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Improving real-time reservoir operation based on combining demand hedging and simple storage management rules

Nesa Ilich

ABSTRACT

A number of deterministic reservoir optimization models are capable of finding optimal basin allocation over multiple time steps simultaneously. This is commonly referred to as Multiple Time Step Optimization (MTO). However, such solutions are predicated on perfect foreknowledge of incoming runoff over the entire simulated period (typically one year), which is not available to reservoir operators in real time, thus creating a gap between the results of MTO-based modeling and their practical use. There is no universally accepted methodology on how the results of MTO should be used to develop practical and easy-to-understand operating rules. This paper offers a simple approach to bridge this gap and suggests additional avenues for further research in this direction.

Key words | optimization, reservoir operating rules, simulation, storage hedging

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INTRODUCTION

Early efforts to use computer models in the water resources field were aimed at simulating rainfall–runoff processes (Hydrologic Engineering Centre 2006) or to model propagation of flood waves using the mathematical relationships and empirical coefficients that describe them. Modelling of river basin management introduced additional complexity, requiring that the modellers identify target demands for various types of water use and handle different deficit-sharing policies among them. Depending on the allocation priorities, the available flow could completely bypass an upstream user and be allocated to a downstream user, or vice versa. A major departure from previous modeling of physical processes was the need to either define a complex set of rules that account for every possible combination of supply and demand conditions, or to rely on the model to find the best way to regulate flows in the system, given the priority of supply assigned to each water use, in which case a built-in optimization solver treats the allocation problem as a mathematical program. A review of reservoir operation models for basin planning purposes was compiled by Wurbs (1993) and subsequently updated by Labadie (2004).

The priority of supply represents the water rights (or water license) system in North America from where most of the early model development originated. The water licensing system can be represented using a linear programming (LP) formulation. Hence, early efforts focused on the search for efficient LP solvers, with typical objectives of finding an optimal set of network flows. This led to a widespread use of Network Flow Algorithms (NFA), with the earliest application of the Out-of-Kilter algorithm (Fulkerson 1961). A number of models were originally built around this concept, such as the SIMYLD (Evenson & Moseley 1970), ARSP (Sigvaldason 1976), MODSIM3 (Labadie *et al.* 1986), WASP (Kuczera and Diment 1988), DWRSIM (Chung *et al.* 1989), CRAM (Brendecke 1989), KCOM (Andrews *et al.* 1993) and WRMM (Ilich 1993). Most of these models are still in use, and some early versions have evolved into more sophisticated models such as CALSIM (Draper *et al.* 2004), which uses a Mixed Integer Programming (MIP) solver, and which is still maintained and used actively by the California Department of Water Resources. In some models, such as SIMYLD or WRMM, the original version of the out-of-kilter algorithm

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has been replaced with alternative variants which were proven to be significantly faster such as the SUPERK algorithm of Barr *et al.* (1974) or, as in the case of the MODSIM model, the Relax4 network flow solver of Bertsekas & Tseng (1988), which is also used in the REALM model (REALM 2006).

In recent years a number of vendors have been abandoning the use of NFA in favour of fully functional commercial LP solvers. Although recent advances in commercial solution procedures have narrowed the gap in the computational effort between NFA and standard LP techniques, the principal reason for departure from NFA is its inability to properly account for non-network constraints, since NFA does not allow an easy inclusion of mutual dependences of flows that may exist among various network components. For example, return flows should be set to a fraction of consumptive use. This is an easy constraint for an LP solver: however, the NFA solvers can only handle it in an iterative fashion, requiring multiple NFA calls and an external algorithm for re-setting the bounds on the return flows for each subsequent NFA call. Even more troublesome are dependences between the maximum outflow from a reservoir and its storage levels, some of which have recently been published (Ilich 2008; Ilich 2009). In addition to the CALSIM model already mentioned above, a number of other vendors have proceeded to the deployment of Mixed Integer Programming (MIP) solvers in their models. These include among others RIVERWARE (Zagona *et al.* 2001), HEC-FCLP (Needham *et al.* 2000), VISTA (Vista DSS 2006) and OASIS (Dean *et al.* 1998). After having realized the limitations of NFA, Alberta Environment initiated re-development of WRMM using the object-oriented approach and the MS Visual C++ compiler. The model relies on the use of the LINDO MIP solver library. This development started in 2000 and it will continue in the future subject to the levels of available funding. The MIP solution procedure was incorporated and tested in 2003. The model feature that is the subject of this paper is the recently added capability to solve water allocation programs for all time steps simultaneously for one hydrologic year or for all simulated years. It should be noted that other models such as RIVERWARE, VISTA, HC-FCLP and OASIS are also capable of optimizing allocation over single or multiple time steps. While there seems to be no universally accepted methodology on how to utilize multiple time step solutions for the development of practical short-term operating rules, this is one area of on-going research that holds out promise for improved future reservoir operations and overall river basin management. This paper explains the multiple time step optimization (MTO) feature and offers some insight into its potential benefits for reservoir operators and river basin planners. The next section discusses the model set-up for single time step (STO) and multiple time step optimization while the third section provides a numerical example, followed by conclusions and recommendations in the final section.

The Water Resources Management Model (WRMM) of Alberta Environment has been used as a principal river basin planning tool in Alberta since the early 1980s. The model has also been applied in overseas studies and it has gained acceptance in other Canadian provinces. Initially developed for use on mainframe computers in 1979, the program has since been considerably improved. The most significant changes were migration to the PC, use of a commercial linear programming solver along with a number of algorithmic enhancements, and re-writing of the FORTRAN source code in C++ using an object-oriented approach. Until recently the model could optimize (i.e. solve) the problem of allocating a scarce water resource among competing demands over a specified time step. Each consecutive time step is independently solved by the model. The new MTO feature recently added to the model allows simultaneous optimization over any number of multiple time steps.

SINGLE TIME STEP VERSUS MULTIPLE TIME STEP OPTIMIZATION

A simple schematic of a river basin system with two reservoirs and two irrigation blocks is shown in Figure 1.

Flows in links that are identified by Y_i are the decision variables for the model, and they typically relate to reservoir releases and diversion rates from the stream. Without storage reservoirs and water intake structures, there would be no modification to the natural flow regime. Identifiers labelled with X_i are constraints, where X_1 and X_2 represent inflow series while X_5 and X_6 represent a time series of water demands for the two irrigation blocks. A unique cost vector C_i is associated with all components in the system to represent priority of allocation. To provide a solution for a single

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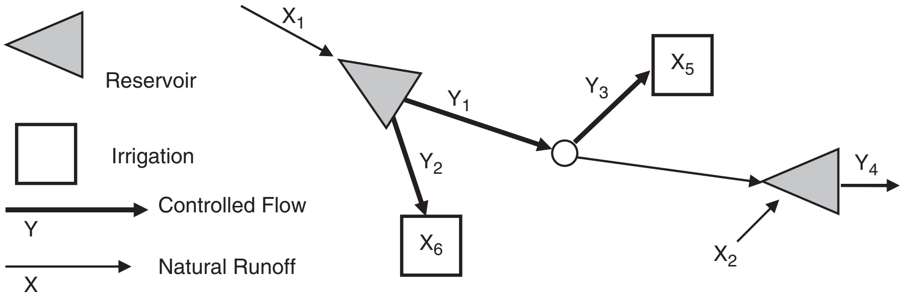

Figure 1 | River basin schematic example.

time step, the model is effectively asked to find values of Y_i such that the objective function of maximizing flows according to the prescribed priorities is satisfied, i.e.

$$\text{Maximize } \sum_{i \in A} C_i Y_i \tag{1}$$

where A is the set of all components in the system while i is an index of an individual component. The constraints to the above mathematical program include the mass balance equation at each node, along with the flow capacity constraints for each flow link, which may be either fixed (such as the design canal capacity that should not be exceeded) or which may be related to flows in other components through a functional relationship, as is the case with the dependence of return flows on consumptive use, or the dependence of the storage outflow capacity on the average storage levels over a simulated time step.

Optimizing each individual time step may be useful when studying impacts of various deficit-sharing policies among a multitude of different water users in complex river basins. However, the principal drawback of single time step solutions is that they require a user-defined operating rule for reservoirs. Such a rule is supplied in the form of a curve that designates the maximum permissible drawdown and the minimum required refill over a typical year, aimed at preventing the storage reservoir from premature emptying and enabling the start of the subsequent season with some guaranteed minimum storage. A user-defined rule adds additional soft constraints to the model, but because the rule is user-defined, it affects the solution without a guarantee of finding the optimum. Without the reservoir rule curve the solution for the entire year may look like the one shown in Figure 2, where irrigation supply is shown together with irrigation demand over the entire season for a typical dry year. This is a case of selfish allocation that disregards the risk that the storage may run out. In the first two months of an irrigation season, the model allocates 100% of the demand: however, in the third month the allocation drops down to 0 due to a lack of storage and available runoff. After an entire month with no supply, the crop would fail to deliver the expected yield. In hindsight, the previous first two months of full allotment would seem like unnecessary waste. Even worse is the fact that most models do not include additional intelligence to completely cut down supply after the failure in the third month shown in Figure 2, but they instead try to revive the supply in the last month, which is yet another avenue for wasteful mismanagement within the model.

The graph in Figure 2 raises two issues:

(a) How should the starting storage and the forecasted runoff from snowmelt be related to a decision to set the target level of supply for a given season? And,
(b) How can the best reservoir rule curve be "guessed" for a given year, given that the best shape of the rule curve is

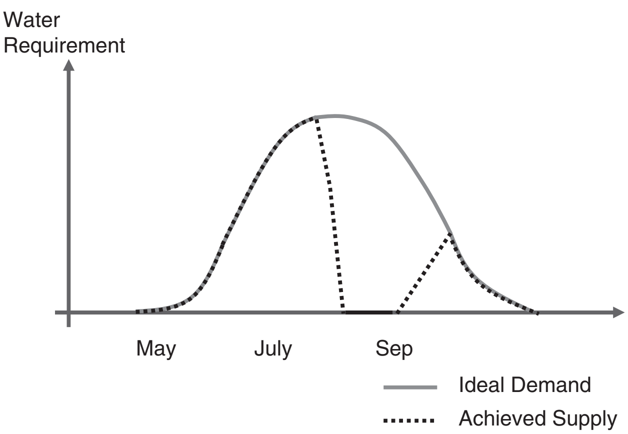

Figure 2 | Possible STO allocation to an irrigation demand.

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defined by both the target supply levels as well as the incoming flows into the upstream supply reservoir?

The above issues have been studied and they are known in the literature as the "reservoir hedging rules" (Shih & ReVelle 1994). The point raised in (a) refers to a systematic methodology that would help the operators make a decision at the beginning of an irrigation season on a reasonable target supply level that could be supported for the entire season, based on the starting storage level on 1 May and the snow-pack surveys and satellite images. It is obvious from Figure 2 that, if a decision was made at the beginning of the season to support 75% of the target demand instead of 100%, it may succeed. The question is, how can a good guess be formulated, and how to measure the reliability of the methodology employed in making such a guess? Point (b) refers to the ability to dynamically generate and possibly adjust the rule curve for each individual hydrologic year based on the ability to learn from a multitude of perfect solutions that were obtained in the planning study phase. It is here that the MTO solutions begin to play an important role, since they provide the ability to gain insight into what constitutes a "perfect operation" for each hydrologic inflow sequence and allow inspection of various heuristics to derive learning algorithms and pattern matching techniques that may become applicable in the daily operation of large river basins.

MTO can be formulated in the same manner as STO, but with the additional summation of the objective function over all time steps t that are solved simultaneously:

$$\text{Maximize } \sum_{t}\sum_{i \in A} C_i Y_{i,t} \tag{2}$$

The same mass balance and flow capacity constraints are in effect when deriving MTO solutions. The principal difference is that MTO solutions are derived over the extended network, also termed the *dynamic* network. Figure 3 shows an example of a dynamic network for a small system consisting of one reservoir, one irrigation block, one diversion channel and two natural channels representing two river reaches. Symbols T_1, T_2 and T_3 represent inflows into the same reservoir in time steps 1, 2 and 3, respectively. In the first time interval, the total available water is defined as the sum of the initial storage (V_{initial}) and inflow T_1. Note that the ending storage of one time step is the beginning storage of the subsequent time step. Storage at the end of the final time step is defined as V_{final}.

An MTO solution for three simultaneous time steps would therefore be applied on a network which is three times the size of the original network. This means that MTO solutions are much more difficult to obtain in terms of the required computational effort. For example, a moderate size problem with 300 variables in STO becomes a problem

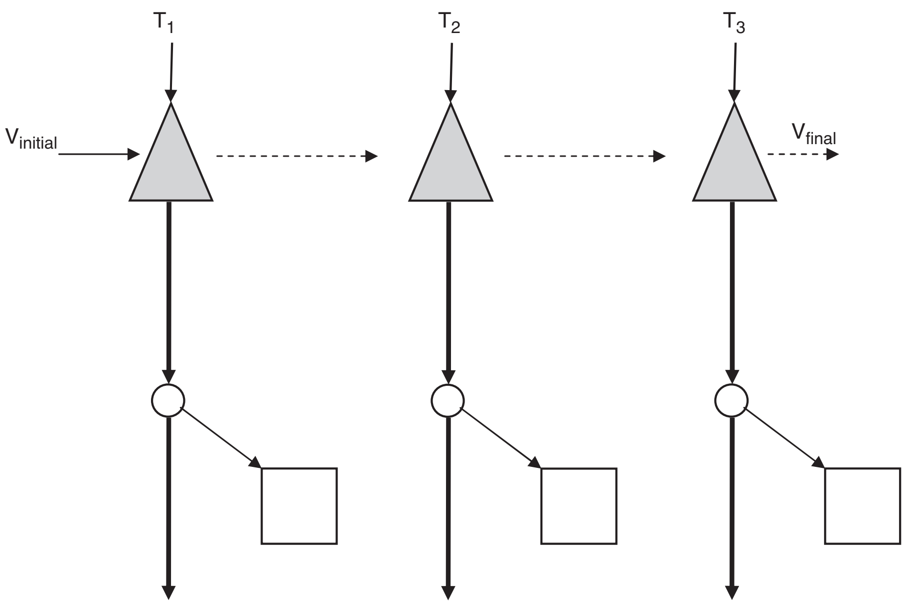

Figure 3 | Example of dynamic network for three simultaneous time steps.

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with over one million variables in MTO when solved on a weekly basis over 68 years of available data ($300 \times 52 \times 68$). The advantage of MTO solutions is that they provide the upper bound on the best possible basin operation, given the available supply and demand levels for the period under consideration, since they rely on perfect foreknowledge of inflows and demands over the entire period. For systems without carryover storage from year to year (i.e. systems where reservoirs are guaranteed to spill every year), it is usually sufficient to run MTO over a single hydrologic year, starting from the beginning of the high flow season and running for a period of one year. For systems with carry-over storage, the best solutions are obtained over all years simultaneously.

There are two outputs from MTO solutions that are not available in the STO mode. The first is the best reservoir rule curve (time series of storage levels) for each simulated year. The second is the best possible supply that could have been achieved given the starting storage, inflow sequence, demand levels and priorities of supply. The best possible supply is achieved by placing each water use target delivery in its license priority list (based on the currently established water rights system), and by introducing an additional constraint that equalizes deficits "in time". For example, this kind of constraint ensures that irrigation deficits for a particular block are shared over all time steps within an irrigation season. Mathematically, these constraints take the following form:

$$\frac{Y_t}{D_t} = \frac{Y_{t+1}}{D_{t+1}} \text{for } t = 0, n-1 \tag{3}$$

where Y_t is the supply to an irrigation block in time step t, while D_t is the target demand for the same irrigation block in the same time step and n is the total number of time steps solved simultaneously. Inclusion of this constraint in the solution process can help determine the maximum possible irrigable acreage for each simulated hydrologic year and offer guidance for developing demand hedging rules. The MTO solutions are thus the best possible solution for a given system configuration, the target demand levels and the available supply, since they are based on perfect foreknowledge of the incoming hydrologic series. The challenge is then to find a way to use the information obtained from MTO solutions to improve reservoir operation and basin management. To start addressing this, the concept of developing reservoir operating zones based on MTO solutions is first introduced in Figure 4.

Solutions for only three years are depicted in Figure 4, each one showing the reservoir levels that were the "best" for a particular year. For a simulation with many years, there would be a lot more than three curves, but only three were shown in Figure 4 for brevity. As it turns out, the more years solved with MTO, the better, since the subsequent analyses involves application of standard statistical methods. If, for example, there are n years of solutions, there would be n curves instead of 3, and putting them all on a single graph would not be legible. However, they could be summarized and represented by several selected percentile levels, since for each time step there are n points of reservoir elevations from n simulated years. In other words, one can define a probability density function based on n reservoir elevations for each of the 52 weeks (assuming weekly MTO solutions have been obtained). If a median point was connected for all weeks, it would represent the median elevations (the most likely elevations to be expected for the end of each week), and such a curve could be considered a guideline for reservoir elevations in a median hydrologic year. On the other hand, if the points with 20 percentile probability were connected for all time intervals, as shown in Figure 4 for two subsequent time intervals, they would form an estimate of reservoir elevations to be expected in a dry hydrologic year with a 5 year return period. A similar statistical analyses of obtained reservoir levels was used by Lund and Ferreira (1996), except that their attempts to derive operating rules did not extend to downstream demand management, but rather focused on the anticipated reservoir levels for different times of the year.

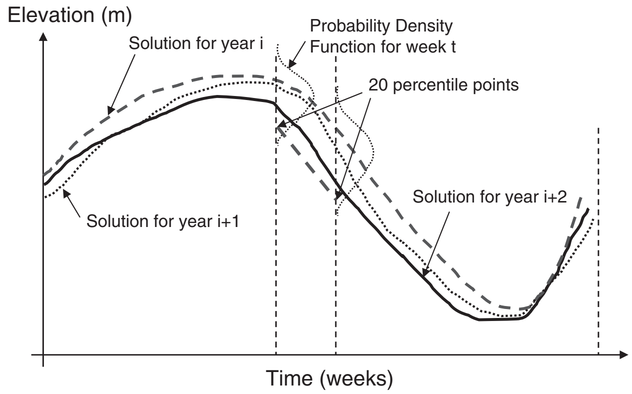

Figure 4 | Reservoir operating zones derived from MTO solutions.

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They based their study on a monthly time step, which provides only 12 points within a year of assessing target storage levels, thus requiring linear interpolation between the points to make the suggested rules applicable for any day of the year. Another attempt to derive operating rules was based on an estimate of economic value function for carry-over storage (Draper & Lund 2004). The authors discuss difficulties related to defining the most appropriate mathematical form of this function and admit that this is not a resolved issue. Also, even if the function could be formulated in an acceptable manner, it is applicable to large storage systems where the total live storage exceeds annual runoff by a factor of 2 or 3 times. Most storage reservoirs are not in this category. Finally, the proposed carryover storage function was based on assuming that reservoir releases are made exclusively for allocation purposes, while in reality they are used for multiple in-stream and off-stream water uses, with a mix of various objectives which are not always easy to quantify economically.

In addition to the information related to the expected storage levels, it is also possible to analyze supply deficits to various water users. Typically, river basin modelling assumes target allocation based on the water license limits. This, however, may not be possible in dry years, especially when coupled with below-average starting storage levels at the beginning of the hydrologic year. Having valuable insight into the levels of deficits that can be expected as a result of the anticipated supply conditions and starting storage levels can be useful for building short term or seasonal operational models. This is especially of interest in temperate climatic regions to which Canada also belongs, where satellite monitoring of snowpack conditions as well as snowpack surveys can be used as a basis for generating seasonal runoff forecasts. The numerical example that follows demonstrates a process to develop a short-term operational model based on the development of reservoir rule curves as well as on a forecasting tool for defining the level of irrigation supply based on the starting storage and the snowpack conditions assumed to be inherent in the realized runoff in May and June.

NUMERICAL EXAMPLE

Figure 5 shows a small schematic consisting of one reservoir, one irrigation block with a diversion channel and a return flow, and two river reaches. Although the available 1928–1995 inflow series of natural flows for the Oldman Dam was used in this study, and the reservoir capacity curve for the Oldman Dam was also selected, this was not an attempt to study any features of the Oldman Dam operation, but merely a case of using real-world data.

Reservoir operation has the following goals:

(a) Maintain the in-stream flow target (IFT) of 15 m^3/s at all times within the designated IFT channel (the highest priority). Although this target is set arbitrarily, it should be noticed that the total South Saskatchewan minimum maintenance flow at the border of 42.5 m^3/s is to be met by a combined contribution from three rivers, one of which is the Oldman River. Each of the three rivers contributes approximately the same amount of annual runoff to the apportionment agreement.

(b) Restrict the flows released from the dam to be below 300 m^3/s in order to minimize the negative impacts of flooding; and

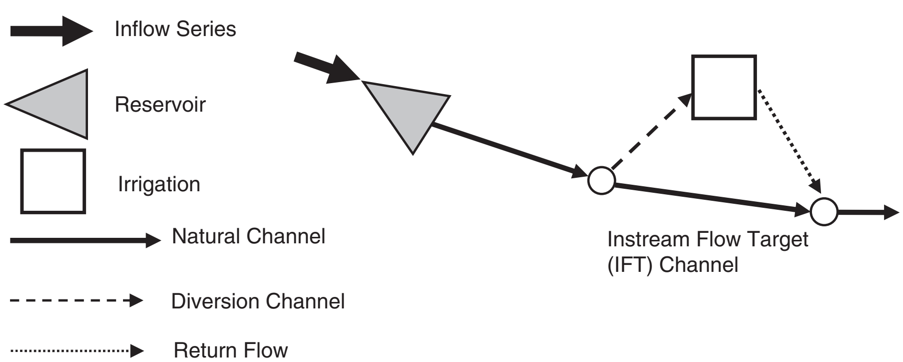

Figure 5 | Test problem modeling schematic.

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(c) Minimize deficits in supply to a 140,000 ha irrigation block which also has a return flow channel that returns 30% of the gross diversion into the block to the downstream river reach. A series of gross irrigation demands, which were the same from year to year, was used at this point. Further refinement of this approach could involve adjustments based on inclusion of precipitation series, which was beyond the scope of this project.

The following strategy was deployed in the development and testing of the short-term operating rules:

(a) Obtain MTO solutions for the series that excludes the first 10 years, i.e. use only the data from 1938 to 1994. The last year (1995) also had to be excluded since MTO was run for a hydrologic year, starting on Julian day 119 for the entire 52 week period. The MTO solutions were obtained for single-year optimization (i.e. solutions were obtained by optimizing 52 weeks of inflows for each year simultaneously for each of the 57 years).
(b) Using the MTO solutions obtained in step (a) for the 1938–1994 period, develop the reservoir operating rules and the methodology to assess the reasonable level of demand that can be supported given the starting storage level and the two months' inflow forecast at the start of May (assumed to be based on the snowpack data).
(c) Apply the short-term operating rules developed in step (b) to the remaining 10 years of the hydrologic series (1928–1937) that were not used in step (b). By doing so, we avoid the bias of applying the rules on the data from which they were developed. The operational model is executed in STO mode, meaning that there was no forecast of inflow known to the model beyond the current time step.
(d) Obtain the MTO solution for the 10 years series (1928–1937) and compare it with the results of the short-term operational model obtained in step (c). This comparison can tell us how far the operational model was from the best possible solution obtained using MTO. Also, conduct a simulation without proposed reservoir operating rules and include its output into a comparison with the other two scenarios (MTO and the selected short-term operational model).

Results from step (a) are presented as a summary of the suggested rule curves for inflow series with various return flow periods shown in Figure 6, as well as an empirical relationship between the sum of the available storage and the two-month runoff forecast as of 1 May for every year, shown in Figure 7 (the runoff forecast is assumed to be available as the total flow volume based on the May and June historic natural flows, without temporal distribution among the weeks during the two-month period). The assumption is that the snowpack survey could have provided accurate combined flow volume forecasts for May and June of each year.

The lines in Figure 6 were obtained by applying the statistical probability plotting position formula (approximated here by the percentile function from Microsoft Excel software) on all reservoir elevations obtained from the MTO output for the 1938–1994 period. For example, the gray line

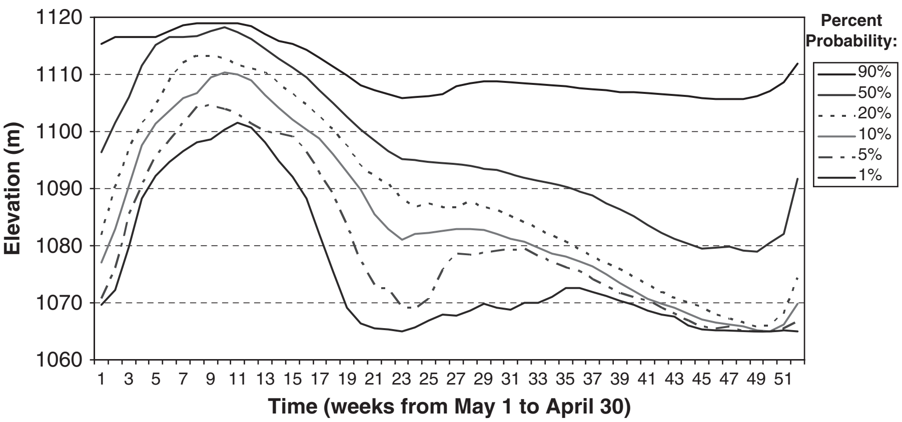

Figure 6 | Storage levels as a function of probability of occurrence in MTO solutions.

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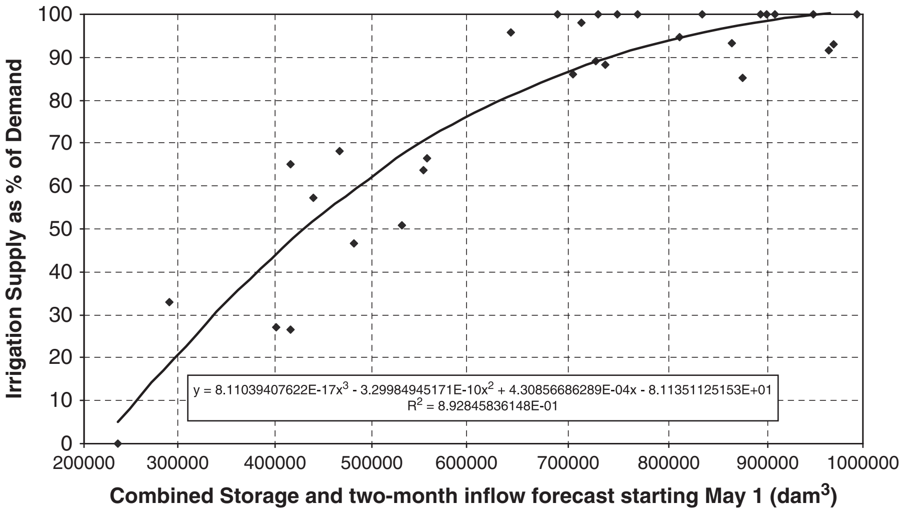

Figure 7 | Irrigation supply vs forecasted snowmelt and storage level on 1 May.

in Figure 6 was created by connecting the median (50 percentile) elevations for the end of each week from the MTO output. The dotted line shows the 20 percentile elevations for the end of every week. The span between the two lines is about 10 m in elevation from May to the end of September, from where it gradually increases to 15 m by April of the subsequent year. These two lines define an operating zone for a median to 1 : 5 dry hydrologic year, which may be a useful guideline for the reservoir operators. The bottom-most zone with 1% probability should never be violated. This zone defines the minimum refill and maximum permissible drawdown for any year.

Figure 7 shows the empirical relationship between the sum of the two-month inflow forecast as of 1 May (due to snowpack surveys) and the available starting storage on 1 May with the achieved irrigation deficits for the entire season obtained from the MTO solutions.

An empirical relationship is represented with a polynomial fit with $R^2 = 0.89$, which may seem reasonable: however, the unsettling part is the individual deviations from the curve that are in the range of up to 20% of the annual target demand. One of the reasons for this may be that the empirical relationship is overly simplistic, in a sense that it only takes one look at the conditions on 1 May, without attempting to update the situation on 1 June, for example, or even better on a weekly basis. Deficits to irrigation occur as a result of insufficient total supply to maintain the higher priority of IFT for the entire year in a channel located downstream of the irrigation diversion structure. In MTO solutions, the model saves just enough water to maintain the downstream IFT target in winter months by saving storage at the expense of reducing irrigation supply during the irrigation season.

Simple short-term operating rules were developed and tested in step (b) on a 10 year series of the available data from 1928 to 1937. The rules employ the use of five reservoir storage zones, corresponding to 50, 20, 10, 5 and 1 percentile lines shown in Figure 6, which were matched with the shorting of irrigation demands to 85% of the target if the storage level falls to the 50% zone, followed by 75%, 65% and 55%, if the storage level falls below the 20, 10 and 5 percentile lines, respectively. Also, the empirical relationship was applied once a year for each year to adjust the target demand. Table 1 shows the adjusted target demands based on the percentage of the licensed withdrawal which represents the 100% demand level. For example, given the starting elevation and forecasted runoff volume in May and June of 1930 (this is assumed to be available on 1 May of each year based on the snowpack survey), the realistic target is adjusted to 97% of the entire water license, while in other years such as, for example, 1936 this target is reduced to only 52.4% of the license. The modelling assumption is that the nonlinear regressive relationship shown in Figure 7 is used by the operators to adjust target acreage at the beginning of each irrigation season based on the reservoir storage as well as the showpack survey available on 1 May.

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Table 1 | Adjusted irrigation demands for the 1928–1937 period

Year	Demand (%)
1928	100.0
1929	100.0
1930	97.20
1931	22.03
1932	97.15
1933	86.48
1934	100.0
1935	83.33
1936	52.42
1937	100.0

Since the 1928–1937 period is known to have several dry years, the empirical relationship from Figure 7 provided demand adjustments, which are particularly severe in 1931 and 1936. The major impact of these adjustments was to enable the model to meet the IFT in the later part of the hydrologic year, based on the reductions to irrigation supply that could be deduced from the MTO solutions. Three scenarios were run and compared:

(1) The Unrestricted Supply Scenario which has no operational rules at all other than to supply water from storage whenever it is available, first to meet the IFT and then to meet the irrigation requirements, without any application of the proposed demand hedging rules.
(2) The short-term operational scenario was run according to step (c) above using the STO mode with the adjusted demand levels which were prorated to all weekly demands, as well as with the storage zones constructed based on the 1938–1994 MTO solution.
(3) The MTO solution for the 1928–1937 hydrologic series using the same (adjusted) demand levels in order to give the upper bound on how well the model could perform for this configuration of inflow and demand series.

The resulting comparisons include the following statistical measures: percent of time the IFT demands are not met, percent of time the live storage was below selected thresholds, and the percent of annual irrigation deficits. Note that the highest priority is reserved for the IFT. Since the 1928–1932 series is drier than average, weekly outflows exceeding 300 m^3/s were not an issue in any of the scenarios.

The fact that the MTO scenario could not deliver a solution without irrigation deficits means that the empirical model for adjusting the irrigation demand on 1 May is not perfect; it should, in fact, have been set to a demand level on average 13.4% below the current estimate. In view of the fact that the 1928–1937 hydrologic series has some very dry years, this should not be considered a failure, but rather an encouragement for expanding on the ideas of how to best extract information from MTO solutions to improve the guess on the supply policy at the beginning of an irrigation season. Taking this into account means that the proposed operational model has achieved irrigation supply with only about 10.6% deficits, since out of the 24% annual deficits shown in Table 2 the first 13.4% were unavoidable. The model also managed to keep the IFT demand met at all times. The Unrestricted Supply Scenario, on the other hand, shows lower irrigation deficits, but at the expense of a massive failure to maintain the IFT target 32.4% of the time. It also shows serious failure to conserve storage, since the storage levels are below 10% of the full supply level some 55% of the time, while the reservoir is completely empty 36% of the time. Figure 8 shows a comparison between the MTO solution for the 1928–1937 period with the STO solution obtained from the proposed operating rules as well as from the Unrestricted Supply Scenario, which is referred to as STO with no rules in Figure 8. It can be observed that the reservoir levels from the two solutions are strikingly similar for some years, although the MTO solution was obtained with "perfect hindsight", while the STO solution was obtained by solving each time step individually using the proposed operating rules. In fact, one of the ways to assess the quality of the proposed operational model is to study the differences from the MTO and STO solutions for the same input series. The smaller the differences, the better the operational model. On the other hand, the Unrestricted Supply Scenario (STO without rules) shows that the consequences of exercising water licenses selfishly without thinking ahead can lead to a disaster. In seven out of ten years the storage is completely empty for periods longer than five months, and in one year the storage remains empty for two months. It is obvious that this kind of operation would lead to crop failures and a failure to meet the instream flow obligations in eight out of ten years.

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Table 2 | Summary of model results for three scenarios for the 1928–1937 period

		Unrestricted Supply STO Scenario	Proposed Operating Rules Scenario	MTO Scenario for the entire hydrologic year
Percent of time IFT was violated		32.4	0	0
Percent of time live storage was below:	50% FSL[1]	77.7	61.1	59.8
	20% FSL	60.5	17.6	22.4
	10% FSL	55.3	7.6	9.1
	5% FSL	48.6	2.2	3.35
	2% FSL	36.2	0.1	0.5
Annual irrigation deficits (%)		14.35	24.01	13.4

[1] FSL = Full Supply Level

CONCLUSIONS AND RECOMMENDATIONS

This paper shows one possible avenue on how MTO solutions can be used in improved river basin planning and operation. In planning mode, it is assumed that the planners would model both the existing structures together with the proposed structure(s) that are in the planning stage, develop the operating rules and short-term operational models for the entire system, evaluate the system output and test the possible benefits of added structures to assess the return on the capital investment. In operational mode, the seasonal and short-term operating rules may be beneficial if they can demonstrate improved operation when compared to the previous management practices that are on record from recent years.

There are several avenues for adding possible improvements in the logistics presented in this paper:

(a) Instead of the use of historic natural flow series, the use of stochastic hydrology with lengthy series of 1000 years of possible flow realizations which are statistically indistinguishable from the historic series may provide significant benefit to the proposed methodology, since this would free up the entire historic series for testing of the short-term operational model. Testing would not be limited to 10 years, but would rather be carried out for

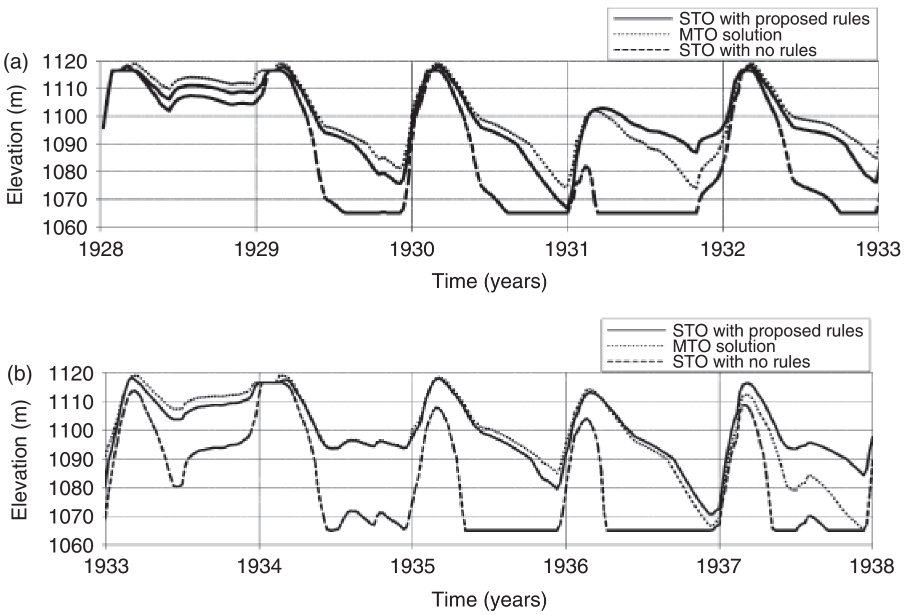

Figure 8 | Comparison of reservoir levels for 1928–1937 hydrologic series.

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the entire historic record from 1928 to 1995. This would provide more confidence in the overall methodology. Recent developments in stochastic hydrology provide algorithms that can generate synthetic weekly flow series at multiple sites and for any significant lag required to preserve autocorrelations and cross-correlations (Ilich & Despotovic 2007), offering a high degree of statistical compatibility with the historic series, which may be useful in studies of reservoir operation and basin management. This is considered more reliable than the deterministic methods for generating synthetic stream flow series which are typically based on rainfall–runoff transformation or other regional analyses techniques. Stochastic techniques also provide an opportunity to introduce a bias in the generated series to reflect anticipated changes in the statistical properties of flows as a result of the assumed climate change impacts (e.g. longer droughts and more severe floods).

(b) More research is needed for improvement of the algorithm for adjustment of water demands at the start of the hydrologic year. It is felt that this algorithm can be improved in various ways. More frequent adjustment based on monitoring the accumulated runoff since the start of the snowmelt, updated surveys of snowpack and storage levels, and the use of more powerful techniques such as ANN or SVM instead of multiple regression may yield more encouraging results. This is an area where recent advances in artificial intelligence could be applied with significant success, filling the huge gap between the available tools and current practice that often still relies on a rule of thumb.

(c) Inclusion of rainfall and soil moisture as variables needed for timely adjustment of water demands could also provide more realistic assessment of the model outputs and improved performance.

(d) Inclusion of additional features in MTO solution capabilities is also desirable, such as the ability to equalize deficits in time for a given component or a selected group of components, including dynamic allocation of the irrigation diversion license limits as well as the apportionment agreement constraints, which have yet to be incorporated in the MTO solution procedure. These features would improve the quality of the MTO solutions that are key to the development of the proposed methodology, especially from the standpoint of being applied on river basins in Alberta where these constraints are the norm.

In closing, it should be mentioned that the proposed methodology addresses the key issues of both design and operation of water resource structures that act together as a system in complex river basins. Although only a single reservoir and two downstream demands are used in the numerical example, the method presented in this paper is applicable to systems with multiple reservoirs and a variety of water demands for which both the quantities and the temporal distribution is assumed to be predictable. There is neither a universally accepted methodology on how to optimize the design of an entire system, nor how to develop and verify a reliable short-term operational model that the operators would trust and use. The view expressed here is that the issues of optimal operation and optimal design are two faces of the same coin, since the design of complex systems cannot be achieved without first being able to find out how they should best be operated.

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