Dynamic operating rules for water supply reservoirs in La Paz

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Abstract Dynamic operating rules have been applied to the drought-prone Andean water supply reservoirs near La Paz, Bolivia. The water supply reservoirs are not using conventional reservoir operating rule curves. Instead, dynamic operating rules opportunistically supply surplus water for soft demands, and proactively adjust the water supply before a drought causes a water shortage. The conventional approach of forcing water levels to follow a set rule curve is replaced with notions of tradeoffs between long-term reliability and short-term supply opportunities. Operators can customise the dynamic rules based on their tolerance of shortages, and can choose to operate more aggressively during wet periods. In this way, the dynamic rules offer a flexible tool for making short-term decisions while managing medium and long-term performance goals. In the case of La Paz, it is possible to utilise the water sources more efficiently in the short-term without significantly reducing the long-term water supply reliability. The dynamic rules will reduce the severity of future water shortages (if they occur) by 60%, and provide opportunities to increase the firm water supply by up to 8% without affecting the long-term reliability.

Keywords Drought planning; dynamic operating rules; reservoir management; soft demand; water supply

Water supply reservoir management

Water supply reservoirs for municipal, industrial, or agricultural use are relatively simple to manage in that they must maximise the supply of water for their (minimum) size. Usually, sufficient storage is required to meet a certain design specification such as a firm water supply during an extreme drought. Other reservoir management objectives, such as flood management, recreation, and fisheries may further complicate or constrain management options. In the simplest case, however, a surplus water supply is wasteful. Similarly, an insufficient supply results in unwanted disbenefits. A water demand should be supplied 100% of the time with no waste of water. This, of course, never happens. So, management tools are constantly being refined to minimise the waste of water while trying to satisfy the water demand at least most of the time.

Reservoir management is commonly based on a reservoir operating rule curve that defines the “optimal” reservoir water level. The “optimal” water level should maximise the net present value benefits of the reservoir. There are numerous optimisation techniques for determining an “optimal” rule curve. Optimisation procedures vary according to their approach for dealing with uncertainty (Yeh, 1985; Wurbs, 1996). For instance, deterministic methods (those that ignore uncertainty) typically assume that inflows are perfectly known months ahead, when in reality the inflows may not be accurately known 2 days ahead! For this reason, stochastic optimisation methods were developed (e.g. Young, 1967; Askew, 1974; Loucks et al., 1981; Simonovic, 1987; Ilich et al., 2000). Some techniques provide flexibility in the operating constraints by allowing water supply rationing (Shih and ReVelle, 1995) and flood storage reallocation (Wurbs and Cabezas, 1987; USACE, 1988). Recently, other methods have been developed based on fuzzy programming and genetic programming (e.g. Russell and Campbell, 1996; Bijaya et al., 1996; Oliviera and Loucks, 1997; Milutin, 1998).
However, optimisation models are often difficult for operators to interpret and implement when real conditions differ from the assumptions inherent in the optimisation model. Perhaps the most difficult task is not the calculation of an “optimal” solution, but rather it is the translation of a solution into a pragmatic rule that can be understood and applied by reservoir operators. In the final analysis, operators may not be further ahead if the optimal solution makes the operator more dependent on a “black box” (Rogers and Fiering, 1986; Loucks, 1992; Parker et al., 1995).

There may not be a single optimal (i.e. static) rule curve for even the simplest of reservoir systems. That’s because it may rain today and not tomorrow, and there isn’t a single meteorologist who can correctly predict the future amount of rainfall (or snowmelt, or glacier runoff) for even the shortest of forecast periods. Opportunities for short-term improvements are easily lost, because surplus water may not be fully utilised, and because rule curves may help to create shortages during drought periods. Rule curves are insufficient, on their own, for determining the corrective management decision when water levels are too high or too low. How quickly should an operator return to the “optimal” water level? For that matter, is the “optimal” water level really optimal?

The reservoir storage is constantly changing, and is continuously deviating from “normal”. The reservoir system is dynamic. Therefore, the marginal value of each unit of water is in constant flux. So, if the reservoir system is dynamic – perhaps the reservoir operating rules should be dynamic too!

**Dynamic operating rules**

Reservoir operating rules should allow an operator to adjust the reservoir management actions as previous inflow predictions turn out to be wrong. They should also provide a framework for incorporating personal experience and attitudes toward risk (Holling, 1978; Bender et al., 1999). One approach for realising these goals is to devise a set of dynamic operating rules that balance tradeoffs among competing objectives. There are always at least 2 objectives: 1) to maximise water supply reliability, and 2) to maximise net benefits (Hashimoto et al., 1982; Burn and Simonovic, 1996; ASCE, 1998; Milutin, 1998). Therefore, there is no “optimal” answer – only “acceptable” tradeoffs among the objectives.

The dynamic operating rules act to limit the management actions to an appropriate range of actions. A reasonable approach is to simulate the historical record to “see” how operating rules would have performed if some conditions repeat. There are many techniques for exploring this multi-objective decision space (e.g. Duckstein and Opricovic, 1980; Goicoichea et al., 1982; Gal et al., 1999; Bender and Simonovic, 2000), but the following discussion focuses on the dynamic operating approach.

The mechanism for resolving the tradeoffs is based on the relative willingness of an operator to incur future shortages by increasing the current water supply. This mechanism can be divided into two types of dynamic operating rule:

- **Surplus rules**, to opportunistically use surplus water to intermittently supply “soft” demands (i.e. a customer who can intermittently accept additional water).
- **Deficit rules**, to proactively manipulate the water supply before a shortage occurs.

Both types of dynamic operating rule use a water balance forecast with a set of operating constraints (e.g. fill the reservoir before the start of the dry season). The water balance forecast can either be in a surplus or deficit situation. A forecast surplus implies that excess water is likely to be available in the coming weeks or months. A forecast deficit signals that a shortage may occur. Of course, the real outcome depends on how much it rains in the future!

The dynamic operating rules do not require operating constraints to be strictly met. An explicit rule to satisfy the constraints would be inappropriate in this case because the inflow
forecast will inevitably be wrong. For example, a prudent constraint would be to fill the reservoir(s) before the start of the dry season (i.e. a single point on a reservoir rule curve). However, a shortage may not occur if the reservoirs are just slightly less than full. It may simply be too difficult to fill them in time, and forcing them to fill may cause unnecessary disbenefits in the short-term. The operator must either hope for more rain, or adjust the water supply. An optimisation model might tackle this dilemma by minimising some arbitrary penalty functions that are assigned when the full reservoir objective is not achieved. The dynamic operating approach is to find a range of “well-behaved” management actions that are consistent with (competing) management goals.

Based on the forecast, the operator must choose to maintain the current water supply (equal to the water demand), reduce the water supply (within acceptable limits), or increase the water supply (for a soft demand customer). Figure 1 illustrates how surplus water could be supplied before the reservoir starts to overflow, and how a shortage might be avoided by reducing the water supply before the shortage occurs.

The idea is to act proactively without over-reacting. The speed of the reaction, and the magnitude of the change are both analogous to the weights of a multi-objective analysis. They are not “optimised”. Instead, the selected speed and magnitude of the supply adjustment is the control mechanism for operators to implement their attitude toward risk (i.e. conservative or aggressive). In some ways, this approach is similar to Goal Programming at each time step. In practice, dynamic operating rules can be transparent and easy to implement, as well as near-”optimal”.

**Surplus management rules**

Surplus rules identify water that can be supplied opportunistically during a wet period, pushing the upper limit of the firm water supply. Of course, this type of rule is only applicable to situations where a “soft” demand has been identified. For example, a large industry may use a local groundwater well instead of the regular water distribution network. It may be possible to target this potential client with discount pricing when surplus water is available.

First, a forecast net surplus is calculated (i.e. a water balance). Then, a surplus rule equitably “spends” the surplus over time. This “equitable” method should attempt to maximise both the surplus volume and duration, to the benefit of the customer. The net surplus is calculated as follows:

Net surplus = Cumulative inflows – Cumulative demand + Current storage – Target storage

Water supply = Water demand + (Net surplus × Release portion/Planning period)
The net surplus will change over time, depending on the inflows, and as the operator become more aggressive or cautious with the forecast. Therefore, the beginning of an unexpected wet period may see the water supply gradually increase as surplus water is detected by the net surplus forecast. The water supply may also be increased in a more step-like fashion depending on forecast strategies. In either event, surplus water can be utilised in such a way that the risk of a future shortage is not increased.

**Deficit management rules**

Potential water shortages may be avoided or lessened if a deficit rule is activated during a forecast net deficit. If the deficit is greater than a minimum threshold, the water supply could be gradually reduced or rationed until the net surplus is no longer in deficit. The idea of the deficit rule is to reduce the severity of the water shortage by spreading the shortage volume over a longer period. This is a dynamic extension of static hedging rules for rationing the water supply when storage is low (Shih and ReVelle, 1995). The general form of the deficit rule is:

Net deficit = – (Cumulative inflows – Cumulative demand + Current storage – Target storage)

Water supply = Water demand – (Net deficit × Drought sensitivity/Planning period)

The water supply reduction depends on both the operator’s optimism regarding future inflows, and on the operator’s sensitivity or aversion to shortages. A high sensitivity will result in a rapid decline of the water supply prior to an expected shortage. However, a real shortage may not occur (that is, if it unexpectedly starts to rain), so there is a chance that the reduction was not necessary. An appropriate rule should balance the potential reduction of water shortage severity with the potential financial loss that occurs when expected shortages do not occur.

In practice, a deficit rule can behave very differently at different reservoirs, and according to the selected surplus rule. Implementation of the deficit rule requires an investigation so that the desired management effect can be calibrated. For example, an operator may need to be very drought sensitive if the surplus rule is relatively aggressive. At the same reservoir, however, the operator may not need to be drought sensitive if surplus rules are not used!

**Application in La Paz, Bolivia**

**Setting**

Aguas del Illimani (AdI) provides water services to La Paz, Bolivia. One of the raw water treatment plants (WTP) is located in a rapidly growing area of the city. The water sources consist of a series of surface water reservoirs above 4,000 m altitude located in the mountains about 10 km east of La Paz (see Figure 2). Water is transported to the WTP via a canal in one valley, and a pipe in a second valley. The reservoir storage capacity and the variability of precipitation both affect water availability. Water demand is currently 50 MLD (about 1.5 mm³/month), near the safe water supply limit. Shortages are possible during the dry winter season from May to November, resulting in penalties imposed by regulatory agencies. AdI is currently implementing management measures to avoid these shortages while meeting future water demand increases.

**Implementation**

A water balance model, calibrated to 17 years of monthly rainfall-storage-discharge data, simulates up to 91 years of historical data (based on rainfall records in La Paz) and recalculates reservoir water levels on a daily basis. This model allows operating rules to be tested for a broad range of realistic operating conditions. The rules include rules for normal operations to: 1) allocate water supply among the two main water sources; and 2) trigger releas-
es from upstream reservoirs. The dynamic rules supplement the rules for normal operations by providing specialised policies during wet and dry periods. Because there is no “optimal” dynamic rule, simulation experiments were conducted to:

- Identify appropriate management “attitudes” toward deficits and surpluses.
- Delineate the tradeoffs between water supply reliability and net income (note: net income = revenue + revenue from surplus supply – treatment cost (chemical + energy) – shortage penalties).

The dynamic operating rules developed in La Paz are illustrated by the four steps of the following example. These steps can be repeated every day, week, or month. Input information for the example is listed in Table 1.

**Step 1.** Forecast the net inflows to April 1, based on the selected safety level and the exceedance probability curve for rainfall in each month (see Figure 3 for a forecast cumulative inflow example).

Cumulative inflow = Jan inflow + Feb inflow + Mar inflow = 4.5 + 4.21 + 2.55 = 11.3 mm$^3$

**Step 2.** Forecast net surplus to April 1.

Net surplus = Cumulative inflow – Cumulative demand + Current storage – Target storage
Net surplus = 11.3 – (1.5 × 3) + (12.65 × 50%) – 12.65 = + 0.47 mm$^3$

**Step 3.** Allocate surplus water if the forecast net surplus is greater than the minimum threshold for surplus water supply.
Water supply = Water demand + (Net surplus x Release portion/Planning period)
Water supply = 1.5 + (0.47 × 100%/3) = 1.66 mm³ per month

Step 4. Reduce the water supply if the forecast net surplus is larger than the minimum threshold for the deficit rule (not activated in this case because there is a forecast net surplus).

Net deficit = – (Cumulative inflow – Cumulative demand + Current storage – Target storage)
Water supply = Water demand – (Net deficit × Drought sensitivity/Planning period)
Water supply = 1.5 – (0.0 × 0.3 / 3) = 1.5 mm³ per month

Results

Current water demands in La Paz are near the safe water supply limit. The safe water supply cannot be increased without new capital investments. However, the surplus rules can be used to supply “soft” demands, effectively increasing the safe water supply by up to 8% (i.e. without affecting long-term water supply reliability). This would increase net income by up to 5%, accounting for additional treatment costs and shortage penalties (see Figure 4).
The operating limits shown in Figure 4 are based on scenario results of different forecast safety levels used with the surplus rule, and different “drought sensitivity” deficit rules. The selected management factors are then tested using the water balance simulation model, to see how the dynamic rules behave during various combinations of historical conditions. The reported benefits could be greater depending on the experience of the operator, because the operator can adjust the dynamic rules at any time by selecting a different forecast safety level or drought sensitivity.

Overall, drought sensitivity was not required when the reliability is already high (say, over 90%). With high reliability, the surplus rule could be used aggressively to increase net income. However, reliability of less than 90% could only achieve favourable tradeoffs between reliability and net income by using a careful balance among the forecast safety level and drought sensitivity parameters.

The local El Niño response is a 20% reduction in annual precipitation. This trend may be used to improve the dynamic operating rules. Some of the historical El Niño responses are correctly predicted by this adjustment. However, other El Niño events are not correctly predicted and the El Niño response is not consistently a drought. Tests of the dynamic operating rules showed that there is no long-term financial benefit of always adjusting precipitation forecasts based on El Niño. Of course, each El Niño is different and the operator should decide whether to add the El Niño response to the net surplus forecast.

Conclusions
Dynamic operating rules have been introduced, using a simple implementation scheme developed for the city of La Paz, Bolivia. Dynamic operating rules improve water utilisation by eliminating short-term inefficiencies that often occur with conventional rule curves. The dynamic rules also avoid the trap of relying on static rules or “black box” optimisation models, and provide a formal approach for utilising the experience and outlook of operators. An interesting advantage of the dynamic approach is that the statistical probability of a shortage is converted to a “safety level”, and used constructively to generate the appropriate management action.

The application in La Paz shows the benefits of a dynamic reservoir operating policy in a location with high seasonal rainfall variability between wet and dry seasons. The benefits include periodic water supply increases up to 8% of the annual safe water supply limit, and net income improvements up to 5% due to fewer water shortage penalties and extra income from selected customers.
References

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