A Flexible Multi-Scale Framework to Simulate Lakes and Reservoirs in Earth System Models

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Key Points:

- Multiple water balance models of lakes and reservoirs are implemented in the mizuRoute vector-based routing scheme.
- The impact of the lakes and reservoirs on streamflow is shown globally.
- The mizuRoute lake implementation provides a platform to integrate Earth System, water management models, and remote sensing data.

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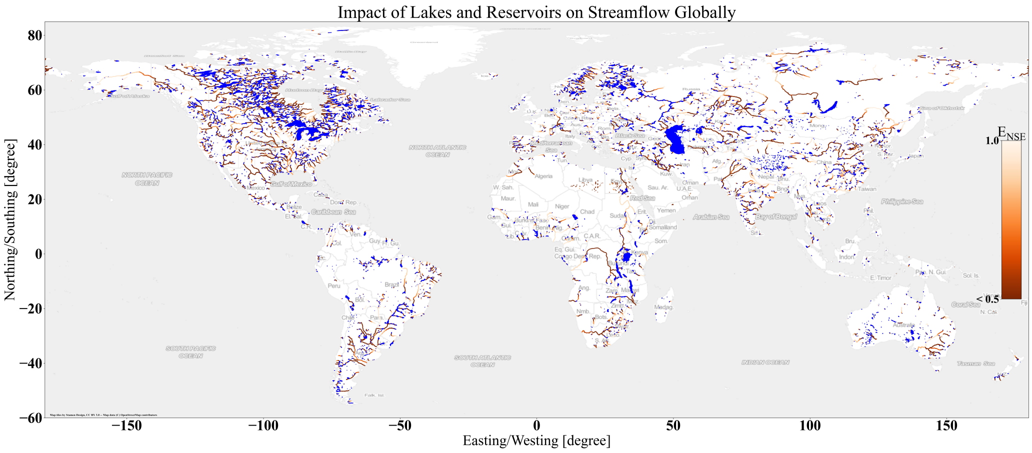
Abstract

Lakes and reservoirs are an important part of the terrestrial water cycle. However, relatively little attention has been given to lake and reservoir water balance modelling, their impacts, and interaction with complex terrestrial system processes. In this work, we present the implementation of lakes and reservoirs into mizuRoute, a vector-based routing model (termed mizuRoute-Lakes) that is agnostic to the choice of hydrologic or land model. In this work, we demonstrate capabilities of mizuRoute-Lake in modeling the water balance of lakes and reservoirs namely (1) data-driven lake/reservoir models; (2) multi-model lake models; and (3) abstraction from lakes, reservoirs, and river segments. Applications presented in this work are at global, regional, and local scales. The data-driven and parametric capabilities that are provided in mizuRoute enable incorporating past or future altimetry data (e.g. from the Surface Water and Ocean Topography, SWOT, mission for estimation of lakes and reservoirs storage) or information from water management model simulations regarding water demand and reservoir operation under climate change scenarios. We believe the capabilities presented in mizuRoute-Lake will enable the modellers to diagnose and compare water balance models in a more rigorous manner.

Plain Language Summary

Lakes and reservoirs are an integral part of the hydrological cycle. However, a systemic and unifying framework that can include various water balance lake and reservoir models and enable the inclusion of human impacts on the terrestrial water cycle is largely missing in large scale Earth System models. The existing lake models are provided in a specific modeling framework which often encompass a single model representation. In this study, we present the implementation of lake and reservoir water balance in the continental-domain vector-based routing model mizuRoute. The lake and reservoir implementation enables both the representation of parametric models and data-driven approaches to simulate lakes and reservoirs. The development opens avenues to test and include a range of lake and reservoir formulations that can be coupled with Earth system and/or water management models, and be validated with current and future in situ and remote sensing data on lake and reservoir surface elevations (or storage).



The impact of lakes on streamflow is simulated using the Döll formulation within mizuRoute (in these simulations reservoirs are represented as natural lakes). The mizuRoute simulations use the HDMA river network topology and 4200 resolvable lakes from HydroLAKES. The impact of lakes on streamflow is presented using the Nash-Sutcliffe Efficiency (E_{NSE}). As expected, the impact of lakes is most pronounced in the downstream reaches of large river basins. Note that the actual impact of water bodies on streamflow is more significant than presented if the regulation of reservoirs are properly represented.

1 Introduction

Lakes store a large fraction of terrestrial water and have considerable impacts on the terrestrial water cycle, global and local climatic variables, and ecosystems (Samuelsson et al., 2010; Biemans et al., 2011; Thiery et al., 2015; Xu et al., 2018; Shugar et al., 2020). Additionally, reservoirs that are constructed to store water for human activity strongly alter natural river systems, and enable irrigation in drier periods of a year, stable water supply for urban or industrial sectors, and hydropower production. From the year 1950 to 2000, the total volume of water in large dams increased from 1,000 to 11,000 km^3, with the enhanced reservoir water storage imparting a detectable reduction in sea level rise (Chao et al., 2008).

Since lakes and reservoirs are an integral part of the Earth System, accurate representation of these water bodies in Earth System models is essential to simulate land-atmosphere fluxes (Vanderkelen et al., 2020). However, representation of lakes and reservoirs in Earth System models is a challenging task. Lakes have an impact on three major conservation laws: (1) conservation of mass which focuses mainly on two aspects of water conservation as well as sediment and nutrient conservation in lakes and reservoirs (Wisser et al., 2013; Yang et al., 2007). (2) conservation of energy that focuses on the head fluxes from and to the water bodies which also include mass transfer such as evaporation, or phase change such as ice cover (Croley & Assel, 1994; Bonan, 1995; Balsamo et al., 2012; Subin et al., 2012; Abbasi et al., 2016; Vanderkelen et al., 2020, 2021); (3) conservation of momentum that focuses on wave propagation in water bodies, circulation of water and events such as dam failure (Xiong, 2011). It is of course preferable that all aspects of lakes are holistically simulated in a unified model, but due to the lack of data and information on millions of small and large lakes and reservoirs around the globe, an accurate representation encompassing all conservation laws is not feasible. Among the above-mentioned conservation laws, water balance has understandably attracted substantial attention. This is perhaps because the inflow and outflow fluxes to lakes are directly linked to human activity for irrigation and food production, or flood prevention and water management and risk mitigation efforts in a larger perspective (Postel et al., 1996; Wada et al., 2014; Pokhrel et al., 2016).

Given the importance of lakes and reservoirs in water management and Earth System modeling, it is somewhat surprising that limited attention has been given to developing a model-agnostic lakes and reservoirs water balance model. For example, river routing schemes are often embedded within existing hydrological, land, or water management models. Additionally, the water management schemes used for water accounting often lack a comprehensive formulation to account for terrestrial system processes such as the vertical water and energy budgets. One reason might be that the time step used in water management models is of order of weeks and months rather than minutes, hours or days as is the case for the hydrological or land models, and hence it is difficult to incorporate terrestrial system processes into the structure of existing water management models.

In this study we introduce the implementation of lakes and reservoirs in the vector-based routing model mizuRoute (Mizukami et al., 2016, 2021). There is a recent trend in moving to vector-based routing models such as RAPID or mizuRoute rather than grid-based routing (David et al., 2011; Mizukami et al., 2016, 2021; Lin et al., 2019; Tavakoly et al., 2017). However given these efforts, only a few recent work consider inclusion of lakes and reservoirs in vector-based models, e.g. Tavakoly et al. (2021), while these capabilities remains in their infancy in comparison to grid based routing models (e.g. MOSART and LISFLOOD; Li et al., 2013; Burek et al., 2013; Thurber et al., 2021). This study aims to bridge this gap and provide a flexible, vector-based routing model, agnostic to host-models (hydrologic, land or water management model). Summarized, the contributions of this work are as follows (with more detailed explanation in Section 2):

1. *Represent rivers, lakes and reservoirs using lines and polygons*: Lakes and reservoirs are embedded as part of the vector-based network topology. Using vector-

based routing removes the traditional difficulties that are often associated with the grid-based routing such as upscaling of parameters and flow-direction corrections across different grid resolutions. Also, representation of lakes and reservoirs in grid-based methods may be challenging as lakes and reservoirs might be represented with multiple grids. Or on contrary, lakes and reservoirs smaller than a grid may not be resolved on the river network while considered to be a in-grid lakes or reservoirs (see Figure-1a). To resolve the smaller lakes, higher grid resolutions are needed which at the same time can complicate the representation of larger lakes, due to many grids cells, while adding unnecessary and unrealistic computational burden (for example smaller grid cells need to have rivers in them which is unrealistic, and adds a significant number of computational units). With a vector-based river network, depending on the density of river network topology, various numbers of lakes can be resolved. For example in Figure-1b one lake is resolved on a low density river network whereas a higher density river network results in many more lakes being resolved (Figure-1c). The line-polygon representation of rivers and lakes is more closely tied to reality than a gridded spatial representation. For further reading, we encourage the reader to refer to WaterML 2, Open Geospatial Consortium 2018 (Blodgett & Dornblut, 2018).

2. *Develop lake/reservoir models in a way that is agnostic to the host hydrological, land or water management model*: The river network topology and lake and reservoirs models are separated from the hydrological model and its spatial discretization. The host model can be set up at hydrological response units (HRUs), subbasins, or gridcell level, while the routing scheme (and its components, such as lakes) can be the same across multiple host models. This simplifies the evaluation and interaction of streamflow and lake and reservoir routing across various modeling platforms. The capability which allows to decouple the configuration setup of hydrological, land, or water management models, referred to as a host model by Nazemi and Wheater (2015), results in a more flexible modeling framework (see also Gharari et al., 2020).
3. *Incorporate multiple [parametric] model and data-driven approaches to simulate lakes and reservoirs*: The mizuRoute lake implementation allows for various implementations of lakes and reservoirs in the fabric of a river network topology. Users can provide parametric models of various complexity, or they can choose to force a lake with observed storage values if these data exist, which can come from in-situ observations or satellite data (such as the prospect SWOT mission). Additionally, alternating between different lake water balance models is straightforward, and therefore the impact of different lake water balance models can be evaluated in isolation from the rest of the simulation of river flow through the river and lake network.
4. *Flexibility to include new lake models*: Additional lake models can be easily added to the code for further development with minimal change in the existing source code.
5. *Flexibility in coupling with land and water management models*: The lake implementation within mizuRoute opens up the possibility for coupling with any real time hydrological or land or water management model that provides reservoir operation (target elevation or storage), or abstraction and injection of water from the river network, lakes and reservoirs based on hydrological variables and irrigation demand. These values can be provided from various sources such as more traditional water management models (e.g. Water Evaluation And Planning System, WEAP, Yates et al., 2005) or more computationally expensive water management models such as Artificial Neural Network or Agent-Based Models (Giuliani & Castelletti, 2013; Ehsani et al., 2016).

In the following sections we elaborate on the mizuRoute lake and reservoir implementation and provide local, regional and global applications of mizuRoute-Lake. Sec-

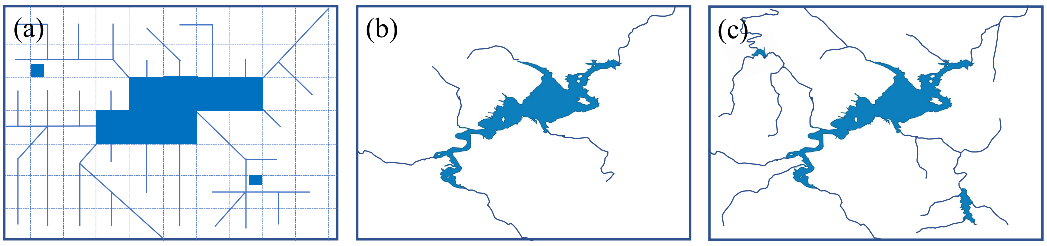


Figure 1. (a) the fabric of grid-based routing including lake; the larger lake are resolvable lake on the river network; smaller lakes are considered in-grid lakes (b) a fabric of vector-based routing with lakes, using a low density river network with only one resolvable lake (c) and fabric of vector-based routing with higher density river segments resolving more lakes on the river network.

tion 2 outlines the advantages and possibilities that mizuRoute offers for lake and reservoir modeling at local or continental scales. Section 3 includes global and local examples of using mizuRoute. Final concluding remarks are provided in Section 4.

2 mizuRoute-Lakes

2.1 Features:

2.1.1 A standalone vector-based river-lake routing

mizuRoute is a vector-based routing model. A key advantage of vector-based routing models over grid-based routing models, is the greater flexibility in defining the river and lake network topology. The network topology can be refined (if higher resolution data is available), with smaller lakes and reservoirs integrated into a higher-resolution geospatial fabric (Figure-1c).

Each river segment or lake is treated as an object on the river network. The river network topology identifies which reach is flowing to the next downstream reach or lake, or which reach serves as a lake or reservoir outlet. The lakes and reservoirs are identified with a flag along with the lake type, and associated lake parameters. Currently there are four different options/models for representing the lake and reservoir water balance in mizuRoute (subsection 2.2). Additional lake and reservoir models can be added based on community demand.

mizuRoute is a standalone routing model. Runoff output from land models, often run on a regular grid, or hydrological models, often run on HRU or subbasins, can be used to drive mizuRoute, using an identical river network topology. This flexibility enables the exploration and comparison of various hydrological models through an identical routing model, mizuRoute. Additionally, existing vector-based river and lake network topologies can be used by mizuRoute (including existing grid-based routing configurations), which reduces or eliminates the need for users to develop or translate new river-lake network topologies.

2.1.2 Water balance

mizuRoute is forced by runoff simulated by a hydrological model or a land model or from observations. This is achieved by reading runoff from an input file (in offline mode) or directly from a coupler (online). The input runoff is remapped to the sub-basins of the river network and routed within the basin at hillslope scale and in channels (Mizukami et al., 2016, 2021). When lakes and reservoirs are activated in mizuRoute, additional variables for lake evaporation and precipitation onto lakes must be provided alongside the runoff variable, and mizuRoute will remap those variables to the lake area if remapping is needed. In addition, mizuRoute provides the capability to use or calculate abstraction and/or injection of water to and from a river segment or lake or reservoir. The time series of abstractions and injections to lakes and reservoirs can come from other models, e.g., water management models, or directly from observations.

The water balance of lakes and reservoirs in mizuRoute can be written as:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = I - O + (P - E)A - F_{a,i} \tag{1}$$

in which S (m^3) is the lake or reservoir storage, I and O ($\mathrm{m}^3\ \mathrm{s}^{-1}$) are the inflow and outflow flow of the lake or reservoir, P and E ($\mathrm{m}^3\ \mathrm{s}^{-1}$) are the lake precipitation and evaporation, and A (m^2) is the lake area. $F_{\mathrm{a,i}}$ is the abstraction or injection flux that is provided in a times series in $\mathrm{m}^3\ \mathrm{s}^{-1}$; if positive it is an abstraction, given that there is enough water available in the river segment, lake or reservoir, and if negative it is treated as injection. The abstraction or injection values can be provided by other models, online or offline, such as groundwater models or water management models.

2.1.3 Including a diversity of lake and reservoir models

The lake and reservoir water balance models that are used in Earth System models are often from engineering, water management or irrigation communities. Typically, these models have been extensively used to better represent water resources in Earth System models. Therefore, a comprehensive understanding of the interaction between the lake and reservoir water balance models and parameters of water management, hydrological or land models is largely missing. Recent efforts have provided insights on the sensitivity of parameter values in lake models (Gutenson et al., 2020) and the impact of lake and reservoir model on inferred parameters of a simple land surface model like the Variable Infiltration Capacity (VIC) model (Dang et al., 2020).

The lake models that are implemented in mizuRoute are both parametric and data-driven to enable flexibility in modeling of lakes and reservoirs. The mizuRoute lake and reservoir implementation is a multi-model approach in which a user can select various types of lake or reservoirs models or even data driven approaches to simulate lakes or reservoirs. Different lake water balance models can be invoked even within the same mizuRoute configuration. For example, smaller upstream lakes can be modelled using a simpler parametric model, while the larger downstream reservoirs can be modelled using more complex methods.

2.2 Lake and reservoir models

Lakes can be generally classified as exorheic or endorheic lakes. Exorheic lakes are lakes that have at least one outlet. In the current implementation, mizuRoute assumes one outlet only for the exorheic lakes and reservoirs. Endorheic lakes have no outlet, meaning that the water that enters these lakes is lost by other means, such as infiltration from the bottom of the lake bed, abstraction, or evaporation from the lake surface. In mizuRoute-Lake, lakes and reservoirs can be simulated using two parametric or data-driven approaches, which are described in detail in the following section. The parametric models used are for exorheic lakes only. Endorheic lakes are treated as water bodies in which outflows from the outlet, O from Equation-1, is assumed to be zero.

2.2.1 Parametric lake and reservoir models

The parametric models link the outflow, O, to inflow, I, and storage, S, of a lake or reservoir by a set of functions and parameters. The parametric lake models can be categorized into time-invariant and time-varying (or hyper-parametric) models. The lake and reservoir models that are implemented in mizuRoute are described in the following subsections.

Time invariant parametric models

The simplest outflow models for lakes and reservoirs are the time-invariant parametric models. Examples of these models are Döll (Döll et al., 2003), Wada (Wada et al., 2014), HYPE (Arheimer et al., 2019), and the LISFLOOD (Burek et al., 2013) lakes and reservoir formulations (for a more extensive list of models refer to Gutenson et al., 2020). Currently there are two time-invariant parametric models implemented in mizuRoute:

- **Döll**: The simplest lake model implemented in mizuRoute is the formulation of Döll et al. (2003) (based on Meigh et al., 1999). This model relates the outflow from a lake or reservoir to the current volume of water stored in the lake, its maximum capacity and an empirical power relationship identified by a coefficient and power (three parameters). The Döll formulation is often used for natural lakes (no regulation) or if there is limited knowledge on how to operate reservoirs. Appendix A describes the implementation of the Döll model in mizuRoute.
- **HYPE**: The second time-invariant parametric model in mizuRoute is the HYPE formulation of lakes and reservoirs (Arheimer et al., 2019). Currently we have only implemented the "one-outlet" formulation of HYPE in mizuRoute. The operation rules for the HYPE one-outlet reservoir model depends on four input parameters that define different critical reservoir levels: (1) the elevation of the emergency spillway, E_{emg}; (2) the elevation under which the release from a primary spillway is restricted, E_{lim}; (3) the elevation of the primary spillways E_{prim}; and (4) an elevation which defines the volume of the so-called inactive or dead storage of a lake or reservoir, E_{min}. When the lake elevation is between the minimum elevation, E_{min}, and the elevation of the primary spillway, E_{prim}, the outflow is effectively zero and the reservoir accumulates (and evaporates) water. For lake elevations higher than primary spillway, E_{prim}, and lower than the limiting elevation, E_{lim}, the primary spillway is partially activated by scaling the primary spillway amplitude outflow parameter. For lake elevations greater than the limiting elevation, E_{lim}, the primary spillway is fully activated (no scaling is needed). Finally, for values higher than the emergency spillway, E_{emg}, the emergency spillway is also activated (alongside the primary spillway) and maximum value is selected as reservoir outflow (this can be changed to sum of primary and emergency spillway outflows). Appendix B describes the HYPE formulations and parameters.

Time varying parametric models

Capturing the reservoir operation due to change of rules from reservoir to reservoir and period to period with mechanistic models are rather difficult. Time varying model parameters are often used to capture time dependent changes in reservoir operations over the course of months, seasons, years, decades reflecting on wetting or drying period. To address this, we have implemented the "Hanasaki with memory" parameterization as follows:

- **Hanasaki with memory**: The Hanasaki formulation is among the most well-known formulations that is used to inform the water balance model of a reservoir based on time varying, often monthly, inflow and demand terms (Hanasaki et al., 2006). The model scales the demand term based on the state of the reservoir (the amount of water stored). In our implementation, we have made the monthly inflow and demand parameters variable over time by allowing the model to adjust the inflow and demand parameters based on the memory of the system (e.g., the reservoir storage over the past 5 years; for further information refer to Vanderkelen et al., 2022). This enables adjustment of time varying parameters by considering how long term changes in environmental conditions, such as climate change affect inflow or by how demand changes over time due to changes, for example, in irrigation technology, irrigated area, or irrigation intensity (Appendix C). The performance of using the Hanasaki formulation for reservoirs compared to the natural lake model of Döll in mizuRoute is globally evaluated by Vanderkelen et al. (2022).

Additional time-varying parameter formulations were recently proposed based on existing models in which time-invariant parameters are varying in time at a given resolution such as monthly (Yassin et al., 2019; Tefs et al., 2021). The monthly parameters are perhaps reflecting the resolution of water management models or available data, however and in principle, these parameters can be changed per modeling simulation time step (instead of every month). The capacity of changing the parameters per time step provides flexibility for the routing model to adjust parameters at the user request instead, for example, weekly or seasonally, rather than only monthly parameters. Consequently, changing the parameters per time step pushes the envelope from parametric to data-driven models, as is explained in the next paragraph.

2.2.2 Data driven lake and reservoir modeling; coupling capabilities

Parametric models have rigid assumptions that may limit their applicability. For example, many models, such as water management and hydrological models, might be based on agent-based or artificial intelligence, and the time series output from these models provides information on reservoir operations that can be used in Earth System models. Therefore, for mizuRoute, users can provide a time series of abstraction and injection fluxes (m^3 s^{-1}) for each object (i.e., river segments, lakes or reservoirs) on the river-lake network topology. Also, for reservoirs on the river-lake network topology, a user can identify target volumes (at the resolution of the model simulation). The model then adjusts the outflow in a way that the water is stored if the current target volume is greater than the current reservoir volume. On the other hand, the model releases water if more water is stored in the reservoir than the target volume. The target volumes of lakes, abstractions, and injections to/from river segments or lakes or reservoirs can be provided to mizuRoute in a time series format using the coupler. This simplifies the coupling of mizuRoute and water management models. Additionally, this capability in mizuRoute provides users with the option to simulate lakes and reservoirs with altimetry data that may be available from future SWOT missions (or any other sources) or operational scenarios.

3 Case studies

3.1 Global simulation of lakes and reservoir using parametric models

In the first case study, we evaluate the difference of streamflow simulation in river segments globally with a network topology that does not include lakes versus one that does include lakes. The network topology is based on the Hydrologic Derivatives for Modeling and Applications with approximately 300,000 river segments worldwide (HDMA; Verdin, 2017). The river-lake network topology also utilizes the HDMA river network and adds in approximately 4200 resolvable lakes and reservoirs globally from the 1.5 million lakes in the HydroLAKES dataset (Messager et al., 2016). The resolvable lakes are the lakes that can be captured by the length and coarseness of the selected river network topology (note that a higher density river network would mean that more lakes can be resolved). For the river network with lakes and reservoirs, the river segment length and sub-basin areas are corrected for the portions that fall under lakes and reservoirs. This exercise can be seen as vector-based analogue to recent advances with grid-based routing models that consider lakes and reservoirs globally (Zajac et al., 2017)

The runoff used to force mizuRoute in this case study is from the Community Land Model version 5.0 (CLM5) with spatial resolution of 0.5 degree and aggregated temporal resolution of one day (Lawrence et al., 2019). This forcing data is the same as that used in Mizukami et al. (2021), and is selected to demonstrate capabilities of mizuRoute-Lakes for Earth System modelling applications. Additionally for lakes and reservoirs, lake evaporation, as calculated by CLM, and precipitation over lakes, as input to CLM, are provided in the mizuRoute input files. The runoff, precipitation and evaporation obtained from CLM5 are remapped to HDMA sub-basins using mizuRoute's internal remapping capabilities.

The simulations are evaluated in two ways. First, we examine the difference in river segment streamflow for network topologies with lakes and without lakes. To evaluate this difference we use the Nash Sutcliffe Efficiency (E_{NSE}), which is a normalized root mean square difference between the mizuRoute simulations with and without lakes. The second comparison is based on the routing simulation with and without lakes and reservoirs for a handful of large river basins in comparison to monthly observed river discharge data from (Dai, 2017).

Figure 2a depicts the differences in the mizuRoute simulations with and without lakes. The result shows the impact of lakes and reservoirs on the streamflow in each river segment globally. Figure 2a only includes the impacted river streamflow that has upstream lakes and reservoirs and an E_{NSE} value lower than 0.999. As expected, Figure-2a shows that the larger lakes have a higher impact on streamflow downstream.

Figure 2a also provides details of the South Saskatchewan River basin up to the city of Saskatoon. The river network has 7 resolved lakes and reservoirs upstream of Saskatoon, with Lake Diefenbaker being the largest lake both in area ($4.3\text{x}10^8$ m^2) and volume ($9\text{x}10^9$ m^3). In the next case study we simulate the reservoir operations in the Saskatchewan River basin using the available parametric models in mizuRoute (Hanasaki and HYPE) and evaluate their impacts.

For selected river basins (the Nelson, the Rhine, the Mackenzie, and the Paraná), we compared the mizuRoute simulations with streamflow observations from Dai (2017) (Figure-2b-e). The results indicate that the lakes and reservoirs improve the simulation closer to better conform with observations at selected streamflow stations. However, as mentioned earlier, in this comparison reservoirs are treated the same as unregulated lakes (using Döll formulation)k.

3.2 Multi-model simulations for Lake Diefenbaker, Canada

In the second case study, we present a regional application of the mizuRoute lake and reservoir implementation. The application focuses on the South Saskatchewan River to the city of Saskatoon (identified by red triangle and zoom in area in Figure-2a) with a total area of 141,000 km^2. For this regional application we use the Merit-hydro network topology (Lin et al., 2019; Yamazaki et al., 2019) which is 10 times denser than the HDMA topology used in the global application. This higher density river network results in more lakes and reservoirs being resolved, increasing the number of resolved water bodies from 7 to 70 over this domain. The runoff forcing data used in this regional study is the same as the global application (CLM5 with resolution of 0.5° spatially and daily temporal resolution). However, to emulate the regional hydrological model application that are setup at subbasin configuration, we remap the CLM5 runoff and the other variables of precipitation and evaporation to the sub-basins and lakes using EASYMORE python package (Gharari & Knoben, 2021) and pass this remapped runoff to mizuRoute without using mizuRoute remapping capabilities (modeling/input unit and routing units are identical and the same as subbasins).

We evaluate four model configurations based on the information we have for this region:

1. No lake is simulated in the network topology (no lake).

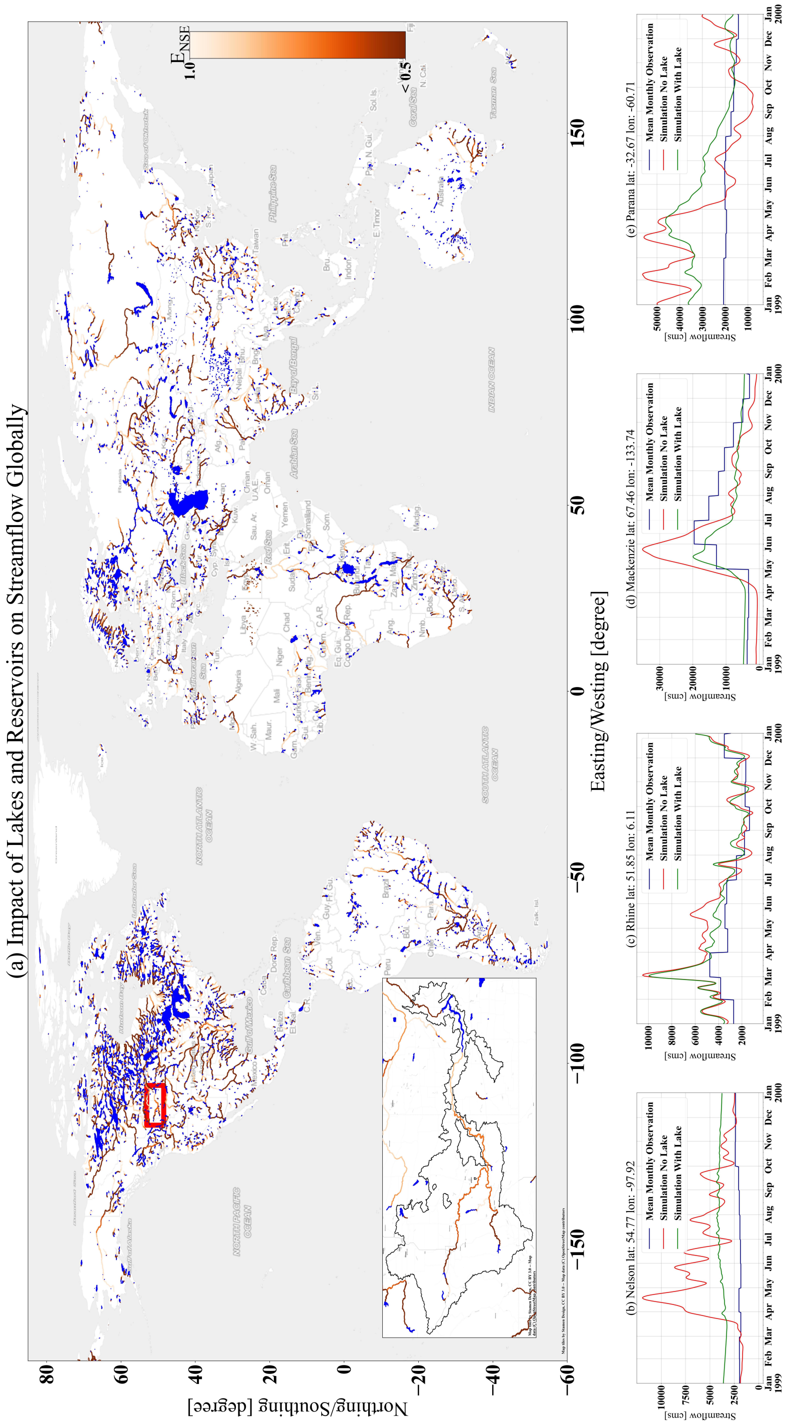


Figure 2. (a) The impact of lakes and reservoirs on river segment streamflow using the HDMA river network topology and approximately 4200 lakes and reservoirs from the global HydroLAKES dataset. The impacted river segments are the river segments that have E_{NSE} values lower than 0.999 (1.0 being the best E_{NSE} values). The figure inset shows the South Saskatchewan River, with 7 resolvable lakes and reservoirs upstream of the city of Saskatoon (for details refer to Figure-3a-b). The comparison of observed mean monthly streamflow simulations with and without lakes are shown for (b) the Nelson, (c) the Rhine, (d) the Mackenzie and (e) the Paranà rivers.

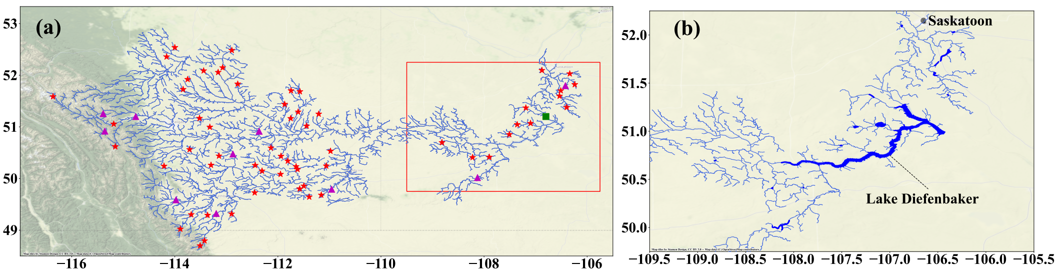


Figure 3. (a) Representation of resolved lakes and reservoirs in the South Saskatchewan River upstream of Saskatoon. The symbols denote natural lakes or reservoirs: Red stars denote natural lakes (simulated using the Döll formulation), purple triangles are lakes simulated with the HYPE formulation, and the green square (Lake Diefenbaker) is simulated using the Hanasaki formulation. (b) A zoom in to the Lake Diefenbaker area upstream of the city of Saskatoon. Coordinates are in degree northing and westing.

2. All 70 resolvable water bodies are considered to be natural and simulated using the Döll parameterization (Döll).
3. 11 water bodies are treated as reservoirs, parameterized using the HYPE model, and the rest are considered natural lakes (Döll+HYPE). The HYPE parameters are defined based on information from various sources (Tefs et al., 2021; Stadnyk et al., 2020; Andersson et al., 2015).
4. 1 reservoir (Lake Diefenbaker) is parameterized using the Hanasaki formulation, 10 reservoirs are parameterized using the HYPE model, and the rest are considered natural and simulated using the Döll parameterization (Döll+HYPE+Hanasaki; Figure-3b shows a zoom in to the Lake Diefenbaker area.).

This example illustrates the impact of the capability to use different lake and reservoir models across the domain. Figure-4a depicts the differences in simulated streamflow at Saskatoon under the four model configurations. It is clear that the presence of lakes and reservoirs upstream dampens the peak flow (comparison between No lake and Döll). The comparison of the second and third scenarios, Döll and Döll+HYPE respectively, illustrates that the peak flows are further reduced using the HYPE formulation. Additionally, including the Hanasaki formulation for Lake Diefenbaker flattens the peak and delays it for a few months. Similarly, Figure-4b compares Lake Diefenbaker storage for the scenarios with lakes (scenario 2 to 4), illustrating that the various model configurations have substantial impacts on the simulation of lake storage. Note that the reservoir model parameters used in this case study are default values. Parameter calibration or adjustment of the reservoir models could further improve model simulations, though biases in the simulated CLM5 runoff are also likely to be a significant contributor to the remaining biases.

3.3 Simulations of Lake Diefenbaker for the flood of 2013

To illustrate the relevance of the mizuRoute lake and reservoir scheme for local scale applications, we provide an example on Gardiner Dam and Lake Diefenbaker on the South Saskatchewan River. We specifically focus on the flood of June 2013 in which intense rainfall and rapid snowmelt in the Canadian Rockies caused flooding (Vionnet et al., 2020). The streamflow at the city of Saskatoon during this flood was as high as 2300 m^3 s^{-1} (normal June streaflow is in order of 100 m^3 s^{-1}). The question we utilize the mizuRoute-Lake modeling system to try to address is: “How different would the streamflow discharge have been in Saskatoon if the initial water level at Lake Diefenbaker prior to the flood

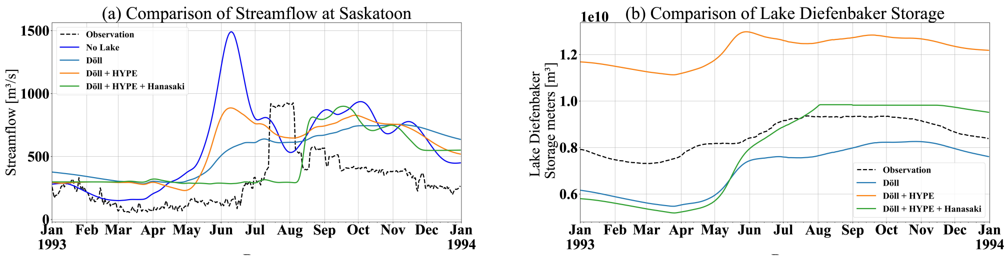


Figure 4. (a) Comparison of daily streamflow vs observed flow at Saskatoon for the four different model configurations. (b) Comparison of Lake Diefenbaker Storage for three of the four scenarios (the scenarios that include lakes).

event was substantially lower?" The answer to this question could potentially help water managers rethink the operational rules of Lake Diefenbaker, in the context of the joint requirements of flood mitigation and irrigation and hydropower generation needs.

First, we describe the network topology of Lake Diefenbaker. The upstream streamflow is measured by the Water Survey of Canada at two places in the province of Alberta, namely South Saskatchewan at Medicine Hat and Red Deer at Bindloss (station ID of 05AJ001 and 05CK004 respectively). The Red Deer River drains into the South Saskatchewan River and the South Saskatchewan River flows into Lake Diefenbaker. There are many other local tributaries that directly flow to Lake Diefenbaker; among them the Swift Current River is the major contributor (station ID of 05HD039). Lake Diefenbaker has two outlets, one outlet is the main outlet on the natural outflow path to the south Saskatchewan River, which includes two sets of spillways from Gardiner Dam, large emergency spillways for flood mitigation and primary spillways that are used for hydropower generation and regulating flow for agricultural use. The streamflow from Gardiner Dam is measured at Saskatoon (station ID 05HG001). The secondary outlet from Lake Diefenbaker is a canal that drains from the Qu'Appelle Dam with limited capacity, on the order of 10 m^3 s^{-1}), in comparison to the main reservoir outlet at Gardiner Dam which can be on the order of 1000s m^3 s^{-1}). This secondary outlet is measured (station ID 05JG006). In addition to the inflows to Lake Diefenbaker, Lake Diefenbaker storage can be approximated using elevation-storage relationships from the elevation measured at Gardiner Dam (station ID 05HF003). The information on the network topology, along with the location of stations, are provided in Figure 5. Note that the network topology presented in Figure-5 resembles the topology of water management models (such as WEAP); this example is used to illustrate the potential to couple mizuRoute with existing water management models (online or offline). In this example, the model parameters in mizuRoute are calibrated, diffusivity and velocity, to improve streamflow simulations at Saskatoon.

Next, the streamflow at Saskatoon is simulated assuming different scenarios for operating Lake Diefenbaker: (1) initial storage of Lake Diefenbaker at the beginning of June 2013 is 0.5, 1.0, 1.5 and 2 meters lower than observed lake elevation; (2) the day preceding 24 of June that the dam operators begin to release water to provide more room for the flood water (lead time of forecast and action); and (3) the days after 24 of June that the storage gets back to historical value (the lead storage is fully used to stored flood water). It is expected that the simulated flood should be reduced in a scenario with lower initial storage conditions, earlier reaction times, and steep accumulation of the storage after the flood peak. For example, the scenarios in which the initial water level is 0.5 meter lower than historical and the reaction starts 2 days earlier than historical and after 5 days after 24 of June the storage reaches the historical value is called S-0.5-2-5. The combination of all possibilities results in 40 scenarios.

Figure-6a shows example reservoir management scenarios during the 2013 flood. Figure-6b illustrates the streamflow at Saskatoon and hence the reduction in peak flow.

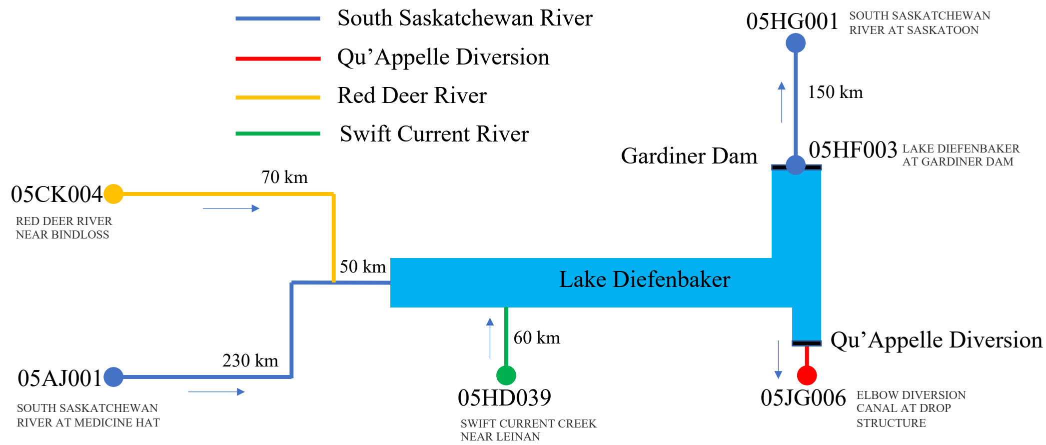


Figure 5. Illustration of Lake Diefenbaker and configuration of network topology and water level and streamflow measurement stations.

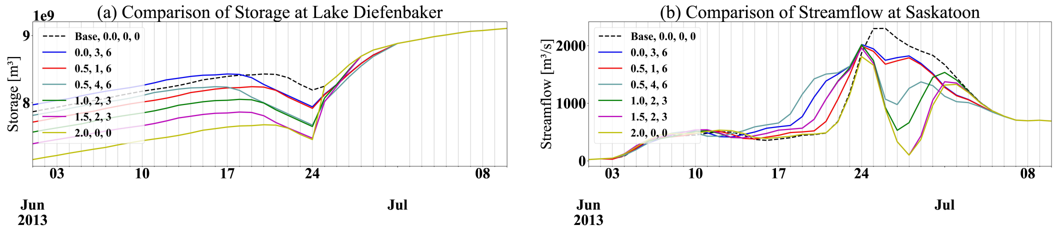


Figure 6. The peak discharge at Saskatoon for the flood of May 2013 for various scenarios in which the initial lake level is lower (0.5, 1.0, 1.5 and 2 meter) than the historical values. The horizontal axis describes the day in May in which the storage starts increasing and the end data indicate the day in may that the storage reaches the historical values.

As an example, for S-2.0-0-0 in which the streamflow is reduced to 1800 m^3 s^{-1}) from base simulation of 2300 m^3 s^{-1}) because the bulk of the flood can be fully absorbed by the reservoir (2 meter storage is filled over a period of a day). Note that this management response would not be used in practice given the stress this quick increase in storage can have on an earth-filled dam. The scenario illustrates, hypothetically, that it is possible to store the flood water fully in the Lake Diefenbaker if there is large storage available. As another example, scenario S-0.0,3,6 resulted in a reduction of approximately 400 m^3 s^{-1}) at Saskatoon (blue line in Figure-6b). There are many other combinations of scenarios not shown here.

In this example, we illustrate that the initial storage plays a more important role than the forecast lead time. Note that the scenarios constructed here are ad hoc and meant to illustrate the capabilities of mizuRoute's data-driven methods to provide potential flood control guidance. Of course, more realistic reservoir operation scenarios based on expert knowledge are needed to comprehensively evaluate and optimize management strategies for future floods considering the reservoir operation limits.

4 Concluding remarks

We have presented the implementation of lakes and reservoirs water balance in a vector-based host-model agnostic routing scheme, mizuRoute. The host-model agnostic nature of mizuRoute provides modellers with capability to alternate between vari-

Table A1. Parameters, state and fluxes for Döll formulation in mizuRoute

Symbol	Nature	Description	Unit
S	State	Storage at the current time step of simulation	[m^3]
I	Flux	Inflow at the current time step of simulation	[$m^3\ s^{-1}$]
O	Flux	Outflow at current time step of simulation	[$m^3\ s^{-1}$]
K_r	Parameter	release coefficient (suggested as 0.01)	[d^{-1}]
S_max	Parameter	Maximum or total storage of the reservoir	[m^3]
α	Parameter	power scaling the storage value impact	[-]
C	Constant	Converter from mean daily values to per second (1/86400)	[$d\ s^{-1}$]

ous configurations of hydrological or land surface models with ease (while the routing setup and parameters remain identical). We showed that the mizuRoute lake and reservoir model can be used at global, regional and local scales. So far, we have implemented three parametric lake or reservoir models in mizuRoute (Döll, HYPE, and Hanasaki) as well as the capability to simulate the water bodies using data-driven methods. The source code is available in the Earth System Community Modeling Portal GitHub repository (https://github.com/ESCOMP/mizuRoute). We welcome community contributions to mizuRoute to enhance lakes and reservoirs capabilities based on needs and demands. This modeling framework is intended to facilitate the exploration of how lake and reservoir parameterizations and their interaction with hydrological and land surface models impact downstream flow under a range of environmental and demand-driven change scenarios. If coupled, mizuRoute lake and reservoir implementation can serve as a bridge to reduce the gap between water management and complex physically-based land models.

Appendix A Döll

The least complex lake model in mizuRoute is the Döll formulation (based on Döll et al., 2003). Döll state, input and output fluxes and parameters:

$$O = CK_\mathrm{r}S(\frac{S}{S_\mathrm{max}})^\alpha \tag{A1}$$

Appendix B HYPE with one outlet

$$F_\mathrm{sin} = max(0, 1 + A_\mathrm{amp}\sin(\frac{2\pi D_\mathrm{julian} + B_\mathrm{phase}}{365})) \tag{B1}$$

$$F_\mathrm{lin} = min(max(\frac{E - E_\mathrm{prim}}{E_\mathrm{lim} - E_\mathrm{prim}}, 0), 1) \tag{B2}$$

$$Q_\mathrm{main} = F_\mathrm{sin}F_\mathrm{lin}F_\mathrm{managed}Q_\mathrm{avg,rate} \tag{B3}$$

if reservoir elevation, E, if larger than E_emg, the emergency spillway is activated:

$$Q_\mathrm{emg} = (E - E_\mathrm{emg})^{P_\mathrm{emg}}Q_\mathrm{emg,rate} \tag{B4}$$

Table B1. Parameters, state and fluxes for HYPE formulation in mizuRoute

Symbol	Nature	Description	Unit
S	State	Storage at the current time step of simulation	[m^3]
E	State	Elevation at the current time step of simulation (corresponding to the storage at current time step)	[m]
I	Flux	Inflow at the current time step of simulation	[m^3 s^{-1}]
O	Flux	Outflow at current time step of simulation	[m^3 s^{-1}]
E_{emg}	Parameter	Elevation of emergency spillway	[m]
P_{emg}	Parameter	The power of the spillway flow exponential curve (linear relationship between depth above spillway and outflow if 1; recommended range: 0.25 to 5)	[-]
$Q_{\text{emg,rate}}$	Parameter	The coefficient of the spillway flow exponential curve (recommended range: 1 < x < long-term maximum streamflow)	[m^3 s^{-1}]
E_{lim}	Parameter	Elevation below which primary spillway flow is restricted	[m]
E_{prim}	Parameter	Elevation of primary spillway	[m]
$Q_{\text{avg,rate}}$	Parameter	The average long term output from main spillway	[m^3]
A_{amp}	Parameter	Day of the year from the first of January, phase difference to shift the maximum over time.	[-]
B_{phase}	Parameter	Amplification of the outflow from the main spillway (recommended range: 0 to 4)	[-]
E_{min}	Parameter	Elevation that corresponds to zero storage	[m]
F_{managed}	Parameter	Flag to identify the conditional reservoir purpose (hydropower = 1, else 0)	[-]
A	Parameter	Average lake surface area	[m^2]

$$O = max(Q_{\text{emg}}, Q_{\text{main}}) \tag{B5}$$

Appendix C Hanasaki with memory

The following is Hanasaki formulation based on Hanasaki et al. (2006). All the hard coded values in Hanasaki formulation are coded as parameters so users can either use the suggested or default values or test other values (sensitivity).

The first step is to popularize the memory and demand matrices if the memory flag for one or both of inflow and demand is activated. The size of the memory matrices are 12 (number of month) rows and 366*(1/simulation time step in days)*years of memory (L_{im} or L_{dm}). At each model time step the memory is shifted for one time step and new inflow or demand is added:

$$M_{\text{i}}[i, 2 : \text{end}] = M_{\text{i}}[i, 1 : \text{end} - 1] \tag{C1}$$

$$M_{\text{i}}[i, 1] = I \tag{C2}$$

$$M_{\text{d}}[i, 2 : \text{end}] = M_{\text{d}}[i, 1 : \text{end} - 1] \tag{C3}$$

$$M_{\text{d}}[i, 1] = D \tag{C4}$$

in which i is the month of the year (January to December or 1 to 12). In case any of the memory flags, F_i or F_d, are activated at each simulation time step the irrigation demand (given as a time series to the model) and inflow which is simulated internally by mizuRoute from the upstream contributing area, the last column of the matrix are removed, columns are shifted for one time step and new simulation, from the current simulating time, are added. This way we keep track of past inflow and demand for each reservoir in case if deemed necessary. If the memory is activated, the inflow and demand parameters are updated every time step averaging the past record in the memory matrix depending on the length of the months and simulation temporal resolution (some months are shorter than others). This allows the Hanasaki inflow and demand parameters to be variable in time reflecting the change in amount of runoff from the basin and also demand for irrigation

In the following step, the yearly average from the inflow and demand parameters are calculated:

$$I_{\text{y}} = \frac{1}{12} \sum_{\text{j=jan}}^{\text{dec}} I_{\text{j}} \tag{C5}$$

$$D_{\text{y}} = \frac{1}{12} \sum_{\text{j=jan}}^{\text{dec}} D_{\text{j}} \tag{C6}$$

$$c = \frac{CS_{\text{max}}}{365 I_{\text{y}}} \tag{C7}$$

$$E_{\text{r}} = \frac{S}{\alpha S_{\text{max}}} \tag{C8}$$

Table C1. Parameters, state and fluxes for Hanasaki formulation in mizuRoute

Symbol	Nature	Description	Unit
S	State	Storage at the current time step of simulation	[m^3]
I	Flux	Inflow at the current time step of simulation	[m^3 s^{-1}]
O	Flux	Outflow at current time step of simulation	[m^3 s^{-1}]
D	Flux	Demand at current time step of simulation (if provided as a time series)	[m^3 s^{-1}]
F_p	Parameter	logical parameter to identify the reservoir type (0 is non-irrigation, 1 is irrigation)	[-]
S_{max}	Parameter	maximum or total storage of the reservoir	[m^3]
$I_{jan} - I_{dec}$	Parameter	monthly mean inflow to the reservoir	[m^3 s^{-1}]
F_i	Parameter	logical parameter to activate memory for inflow	[-]
L_{im}	Parameter	the length of the memory in years for inflow (should be integer)	[y]
$D_{jan} - D_{dec}$	Parameter	monthly mean demand from the reservoir	[m^3 s^{-1}]
F_d	Parameter	logical parameter to activate memory for demand	[-]
L_{dm}	Parameter	the length of the memory in years for demand (should be integer)	[y]
α	Parameter	fraction of active storage compared to the total storage	[-]
β	Parameter	fraction of yearly mean inflow that can be used to meet demands	[-]
c_1	Parameter	first coefficient of target release calculation	[-]
c_2	Parameter	second coefficient of target release calculation	[-]
e	Parameter	exponent in actual release calculation	[-]
d	Parameter	denominator in actual release calculation	[-]
C	Constant	Converter from mean daily values to per second (1/86400)	[d s^{-1}]
S_{init}	Auxiliary Parameter	For the current simulation, it is possible that the simulation start from a month which is different from the first month of Hanasaki formulation, therefore an initial storage parameter that represents past year storage at the first Hanasaki month is needed. This is different from initial storage for restart of the model. In Hanasaki, the first month is defined as the month that monthly inflow surpass mean yearly inflow	[m^3]

in case of starting simulation different from Hanasaki first month S should be replaced by S_{init}; In Hanasaki, the first month is defined as the month that monthly inflow surpass mean yearly inflow ($I_{\text{y}} \leq I_{\text{m}}$) [$\text{m}^3$].

In case the reservoir does not have an irrigation purpose (flag F_{p} is set to zero or false) and the target discharge is calculated based on:

$$Q_{\text{target}} = I_{\text{y}} \tag{C9}$$

In case the reservoir is an irrigation reservoir (flag F_{p} is set to one or true) and the annual demand is larger than the fraction of inflow that can be used for demand (β I_{y} $\leq$ D_{y}):

$$Q_{\text{target}} = (1 - \beta)I + \beta D \frac{I_{\text{y}}}{D_{\text{y}}} \tag{C10}$$

In case the reservoir is irrigation reservoir (flag F_{p} is set to one or true) and the annual demand is larger than the fraction of inflow that can be used for demand (D_{y} < β I_{y}):

$$Q_{\text{target}} = D + (I_{\text{y}} - D_{\text{y}}) \tag{C11}$$

Finally the reservoir outflow can be calculated for multi-year reservoir ($0.5 < c$):

$$O = E_{\text{r}} Q_{\text{target}} \tag{C12}$$

And the outflow can be calculated for within-a-year reservoir ($c \leq 0.5$):

$$O = (\frac{c}{d})^e E_{\text{r}} Q_{\text{target}} + (1 - (\frac{c}{d})^e) I \tag{C13}$$

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