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The battle of river basin models: the Narmada River Basin challenge

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ABSTRACT
This paper presents a numerical test problem that was used as the basis for ranking the river basin management models that participated in a tender for a World Bank-funded project in India. The problem is deterministic, and it involves a set of constraints and management objectives that were of interest to the Narmada Control Authority. The test problem had five reservoirs, seven off-stream and four on-stream water demands, steady-state inflows based on a 10-daily time step over a period of nine years, and relatively simple reservoir operating rules. The paper describes the problem and discusses the solutions that were obtained from various vendors. The principal finding is that simulation models should not be used to solve optimization problems. The paper also highlights the importance of establishing benchmarks as an important tool for model evaluation. Input data and the current benchmark solution are available for download.

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1 Introduction

Computer modelling has become an integral part of modern water resources planning and management. While a large number of water resources models have been created for various purposes, this paper addresses the evaluation of river basin management models. Such models are designed to find the best set of reservoir releases and water abstractions subject to a specified set of water demands, available runoff, the capacity of the impounding structures and clearly defined management objectives. Typically, water management models have solution algorithms that are based on either user-specified "what-if" rules, or use some type of optimization algorithm that drives water allocation in the basin with a user-defined objective function. An important feature of management models is that they simulate decisions of reservoir operators and basin managers. During times of water shortages, they are able to bypass upstream users and provide water to downstream users with higher priorities. Several authors have provided summary papers with short reviews of the existing reservoir operation models, such as Wurbs (1993), which was subsequently updated by Labadie (2004). Each of those papers contains a short review of more than 50 models.

When it comes to specific areas such as modelling of river hydraulics, there are undisputed and universally accepted models that set the standard in terms of the reliability or quality of their solutions, for example Hydrologic Engineering Centre - River Analysis System (HEC-RAS) (Hydrologic Engineering Centre, 2006) or Mike 11 (Danish Hydraulic Institute 2019). There is no equivalent universal acceptance among water management models. While some model vendors have invested considerable effort in advertising and promotion of their models, an objective evaluation of models' capabilities and their performance can only be demonstrated by evaluating their solutions to the test problems such as the one presented in this paper. A list of challenging real-world test problems has yet to be established and agreed among the practitioners in this field, which motivated the work presented in this paper. Established benchmark tests are important for several reasons:

- They allow practitioners to perform an unbiased evaluation of model solution capabilities, including both the quality of the final solution and the execution efficiency;
- They allow model developers to present and compare their solutions to new and challenging problems that could not be solved successfully in the past; and
- They create a tangible link between the needs in the industry and the researchers who try to address those needs.

Literature on the existence of test problems for water management models is surprisingly scarce. One of the first test problems, which was published in 1974 (Chow, Cortes-Rivera), still seems to dominate this scene, as it has been used by numerous researchers to this day, in spite of its overwhelming simplicity. The original problem was posed as a linear programming (LP) problem with four reservoirs that had known monthly inflows, starting levels and a pricing vector for target outflows, to be solved for 12 consecutive time steps. Due to the simplicity of this problem and the availability of the LP solution, many papers that provided their solutions focused on attempts to investigate novel solution techniques. This began with dynamic programming by Murray and Yakowitz (1979). The original problem also evolved into a larger version (Murray and Yakowitz 1979) with 10

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reservoirs to be solved over four years (or 48 monthly simultaneous time steps), with a similar set of fixed outflow targets for each reservoir. The absence of any constraints typically found in water resources networks trivializes the solution and makes even the "larger" problem of 480 variables a mere academic exercise. There are no withdrawals with return flows, and the only water demands are the target monthly releases (presumably made for hydropower generation but without taking into account the available head in the objective function). There is also no net evaporation on reservoirs, and no dynamic dependence of maximum reservoir outflows on the available storage. The authors who have recently proposed heuristic solvers ignored the simplicity of the problem definition, and attempted to replicate the values of the objective function obtained with LP by using their proposed solvers. For example, the problem with four reservoirs has a reported LP solution with an objective function value of 308.26. Bozorg-Haddad *et al.* (2015) used genetic algorithms (GA) available in Matlab to solve the same problem. Similarly, for the problem with 10 reservoirs, several researchers claimed to have found solutions with close to the maximum value of the objective function of 1194.44 obtained by LP. Examples include publications by Bozorg-Haddad *et al.* (2017), who used the honey bee mating optimization algorithm to report the value of the objective function of 1146.79, and Jalali *et al.* (2007) who used ant colony optimization to report a range of solutions with objective function values between 1180.73 and 1192.39. Researchers who published solutions to this problem were primarily inspired by a desire to investigate new solution algorithms in their work, rather than to scrutinize the capabilities of the existing water management models.

A more recent review (Rani and Moreira 2010) of the available optimization models covers a range of solution techniques which have been studied in academia, such as stochastic optimization or multi-objective optimization. While these seem to be of significance in academia, the instances of continual real-world applications of those techniques by water management agencies in their day-to-day or seasonal operation has been negligible. Also, all model evaluations reported so far have been based on the reports of the model vendors, without any attempts to independently compare model solutions based on using the same test problems with identical input data. Dobson *et al.* (2019) provided a comprehensive review of the use of optimization, distinguishing between rule curve-based models and models that utilize multiple time step solutions (multiple time step optimization, MTO), and outlined the need to apply artificial intelligence algorithms that can learn from numerous MTO solutions and apply their results in real-time operation. The same paper also provides an in-depth survey of the available literature on heuristic solvers, highlighting the importance of non-linear programming (non-LP) while offering little justification for it.

Based on the coverage of the work of others in these papers by Rani and Moreira (2010) and Dobson *et al.* (2019), one can conclude that huge efforts are currently being invested to optimize river basin allocation heuristically or by using non-LP_Solvers, while the numerical tests presented are so simple that they can be easily solved using a spreadsheet solver or Matlab. Giuliani *et al.* (2021) provide a review of over 300 papers, with a focus on "how the optimization problem is formulated rather than how it is solved," and attempt to reconcile the "curse of dimensionality" associated with stochastic dynamic programming with the methods that simplify the optimization process identified as approximation in value and approximation in space. The authors acknowledge the "limited uptake" of the proposed method by the practitioners. In another publication, Giuliani *et al.* (2014) focused on the refinement of the policy in water management of the Lower Sesquehanna River in the Eastern United States. This paper identifies six objectives that are not distinguished from each other in that they are assumed to be of equal value, so there is no firm definition of the priorities of allocation or deficit-sharing policies. Such performance metrics render the problem suitable for multi-objective optimization, which produces a multitude of Pareto-optimal solutions. The paper claims that significant benefits are possible as a result of adopting "the recommended solution" extracted from the Pareto optimal front, although there is no clear definition of what that solution is, nor are there instructions suggesting how to implement such a solution in practice through alternative operating rules or release strategies. Obtaining the input data for a selected problem solution would help verify the claims made by the authors, but the paper did not provide a link to the model input data and results.

On another front, covered extensively in a well-organized review paper by Macian-Sorribes and Pulido-Velazquez (2020), an attempt was made to survey the literature that links the results of optimization to the improvement of reservoir operating rules, given the recognition of the importance and acceptance of the "rule curve" concept among the practitioners. Their findings contradict of Guliani's claim that the way the problem is formulated is more important than how it is solved (Giuliani *et al.* 2014). They established that optimization models, and in particular the LP-based models, can handle all sorts of complexities as linearized constraints, along with using stochastically generated inflow series to obtain solutions effectively over large search spaces. This was also attested by Turgeon (2007), who compared the results of an LP-based implicit stochastic optimization with the results of stochastic dynamic programming.

In general, the purpose of river basin management models should be to facilitate studies of managing water use in the basin for the benefit of the stakeholders in an effort to help find ways to improve basin operation under various hydrological conditions. Comparison of various model results is greatly facilitated by adhering to the following principles:

1. the use of identical deterministic input data series of inflows and water demands;
2. clear definition of physical and operational constraints; and
3. clear definition of the management objectives.

Even when the above principles are followed, the use of models that make decisions only in a single time step framework and rely on user-defined rule curves will show different results unless the assumed rule curves for all reservoirs in both models are also identical. Since the final shape of the rule curve depends on the skills of the modeller, the likelihood of two modellers arriving independently at the same rule curve is small. Consequently, numerous comprehensive simulation studies published in the literature, such as the one by Elsayed *et al.* (2020), do not provide results that could be considered a firm benchmark of the model, since their comparison with similar model results would end up being a comparison of the modeller's skills at least as much as a comparison of the model itself. However, this is not the case with optimal solutions that are found by solving multiple time steps simultaneously over the entire year, under the assumption that the conditions (1), (2) and (3) above are adhered to. In that case, a comparison of the values of the objective function (assuming compliance with the constraints) becomes the best way to gauge the performance of various optimization models.

Inclusion of net evaporation, defined as evaporation minus precipitation, is often an important component in modelling of reservoir operation. Typically, evaporation and precipitation time series are given in mm and they can be presented as historical data or as a result of stochastically generated series, which are then applied during simulation to the average water surface area for each simulated time step. In some instances, when simulated time steps are very short (for example, four hours), the change in storage level may not be sufficient to warrant the averaging of the starting and the ending water surface area, so the model can get away with applying net evaporation at the starting or at the ending water surface. Biglarbeigi *et al.* (2018) have used the same approach of applying evaporation at the end of the time step although they used a monthly time step, which could lead to inaccuracies since the average water surface area for a month may be quite different from the area at the end of the month. Much attention in this publication is devoted to generating stochastic evaporation series. However, precipitation that falls directly on the reservoir water surface area often exceeds evaporation in a rainy period, while its treatment is not mentioned in the above two studies. There are instances of taking evaporation into account properly by applying it on the average water surface area over a time step, as attested by Asadieh and Afshar (2019); however, they also failed to take into account precipitation on the water surface area. Much like many other publications based on the use of heuristic solvers, in this study the objective function is defined by using a quadratic term $(D_t - R_t)^2$ for the difference between water demands D_t and achieved releases R_t to minimize the deficits, although the linear formulation $min(D_t - R_t)$ in the objective function would have the same effect, since LP algorithms would not consider any instances where $R_t > D_t$. Even more disconcerting is a consistent tendency to set the limits on the reservoir outflows to a constant ($R \leq R_{max}$) rather than using an elevation vs outflow relationship, which could limit the turbine flows significantly below R_{max} at times when the reservoir is half full. This paper quotes the results of using several different solvers by evaluating the objective function for each of them, so it could potentially be used as a benchmark for testing other models by practitioners. However, no effort has been made to reformulate the problem as a linear program to obtain a solution that would guarantee finding a global optimum. There were no links to the data used in the paper and our efforts to obtain the data from the authors failed.

Heuristic models can proceed from one time step to another by incorporating a water balance equation where the reservoir releases are the only unknowns. Hence, heuristic models enable the inclusion of net evaporation terms in the reservoir balance equations, since the average water surface area can be evaluated independently for each time step. The effects of net evaporation are much more difficult to incorporate when deriving simultaneous multiple time step solutions with LP or non-
LP_Solvers, where the net evaporation adjustments to the storage volumes passed from one time step to another need to be applied to the water surface areas that are not known, since the trajectory of perfect reservoir levels is part of the model's solution. For these problem formulations, net evaporation becomes a net gain or a net loss along the reservoir carry-over storage arcs, and is best handled as a model constraint. Applying net evaporation to solutions over multiple time steps is particularly difficult for network flow algorithms that do not allow the loss or gain of flow along the flow arcs.

Thelarge volume of publications based on the use of heuristic solvers is justified by the claims that they were selected to deal with the non-linearities in river basin networks. However, most constraints in river basin models have been successfully linearized, and the best-known models such as RiverWare (Zagona *et al.* 2001), Hydrologic Engineering Centre Prescriptive Reservoir Model (HEC-ResPRM) (Hydrologic Engineering Centre 2019), Oasis (Dean *et al.* 1998) or Water Evaluation Assessment Planning (WEAP) (Yates *et al.* 2005) rely on LP, which provides unmatched speed, stability of solutions and a guarantee of finding the global optimum. Hydropower plants are often quoted as a non-linear component that warrants the use of non-linear solvers, but this component can also be successfully linearized in most instances, as shown by Kang *et al.* (2018). Common wisdom in the operations research community suggests the use of LP whenever problems can be effectively linearized, since (a) there are proven LP algorithms that are very efficient and stable even when solving problems with hundreds of thousands of variables; and (b) each of these LP algorithms guarantees finding the global optimum. It is well known that non-LP and heuristic solvers fail on both (a) and (b), except in very few special cases such as the case of quadratic programming in convex search space, as outlined in any operations research text book (Radin 1997).

A comparison of four different models, including HEC-ResPRM and MODSIM, used to solve the same problem was presented by Rozos (2019), but the input and output data were provided by the author only in the binary form that can be read by the models that created them, while the HEC-ResPRM is no longer supported by the US Corps of Engineers. Similarly, a specialized textbook compiled by Watkins (2013) contains some numerical examples of case studies that could possibly be used as potential benchmarks by other models, but as noted by Simonovic (2015), it is plagued by a similar problem of providing data only in the format that can be read by the models that were used in each individual study, which implies familiarity with the models that were used in the studies. Hence, provision of input and output data in a format that is independent of the previously used applications should be a standard requirement for producing future benchmarks.

The need for benchmarking has long been recognized in other modelling sectors, attracting numerous participants in some sectors so as to gain wider acceptance and credibility of their work. Examples are the The Agricultural Model Intercomparison and Improvement Project (Rosenzweig *et al.* 2013) focused on improving crop and economic models in agriculture, or the Inter-Sectoral Impact Model Intercomparison Project (Warszawski *et al.* 2014), focused on comparing climate impact projections at various sectors and scales. It would appear that the need to agree on the interpretation of model results seems to be strong enough in some sectors to warrant the creation of working groups and ongoing model comparison projects. There is nothing similar going on in the river basin management modelling sector.

Real-world studies involve a large number of variables, much longer solution periods, and often complex constraints where the feasible range of values that some variables can take is a function of the values of other variables. As an example of the challenge related to problem size, consider a California statewide water management study (Lund *et al.* 2003) which involved simultaneous monthly optimization of all reservoirs in California using the LP-based HEC-ResPRM model with a monthly time step for all years of available data and multiple water uses, resulting in over 5 000 000 variables that were optimized simultaneously. Examples of challenging real-world reservoir optimization problems for which input data and objectives are freely accessible have yet to be published in the literature.

A unique feature of the test problem presented in this paper is that was included in a World Bank tender documentation in India, requiring solutions from the participants in the tender. Prior to this tender, the Narmada Control Authority (NCA) did not have any in-house expertise in the use of computer models for river basin management prior to this tender. Hence, the main purpose of the tender was to select a consultant that will (a) develop and set up the model for NCA; and (b) provide the necessary training and maintenance during the 24-month duration of the contract. Since all tender participants claim excellent modelling skills and propose teams with impressive CVs, it was decided to test their skills on a problem that addressed the needs of the NCA. The unique feature of this tender was that 50% of the score was awarded to the quality of the solution to the test problem, while the other 50% was given to the corporate qualifications of the bidding team. The important detail to note is that the 50% score related to the quality of the solution did not require the use of an existing or a well-known model. It merely required a display of the skills to solve the test problem, attested by the quality of the solution. Also, NCA did not care what strategy or tools were used by the consultants to obtain the solution, implying that consultants could have used an existing model, or they could have used other generic solution tools such as the spreadsheet solver or Matlab. Indeed, one of the best performances was obtained from the team that used the “LP_Solve” public library of Mixed Integer solvers. The tricky part here is to know how to set up the matrix of constraints that would be passed to the library of solvers in the argument list, implying that the proper setting up of the constraint matrix attests to the understanding of the problem and knowledge of how to use optimization to solve it. The process trusts that the successful bidder who does not have a model but has the ability to provide the best solution will be able to instruct the programmers in how to develop a user-friendly model that maintains the required model performance. The tender was listed on the Government of India tendering website for two months, and an additional alert to this tender was sent by the NCA management to more than 60 corporations and established researchers in the field of river basin management modelling.

As a backup for the whole process, and to ensure that the test problem does have a solution, NCA requested help from the National Hydrology Project (NHP) office in New Delhi in developing an initial benchmark solution to the test problem, which was developed using the Web Basin Management (WEB.BM) model (Ilich 2022). There was no guarantee at that time that some of the participating vendors would not eventually find a better solution. Since this paper discusses and compares different model solutions, it is legitimate to include the WEB.BM solution in the analyses, although this solution was not obtained as part of the tendering process. It was developed as an initial “benchmark” solution, with the aim of replacing it with a better benchmark once it is found. Again, the focus in this paper is the qualities of the rendered solutions, and all solutions that were obtained should be included in the analyses on equal footing, regardless of whether they participated in the tender process or not. The same should hold for any future solution that other researchers may develop that surpasses the current benchmark in terms of the values of the objective function, while complying with the required model constraints.

The tender was listed on the Government of India tendering website, and an additional invitation was sent by the NCA to more than 60 corporations and established researchers in the field of river basin management modelling. The NCA is one of the most reputable inter-state water management agencies in India. The NCA management, in collaboration with the NHP office in New Delhi, made a decision to conduct model selection via tender, thus essentially conducting a survey of the existing models’ capabilities.

This paper is organized as follows: section 2 lists the required model features considered essential in this study; section 3 provides a basic introduction to Narmada River Basin and is further divided into subsections that describe various aspects of the test problem, including its physical, hydrological and operational input data, modelling objectives and constraints. Section 4 contains a list of participating models, including brief descriptions and references, while section 5 discusses the model results. Finally, section 6 provides conclusions and recommendations.

2 Required model features

The following modelling features were essential for solving the test problem presented in this paper:

- MTO: models are expected to be able to find the best possible reservoir operation for any simulated year, which means that they should be able to solve 36 sequential time steps simultaneously for the entire hydrological year.

- Flexible time step length: India, like most countries in Asia, resets the target flows for irrigation diversions three times a month. Hence, the time step length should be able to accommodate durations of 10 or 11 days. In general, the model is expected to have flexible time step lengths which can be any multiple of one day.
- Ability to model net evaporation accurately: large reservoirs in tropical countries may have significant net evaporation losses. Within the MTO framework, net evaporation should be modelled as a loss or gain of water within each time step, thus taking into account the relationship between storage and the surface area, and applying the net evaporation given in mm to the variable surface area. Some vendors like RiverWare (Zagona *et al*. 2001) include a short summary regarding this in their user manuals; however, there is only one publication in a peer-reviewed journal (Yung-Hsin *et al.* 1996) that deals with this issue by applying penalty functions for not meeting the target net evaporation losses within a generalized network flow algorithm that allows gains and looses of flow along an arc. This issue is complex for LP_Solvers within the MTO framework.
- Reservoir outflow limits as a function of storage: maximum flow in a diversion canal may be restricted by the amount of storage during periods when storage levels are low and close to the invert of the outlet structure of the canal. Hence, the selected models should have the capability to set the outflow constraint on the diversion canal dynamically as a function of storage, and this should be done internally as part of the optimization process. This is a non-linear constraint, which can be linearized. A more in-depth technical review of issues related to this constraint can be found in Ilich (2008) and Needham *et al.* (2000).
- Equal deficit sharing: there are equal deficit sharing policies among some irrigation blocks, both in space and in time, implying that deficits, when inevitable, are evenly distributed throughout the hydrological year.
- Operational constraints: test simulation begins on 1 July 2008, and ends on 30 June 2017, lasting nine years in total. Since these are historical years with estimated runoff series for all years, model solutions are derived assuming a perfect hindsight of runoff and demands for 36 time steps ahead starting on 1 July of each of the nine years. There are also minimum storage level targets that have to be maintained on 30 June of each year. These minimum storage levels were provided by the NCA, and the model can exceed them in wet years, but it should maintain them in dry years.

3 Narmada River Basin

Narmada is the fifth largest river in India and the largest west-flowing river on the Indian peninsula, with a total length of over 1300 km. The basin area, shared by four states, lies between the longitudes of 72°32’ and 81°45’E, and between the latitudes of 21°20’ and 23°45’N. The development of the Narmada water resources is significant, with its five largest reservoirs accounting in total for over 28 billion m^3 of live storage, making it one of the most prominent river basins in India. The Federal Government of India helped establish the NCA in 1980. A map of the Narmada River Basin is shown in Fig. 1.

3.1 Description of the test problem

A simplified version of the Narmada River Basin is represented by a modelling schematic shown in Fig. 2. This schematic includes only the largest structures in the river basin. NCA has provided 10-daily time series of historical runoff from four sub-catchments which conceptually drain into the nodes shown at the ends of short, dark arrows in Fig. 2, and which were estimated by removing the historical effects of regulation and water use. NCA also provided the elevation-area-capacity curves for storage reservoirs and estimates of in-stream and off-stream water demands.

The test problem was deterministic, meaning that it included known inflow and demand series for all model components. The modelling schematic in Fig. 2 shows a list of components and their connectivity. River reaches or channels connect downstream and upstream nodes, which can be reservoirs, irrigation blocks or simple junctions that are used to join flows from two or more tributaries or split flow at the point of diversion from a river reach into a diversion canal. Reservoirs model storage, releases, and net evaporation losses. Irrigation blocks model total consumptive water use. Model inputs are briefly discussed in the following. In a nutshell, the test problem focused on finding the best way to operate reservoirs such that:

(1) Flood damage in channels 10, 11 and 15 is minimized as the highest priority goal;
(2) Environmental flow targets on channels 10, 11, 12 and 15 are maintained as the second highest priority goal; and
(3) Consumptive use demands of all irrigation blocks are met as much as possible as the third priority goal.

The above goals are subject to physical and operational constraints, which are explained in more detail in the following sections.

3.1.1 Physical data

Physical data include storage capacities of reservoirs as well as flow capacities of diversion channels. Outflow vs elevation curves of spillways or bottom outlets also define physical flow limits, assuming all operational gates are fully open such that the outflow represents the maximum achievable flow as a function of the average storage over a time step. The other important aspect of the physical model data is the network definition. Elevation area: volume curves of the Narmada River basin reservoirs are also provided as part of the required input data.

3.1.2 Hydro-meteorological data

There is no rainfall-runoff modelling in this test problem. Instead, the model uses inflow estimates based on the historical reservoir levels and outflows. Four inflow series were

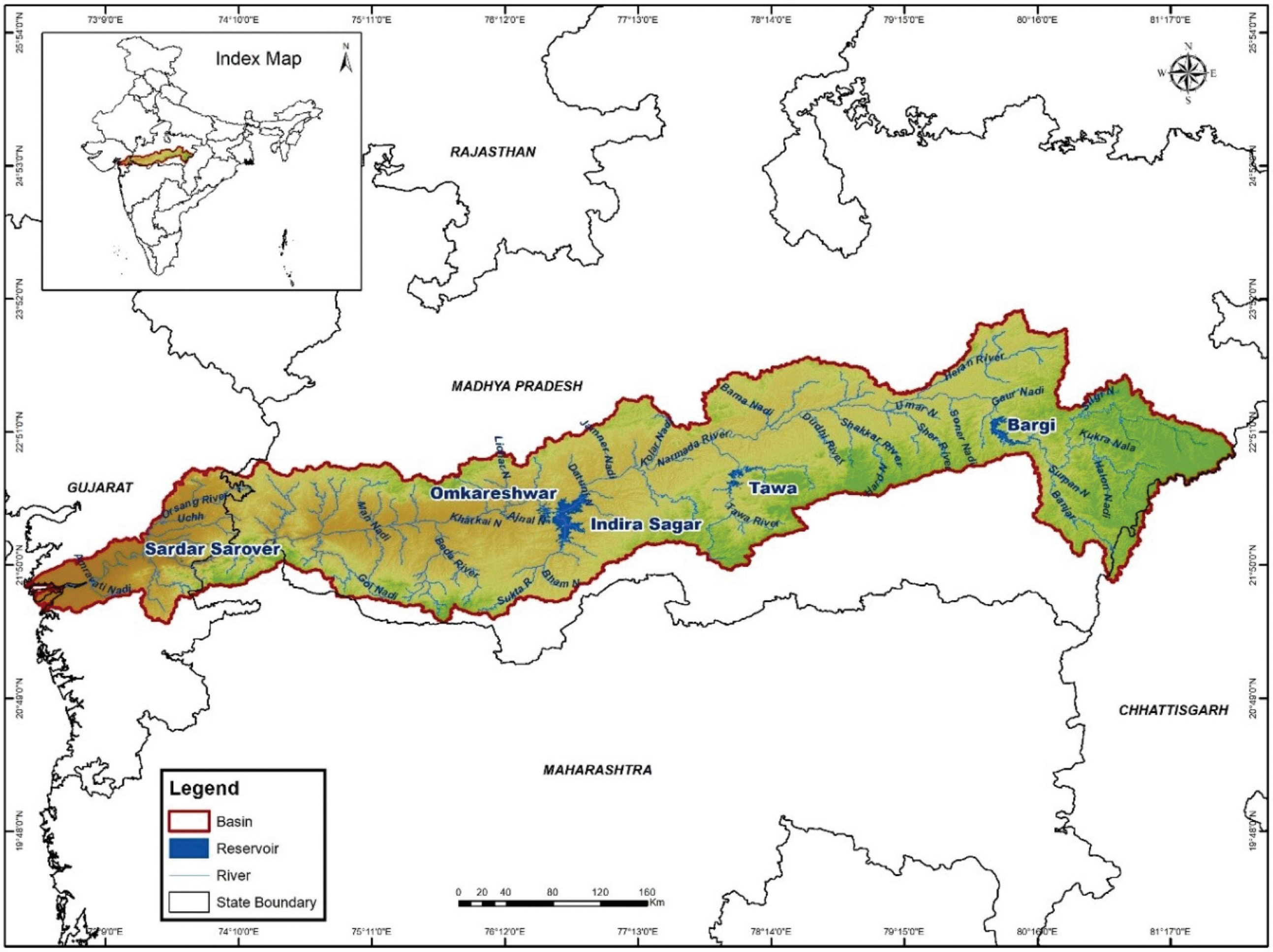


Figure 1. The Narmada River Basin.

developed for the Narmada River Basin study. The most upstream inflows are at Bargi and Tawa reservoirs. Local runoff over the part of the catchment delineated between Indira Sagar Project (ISP, shown as node 3 in Fig. 2) on the downstream end, and on the upstream end with Bargi and Tawa reservoirs is shown as inflow into node 7. The input data file provides complete natural flow at node 7. The local inflow should be calculated by subtracting Bargi and Tawa inflows from the natural flow at node 7. Similarly, runoff between Indira Sagar and Sardar Sarovar Project (SSP) is calculated as the difference between the natural flow at node 5 (located immediately upstream of SSP) and the natural flow at node 7.

NCA provided input data for evaporation and precipitation in mm. However, the water surface areas to which those inputs should be applied are not known in advance as they depend on the model solution for each time step, while the model is expected to solve 36 time steps simultaneously. Hence, net evaporation should be included as a non-linear constraint in the optimization problem, since the relationship between storage volume and water surface area is not linear. The final model solution is expected to include estimates of net evaporation that can be manually verified by multiplying the average surface area (based on the simulated storage levels) and net evaporation for each modelled time step. The combined surface area of all five major reservoirs in Narmada River Basin at their full supply levels is over 1700 km^2 and evaporation losses can occasionally exceed 10 mm/day, resulting in net evaporation losses that often exceed 100 m^3/s during dry season months, while they may account for a net influx of more than 200 m^3/s during time steps with high precipitation.

3.1.3 Water demand data

Future water requirements estimated by NCA were provided as input into the test runs. In addition to this, mandatory flow releases were assessed as a seasonally dependent fraction of natural flows for channels 10 and 11 (outflows from Bargi and Tawa, respectively), channel 12 (inflow into ISP) and channel 15 (inflow into SSP) based on the percentage of natural flows, which varied from 10% in the dry season to 30% in the wet season, with transitional months having their maintenance flow targets set to 20% of natural flows. Reservoir outflows are driven by water demands, which are a combination of downstream mandatory releases and consumptive use requirements. Mean annual water demands in the 2008–2016 period were on average 11.5 billion m^3; however, they are projected to double by 2025. Irrigation accounts for 86% of the total water demand.

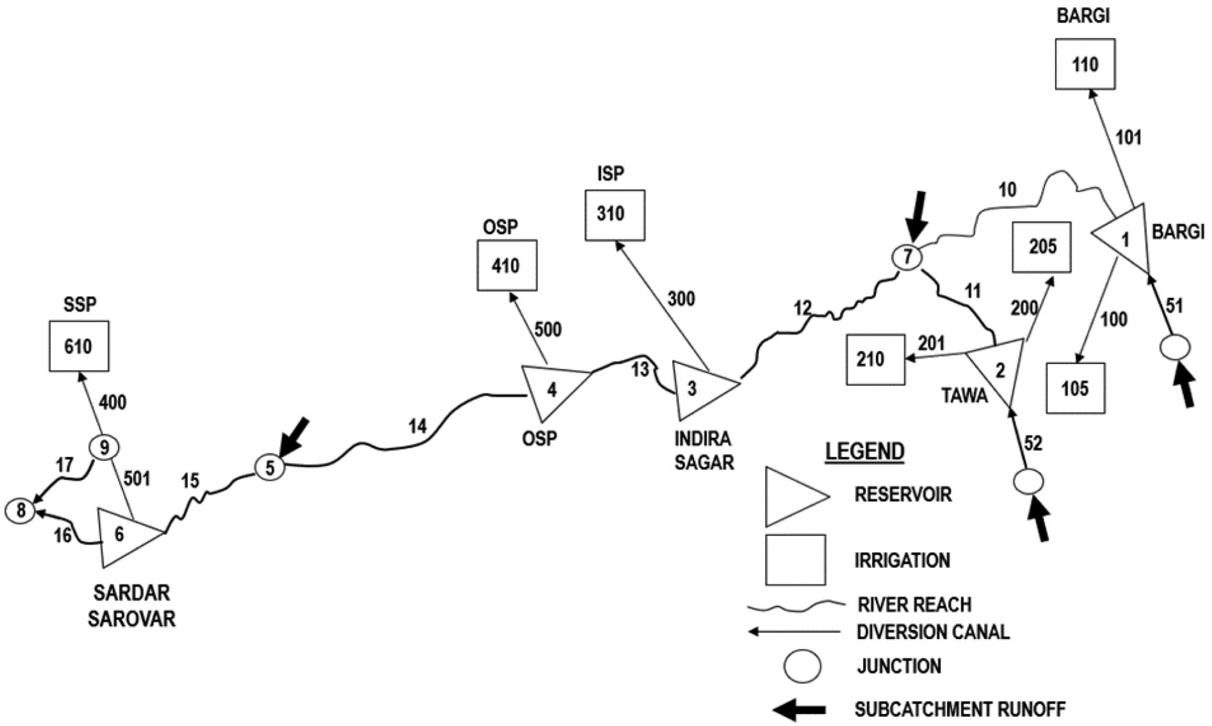


Figure 2. Narmada River Basin modelling schematic.

3.1.4 Simulation control data

Simulations are to be conducted using 10-daily times steps for the hydrological year that begins on 1 July of each simulated year and ends on 30 June of the following calendar year. Input data are given in units of volume, which gives users a choice of what length of time steps to select. This was considered a flexible approach since some models take into account leap years and some do not. The exact time step length is 10, 10, 11 for months with 31 days, 10, 10, 8 for February (10, 10, 9 in a leap year), and 10, 10, 10 for months with 30 days.

The primary purpose of the test run is to find the best way to operate the available storage so as to meet the stated objectives. There are operational constraints that models must take into account when searching for the best set of reservoir releases. These include limits on the available storage, canal capacities and demands, as well as the stated operational goals, which are typically related to the deficit-sharing policy among various components that should be implemented in periods of water shortages. There were no limiting flow capacities on the diversion channels that supply water to irrigation blocks. The existing reservoirs have several key target elevations included in the model. These elevations define dead storage, conservation storage (full supply) and flood control storage (maximum water level), and they are the same for all four simulated test scenarios. The assumed key elevations are listed in Table 1.

The minimum target volume at the end of the hydrological year on 30 June is aimed to ensure that there is sufficient storage to meet demands for the first two weeks of the monsoon season in case the start of the monsoon is delayed. While this minimum target volume can be exceeded in wet years to ensure carry over storage, it is up to the model to find the best way to reach these minimum target elevations at the end of a dry hydrological year. A simulated elevation below the target level for 30 June would be considered a failure to meet the required test problem constraint.

Table 1. Key reservoir elevations used in the test runs.

Reservoir	Maximum water level (m)	Full supply water level (m)	Dead storage water level (m)	Minimum water level (m) on 30 June	Starting reservoir elevation (m)
Bargi	425.70	422.76	406.00	409.00	417.00
Tawa	356.66	355.40	334.24	336.45	351.00
Indira Sagar (ISP)	263.35	262.13	243.23	245.00	260.00
Omkareshwar (OSP)	199.62	196.60	196.60	196.60	196.60
Sardar Sarovar (SSP)	140.21	138.68	110.64	110.64	122.00

The Omkareshwar (OSP) reservoir was designed primarily as a hydropower generation facility. Consequently, its level is kept at 196.60 m at all times except during catastrophic flood events when its flood control storage zone, which ranges up to 199.62 m, may have to be utilized to help reduce downstream flooding.

3.1.5 Basin management objectives

There are three management objectives in this basin: (a) minimize flood damage; (b) maintain environmental flow targets; and (c) minimize consumptive use deficits. More details on these objectives and their related constraints are provided below. Environmental flow targets have been created for the purpose of the test runs for channels 10, 11, 12 and 15, and they are provided in the model input data set. They were developed using guidelines based on the fraction of the respective four natural flows developed for the upstream end of those channels.

3.1.5.1 Flood management.

River basin models are typically used for studying reservoir operation within the normal flow regime. Time steps that are weekly or 10-daily are not ideally suitable for studying detailed flood management. However, reservoir operation often involves drawdowns during the monsoon period when the likelihood of flooding is high. The flood management component was included in the test problem since the timing and the amount of drawdown can be determined as part of the model solution for each reservoir in each simulated year.

To define flood protection objectives, it was necessary to define the full bank flow capacities for critical river reaches where flooding can cause significant damage, and including the objective to minimize flooding on designated channels. The following flow limits have been identified as full bank flow capacities in the Narmada River Basin test runs (channel numbers refer to the river reaches in Fig. 2):

Channel 10 (Bargi Reservoir outflow): 4000 m^3/s
Channel 11 (Tawa Reservoir outflow): 2800 m^3/s
Channel 15 (Sardar Sarovar Reservoir outflow): 7600 m^3/s

Due to large cost factors per unit of flow associated with flows above these targets, the model is expected to handle the objective of keeping river flows within the above limits for the specified river reaches whenever possible, and all reservoirs are allowed to contribute to this reduction using a combination of their flood control storage and pre-flood drawdowns which should not begin before 1 July of any year, since the model is supposed to have perfect foresight for 12 months starting on 1 July.

3.1.5.2 Irrigation supply.

There are two diversion canals from Bargi reservoir, as shown in Fig. 2. The left canal has a sill that is just over 6 m below the sill of the canal on the right side, which is located at an elevation of 406 m. Since the simulation runs involve the policy of equal deficit sharing in space and time between the water use from the right and the left canal, restricting the flow in the right canal due to elevations that are close to 406 m would also affect water supply in the left canal. Maximum flow in the Bargi right canal is limited by the outflow vs elevation function shown in Fig. 3.

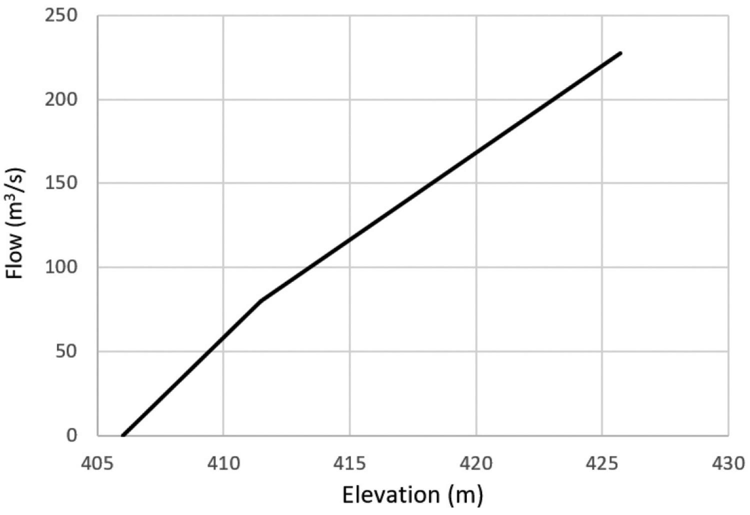
The model must determine the minimum storage for each time step within a year by balancing the outflow constraint on the right diversion canal such that the flow limit does not exceed the limits defined by the maximum outflow shown in Fig. 3, while irrigation deficits in both canals are spread evenly in time and among the two irrigation blocks throughout the year. The minimum operational storage is 406 m throughout the year, except on 30 June, when the minimum storage level should be greater than or equal to 409 m.

3.1.5.3 Reservoir operating rules.

Reservoir levels should be between the top of the dead storage zone and the top of the conservation zone (full supply level in Table 1) at all times except during extreme flood events, when the flood storage zone can be utilized only in those time steps when one of the downstream channels has flow that is equal to or greater than the full bank flow capacity. Reservoir levels should also end the hydrological year on 30 June of each simulated year with a level that is greater than or equal than the designated minimum storage levels defined in Table 1.

Bargi Reservoir releases are driven by environmental flows in channel 10, and by irrigation requirements on blocks 105 and 110. These two irrigation blocks are expected to share deficits evenly in time and in space within each year in all scenarios. This means that in dry years when irrigation deficits are inevitable, the model should (a) minimize the deficits relative to the target, and (b) ensure that the same relative deficit is maintained throughout the year for both irrigation blocks 105 and 110. This constraint ensures simultaneous optimization of reservoir operation and demand hedging, if and when there is insufficient water to meet all demands.

During high floods, Bargi storage will be operated to help reduce flows in any of the downstream channels (10 or 15) such that overbank flooding is minimized. Storage levels above



Elevation (m)	Flow (m3/s)
406.00	0.00
411.48	80.00
425.70	227.44

Figure 3. Assumed maximum outflow vs storage levels for Bargi right canal.

the normal water levels are allowed only during time intervals when the full bank capacity is reached or exceeded on either or both of channels 10 or 15.

Tawa Reservoir releases are driven by environmental flows in channel 11, and by irrigation requirements on blocks 205 and 210. These two irrigation blocks are expected to share deficits evenly in time and in space. During floods, Tawa reservoir storage will be operated to reduce flows in the downstream channels 11 or 15 and minimize overbank flows. Storage levels above the normal water levels are allowed only during time intervals when the full bank capacity is reached or exceeded on channels 11 and 15.

ISP releases are driven by environmental flows in channel 15, and irrigation requirements on blocks 310 and 410. These two irrigation blocks are expected to share deficits evenly in time and in space within a year. During floods, ISP storage will be operated to help reduce flows in the downstream channel 15 such that overbank flows are minimized. Storage levels above the normal water levels are allowed only during time intervals when the full bank capacity is reached or exceeded on channel 15.

SSP will first provide environmental flow targets of 17 m^3/s for channel 17 at all times, and then provide flows for its irrigation block 610. If deficits are inevitable in irrigation block 610, they should be shared evenly in time over the 36 time intervals within a dry year in which they occurred. In addition to meeting their environmental flow targets on their respective outflow channels 10 and 11, reservoirs Bargi and Tawa have a shared responsibility to meet environmental flow targets on Channel 12. The model should decide how much each reservoir contributes in each time step to meet the environmental flow targets at channel 12.

Reservoir operation is conducted with a single-year forecast, i.e. the starting levels and a series of 36 forthcoming inflows and demands are considered to be known, thus covering one year of the assumed forecast of demands and inflows. The model is thus tested on a set of nine years and each of them is solved individually, with full foreknowledge of the hydrological conditions within a year, but without any knowledge of the hydrological conditions in subsequent years. Hence, modelling is set up to optimize all 36 time steps simultaneously in each year, such that the ending storage at the 36th time step is considered to be the starting storage for the subsequent simulated year.

3.2 Objective function

An objective function can be calculated and its values used to compare different model solutions. Although selected arbitrarily in this exercise in order to test the models' capabilities, the loss associated with flooding can be assessed and expressed as the sum product of the assumed flood damage and the excess overbank flow. For example, it can be assumed that 1 m^3/s of flow above the full bank capacity causes \$1000 worth of damage in any channels where flood control is to be managed by the model (channel 10, 11 or 15). The objective formulated using the units of flow for channels 10, 11 and 15 can be expressed as:

$$\mathrm{OF_f}=\mathrm{Min}\sum_{(t=1)}^{(t=36)}\left\{\begin{array}{r}\$1000[\max(\mathrm{Q}_1 5(t)-7600,0)\\+\max(\mathrm{Q}_1 0(t)-4000,0)\\+\max(\mathrm{Q}_1 1(t)-2800,0)]\end{array}\right\}\quad(1)$$

The above is the objective function related to reducing flood damage (hence the subscript f in "$\mathrm{OF_f}$"). A similar expression can be applied to reducing failure to meet environmental flow targets $\mathrm{T_i}(t)$ as in the objective function $\mathrm{OF_e}$, but with a lower priority factor of \$100 instead of \$1000 per unit of flow summed over 36 time steps, i.e.

$$\mathrm{OF_e}=\sum_{t=1}^{t=36}\left\{\$100\left[\begin{array}{r}\max(T_{10}(t)-Q_{10}(t),0)\\+\max(T_{11}(t)-Q_{11}(t),0)\\+\max(T_{15}(t)-Q_{15}(t),0)\end{array}\right]\right\}\quad(2)$$

Selecting between zero and the difference between the target and the achieved flow is necessary since the achieved flows can sometimes be higher than the target flows during the monsoon period when the reservoir is spilling, while the purpose of the above expression of the objective function is to minimize deficits that are defined as flows below the specified environmental target. Finally, the third component of the objective function is related to the failure to meet the specified irrigation demand Di(t). It is written as a sum product of the loss of \$10 per unit of deficit flow for all components over all 36 time steps:

$$\mathrm{OF_i}=\ \mathrm{Min}\sum_{t=1}^{t=36}\sum_{i=1}^{i=7}\{\$10\ [\mathrm{Di}(t)-\mathrm{Qi}(t)]\}\quad(3)$$

Since the flows to an irrigation block are never greater than the target $\mathrm{D_i}(t)$, there is no need to use the $\max\{0, \mathrm{D_i}(t) - \mathrm{Q_i}(t)\}$ function in formulating this part of the objective function. The ultimate objective function is the sum of the three constituents related to flood, environmental flows and consumptive use, i.e.

$$\mathrm{Minimize}\ \{\mathrm{OF_f}+\ \mathrm{OF_e}+\ \mathrm{OF_i})\}\quad(4)$$

The above objective function is a measure of model performance represented by a single number for each simulated year, equal to the total of the three objective functions components. However, the above approach is valid only if none of the stated constraints have been violated. Hence, the evaluation of model results begins by first verifying compliance with model constraints. The objective function values can be compared only after successful verification of this condition.

3.3 Model constraints

Evaluating the objective function only makes sense if there is compliance with model constraints. The following constraints have been evaluated in the model outputs provided by the vendors:

- **Reservoir storage constraints**. Simulated values are compared to the target values in the case of reservoir target levels (full supply, dead storage, minimum storage on 30 June, or maximum level during floods). A violation of more than 0.01 m of the prescribed operational limits is considered a failure.
- **Bargi Reservoir outflow constraint** for diversion channel 101 are compared to the maximum possible outflow limits as a function of average Bargi reservoir levels over all

simulated time intervals. The outflow limit function is given in Fig. 3. An exceedance of outflows by more than 5% above the limits defined by this curve is considered a failure.

- **Reservoir evaporation constraints**. Due to the different ways net evaporation is calculated within various models, the expected tolerance limit is 2% for the difference between the cumulative net evaporation over nine years produced by the model compared to the results of the manual calculation. The manual calculation will be based on the use of the average area over a simulated time step multiplied by the net evaporation in mm used as input data in each simulated time step.
- **Irrigation deficit constraints**. When irrigation deficits are inevitable, the relative deficits expressed as a fraction of water demand in every time step must be shared evenly for all time steps within a year among the blocks that are supplied from the same storage reservoir. Relative Deficits Rd are expressed as:

  $$Rd = \frac{D_t - Q_t}{D_t} \tag{5}$$

  where D_t is water demand in time step t while Q_t is the supplied quantity of water within the same time step. Deficit-sharing constraints are to be spread evenly within a year for each irrigation component, and also among the components that are aimed to share deficits. Also, there are three pairs of irrigation blocks that share the same relative deficits for all simulated time steps: 105/110, 205/210 and 310/410. Block 610 should have equal distribution of its own deficits in time within a year when deficits are inevitable.
- **Mass balance constraints** were verified on every node of the modelling schematic in Fig. 2. Any imbalance between all inflows and all outflows for a node that is greater than 0.01 m^3/s is considered a violation.

4 Participating river basin models

Among the known modelling tools, the participating models included Oasis (Dean *et al.* 1998), Mike-Basin (Danish Hydraulic Institute 2019), and Optiges (Haro *et al.* 2012), which was at a bit of a disadvantage due to being restricted to monthly time steps that were subsequently broken into 10-daily time steps to refine the solution to the required 10-daily time step resolution. The authors invested additional efforts after the closure of the tender to significantly improve their solution and create a variable time step version of their model, which they named OPTIGES-VTS, but even the improved solution of OPTIGES-VTS would not rank among the top three solutions received during the regular tendering process. The primary reason for this is likely associated with the use of a network flow solver, which cannot directly include the Bargi right canal constraint in the solution process and reservoir evaporation as constraints, where the upper limit on the canal flow is set as a linear function of storage, and it cannot properly model net evaporation within the MTO solution framework unless it uses a network flow algorithm (NFA) solver that can model loss or gain of flow along an arc. Although the vendors of RiverWare initially expressed interest in this tender, they eventually decided not to participate.

Mike-Basin used the rule-based search engine, OPTIGES-VTS used an NFA, Modsim-GA and the Nasim software package used heuristic solvers, while Oasis and other participants used mixed integer LP_Solvers, which were also used by the new WEB.BM model. The test problem contains nonlinearities in the reservoir outflow constraints as well as in the net evaporation constraint, both of which required skilful linearization if LP were to be used. A publicly available library of LP_Solvers was used by the solutions designated as LP_Solve (2019) and Bhama in Tables 2 and 3.

Modsim-GA, a modified version of Modsim model coupled with a genetic algorithm, should be considered another customized solution to the problem. The Modsim model solves only one time step at a time by using the network flow solver which can guarantee compliance with most of the problem constraints. The genetic algorithm is used to conduct the search on the macro solution parameters, such as the assumed irrigation deficits or environmental flow targets, whose settings were subjected to the GA evolutionary search engine over multiple time steps. The coupling of the two modelling approaches was conducted by the Research Triangle Institute, USA. Similarly, the NASIM Software Package (2019) relied on the use of a heuristic solver known as the shuffled complex evolution method.

5 Model results

The first surprising finding was that four out of seven models failed to properly model the problem constraints. The list of model failures in terms of the constraints is shown in Table 2. Although the above models violated the problem constraints, their objective functions were still evaluated to assess their ability to address the optimization criteria; results are shown in Table 3. Each of the three components of the objective function was calculated individually and is summed up in the final column. The performance of the Mike-Basin model in Table 2 was the worst of all participating models both in terms of violating constraints and in terms of the value of the objective function, although it was used by two vendors independently. Where optimization works well, violated constraints should in general produce better values of the objective function. However, despite violating constraints, the Mike-Basin optimization (based on "what-if" rules) also failed to deliver a reasonably optimal solution to this problem, as attested by the values of the objective function in Table 3.

Table 2. Violation of problem constraints.

Types of constraints violated by the selected models

Model	Min/max reservoir levels	Bargi right canal flow limits	Net evap. constraint	Equal deficit constraint	Mass balance constraint
Optiges	✓			✓	
Nasim			✓		✓
Bhama		✓		✓	
Mike-Basin^1			✓	✓	✓
Mike-Basin^2	✓		✓	✓	✓

Note: Two vendors submitted solutions based on the use of the Mike-Basin model.

Table 3. Participating models and their values of the objective function.

Model name	Solution engine	Objective function values Flooding	Environ-mental flows	Irrigation supply	Total objective function
LP_Solve	LP	0	0	134 334	134 334
WEB.BM*	LP	0	0	138 015	138 015
GA-Modsim	Heuristic (GA-LP comb.)	0	0	138 392	138 392
Oasis*	LP	31 145	8267	140 271	179 683
Optiges-VTA	NFA	2 037 684	198 254	124 773	2 360 711
Nasim	Heuristic (complex shuffle)	4 906 223	3139	68 946	4 978 308
Bhama	LP	3 033 479	2 458 465	930 966	6 422 910
Mike-Basin^1	Rule Based Simulation	6 302 746	2 419 094	210 822	8 932 662
Mike-Basin^2	Rule Based Simulation	153 932 450	895 026	3 015 142	157 842 618

*Note: Oasis and WEB.BM are the only models that did not violate any constraints and operating rules.

It should also be obvious from Table 3 that the best solutions do not violate the overbank flow during the excessive 2013 flood, and also never fail to deliver the environmental flow targets. The only component that is featured in the objective function with positive values in all years is related to irrigation deficits. Given that the models listed in Table 2 failed to meet the problem constraints, the remainder of the paper is focused on the three solutions that comply with the constraints obtained by LP_Solve, GA-Modsim and the Oasis model. Two solutions were provided by each GA-Modsim and Oasis model which were compared with the benchmark solution obtained using the WEB.BM model.

5.1 Oasis model results

Oasis is an established model with a solid history of being used in river basin planning and management. Two alternative solutions that were provided fully satisfy the problem constraints; however, they both fail to meet the problem objectives in the best possible way. This failure may be related to an iterative procedure used for calculating net evaporation in the third simulated year, where irrigation deficits in the Oasis solution are higher than those in the benchmark solution.

Table 4 shows the objective function values for all three constituents (flooding, environmental flows and irrigation supply) for both the Oasis and the benchmark WEB.BM solutions. It should be noted that irrigation deficits are somewhat higher in the Oasis solution for the first three years than in the benchmark solution. While the differences in deficits are very small in the first two years, in the third year they are over 8%. Storage levels are different at the end of this year, which makes the comparison of other years that follow less meaningful. The storage in Oasis is not depleted as much as it could have been on Bargi reservoir, where the minimum elevation for the year remains more than 1 m above the minimum achieved by the benchmark solution. It is not completely clear why this happens only in one out of nine years. It might be attributable to the iterative scheme that Oasis used to calculate net evaporation, resulting in a converged solution that is not completely optimal, while the benchmark solution did not require any iterations, since its net evaporation is handled as a constraint within a single LP solution for the entire year. The Oasis model vendors were asked to explain their model's performance (personal communication), but no comments have been received so far. The Oasis model solution also floods the river valley in channel 15. This seems to be caused by improper set-up of the weight factors, which did not allow the upstream reservoirs (Bargi and Tawa) to help alleviate flooding in channel 15, although the test problem calls for system-wide optimization of all reservoirs simultaneously exclusively for the purpose of flood management. The reported computational time of the Oasis model on this test problem was 15 seconds. WEB.BM solved the same problem in nine seconds. Fig. 4 compares the reservoir levels in the Oasis model solution with the benchmark.

There are two issues with both alternative solutions from the Oasis model:

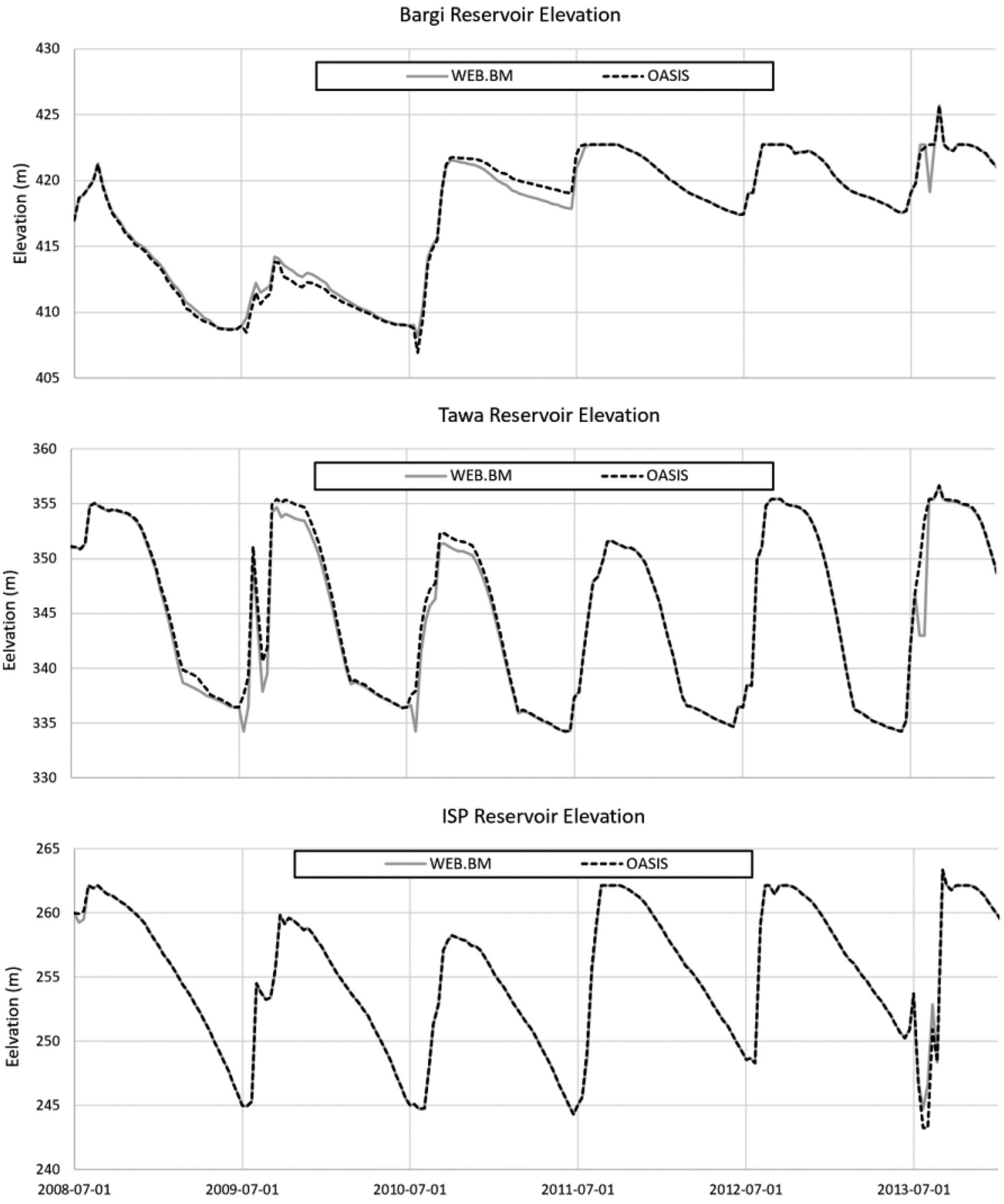
(a) unnecessary retention of water in Bargi reservoir storage during the third year of simulation, which causes higher than necessary deficits on blocks 105 and 110; and
(b) inability to route the 2013 flood through the system without incurring any flood damage in any of the channels that had a designated flood damage function.

5.2 GA-Modsim model results

The Research Triangle Institute has developed a "GA-wrapper" around the Modsim model and provided an impressive solution that avoids any flood damage and does not violate the environmental flow targets or any other problem constraints. However, the solution violates reservoir operating rules, as shown in Fig. 5. The test problem definition clearly states that the upstream reservoir releases will be made specifically only to: (a) maintain environmental flows in the designated downstream channels (i.e. channels 10 and 12 for Bargi, 10 and 12 for Tawa, and 15 for ISP); (b) supply water for irrigation blocks from designated reservoirs; (c) spill additional flows from any reservoir when their respective storage has reached the full (normal) water level and inflow is higher than the environmental flow and irrigation; and (d) provide additional spills as part of pre-flood drawdown releases to mitigate flood damage on any of the designated downstream channels where full bank flow capacity may be exceeded (10, 11 and 15). The GA-Modsim solution violates the above operating rules by releasing more flows from Tawa reservoir than needed to meet the environmental flow and irrigation targets in the third simulated year. In this way, Tawa reservoir is assisting the operation of the ISP reservoir, which was not the intended way to operate the system. Hence, this solution

Table 4. Comparison of objective function values for all simulated years.

	Oasis solution: Alternative 1				WEB.BM benchmark solution			
	Objective function values				Objective function values			
Year	Flood	Environmental flows	Irrigation supply	Total	Flood	Environmental flows	Irrigation supply	Total
2008/2009	0	0	19 703	19 703	0	0	19 658	19 658
2009/2010	0	0	25 173	25 173	0	0	25 168	25 168
2010/2011	0	0	43 326	43 327	0	0	40 093	40 093
2011/2012	0	0	11 684	11 684	0	0	11 690	11 690
2012/2013	0	0	3153	3153	0	0	3171	3171
2013/2014	31 145	8267	2565	41 977	0	0	3551	3551
2014/2015	0	0	12 768	12 768	0	0	12 782	12 782
2015/2016	0	0	15 335	15 335	0	0	15 318	15 318
2016/2017	0	0	6560	6560	0	0	6585	6585
Total	31 145	8268	140 268	179 680	0	0	138 015	138 015



Bargi Reservoir Elevation

Tawa Reservoir Elevation

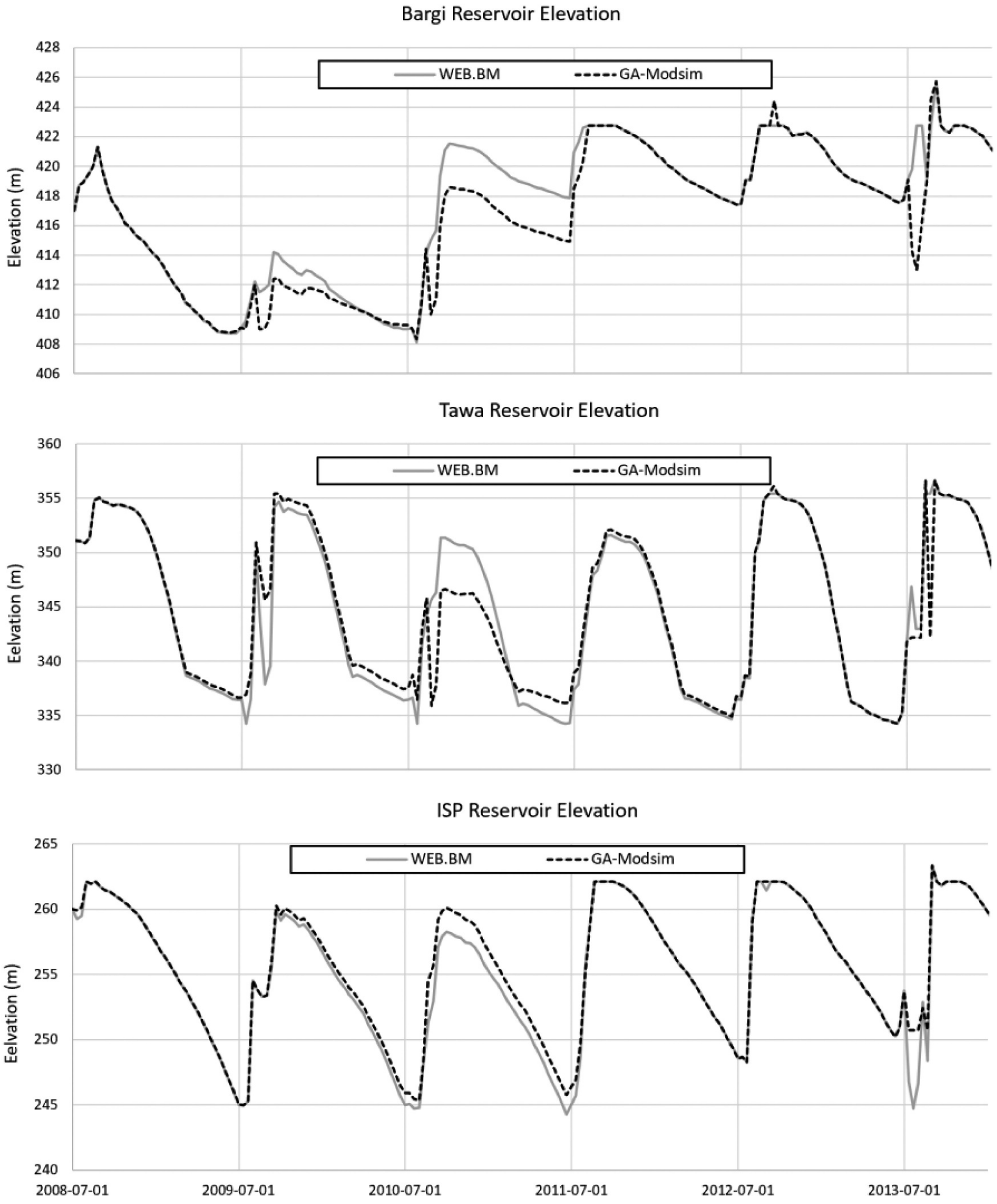
ISP Reservoir Elevation

Figure 4. Comparison of Oasis and WEB.BM model solutions.

violates the requested operating policy. The reported GA-Modsim solution time for this test problem is quoted as variable (“minutes to hours”).

5.3 LP_Solve model results

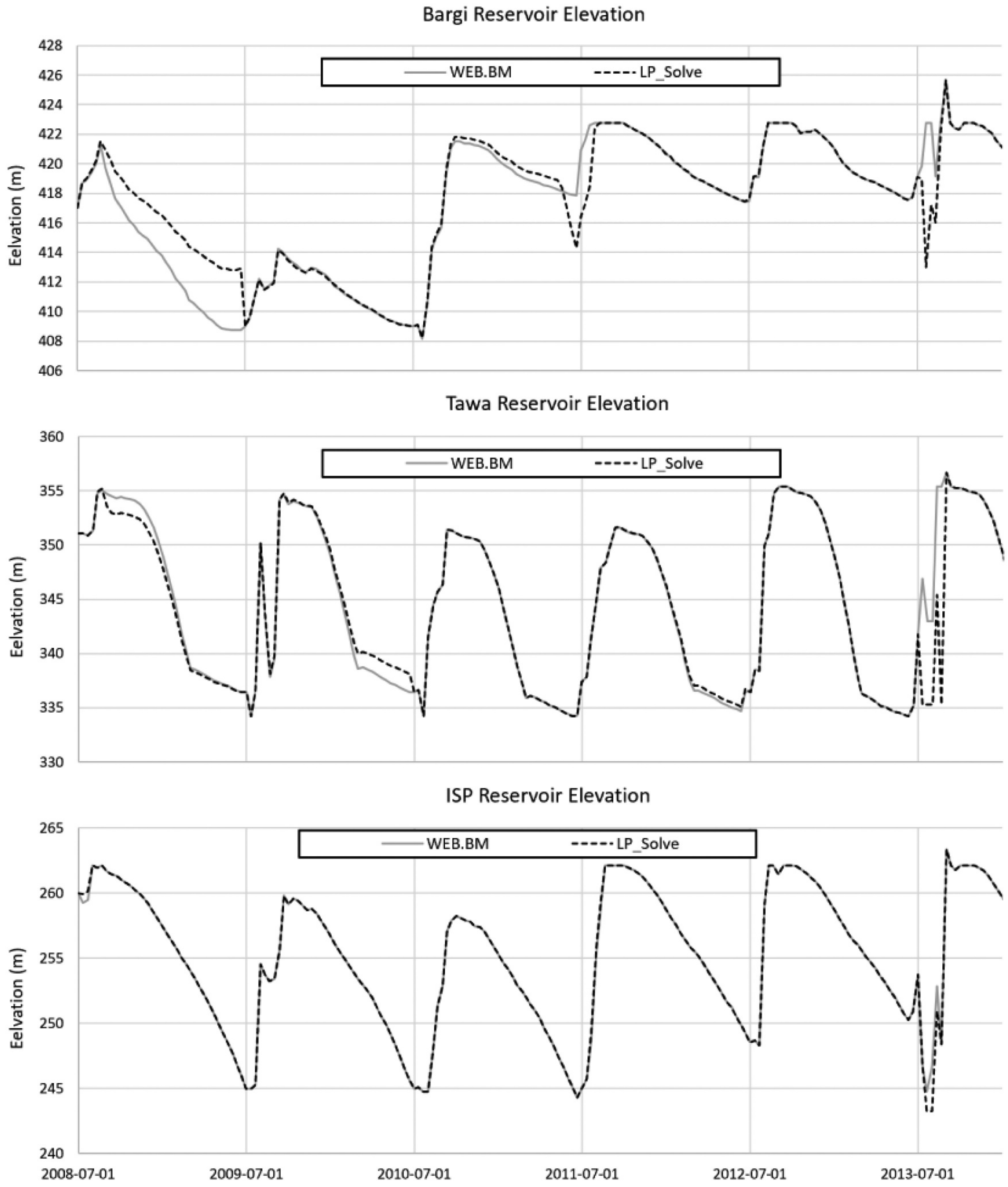
Vassar Labs, an Information Technology (IT) firm from India, built a solution by using LP_Solve, a publicly available (including open source) library of LP_Solvers with mixed integer options. There is a large user community group that supports and uses the LP_Solve library. Their solution has objective function components of 0, 0, and 134 334 related to flooding, environmental flows and irrigation deficits, respectively. Much like the GA-Modsim solution, this solution also fails to adhere to the stated operating policy, as seen in Fig. 6, and this happens in the first and third years. It is obvious that Bargi holds storage in these two years, allowing the ISP reservoir to drop to lower levels, thus simultaneously reducing net evaporation and increasing water supply to blocks 301 and 410, and then provides significant releases in June to make sure ISP reaches the required 30 June level. This was not the intended operating policy requested in the terms of reference. LP_Solve required 62 seconds to solve this test problem.


Bargi Reservoir Elevation

Tawa Reservoir Elevation

ISP Reservoir Elevation

Figure 5. Comparison of GA-Modsim and WEB.BM model solutions.



Bargi Reservoir Elevation

Tawa Reservoir Elevation

ISP Reservoir Elevation

Figure 6. Comparison of LP_Solve and WEB.BM model solutions.

6 Conclusions and recommendations

6.1 Importance of MTO solution capabilities

Water management agencies currently rely on the use of reservoir rule curves for day-to-day operation of reservoirs. So far, the development of reservoir rule curves has been driven by simulation model results and the gut feelings of the dam operators. The use of the MTO solution approach enables water managers and basin planners to obtain a perfect rule curve as part of the model output for each reservoir and for each year of available hydrological data, which can then be analysed statistically to provide insight into the comfort zones for operation during wet, dry and median years. This introduces a systematic and a scientifically based way to construct reservoir rule curves, which can then be implemented in combination with short-term runoff forecasts, as demonstrated by the recent work of Ilich and Basistha (2021). Most importantly, the future of automated reservoir operation will require a combination of reliable runoff forecasts over a short-term period (five days) in combination with MTO solutions, such that optimal reservoir releases can be calculated by taking into account downstream water management objectives, hydrological routing with channel storage change and travel time to the control points of interest in a river basin. In this context, MTO solutions provide a significant improvement over an iterative trial and error approach, which is the only option available with simulation models. Numerical tests provided in the seminal paper on WEB.BM by Ilich (2022) demonstrate the power of optimization combined with both reservoir and hydrological channel routing. On a river basin planning level, adding constraints to enforce equal deficit sharing in dry years, the MTO solutions also provide valuable insight into the amount of demand hedging at the beginning of the irrigation season in dry years.

6.2 Concluding remarks

This paper presents a medium-sized test problem for river basin models with optimization capabilities based on the needs of the Narmada River Basin Authority in India, highlighting the need to establish a set of benchmark tests that should be used as acceptance thresholds in the river basin modelling community. These benchmark tests should reflect the needs of the industry, and they should also include a typical level of difficulty in size and scope that the practitioners routinely face in their work. Without proper benchmarks, many models may remain plagued by bugs and issues that go undetected, which poorly serves the water resources sector. Also, proper benchmarks that reflect the needs of the water management agencies and practitioners can help set the standards for model developers. We therefore propose the establishment of a library of challenging benchmark test problems that can be maintained and reused jointly by practitioners and model developers, thus strengthening the criteria for model testing and acceptance, as is the case in some other (notably, mathematical optimization) industries. This paper contributes one such test problem, which is non-linear in terms of modelling net evaporation and in terms of setting the reservoir outflow limits as a function of the available storage. There is no guarantee that the current benchmark solution presented here is the best possible, since other researchers might eventually obtain better solutions as a result of their work. We also feel that other researchers should provide similar contributions to the benchmarking of river basin models by providing complete input data and problem descriptions, as well as their benchmark solutions. Without the proper benchmarks, river basin modelling will continue to be open to unsubstantiated claims made by various vendors, and to uncertain quality of model results due to the lack of proper checks and balances. Last but not least, this test problem revealed a serious inability of simulation-based models such as Mike-Basin to compete with models that are equipped with solvers based on mathematical optimization algorithms.

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Data availability

The test problem input data and the current benchmark solution are accessible from a public repository at https://data.world/nilich/narmadadata or, alternatively, from https://www.optimal-solutions-ltd.com/Default.aspx?tabid=44. The zipped download archive contains two spreadsheets, one containing the input data, and the other one containing the benchmark solution and several worksheets that can help evaluate its compliance with the required model constraints and calculate the objective function. This could be helpful for testing solutions produced by other vendors.

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