Singapore urban water supply system is that it currently draws water from four "taps": stormwater harvesting, water imported from Malaysia, desalination, and reclaimed water (known locally as NEWater). Looking ahead however, Singapore's ability to tap additional stormwater sources is nearly exhausted, given the extraordinary efforts Singapore has already made. Further, the agreement and ability to import water from Malaysia will eventually terminate. Singapore will thus have to rely increasingly on the 'industrial' sources, that is, on desalination and NEWater (Galelli et al., 2014).

This Singapore case study has potentially interesting implications worldwide. This is because rapidly increasing urbanization (especially in India and China, for example), coupled with rising per capita demand for water, is pushing the limits on the supply of fresh water in many cities. This is turn will lead to widespread use of industrial water, as Noiva (2017) has pointed out.

In the case of urban water, system managers follow "operating rules" to schedule the distribution of water supply. For this analysis, we considered that three parameters characterize any particular operating rule. These relate to the four operational zones of the aggregated storage:

- A flood control zone, space for eventual rainfall surges;
- A conservation zone to be the refilled naturally;
- A second conservation zone to be resupplied by turning on industrial water; and
- A buffer zone that entails some degree of restrictions on water use.

The managers of the water supply system manage the water according to the way they define these zones. For the purpose of this analysis, we assume that three parameters define any operating rule for the case study: one defines the degree of supply restriction when this occurs, and the other two define the trigger levels for initiating the supply restriction and the use of industrial water to maintain desired conservation zones.

3.2 *Performance criteria*

The analysis evaluated system performance using four standard indicators commonly adopted in mainstream literature (McMahon et al., 2006). These deal with aspects of failures to meet demand: How much time? how much volume? how frequently? how big? For the record, they concern:

- Time-Based Reliability: Fraction of days demand fully met;
- Volumetric Reliability: Fraction of demand met over target demand;
- Resilience: Number of Failures / Total time of Failures; and
- Vulnerability: Average Volumetric Failure / Total Demand.

3.3 *Situations simulated*

The analysis considered 3,000 combinations of hydrologic and operational uncertainty. It crossed 50 synthetic rainfall time series from Singapore with 60 different operating rules consisting of combinations of the three parameters mentioned in section 3.1. These simulations provided a representative sample of how the load and management uncertainties interacted to determine performance of the system across the range of possibilities.

4. Results

The results support the hypothesis that operational uncertainties can have a major effect on system performance, and that their consideration should be part of capacity planning. This most obviously applies to the case of urban water supply systems similar to Singapore. They are also suggestive of what may apply to other cases. The sub-sections provide details.

4.1 *Management uncertainty can significantly impact performance*

To illustrate the effect management uncertainty on system performance, we selected 5 of the 60 operating rules. These represent prototypical cases for:

- low, medium, and high supply restrictions;
- medium supply restrictions with a larger buffer zone; and
- medium supply restrictions with a larger conservation zone.

Figure 1 shows how variations in management's future operating rules can substantially impact the performance – by up to 100% in some measures for this case. For this Singapore inspired case, we see that the operating rule uncertainty particularly affects the Time-based Reliability and Resilience. Because much of Singapore's water supply capacity consists of industrial water (desalination and NEWater) uncertainty in operating rules hardly impacts volumetric reliability or Vulnerability; managers can turn on the industrial water at will.

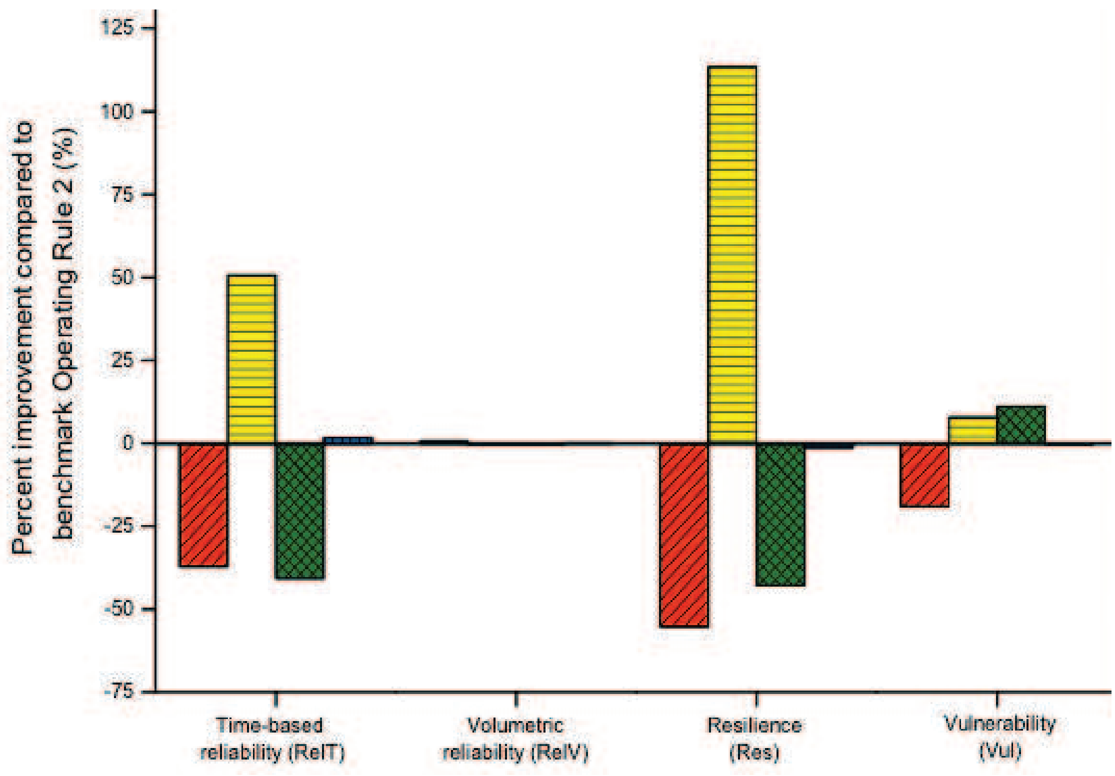

Figure 1. Percent change in performance for sample operating rules. Red: low supply restrictions; Yellow: high supply restrictions; Green: larger buffer zone; Blue: larger conservation zone.

4.2 *Management uncertainty comparable to load uncertainty*

Figure 2 compares the relative impact of operational and hydrologic uncertainty. It clearly shows that the impact of operational uncertainty is comparable to that of hydrologic uncertainty. Moreover, their impacts roughly complement each other, roughly add up rather than negate each other.

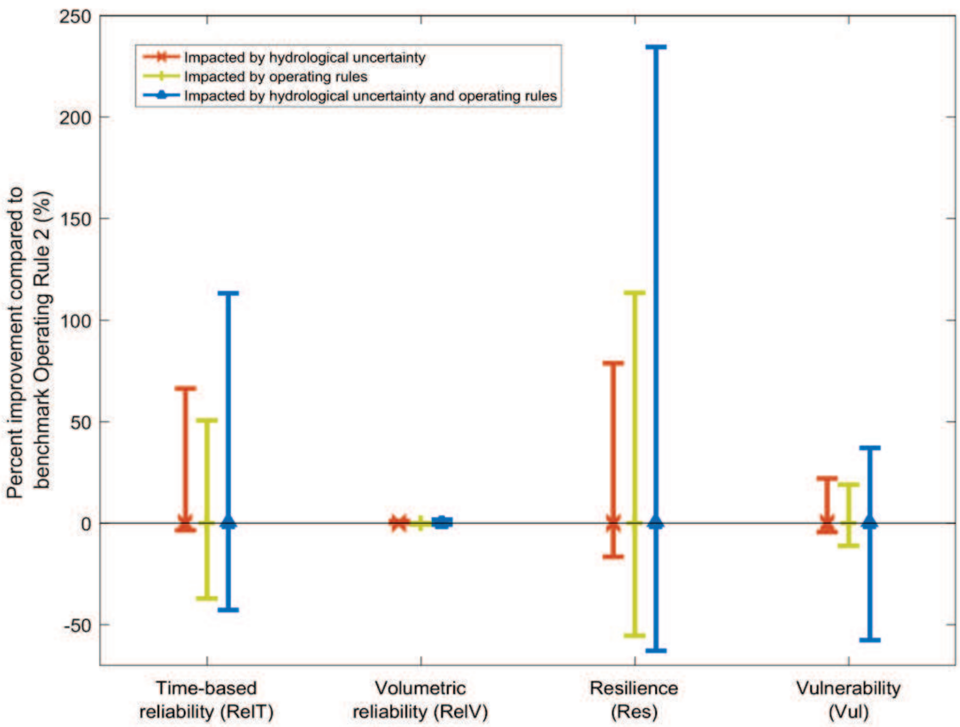

Figure 2. Percent change in performance under uncertainty in operating rules (yellow), in hydrology (red), and both together (blue).

4.3 *Management uncertainty can impact determination of capacity needed*

Table 1 reports the value of capacity expansion associated to the operating rules outlined above. Note that the capacity expansion corresponding to a small change in the operating rules can vary noticeably—a value of about 100 Million liters/day correspond to about 25% of the current desalination capacity.

Table 1. Capacity expansion associated with different operating rules

Operating Rule	**Required Capacity Addition (Million liters/day)**
Low Restrictions	225
Medium Restrictions	178
High Restrictions	281
Larger Buffer Zone	202
Larger Conservation Zone	158

5 Take-Aways from this Analysis

The results demonstrate that:

- Uncertainty in management's operating rules can significantly impact the assessed system performance;
- The effect of operational uncertainty can be both comparable in size to the effect of uncertainty in the hydrologic loads on performance, and moreover additive to it; and
- The consideration of uncertainty in management operating rules can lead to a two-fold range for the assessment of system capacity needed to meet projected requirements.

The overall implication is that planning for capacity expansion should consider both load and management uncertainty.

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References

Beh, E. H., Maier, H. R., & Dandy, G. C., Adaptive, multiobjective optimal sequencing approach for urban water supply augmentation under deep uncertainty. *Water Resources Research*, 51(3), 1529-1551, 2015.

Bradley, S., Hax, A., Magnanti, T., Applied Mathematical Programming, Addison-Wesley, 1977.

Galelli, S., Goedbloed, A., Schwanenberg, D., & van Overloop, P. J., Optimal real-time operation of multipurpose urban reservoirs: Case study in Singapore. *J. of Water Resources Planning and Management*, 140(4), 511-523, 2014.

Herman, J. D., Zeff, H. B., Reed, P. M., & Characklis, G. W. Beyond optimality: Multistakeholder robustness tradeoffs for regional water portfolio planning under deep uncertainty. *Water Resources Research*, 50(10), 7692-7713, 2014.

McMahon, T. A., Adeloye, A. J., and Zhou, S.-L., Understanding performance measures of reservoirs. *J. of Hydrology*, 324(1–4), 359–382, 2006.

Noiva, K., International Comparative Analysis of Urban Water Systems, Ph.D. dissertation, Department of Urban Studies and Planning, Massachusetts Institute of Technology, Cambridge, MA, USA, 2017.

Shapiro, A., Dentcheva, D., Ruszczyński, A., Lectures on stochastic programming: modeling and theory. Society for Industrial and Applied Mathematics, 2009.

Yang, Y., A Screening Model to Explore Manufacturing Planning Decisions in Automotive Manufacturing Systems under Demand Uncertainty, Ph.D. dissertation, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA, USA, 2009.