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ABSTRACT

This paper presents the WEB.BM model for multipurpose multireservoir river basin management that uses Mixed Integer Linear Programming (MILP) solver to optimize basin operation over single or multiple time steps, with flexible time step length and optional use of both reservoir and hydrological channel routing. The principal novelty is the capability of the model to solve multiple time step optimization while simultaneously properly accounting for hydrological channel routing as constraints to optimization, which is demonstrated on two numerical tests presented in this paper, which can be used as benchmark by other researchers. There are no other known optimization-based river basin management models with this capability. The model can include multiple reservoirs, hydropower plants, environmental flow targets, return flows from irrigation, diversion volume licences, apportionment agreements between neighbouring states and net evaporation. Operating priorities among users are represented by a selection of user-defined weight factors. The model can be accessed at www.riverbasinmanagement.com.

1 Introduction

There has been an explosion of publications on reservoir operation models used in river basin management studies in the last three decades. Previous comprehensive literature review papers such as those compiled by Wurbs (1993) and Labadie (2004) included numerous publications, but it is hard to see how a similar all-inclusive attempt could be conducted now given the sheer volume of publications on this topic since 2004. Most recent publications have focused on exploring the use of heuristic solvers, a new family of algorithms that converge to improved solutions by mimicking biological processes found in nature. These algorithms are easy to understand and code, which enables young researchers to publish numerous papers early in their career. Such publications have also been facilitated by the lack of established challenging benchmark test problems that would set the standards for model solutions against the known values of the objective functions and ensure compliance with the constraints. A significant number of these papers rely on simple test problems that were published originally in 1974 (Chow and Cortes-Rivera 1974) with only four reservoirs using 12 monthly time steps. This test problem continues to be reused to this day, along with its slightly larger variant with 10 reservoirs to be optimized over 48 consecutive months that was subsequently developed by Murray and Yakowitz (1979). There is no net evaporation from reservoirs in these problems, and also no dynamic flow limits through the turbines that depend on the available storage, although the problems were originally designed to represent hydropower operation. Both test problems are linear, which is helpful, since it enables all researchers to tweak their search engines to reach a solution that is close to the global optimal solution developed by Linear Programming (LP). This provides useful guidance in the use of heuristic solvers that typically require some form of calibration of their search parameters. Bozorg-Haddad *et al.* (2015) tested genetic algorithms (GA) on this problem, and he also later used the honey bee mating optimization algorithm to solve its larger variant (2017), while Jalali *et al.* (2007) used the ant colony optimization algorithm for the same. Numerous other examples of similar publications abound, with virtually no tangible benefits for the community of practitioners who are faced with much larger networks and complex constraints in real-world problems. There is no known river basin model that utilizes a heuristic solver and that has gained wider acceptance among practitioners. In this context, the term "practitioners" refers primarily to the water management agencies' staff and consulting industry professionals, as opposed to the researchers in academia.

Rani and Moreira (2010) provide a literature review of the more recent publications that includes overviews of multi-objective and stochastic optimization procedures. Multi-objective optimization is also a topic often pursued by academics, while generating very little interest among practitioners, as there seem to be no clear guidelines on how reservoir operators could use the resulting pareto-optimal solutions. How does one choose the right model in this environment? This is a question generally posed by Horne *et al.* (2016), who also expressed concern that many of the objectives are vaguely defined, especially those related to the definition of environmental flow targets, thus questioning the use of optimization algorithms due to the inability to firmly define the objectives and constraints. Their work focused on the review of recent publications by others, and revealed that

the choice of the model was mainly driven by the personal preferences of the researchers. In addition to selecting a model that fits the needs of a particular study, the best way should involve a comparison of model results on the same benchmark problems.

Some attempts have been made to address this question by focusing on the models that have had widespread use, such as that of Sulis and Sechi (2013) who claim that "the results of the simulation models are just as good as those of optimization models." This claim cannot be independently verified without the authors' commitments to post their input and output data on publicly accessible websites, which is still allowed by many publications. Contrary to the findings of Sulis and Sechi (2013), the efforts to find the best water allocation in time and in space with simulation models have rendered solutions drastically inferior to those obtained by optimization models on a recent World Bank tender in India that included a reservoir optimization test problem requiring a solution by the bidders as part of the tender evaluation. The benchmark solution developed by the WEB.BM model has not been matched by any of the seven participating models in the tender, while simulation models that rely exclusively on "what if" rules to drive reservoir operation showed the worst performance in this tender. While this is currently only documented as a conference presentation (Ilich et al. 2019), it is awaiting publication in a peer-reviewed journal.

A more recent review of the use of optimization in river basin modelling is provided by Dobson et al. (2019), where the importance of multiple time step optimization (MTO) solutions is highlighted as a useful feature compared to the models that require user-defined reservoir rule curves. Dobson et al. (2019) also believes that MTO solutions provide good training data for machine learning algorithms (MLA) that could be used in real-time reservoir operation. This claim was investigated by Ilich and Basistha (2021), who found that it seems much better to make an informed guess about the incoming runoff using MLAs and solve the reservoir operation as an optimization problem that minimizes downstream flood damage or drought deficits, as opposed to trying to achieve the same by generating informed guesses of suitable reservoir outflows, which has been an on-going trend among researchers for the last two decades (Koutsoyiannis and Economou 2003).

The study by Ilich and Basistha (2021) revealed the potential for significant improvements in basin operation based on revised reservoir operating zones and the use of optimization assuming the short-term runoff forecasts are available, which was confirmed by comparing the historical operation with an output from the model based on an assuming short term runoff forecast were reliable in the past 35 years. The open source models based on the development environments such as the Python programming language (Tomlinson et al. 2020) may seem appealing to researchers who are familiar with such development environments, but this may be an obstacle for practitioners who are looking for user-friendly tools that can be mastered and used with a minimum of learning effort, and without requiring any expertise in Python or other coding languages.

Practitioners therefore require a model that is user friendly, reliable and affordable, and that has versatile features such as flexible time step length and optimization capabilities in space and in time. There is currently no reservoir optimization model that has gained widespread acceptance among practitioners on the basis of the above criteria.

In addressing the existing disconnect between academia and practitioners, it should be noted that researchers seem to be attracted to nonlinear, heuristic and machine learning algorithms, while the river basin planning models with optimization capabilities that have gained acceptance among practitioners almost all utilize LP-based solvers as the most efficient and most reliable solution technique. Examples are RiverWare (Zagona et al. 2001), Oasis (Randall et al. 1997), Water Evaluation and Planning System (WEAP) (Yates et al. 2005), or Hydrologic Engineering Centre Reservoir Prescriptive Model (HEC-ResPRM) which Lund et al. (2003) used to model the water management plan for the entire State of California, although this model could only use monthly time steps, and it is no longer supported by the US Army Corps Hydrologic Engineering Centre. Modelling of hydropower seems to have been a frequent excuse used by researchers for exploring non-LP solution strategies, although the above LP-based models are able to simulate hydropower generation, which can be successfully linearized in most instances, as demonstrated by Kang et al. (2018). A family of simplified LP-based solvers known as network flow algorithms (NFA) are also used by MODSIM (Colorado State University 2021), Resources Allocation Model (REALM) (Victoria State Government 2021) or AQUATOOL (Andreu et al. 1996), but these models are limited to using only single time step optimization (STO) processes, and they are also limited by the iterative ways in which they handle nonlinear constraints that can often lead to undesirable solutions (Ilich 2009).

The above-referenced LP-based optimization models have so far been applied mainly in river basin planning studies, where either historical or stochastic inflow series are matched with the existing or future levels of water demands and infrastructure development. Real-time applications require runoff forecasts that should extend over a horizon that is at least as long as the travel time of water from the most upstream reservoir to the most downstream water user. Since such travel times are typically longer than one week for most large basins, the use of optimization models in real time has been limited.

The other major limitation that has prevented the use of optimization models in real time is their inability to handle hydrological channel routing constraints properly within the MTO framework. The popular MODSIM model that solves only a single time step has the so called back-routing extension option to implement user-defined pre-release policies to handle this issue, in an effort to adjust the releases to the travel time required to reach the downstream demand (MODSIM User Manual, p. 63). The entire procedure remains limited and approximative in nature, mainly due to the limitation of using the STO solution environment. Previous attempts to model channel routing constraints within the STO framework have failed when reservoir releases are demand driven, as documented in a numerical

example by Ilich (2008), since the optimization algorithm released large amounts of flow that flooded the river valley in dry season in an effort to reduce the travel time to the downstream node within a single daily time step. This excessive release somewhat reduced the deficits at the downstream demand node, but it also caused a significant unnecessary spill in the process, which can only be prevented by a strict enforcement of the reservoir rule curves predefined by the user. This enforcement of releases dictated by the shape of the rule curve defeats the purpose of using optimization and reduces an optimization model to a simulation tool.

Channel routing is available in RiverWare within the Rule-based simulation option, which is only executed for individual time steps, while its RPL Optimization option only supports simple time lag or impulse response options that do not take into account channel storage change (2019, p. 188). The use of OASIS requires significant sophistication to incorporate routing equations within the Object Code Language (OCL), and thus far the use of routing has only been applied in combination with strict adherence to reservoir rule curves and within the STO modelling framework (Dan Sheer, personal communication). Numerous reservoir operation studies have been conducted in STO solution mode by using a daily calculation time step in river basins where the total time of concentration is much longer than one day, thus ignoring the limits of how far downstream the reservoir releases can travel within a single day.

An unfortunate and unnecessary distinction is often made between the terms *river basin management models* and *reservoir operation models*. In general, in most river systems the management of regulated river flows is achieved by reservoir operation, hence the reservoir operation models are de facto river basin management models. In that sense, every reference to river basin management models in this paper refers equally to the reservoir operation models. The best reservoir operation is achieved by using optimization algorithms. Practitioners typically evaluate reservoir operation as part of river basin planning studies that rely on the use of historical natural flows or stochastic flow series as hydrological input. Finally, a real-time reservoir operational model should rely on real-time runoff forecasts obtained from specialized forecasting tools instead of the inflow estimates based on historical natural flows or stochastic flow series.

The current state of the art regarding river basin modelling can be summarized as follows:

- Numerous publications based on a variety of heuristic search algorithms have been tested mainly on very simple problems in academia, without generating much traction among practitioners;
- A handful of models used in practice by water management agencies and consulting firms in the private sector are almost all based on some form of an LP solver, either one of the NFAs or a full LP solver with a focus on multireservoir and multipurpose solution capabilities, as opposed to the multi-objective pareto optimal solutions that are so frequently entertained in academia;
- There is a lack of challenging benchmark problems in the literature that would enable proper evaluation of various models that appear in the literature; and

- Among the established LP-based models, only a handful of them, such as RiverWare and OASIS, can solve optimization problems in time and in space (MTO) – however, without the ability to properly include the channel routing constraints. These two models are also the most expensive.

There is clearly a need in the industry for a model that can be used either as a planning or as an operational tool by handling flexible time step lengths that can address proper modelling of both droughts and floods within the MTO solution framework. This paper presents the new WEB.BM model that has many improvements compared to other LP-based models, including in particular its capability to handle channel routing properly within the MTO solution framework. Section 2 describes the conceptual design of the model and model components; Section 3 describes the model interface; Section 4 discusses the model results reporting tools; Section 5 provides a brief overview of the Stream Synthesis and Reservoir Regulation (SSARR) channel routing method channel routing incorporated in the model; Section 6 provides a numerical example that involves daily time steps with channel routing on the Red Deer River Basin in Alberta, Canada; Section 7 contains conclusions and recommendations; and Section 8 discusses the model and data availability.

2 Conceptual design of WEB.BM

2.1 Model components

The WEB.BM is built by having an SQL database for data storage and retrieval, a flexible copy/paste interface for data entry or retrieval, and a Google Maps interface that provides a modelling schematic layer with visual node and link representations of the same elements that are in the database. There is no rule-based simulation option in the model. All solutions are derived using various optimization options that are explained in this paper. WEB.BM uses the LP solver that is publicly available from the COIN-OR solver library (COIN-OR 2021).

Relational database is built on the definition of a water resources network, which is a collection of ordered sets of nodes and links that are mutually interconnected. The ultimate goal of WEB.BM is to find the best set of network flows for a specified time period, given the available runoff, starting storage, water demands and all other related flow constraints. There are six types of physical structures defined in the WEB.BM network, and each of them has one or more associated functions. The structures designated as nodes include junctions, reservoirs and consumptive use nodes. Those designated as links include river reaches, diversion canals and return flow channels. The associated functions that each of these structures can model are shown in Table 1.

Model inputs are given in the SI units of flow for inflows and water demands, units of mm for precipitation and evaporation, and units of m for key reservoir elevations. Most entries in Table 1 are self-explanatory. Some may require additional details that are outlined below.

Net evaporation on reservoirs is a function of the water surface area, which is not known ahead of time, especially when optimization is done simultaneously over multiple time

Table 1. System components and their associated functions.

	Component	Associated function
Nodes	Junction	Mass balance of all incoming and outgoing links
	Consumptive Use	Evapotranspiration loss associated with irrigation or other water use
	Reservoirs	Mass balance at reservoir nodes
		Storage change
		Net evaporation on reservoirs
Links	River reach	All ranges of channel flow (with or without hydrological routing)
		Hydropower generation
		Apportionment agreements between bordering states
		Dynamic setting of maximum reservoir outflow as a function of storage
		Environmental flow targets (minimum and/or preferred)
	Diversion canal	Diversion flows from the stream with canal capacity limits
		Diversion licence limits
		Hydropower generation
		Dynamic setting of maximum flow limits on diversion flows when used as outlets from reservoirs or in relation to flows in another river reach or a diversion canal
	Return flow channels	Dynamic setting of return flows as percentage of consumptive use of the upstream consumptive use nodes; can be unique for each time step

steps. The model uses piece-wise linearization of volume vs area curve to apply the net evaporation (evaporation minus precipitation) to the average water surface area over a modelled time step. Net evaporation can be either positive or negative depending on the values of precipitation and evaporation in each individual time step, and its impact can be significant on large reservoirs. This poses a challenge for proper modelling over simultaneous multiple time steps where the average water surface areas over each modelled time step are not known in advance, since the ending storage for each time step is part of the model's solution.

Piece-wise linearization of nonlinear objective functions may require that channel flows be broken down into several channel flow zones, of which only one is defined as the ideal flow zone; up to six zones may be created above the ideal and nine zones below the ideal. Flow zones can be visualized as "parallel" channels that form the total river flow when summed up.

Zones above and below the ideal are given weight factors that define the importance of maintaining flow in them in reference to other components such as consumptive use or storage. The actual number of zones for each channel is defined by the user. The zone bounds can be uniquely defined for each simulated time step of every year. Hydrological routing of channel flows is based on the SSARR routing method. It is given more coverage in Sections 4 and 5 of this paper.

Hydropower is generated by using the standard equation:

$$P = 9.807 QH\rho\eta \qquad (1)$$

where P is the average power over a time step (MW), Q is the average flow through the turbines, 9.807 is the gravitational constant (m/s^2), H is the average net head (m) available over a simulated time step, ρ is the density of water (1000 kg/m^3) and η is the combined operating efficiency of the turbine and the generator (typically $0.9 \times 0.9 = 0.81$). The net head is calculated internally in the model as the difference between the head water and the tail water elevations, both given in the

units of elevation (m). For head water elevations, the options are (a) constant elevation; (b) elevation as a function of the channel flow by using the appropriate rating curve relationship between the flow and elevation; and (c) the elevation based on the pool level of the upstream reservoir. The same options can also be used to define the tail water elevations, except that the options for (b) and (c) would refer to the downstream channel or downstream reservoir, respectively.

Apportionment agreements represent an obligation of the upstream state to pass an agreed percentage of the natural flow that originates from its territory to the downstream state, and are frequently encountered among bordering states in North America. This requirement has to be fulfilled on an annual basis for each hydrological cycle, which requires routine naturalization of flows at border crossings by water management agencies and updating the balance of recorded flow volumes that were passed to the downstream state. This process is modelled in planning studies by using historical naturalized flows and represented as a hard constraint using the following expression:

$$V_k \leq \sum_{t=1}^{m} Q_t \, \Delta t_t \qquad (2)$$

where V_k represents the target volume for year k, while Q_i and Δt_i represent the channel flows at the border crossing between the two states and the length of the simulated time step i in the same year, respectively, whereas m is the number of simulated time steps in a year (e.g. 52 for weekly or 12 for monthly). The term V_k is internally calculated in the model as a requested percentage of a designated natural flow series. This constraint ensures that the required amount of total annual flow volume is passed to the downstream state in each simulated year. Diversion licence limits are modelled as a very similar constraint, with the only difference being the change of the sign from $\leq$ to $\geq$, thus limiting the total annual diverted flow volume to be less than the maximum annual volume limit of the respective water licence. Both the apportionment agreement and the diversion licence limits are modelled as hard constraints. They are not part of the priority allocation based on the assigned weight factors. Other instantaneous flow limits can be modelled using the channel zoning representation mentioned above, which is also used by all other LP-based models.

Dynamic settings of the flow limits on either river reaches or diversion canals is provided as a function of the elevation vs outflow curves for various reservoir outlets. Up to four such outlets can be specified for a single reservoir in tabular form, although it is recommended that the key elevations (including the inflection points on the curves) be common to all outlets that operate within the same elevation range, so as to reduce the number of zones that reservoirs create automatically on the basis of the points in the outlet curves. The model automatically inspects the convexity of the outlet curve and resorts to the internal use of binary variables to ensure proper modelling of outflow limits only when necessary. This minimizes the number of required binary variables. The need for binary variables that require the use of mixed integer solvers has been

discussed in earlier publications (Ilich 2008). Return flows are set to a given percentage of consumptive use, which means that they are also allocated dynamically by the model, since the allocated consumptive use is not known in advance. This percentage can be the same for all time steps, or unique for each time step.

2.2 Internal model hierarchy

There are three important structures within the architecture of the WEB.BM that are interconnected through a top-down hierarchy. These are:

- Data objects (nodes and links) which are only accessible to a particular user under his/her user login ID, and which are the basic elements that form water resources networks.
- Projects, which are defined as interconnected subsets of nodes and links accessible to a particular user. They contain physical information related to a particular river basin, such as:
  - Network connectivity (upstream and downstream node for each link)
  - Physical capacities (canal flow limits, storage capacity curves for reservoirs, etc.)
  - References to other relevant input time series that include inflows, evaporation, precipitation, historical recorded flows, water demands or historical reservoir levels which are sometimes needed for verification scenarios that are aimed to repeat the historical reservoir operation
- Modelling scenarios, which are derived from projects. One project can have one or more associated scenarios. Modelling scenarios differ from each other in terms of:
  - The starting and the ending date of simulation (which has to be within the limits of the starting and the ending date for the project to which the scenarios belong to)
  - The starting storage levels at the beginning of the simulation
  - Definition of operational priorities defined as the shapes and sizes of operating zones of each component and the priority (weight) factor for each zone of each component.

2.3 Time-step length and solution mode options

WEB.BM allows for a flexible length of simulated time steps. The default solution mode in terms of the time step length can be monthly, weekly, daily or custom, where the custom length is specified by the user, which can be useful in instances when the user wants to model 10-daily time steps which are typically required in many Asian countries due to the existing 10-daily irrigation scheduling of canal flows. These lengths can vary between 10 or 11 days depending on the number of days in a month, while for the month of February the last 10-daily period would be eight or nine days long for regular or leap years, respectively. An important requirement for custom time step lengths is that

they sum to 365 days in regular years and 366 days in leap years for multiyear simulations. When the channel routing option is used, custom time steps can also include time steps that are shorter than one day, in which case they are to be given as a fractional value of the day. For example, a 6-hourly time step would be specified as 0.25 days. The use of routing also requires equal lengths of all simulated time steps.

In general, LP optimization engines are used to find optimal network flow solutions by minimizing or maximizing the sum product of flows and their respective weight factors. This is typically achieved with one of the two equivalent formulations of the objective function:

$$Max \sum_{i=1}^{n} X_i P_i \leftrightarrow Min \sum_{i=1}^{n} (I_i - X_i) P_i \qquad (3)$$

where X_i is the allocated flow, P_i is the priority assigned to user i and I_i is the value of the upper bounds or ideal target, while n is the number of components with assigned weights P_i. The term P_i should be understood as a dimensionless weight factor set arbitrarily by the user that represents the importance of a particular user relative to other users. The two formulations are equivalent, since maximizing flows is limited to the value of the ideal target I_i, where $I_i \geq X_i$ for each model component, so either form of the objective function produces the same solution for the same problem weights and constraints. The WEB.BM model uses the maximization form since it requires fewer arcs in the network. The objective function can be applied on a single or on multiple time steps simultaneously, thus allowing solutions for complex dynamic networks that may involve multiple years and that are particularly useful when investigating multiyear carry-over storage management options, with the objective function expanded to include simultaneous operation over a range of m time steps, further referred to as MTO:

$$Max \sum_{t=1}^{m} \sum_{i=1}^{n} X_{i,t} P_i \qquad (4)$$

There is more than one set of values of pricing vector P_i that can deliver the same solution $X_{i,t}$. The process of selection of the proper weight factors depends on the user's skills, taking into account the issues initially addressed by Israel and Lund (1999). An algorithm that would facilitate the best automated settings of the pricing vector P_i based on a given set of priorities is still an active area of research.

MTO solutions are particularly useful when combined with the equal deficit constraint available in the WEB.BM model, which forces the model to spread irrigation deficits evenly throughout the irrigation season, expressed mathematically as:

$$\frac{X_{1,t+1}}{D_{1,t+1}} = \frac{X_{1,t}}{D_{1,t}} \qquad (5)$$

The denominator $D_{i,t}$ in this expression represents water demands of component i in time step t. When used in the planning mode with known inflows for the entire year, the above constraint enables the model to determine the optimal level of demand hedging while the MTO solution simultaneously defines the best perfect reservoir operation for each

simulated year, which provides for combined optimal management of available storage, inflows and water demands in a single model solution for the entire year of data. There are three ways in which the Mixed-Integer LP solver can be called within the WEB.BM:

(a) Using an STO mode, which is common to most other models. In this way the model derives demand-driven releases for individual time steps based on pre-specified reservoir operating zones that define a sequence of reservoir releases in a multireservoir system. The shapes and sizes of reservoir operating zones are flexible and they can be uniquely specified by the user in WEB.BM for each year.

(b) Using the MTO solution mode, which can be applied to individual years of data in chronological sequence, or for all simulated years at once (the last option is only available on a steady-state basis, without channel routing).

(c) Combined STO/MTO mode, typically used when shorter time steps are modelled while the total basin travel time and the available runoff forecasts exceed the length of the simulated time step. For example, if a daily calculation time step is used and runoff forecast is available for 5 days ahead, the model proceeds with a series of MTO solutions over a 5-day horizon, while adopting only the part of the solution that refers to the first day, as demonstrated in Fig. 1.

3 Model interface

In addition to flexible time step lengths, the ability to easily include or exclude a variety of constraints, and an efficient and a reliable solution engine, the model also provides a user-friendly interface based on copy/paste functions, as briefly described below. The purpose of the interface is to enable easy data entry and retrieval, selection of model solution options, and tools for viewing and analysing model results. Once a user logs on to the system, the top menu bar provides the options displayed in Fig. 2.

The options are (a) Project, which opens an entry form for defining a project; (b) Data Maintenance, which allows the user to create nodes, channels, recorded flow stations and climate data stations; (c) Map, which opens the Google Maps application that allows users to create a modelling schematic by drawing the components that are within a particular project as a layer in Google Maps; (d) Reporting Tools, which provides functions for statistical analyses of results and plotting options; (e) Solver, which calls the solver and provides the model solution; (f) Solver Logger, which reports all steps undertaken within the solver routines; (g) User Manual, which provides a download link to the User Manual; (h) Terms of Use, which outlines the terms of use of WEB.BM; and (i) the "contact" button, which allows the users to contact the webmaster with their questions. It is not possible to discuss all the options in a single paper, but the most important options for data entry and manipulation are outlined below. The project form shown in Fig. 3 opens after the Project button is pressed.

When opened for the first time, the project form is empty, as shown in Fig. 3. A project can be defined by clicking on the Add button, which will open another form requesting the user to enter the name of the project and the time step of the data series to be read from the database, along with the starting and the ending dates for the project. Another way to create a complete project is by using the Restore command, by which a previously backed up project (possibly even from another user who provided a backup file) can be fully restored in what could be a separate user account. In this way, users can share projects that they back up and send to each other.

The Data Maintenance button opens a drop-down menu that allows users to create Nodes and Channels, as well as to input all necessary hydrological and meteorologic time series data, which can be accomplished by using copy and paste commands, or by direct upload from Microsoft Excel files

MTO Solutions	Days of Operation								
	1	2	3	4	5	6	7	8	9
1									
2									
3									
4									
5									
Legend:									
	Solution used in real time operation								
	Solution based on 5-day runoff forecast								

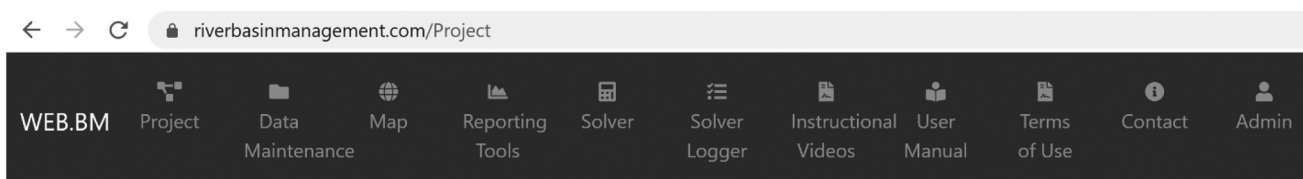Figure 1. Graphical representation of STO/MTO solution mode.
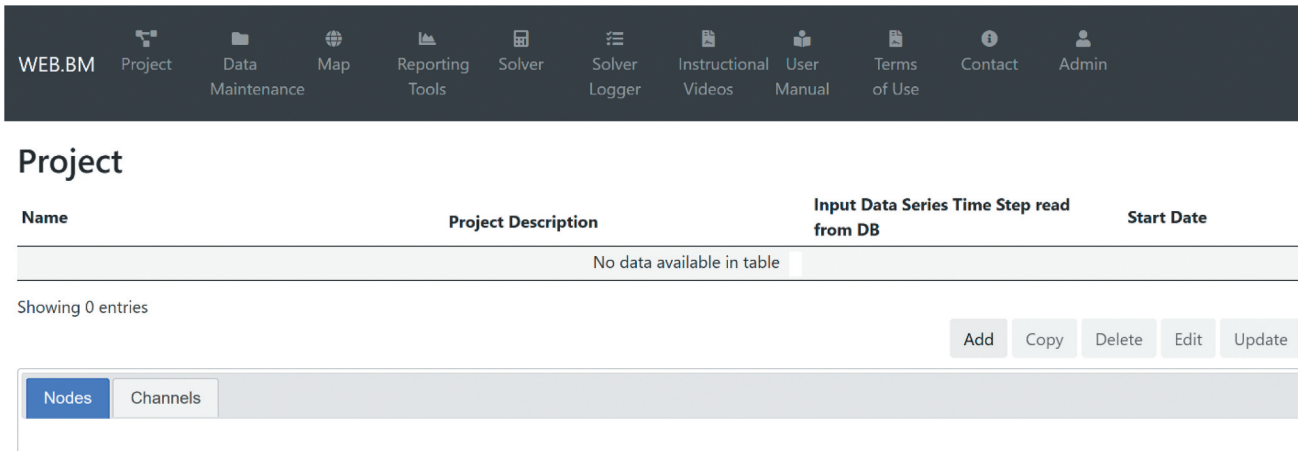

Figure 2. Top menu bar of the WEB.BM model.

Figure 3. Top project entry data form.

that have the data series formatted in a single column. Each of the model components (junction, reservoirs, consumptive users, river reaches, diversion and return flow channels) has its own unique data entry form that provides options to enter all necessary physical data in a single form. These forms are accessed through Data Maintenance. Physical data includes storage capacity (elevation-area-volume) tables for reservoirs, network connectivity for channels (e.g. the definition of the upstream and the downstream node for each channel), outflow vs elevation curve for river reaches or diversion flows that handle reservoir outflows, or time of travel vs flow table for river reaches). The Add button can be used to create new nodes and channels. Nodes should be created first since they will then appear in combo lists for selections as downstream or upstream nodes every time a new channel is created in the database. Once all nodes and channels have been created for a particular basin, they should be included in the project, which is achieved by clicking on the "assigned" check box in front of the name of the channel and node in the Channels and Nodes lists that are shown under the respective tabs in the Project form, as shown in Fig. 4. If this project represents a large river basin with tributaries, the project can then be copied and the name of the copied project can be changed into

the name of a desired tributary. To complete another project that will only include the nodes and channels within the tributary catchment, it is only necessary to uncheck the selection in the check box at the beginning of the component name in the node or channel list for those components that are outside of the tributary sub-catchment. The node and channel list with the check box is shown in Fig. 4.

Once the project components are saved, it is possible to create a schematic in the Google Maps layer by dragging each component from the list of nodes and channels on the left side panel into the Google Map and using the drawing tools to represent them. Reservoirs and irrigation blocks are represented as closed surfaces that can have numerous edges, thus allowing the user to draw a line around the lake shore of the water body created by the dam, which can then be saved as a visual representation of the reservoir node. A similar feature is available for irrigated areas.

Junctions are represented as circles with adjustable radius and location, while all components of "link" type are represented as multilines that can also have an optional arrow showing the direction of flow. Components shown in Google Maps allow users to access input data or simulated results by selecting one of those options from a drop-down menu that shows the component selection. An individual project can have one or more
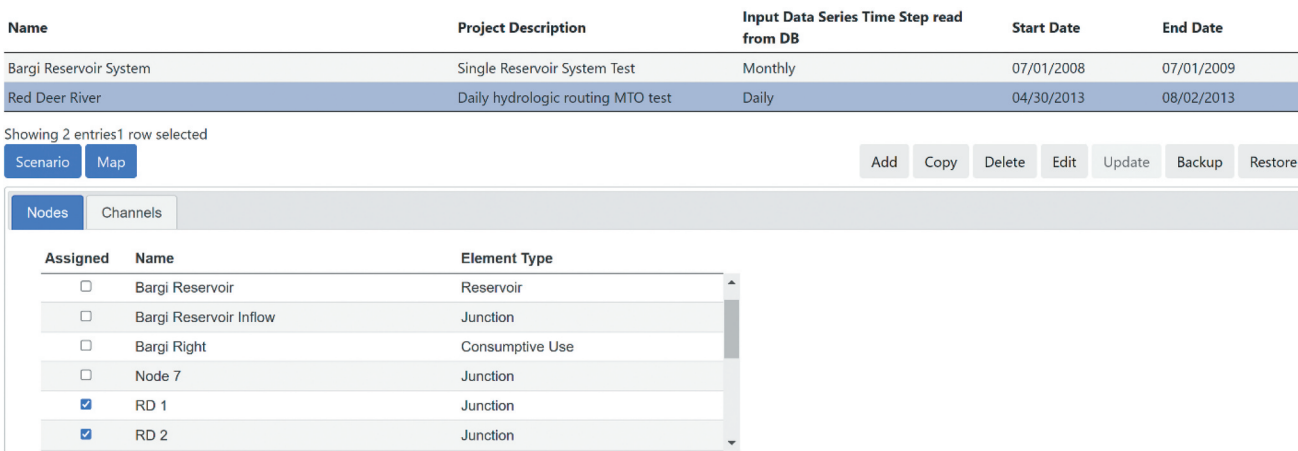

Figure 4. Inclusion and exclusion of nodes and channels into a project via the check box feature.

modelling scenarios, which may have a different starting and ending date, starting reservoir levels and, most importantly, different allocation priority among various stakeholders. Scenarios are therefore defined as subsets of a project, with one project linked to many scenarios in the database, implying that one project can have multiple scenarios. The model offers a very efficient scheme for specifying the zones sizes, their numbers and their weight factors that is briefly outlined below.

Once a project is created and saved, it cannot be submitted to the solver without first having at least one scenario created within the same project. Each scenario inherits the information about the physical connectivity of the project, but adds its own definition of the user priorities, starting conditions for the simulation and the length of the simulated period. To open the scenario creation form for the selected project in the project form, users need to click on the Scenario button shown in Fig. 4. This opens the form shown in Fig. 5, where the existing scenarios are shown for a selected project that is displayed in the project drop-down box. In this case there are two projects that differ only in the units of the resulting simulation, one being the units of flow with reservoir elevation in metres, while the other one shows the results of an identical scenario converted to the units of volume. Although the solver uses the units of flow when deriving a solution, users can select to save the final results in the units of either flow or volume. The quickest way to create a new scenario is to use a copy

command and change only those elements that define the difference between the new scenario and the scenario that was copied.

Each scenario defines a unique set of weight factors (the P_i terms of the objective function) and the flow zones. This is achieved efficiently by placing model components into policy groups, where the pricing vector is specified only for the selected group. Each component member in the group can have a slight variation of the P_i value by having it increased by using a user-specified parameter known as "offset." The primary reason for this is to simplify the input data entry. For example, interconnected reservoirs can belong to the same operating policy, which means that they will have the same number of operating zones. The first reservoir listed in the group will have the lowest priority within the group, implying that every subsequent reservoir listed in the same group will have its P_i factors increased by the value of the "offset" parameter, which is typically set by the user to a small value, such as 0.1, to ensure that the reservoir with the lowest priority (usually the most downstream reservoir in the group) is the first to release water from its top zone to meet the downstream water demand. If the parameter "offset" is set to zero, all reservoirs in the group will have the same weight factors, which is not recommended, since it may create more than one solution in repeated runs with equal value of the objective function. Figure 6 shows a control built into the

Scenario List

Projects: Narmada River Basin Veriffication

	Name	Description	Routing Option Type	Calculation Time Step	Solution Type	Start Date	End Date
◉	All Reservoirs Historic run		Steady State Calculations	Custom	STO	01/01/2000	01/01/2017
◉	All Reservoirs Historic run vol. units		Steady State Calculations	Custom	STO	01/01/2000	01/01/2017

Showing 2 entries

Add Copy Delete Edit

Figure 5. Scenario list for a selected project.

Node Policy Group

Name	Number Of Zones Above Ideal	Number Of Zones Below Ideal	Zone Weights Offset
Storage	1	2	0.03
M & I	0	1	0.01
Unlimited	0	1	0

Showing 3 entries1 row selected

Nodes

Change order	Name
↕	Res 004
↕	Res 005
↕	Res 001
↕	Res 003
↕	Res 002

Showing 5 entries1 row selected

Node Zone Weight

Zone ↕ 1	Zone ↧ 1	Zone ↧ 2
50	50	60

Showing 1 entries

Delete Delete All Edit Update

Node Zone Levels

Initial Reservoir Elevation at the Scenario Start Date for **Res 004** (m) [137.88] Save Initial Elevation

☐ Use Historic Reservoir Levels for Zone ↧ 1

Export Paste from Clipboard Save All

Year	Julian Day	Zone ↕ 1	Zone ↧ 1	Zone ↧ 2
1981	1	151.5	137.88	131

Figure 6. Node zones form.

Table 2. Weight factors calculated internally using the offset parameter of 0.03.

	Zone ↑ 1	Zone ↓ 1	Zone ↓ 2
Res 004	50.000	60.000	50.000
Res 005	50.030	60.030	50.030
Res 001	50.060	60.060	50.060
Res 003	50.090	60.090	50.090
Res 002	50.120	60.120	50.120

WEB.BM which enables users to change the position of any component within the policy group, thus automatically changing their priorities without the need to change the group P_i factors. This is achieved by clicking on one of the components in the "Change Order" column within the Nodes group list on the upper right side of the Node Zones form, and dragging the selected component up or down the list, until its position is changed as desired. The "Change Order" column contains the up/down arrow symbol which signifies the ability to move the component within the group. This "shorthand" inscription in Fig. 6 will result in internal setting of the 15 unique weight factors in the database as shown in Table 2, based on only four parameters that had been entered in the policy group form and successive additions of the offset parameter, which is set to 0.03 in this example.

As mentioned, the weight factors carry dimensionless units and they are arbitrarily set by the user to represent priority of allocation. The same approach is facilitated for river reaches or consumptive use components in the same policy group, except that the optional use of the equal deficit constraints for a particular consumptive use policy group will override the positional priority within the group within the time period (sequence of time steps) for which the equal deficit constraints are activated.

Figure 6 also shows the specification of the starting reservoir storage, weight factors and zone bounds, which can be given with the same value for all time steps, in which case they need to be specified only once, as shown in Fig. 6, or as a series of target elevations for various times of the year (or many years if the targets differ from year to year).

4 Model solutions and presentation of model results

Selecting the Solver option in the main menu shown in Fig. 7 allows users to select the project and scenario to be executed, with the download option check box selected by default. This option creates a zip file that is downloaded following each call of the solver. The zip file contains either the solution (as text files in matrix format that can be imported into Excel) or an error message log if there are errors in the input data. The solver option also allows users to execute a Seasonal Operational run, which will open additional entry forms to paste into the model the current starting reservoir levels, along with the current inflows and water demand forecasts for all components in the schematic. The pasted values will then replace the data previously read from the database. This option is typically executed over shorter time horizons for which runoff forecasts are available during wet seasons. For longer time horizons of up to three months ahead during dry seasons, assuming seasonal volume runoff forecasts are available from other forecasting tools, the model requires the user-specified Aridity Factor visible in the solver form for the Seasonal Parameters option. The Aridity Factor represents the percentile of historical annual runoff that corresponds to the seasonal forecasted volume, and applies this percentile to all historical weekly natural flow duration curves available in the database to help distribute the seasonal volume forecasts into weekly runoff forecasts. Sensitivity analyses automatically create two more scenario runs with ± e deviations of forecasted inflows, where e is the assumed forecast error due to uncertainty of the forecasts (typically between 10% and 20% of the target).

The use of Reporting Tools is optional, and it will eventually be available only to users who subscribe to model use for a small monthly fee, to help offset the web server charges. At this point, users interested in testing the application should use the contact button to request access to the Reporting Tools, knowing that it will be issued free of charge only for a certain period of time suitable for testing. Graphical analyses are useful since most river basin models produce a lengthy series of simulated channel flows, reservoir levels and water use for lengthy sequence of years.

Figure 7. Solver interface form.

Users can plot up to four components simultaneously that can be from the same scenario or from different scenarios; with two different Y-axis scales in either a time series or in a probability format; and with a user-controlled zoom-in feature on the X axis and the automated scaling of the visible data on the Y axes for time series plots, which provides the commonly used flow duration curves. The probability format is flexible, allowing users to plot flow duration curves for individual time steps or for several consecutive time steps, which may include wet or dry seasons. Deficit tables can be created for absolute or relative deficits for selected components on an individual basis, with a feature to display and save the resulting deficit table for all time steps within a given scenario. This feature also allows users to calculate annual deficits for all consumptive use components at once. Similarly, solutions derived by the model for each scenario (channel flows, storage levels and water use) can be displayed in Google Maps for a selected time interval, or as average values for a selected set of consecutive time intervals. This is particularly useful if users choose to print results in the units of volume, since it allows easy manual verification of the mass balance for any node in the system. When this feature is used for a particular scenario in the units of volume, the reservoirs will display starting and ending storage as well as net evaporation all in the units of volume, thus allowing users to quickly calculate storage change for a given period and use it in the balance calculation with other outflows and inflows for a given reservoir. An example that demonstrates this is shown in Fig. 8.

The water balance for the month of August 2008 for the reservoir shown in Fig. 8 can be defined as follows:

$$\text{Inflow} + \text{Starting Storage} = \text{All outflows} + \text{Ending storage} + \text{Net Evaporation} \quad (6)$$

The mass balance for the selected period can be confirmed after substituting the numbers from the model solution for the selected scenario (all units are millions of m^3):

$$1917.775 + 2135.677 = 95.209 + 406.497 + 148.929 + 3419.491 - 16.674$$

Other built-in Google Maps functions allow the user to access the Data Maintenance menu or the Chart plotting facility for the component that is visually selected in Google Maps, along with a display of all or individual component names.

WEB.BM is a multiuser model, implying that each user develops and saves his or her own project using data that may be in the public domain or proprietary. The development environment relies on the use of the SQL Server database, Google Maps application interface, COIN-OR solver library and a comprehensive code written in .NET Core environment. Data and projects developed in one user account are not accessible to other users, unless users back up their project data and send it to others with the intended purpose of sharing projects. The Backup and Restore commands available in the Project form were developed for this purpose. Input data for three sample test problems are provided in the WEB.BM User's Manual. These test problems should be built step by step as instructed in the manual, which can be downloaded from the application at www.riverbasinmanagement.com. Availability for download is discussed at the end of this paper.
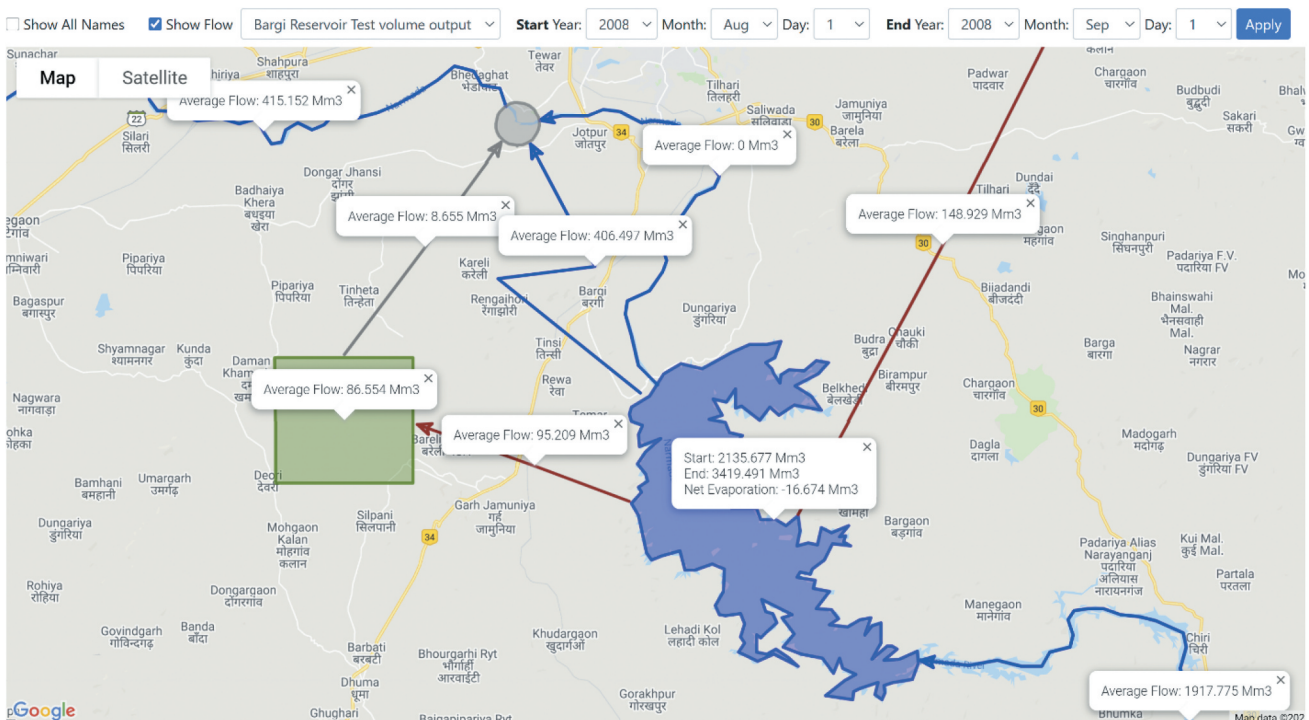

Figure 8. Show flow function in Google Maps.

Other larger projects with multiple reservoirs and many more components in the modelling schematic have been developed in Canada (Ilich *et al*. 2020) and India (Ilich and Basistha 2021), but the data that were used on those projects are not all in the public domain. It may be possible for these data to be shared upon request, but this would require prior permission by the owners of the data. The application by Ilich and Basistha (2021) included a gradually varied time step length between 10 days in the dry season to 3 days in the monsoon season, and an optimization run of a medium-size system for 35 years simultaneously, thus solving a constrained MTO problem with three hydropower plants and five reservoirs totalling over 250,000 constrained variables in less than 11 minutes.

It has often been stated among practitioners that open-source software is a preferable option. However, a professionally developed model usually has over 100,000 lines of code, which requires organized maintenance and upgrades. Typically, open-source codes are exchanged among researchers to test various ideas, but a fully functional professional application software program normally requires a dedicated team to provide maintenance, reliability and documentation updates, all of which also require continuous funding.

5 Hydrological routing constraints

The hydrological routing method incorporated in WEB.BM was originally proposed by Williams (1969) and later adopted by the US Army Corps of Engineers in the development of the the Stream Synthesis and Reservoir Routing (SSARR) model (US Army Corps of Engineers 2021). This choice was driven by the need to introduce modifications in the routing coefficients as a function of the changes in the velocity of the propagation of the flood way, an issue that was originally solved by Cunge (1969) and further improved by Ponce and Yevjevich (1978). Most of these improvements

still required physical parameters such as the bed slope, roughness or channel geometry for calculation of the routing coefficients. Surprisingly, in spite of its elegance, ease of application and minimal input data requirements, very few sources mention the work of Williams (1969) that was used as a basis for the routing equations used in the SSARR model, with the same formulation as in the well-known Muskingum routing expression:

$$O_t = C_1 I_{t-1} + C_2 I_t + C_3 O_{t-1} \qquad (7)$$

where I and O represent inflow and outflow for a given channel while t is the time step counter. The SSARR routing coefficients also sum to 1.0, as in the case of the Muskingum routing coefficients, while the only difference is that the values of the routing coefficients Ci are determined as a direct function of channel flows (Williams 1969), which has some obvious advantages:

(a) The only information required for dynamic update of the values of routing coefficients is the time of travel vs flow relationship for a given river reach and the length of the calculation time step. No other data related to the channel geometry, gradient or roughness are required.
(b) The values of routing coefficients undergo internal dynamic adjustments as the modelling moves through different flow regimes between dry seasons and wet seasons.

Travel times through a river reach can be obtained by using a combination of sources, including flow observations or dye studies, or as an output option from a calibrated Hydrologic Engineering Centre - River Analysis System (HEC-RAS) model for various flow rates. The SSARR routing method has been used routinely in the Prairie Provinces of Western Canada and in other regions of North America over the past four decades. One condition that should be satisfied for

Figure 9. Red Deer River modelling schematic.

a successful application of this routing method is that the calculation time step should be selected such that the travel time along the reach is at least more than twice the length of the calculation time step, i.e. $Ts \geq t/2$. If this condition is not satisfied, the terms that multiply I_{t-1} and I_t become greater than 0.5, and the mass conservation rule that requires the sum of all three coefficients to be equal to 1 can no longer be maintained.

Contrary to other simulation models that use fixed-value routing coefficients, the SSARR routing method relies on coefficients C_i that are a function of flow. This is a nonlinear constraint, and the model conducts a few iterative calls of the solver to update the travel time Ts by using the channel flows obtained from the solutions in the previous calls. The convergence is typically achieved in fewer than five iterations, while the users can set the maximum number of iterations in each scenario.

6　Numerical examples

The test runs briefly explained here demonstrate the power of the model to combine MTO with hydrological channel routing – a feature that is currently not supported by any other known commercially or publicly available optimization-based model. While seemingly simple, the two numerical examples presented here are offered as benchmarks to other model developers who aspire to combine optimization algorithms with hydrological routing of flow through river reaches. This is an important step for the application of optimization-based models in real-time operation, as well as to help find the best ways to operate reservoirs in flood management studies. The modelling schematic is shown in Fig. 9. Two test runs are presented using a daily time step. The basin is regulated by the Dickson Dam which forms Gleniffer Lake at its upstream end, and it contains one tributary inflow at node 5, as shown in Fig. 9. The principal issue demonstrated in these two test runs is that a combined use of MTO and channel routing is necessary to find optimal reservoir releases when the time of travel from the reservoir to the downstream point of interest is longer than the simulated time step, or during floods when a steady-state modelling approach cannot be used. To the best of this author's knowledge, there are no other existing models that can provide an automated solution to the test problems presented here, their implied simplicity and small scale notwithstanding.

6.1　Test run 1

This test run starts on 30 April 2013 and runs continuously in MTO mode over 11 days. The operating priorities in this modelling example are listed below:

(1) Maintain minimum flow of 16 m³/s in Channels RD 20, RD 11 and RD 60 at all times;
(2) Provide water demands to RD 100 and node 8 (as given with the remaining input data); and
(3) Keep the maximum flow through the City of Red Deer at 950 m³/s (Channel RD 11 and entry into the channel RD 40) at all times as much as possible during floods.
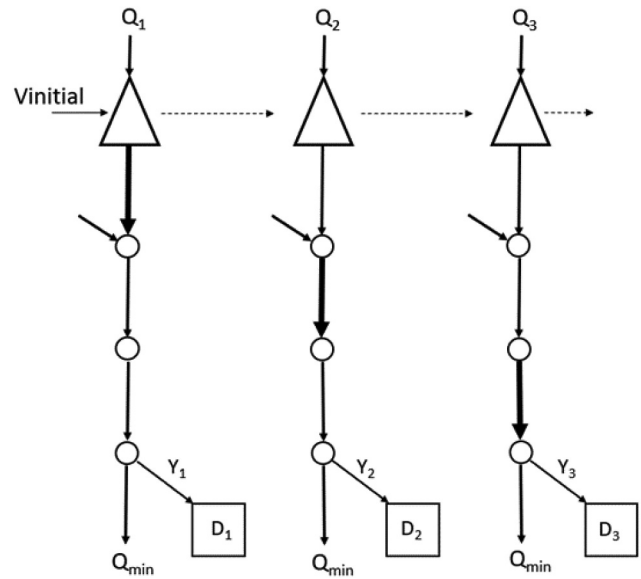

Figure 10. Example of channel routing with MTO solution framework.

The example simulation run relies on the following input data:

(1) Storage capacity table of Glennifer Lake created by the Dickson Dam;
(2) Outflow vs elevation table for combined Dickson Dam bottom outlet and spillway;
(3) Reconstructed historical 2013 daily inflows into Glennifer Lake;
(4) Historical flows at the Little Red Deer River tributary (inflow at node 5 in the schematic);
(5) Travel time vs flow tables for river reaches RD 30, RD 40 and RD 50 (travel time for reach 20 is ignored due to its short length); and
(6) Key reservoir elevations, including the maximum operational water level (949.5 m), the normal water level (944.0 m) and the top of dead storage (926.0 m).

For simplicity, net evaporation has been ignored in these runs. The problem is presented graphically in the schematic in Fig. 10 for only three consecutive time steps, with the same reservoir connected in time via carry-over storage arcs. The storage release movement is shown as a thick line in the schematic, depicting the movement of the release from one river reach to another, assuming that the lengths of channels were chosen such that they correspond roughly to one day of travel time for average flow conditions, while the calculation time step is also conducted on a daily basis. The use of optimization in this framework should determine the amount and timing of the release from the reservoir such that the water demand of 100 m³/s is met at the downstream location on 6 May, along with the minimum flow requirement of 16 m³/s in the most downstream river reach RD 60 of the system which should be met for all simulated days. It should be noted that the above Table 3 shows the flows at the upstream end of each river reach. If a simple time lagging method was employed, the model would release the 116 m³/s on 4 May such that 100 m³/s could be later consumed on 6 May and 16 m³/s used for flow maintenance in River Reach 60. However, this does not take into account the

Table 3. WEB.BM model solution (reservoir units m; all others m^3/s).

Component	No	30 April	1 May	2 May	3 May	4 May	5 May	6 May	7 May	8 May	9 May	10 May
Reservoir	2	942.611	942.544	943.066	943.501	941.830	941.849	941.942	942.038	942.213	942.355	942.485
River reach	10	32.165	24.400	92.651	83.312	53.696	26.155	28.744	29.391	41.459	36.746	34.857
River reach	20	16.000	34.160	16.000	16.000	300.111	23.511	16.000	16.000	16.000	16.000	16.000
River reach	25	10.100	7.700	6.310	6.310	6.460	6.580	6.310	5.970	5.810	5.420	4.890
River reach	30	26.100	41.860	22.310	22.310	306.571	30.091	22.310	21.970	21.810	21.420	20.890
River reach	11	28.957	31.862	31.990	26.828	135.897	161.953	67.366	40.101	29.813	25.499	23.291
River reach	40	28.957	31.862	31.990	26.828	135.897	161.953	67.366	40.101	29.813	25.499	23.291
River reach	50	31.350	30.804	31.452	30.292	65.967	131.535	118.300	72.527	48.717	36.276	29.586
Diversion	100	15.000	15.000	15.000	15.000	15.000	15.000	100.000	15.000	15.000	15.000	15.000
River reach	60	16.456	16.237	16.174	16.000	26.460	68.715	16.000	85.054	57.116	37.861	25.789

requirement to refill channel storage so as to enable the flow of 116 m^3/s to be available at the end of Reach 50 on 6 May. With the starting reservoir elevation of 942.5 m, WEB.BM derived the solution that is displayed in Table 3 (reservoir levels are given in m while all other components are given in m^3/s).

Hence, the flow in channel 40 is shown as 118.3 m^3/s on 6 May, implying that 2.3 m^3/s will end up in channel storage on 6 May, while the amount at the downstream end of this channel will be 116 m^3/s, which is distributed between water demand D$_3$ (100 m^3/s) and river reach 60 (16 m^3/s). Note that there is no additional spill above 16 m^3/s in Channel 60 on 6 May, which means that the model has determined the right amount of storage release on days 4 and 5 to ensure that the available flow at the top of channel 60 is equal to the sum of the required diversion and the minimum flow in Channel 60. The initial storage release of 300.111 m^3/s is increased by the amount of local runoff into node 5 to give the total inflow into Channel 30 of 306.571 m^3/s, and after two days of routing transformations this flow will provide 116 m^3/s at entry of Channel 60.

The process of routing through a sequence of channels is shown in Fig. 11. It should be noted that the actual entry into channel 50 is a sum of two flows, diversion flows at channel 100 and the river flow at channel 60, which are summed up in Fig. 11 for the purpose of analysing the routing sequence. If it is desirable to do this in the model, a channel with no routing can be inserted before node 8 to show the result of routed flows from channel 60.

Based on the model set-up, the incoming flow in channel 60 would have the diversion flows at channel 100 subtracted at its upper end. In conclusion, during low flow conditions,

a sudden increase in downstream water demand from 15 to 100 m^3/s would require a reservoir release of 300.111 m^3/s two days earlier to allow for subsequent travel time and the routing transformation of channel flows.

6.2 Test run 2

This numerical example demonstrates the automated management of storage releases during a severe historical flood in June 2013 assuming the available flow forecasts. While the City of Red Deer (the City) is in a hilly area that can withstand peak flows of up to 1300 m^3/s without suffering any damage to the infrastructure, lowering the flood peak flow through it is beneficial to the downstream communities, especially to the town of Drumheller located some 230 km downstream. The goal of this test example was to demonstrate that the model can find the right timing and quantity of reservoir releases so as to maintain the upper bound on flow of 950 m^3/s through the City. The tributary inflows between the reservoir and the City introduce an additional challenge, requiring the reservoir releases to be adjusted dynamically such that when they are summed with the tributary inflows and routed to the City limits, the prescribed threshold of 950 m^3/s is not exceeded. For comparison, the historical flood peak through the City was 1160 m^3/s, after having routed the peak reservoir inflow of 1650 m^3/s. Figure 12 shows the flows through the three channels in the modelling schematic along with the historical flows at the City. This test run involves an MTO approach over a period of 40 consecutive days starting on 1 June 2013. Figure 12 shows that the reservoir outflow is optimized by the solver in such
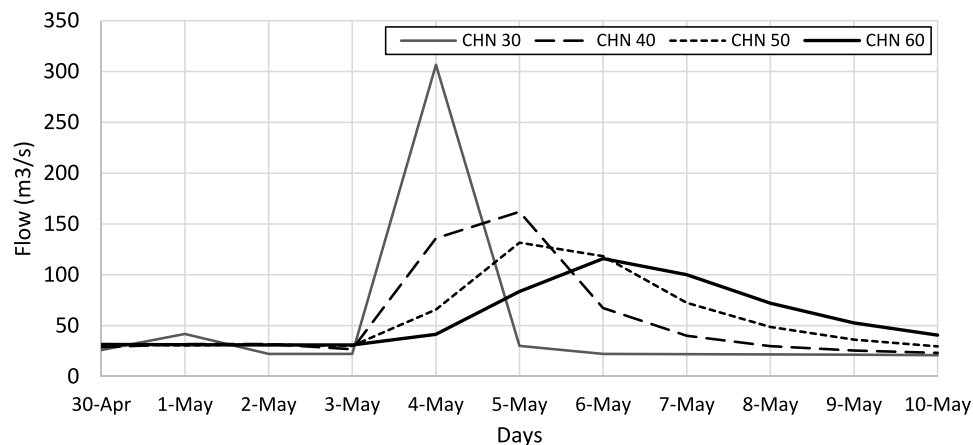
Figure 11. Inflows at nodes 5, 6, 7 and 8 (entry points of channels 30, 40, 50 and 60).
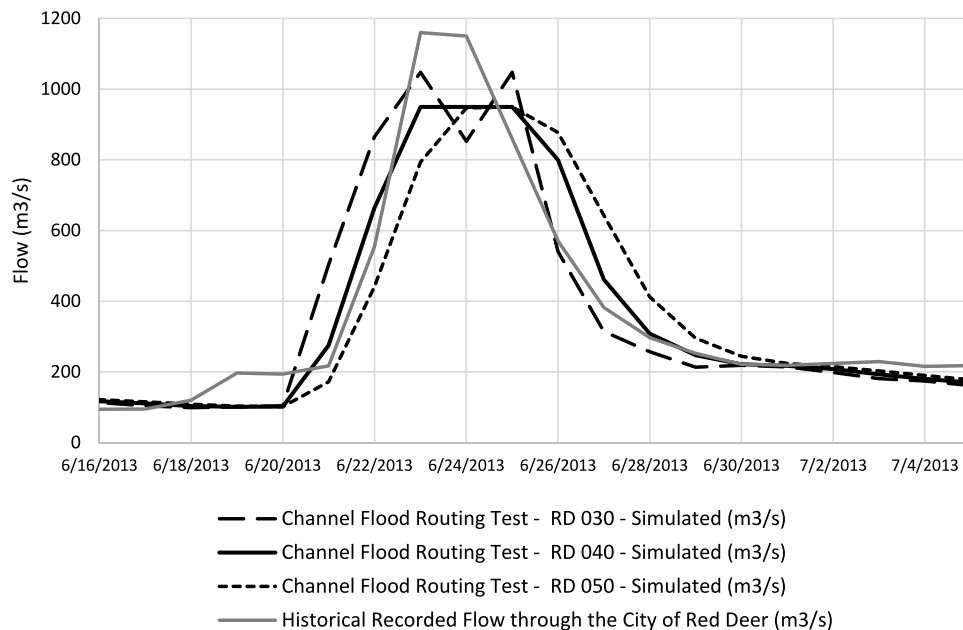
Figure 12. Historical and simulated flows during the June 2013 flood.

a way that after it is summed with the tributary inflow and routed to the City, it does not exceed the limit of 950 m³/s for three consecutive time steps.

Channel 30 shows the sum of the reservoir outflow and the tributary inflow, which is reduced from 1048 to 852 m³/s on 23 June to accommodate the peak flow of 201 m³/s coming from the tributary on the same day, while it is increased back to 1048 m³/s on the next day, thus providing the same routed outflow of 950 m³/s. Finding the appropriate reservoir releases that would result in the same routed outflow downstream for several consecutive days is not impossible using a simulation model, but it requires numerous trial and error runs even on a simple system such as that demonstrated in this example. The true power of WEB.BM is that it could have easily handled multiple reservoirs, tributaries and river reaches requiring flood protection without requiring any repeated runs by the modeller. This makes it possible to find the best way to operate all reservoirs simultaneously for a given hydrological input so as to minimize the flood damage that was previously defined as a piece-wise linearized function of flow for each river channel. Instructions and required input data for the above test run are available in the WEB.BM User's Manual and they can also be downloaded as project backups as per the instructions in Section 8.

7 Conclusions and recommendations

This paper introduces a new web-based river basin management model that relies on a publicly available LP solver. The intent in the design of the model was to provide a single user-friendly web-based software program that can be used either as a planning tool or as an operational tool for multipurpose multireservoir systems, assuming there are reliable runoff forecasting models that can provide inflow forecasts over short-term horizons. The model was professionally developed using the latest .NET Core technology and is user friendly, available free of charge, and capable of

delivering solutions within MTO mode that includes reservoir and channel routing as optimization constraints. While the model can be used as a planning tool in river basin management studies, its ability to properly include reservoir and channel routing in the optimization process makes it possible to use it in real-time reservoir operation. As documented in the numerical examples presented in this paper, the model takes into account both the travel time and the effects of hydrological routing when deciding how much flow to release in each time step so as to meet the downstream requirements, which can be governed by a sudden increase in demand during dry season, or by full bank capacity limits of the downstream channel. In the second numerical example, reservoir releases are determined in each time step during a flood event such that when they are summed with the downstream tributary inflows and routed to the river reach that flows through the city, they do not exceed the prescribed full bank channel capacity threshold. With further increase in the capability of runoff forecasting tools, such use of optimization holds the promise to become a powerful tool for real-time flood management.

The current research is focused on investigating options to use quadratic programming to model channel routing constraints without iterations, as well as to search for a preprocessor algorithm that would convert a given set of priorities into a set of suitable weight factors that will properly model the desired priorities. The model has been tested on recent studies in Western Canada (Ilich *et al.* 2020) and in India (Ilich and Basistha 2021), where a framework for utilizing long-term MTO solutions and their application in combination with short-term runoff forecasts has been developed. The model has sufficient flexibility to serve either as a planning or as an operational tool. As opposed to numerous heuristic solution strategies that have been celebrated in the literature over the past three decades, LP is the only reliable tool that can solve problems with thousands of variables quickly, while guaranteeing to find the global optimum. Hence, for problems

where the constraints and objectives can be represented as linearized functions, LP has no competition in terms of its speed, reliability and accuracy. A set of challenging benchmark tests based on real-world problems could easily prove this claim, but they have been lacking in the literature so far.

8 Data availability

Developers of reservoir operational models are encouraged to test their models by using the numerical examples presented in this paper as benchmarks. More details on the numerical examples along with all required input data to set up these numerical examples are available in the WEB.BM User's Manual which can be downloaded once users open a WEB.BM account and log in for the first time. Also, these numerical examples are stored in the WEB.BM project backup form as two scenarios within the Red Deer River Project that can be downloaded from https://data.world/nilich/webbm-repository, and restored to a WEB.BM account opened by any user. The only requirements to use the WEB.BM software are an email account and a user-defined password. The terms of use are available at www.riverbasinmanagement.com along with the links to the instructional videos and the User's Manual. To help verify the claims made in this paper, the backup copies of the following project along with several numerical examples (including the ones presented in this paper) can be downloaded from the above data link:

(a) Bargi Reservoir Test.zip, which includes an example of simultaneous optimization of reservoir operation and demand hedging over 12 months; and

(b) Red Deer River two hydrologic routing tests.zip, which includes the two numerical examples of MTO with daily time steps presented briefly in this paper.

The "project/restore" command within the WEB.BM will spare the user having to manually enter all data for the above test runs. However, these projects can also be built from scratch by following the instructions in the Manual, which is a good way to learn how to use the model. The use of the same numerical examples as in the benchmark tests is strongly suggested to other model vendors. Although small in scale, these numerical examples will present a serious challenge for most existing models.

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