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Reservoir Assessment Tool 3.0: An open source and user-friendly modeling
platform to Mobilize the Global Water Community

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Abstract

Reservoir Assessment Tool 3.0: An open source and user-friendly modeling platform to Mobilize the Global Water Community

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Rivers, Earth's circulatory system for surface water, akin to human arteries, ensure water distribution for the planet. While these river networks are natural, human intervention has led to the construction of dams. In the modern world, dams and the artificial reservoirs behind them serve the increasing demand for water across diverse needs such as agriculture, energy production, and drinking water. As dams continue to proliferate, monitoring water availability influenced by reservoir operations is now of paramount importance. The Reservoir Assessment Tool (RAT) is a data-driven python package that integrates satellite remote sensing with hydrological models, enabling the estimation of key reservoir parameters such as inflow, outflow, surface area, evaporation and storage changes. The earliest rendition of RAT (version 1.0) was set up for 1598 reservoirs around the world with limitations in functional robustness, updating frequency and

scalability. Some of these limitations on updating frequency and functional robustness were addressed in version 2.0 that was later made operational for the inter-governmental agency of the Mekong River Commission. Recognizing the need for scalability and to lower the barrier of entry to mobilize the global water management community to benefit from satellite remote sensing, we hereby introduce RAT version 3.0 in the form of a modeling platform. This version is optimized for accelerating open collaboration among users for continuous improvement and customization of RAT to enable reservoir management breakthroughs. RAT 3.0 represents a wholesale overhaul from the previous versions to empower the global community of users and developers in the spirit of the open-source movement. RAT 3.0 allows reservoir monitoring advancements and new functional developments that can be freely exchanged and seamlessly integrated for continuous evolution of the software. A centralized web application has also been established to facilitate the storage and dissemination of global reservoir monitoring information along with comprehensive training resources. In addition to making it easier for the community to set up the modelling platform for tracking reservoirs, RAT 3.0 is optimized for conducting digital twin experiments to investigate human impact of surface water regulation and the increasing availability of satellite sensors that now offer multi-decadal and global record of reservoir operations. As uptake spreads, the global impact of the RAT 3.0 modeling platform is expected to play a role in the more sustainable and equitable utilization of our planet's finite surface water resources.

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Note: This thesis is a slightly modified version of the following submitted work for publication on the same topic.

1. Minocha, S., Hossain, F., Das, P., Suresh, S., Khan, S., Darkwah, G., Lee, H., Galelli, S., Andreadis, K., and Oddo, P.: Reservoir Assessment Tool Version 3.0: A Scalable and User-Friendly Software Platform to Mobilize the Global Water Management Community, Geosci. Model Dev. Discuss. [preprint], <https://doi.org/10.5194/gmd-2023-130>, in review, 2023.
2. Minocha, S., Das, P., Hossain, F.: Reservoir Assessment Tool (RAT): A Python Package for monitoring the dynamic state of reservoirs and analyzing dam operations, The Journal of Open Source Software, in review, 2023.

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Chapter 1. INTRODUCTION

Over the past seven decades, the number of large dams constructed globally to manage water for various purposes, has increased 10-fold, with the current count exceeding 58,700 (ICOLD, 2020). Figure 1.1 provides a geographic representation of the major dams, revealing the extensive presence of dams around the world (Lehner et al., 2011). This increase in the number of dams is a direct result of the growing demand for water resources (Gleick, 2012), which is driven by population growth, urbanization, industrialization, and increasing irrigation (Kannan and Anandhi, 2020). Dams create artificial lakes called reservoirs for reliable water storage and distribution, serving as a source for irrigation and domestic and industrial use (Baxter, 1977). From here on, the term ‘reservoirs’ will be used interchangeably with ‘dams’ and also to refer to these artificial lakes. Dams also play a major role in mitigating floods by reducing river flow (Sordo-Ward et al., 2012) and in generating hydroelectricity, thus providing a cleaner energy alternative (Baxter, 1977; Biswas, 2012).

While dams have played a crucial role in providing water and energy to communities around the world, they also have a significant number of drawbacks that cannot be ignored. Dams alter downstream water conditions and sediment flow, change water temperatures, and obstruct the movement of organisms and nutrients (Poff and Hart, 2002). As dams disrupt the natural flow of rivers, they can exacerbate drought and flood conditions and negatively impact the aquatic habitat and ecosystem services. This can further affect the livelihoods of people, such as fishermen and farmers.

Given dams' potential downsides, monitoring their performance to ensure safe operation and mitigating negative effects is extremely important. Moreover, monitoring can also help optimize dam operations and maximize its benefits for all stakeholders. Traditional methods of monitoring,

such as installing gauges, can be costly and time-consuming as it requires regular maintenance and data collection. In the past few years, satellite remote sensing has emerged as a powerful alternative for monitoring dams because of the wide range of advantages it serves (Bonnema and Hossain, 2017; Bonnema et al., 2021). It allows monitoring at a global scale and provides valuable data on the aerial extent and elevation of surface water in the reservoirs. These time-varying observations of the reservoir's water condition allow the derivation of storage change. Satellite remote sensing provides near real-time data, making it possible to respond to changes in reservoir conditions in a timely and efficient manner, allowing for more effective management. Remote sensing can also address the issue of limited availability of data on reservoirs and water usage in transboundary river basins, which is often exacerbated by political or logistical barriers (Hossain et al., 2007).

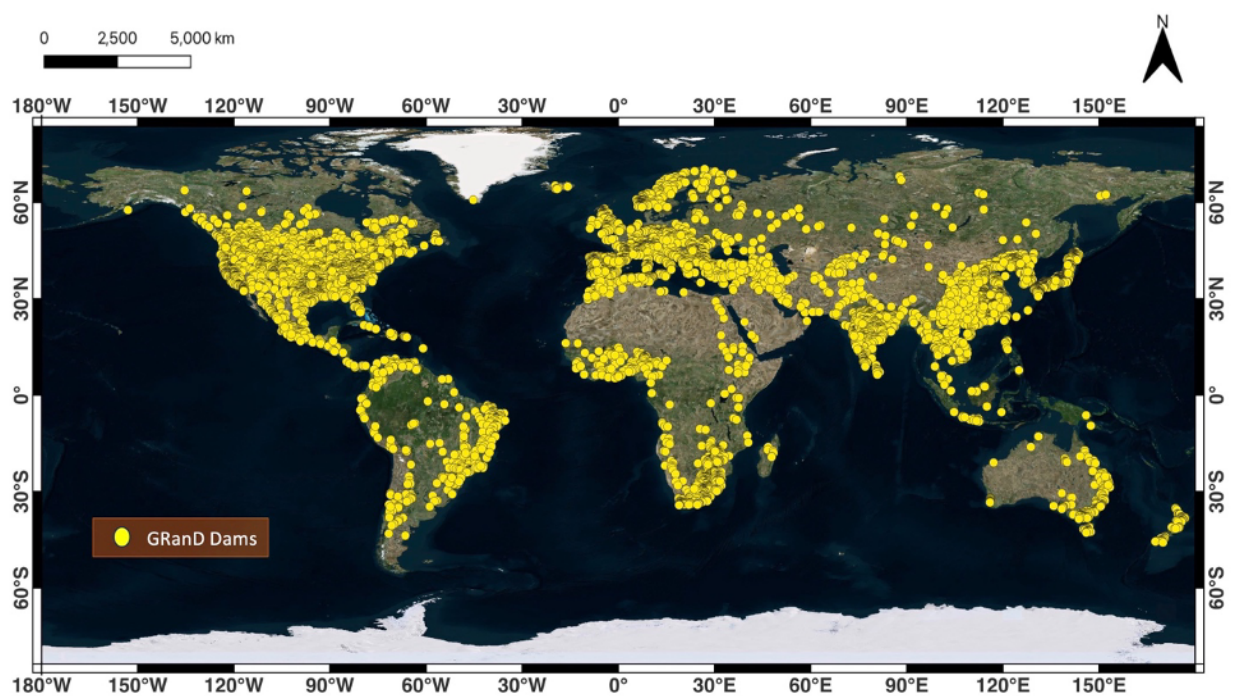


Figure 1.1 Geographic representation of major dams around the world derived from a global dam database known as GranD (Lehner et al., 2011)

Most studies that analyse the reservoir's dynamic state of storage change and inflow/outflow fluxes using satellite remote sensing are usually limited to a specific locations or periods (Vu et

al., 2021; Bonnema and Hossain, 2017; Zhang et al., 2014). There are also satellite-based reservoir monitoring tools that provide information about reservoir state like water level, but are often restricted in terms of spatial coverage, spatial and temporal resolution, or the exclusive community of expert users. For example, the Global Reservoirs and Lakes Monitor (G-REALM) database, developed by the U.S. Department of Agriculture's Foreign Agricultural Service (USDA-FAS), routinely monitors lake and reservoir height variations every 10 days based on Jason series nadir altimeter data. The Hydroweb database, developed at the LEGOS laboratory (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales) in Toulouse, France, contains time series of water levels over large rivers, lakes and wetlands at the global scale (<http://hydroweb.theia-land.fr/>). Most reservoir monitoring studies or systems that are available today assume simplified operating rules based on reservoir storage capacity rather than the time-varying nature of the reservoir's actual operations driven by changing hydrology (supply) and user needs (demand). In 2021, Biswas et al. (2021) addressed these gaps by introducing an assumption-free and satellite data-driven reservoir monitoring tool called Reservoir Assessment Tool (RAT) version 1.0 (RAT 1.0). This version was later upgraded with a few enhancements by Das et al. (2022) as RAT version 2.0 (RAT 2.0).

RAT helps water managers to track a reservoir's dynamic state comprising inflow, outflow, evaporation, storage change, storage level and extent, and evaporation. RAT 1.0 was operational for 1598 reservoirs worldwide, at a monthly update frequency that was used to generate monthly estimates of reservoirs' dynamic states (Biswas et al., 2021). Readers can still access the outputs of this original version at http://depts.washington.edu/saswe/rat_beta. In RAT 2.0, the updating frequency was improved to sub-weekly by leveraging data from multiple satellites. RAT 2.0 further enhanced the accuracy of storage change and outflow as Das et al. (2022) devised a more

advanced multi-sensor surface water classification technique called ‘TMS-OS.’ RAT 2.0 operations have so far been primarily limited to the Mekong River basin and inter-governmental agency stakeholders, with scalability and reproducibility for the broader water management community remaining unexplored (Das et al., 2022). For an interested user with limited literacy on satellite remote sensing data, operationalizing RAT 1.0 or 2.0 for tracking reservoirs in a river basin of their choice requires significant training.

This thesis describes an improved version of RAT (version 3.0), hereafter termed as RAT 3.0, driven by the need to lower the barrier of entry for first-time users and to improve scalability, robustness and reproducibility. RAT 3.0 is designed to be easy-to-install and easy-to-operate within an open-source software architecture. Software that is built on these design features can potentially mobilize the global water community to explore, use and improve RAT in the spirit of open-source development similar to Linux development. RAT 3.0 can benefit not only governments, hydrologists, researchers, and stakeholders but also the individual user who rely on water resources for their livelihood, such as farmers, city residents, and fishermen. Access to near real-time information on the reservoir’s dynamic state can empower the individual user or a community by first quantifying any potential negative impact of floods and droughts, preparing for them, and optimally utilizing available water resources. The user-friendly installation and operation feature of RAT 3.0 can help farmers make informed decisions on irrigation and crop planning, assist city residents in water conservation efforts and future usage planning, and aid fishermen in identifying the best fishing locations while avoiding areas with low water levels. Additionally, a scalable software like RAT 3.0 can be used to plan and optimize hydroelectricity generation (Chowdhury et al., 2022). These are just some of the many examples of what may be possible when a reservoir monitoring tool is made scalable and easy to install and operate. Our

motivation for developing the RAT 3.0 software is to accelerate breakthroughs in the broader field of managed water resources driven by the grassroots needs of global users.

The architecture of RAT 3.0 has been designed in such a way that it requires minimal user input with additional flexibility added for the more advanced users. It is more robust and less susceptible to data gaps or instability that satellite remote sensing systems can sometimes experience. Operational efficiency has also been improved as RAT 3.0 can remember the equilibrium state of the basin at each time step, making the need for model spin up unnecessary in a cron job. The directory structure for major and intermediate outputs of RAT 3.0 has been reorganized for better database management. These attributes of the architecture of version 3.0 of RAT have been instrumental in the development of this Python package. With this release of RAT 3.0, the conventional water management community can be more empowered with the vantage of space by providing an easy-to-use, scalable software architecture to monitor reservoirs. We believe such a software has the potential to build a self-sustaining community of users who can actively contribute to the continuous improvement and upkeep of the reservoir monitoring software.

Chapter 2. FOUNDATION OF RAT 3.0

2.1 HISTORY AND PURPOSE

Reservoir Assessment Tool (RAT) is a framework that employs satellite-based remote-sensing data and hydrological modeling to estimate the outflow of a reservoir via a mass balance equation. To estimate the inflow, RAT uses meteorological data and hydrological modeling. In RAT 1.0 (Biswas et al., 2021), the hydrological model used was the Variable Infiltration Capacity (VIC) version 4.2.d, which was later replaced with VIC-5 (Hamman et al., 2018) in RAT 2.0 by Das et al. (2022). To compute storage change in a reservoir, two inputs are required: the area elevation curve (AEC) and the change in the surface area or elevation of the reservoir. The AEC is also known as Area-elevation volume (AEV) or hypsometric curves. The AEC curve summarizes quantitatively the bathymetry of the reservoir and helps compute the inundated area of the reservoir for a given storage level or vice versa. Consequently, with two successive satellite observations of water elevation or surface area, the storage change can be derived. In RAT 2.0, the user had to provide the AEC for all reservoirs, which could be retrieved from either in situ pre-dam topographic maps or an available digital elevation model (DEM). The change in the surface area of the reservoir is estimated by observing the alteration in the number of water-classified pixels of the satellite imagery within the reservoir's region of interest. Alternatively, if the reservoir's water surface elevation information is available, such as from nadir-looking radar altimeters, surface area can be estimated from the AEC. The Penman Equation (Penman, 1948) is used in RAT 2.0 to calculate evaporation from a reservoir, leading to the estimation of reservoir outflow using the mass balance equation (Figure 2.1). Readers are encouraged to refer to Biswas et al. (2021) and Das et al. (2022) for a process-based understanding of RAT. This paper will hereafter focus mostly on the software model development aspect of RAT 3.0.

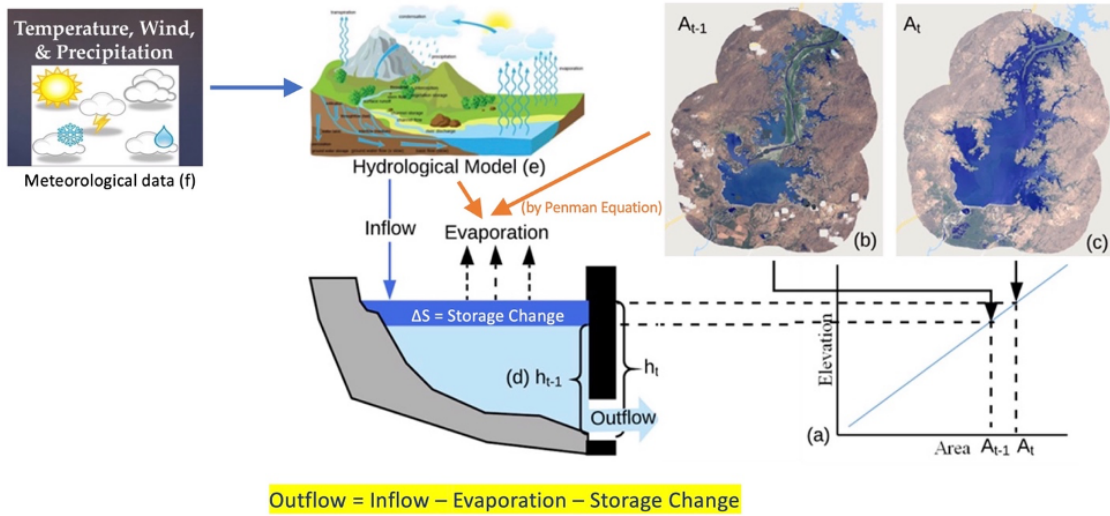


Figure 2.1. Conceptual model of RAT and the mass balance equation.

RAT was developed as a first-of-its-kind reservoir monitoring tool that could remotely monitor the changing dynamics of reservoirs, providing the global community with a comprehensive understanding of how they impact natural river flow. One of its original purposes was to serve as a decision-making tool for forming and evaluating water-sharing agreements between countries in a river basin. Despite the success of RAT 1.0, the monthly frequency of updating for reservoir state, limited its use. Monthly estimates of reservoir outflow and storage fail to capture the operating patterns of a reservoir at finer scales, such as hydropeaking, often required for many decision-making needs of the water manager. RAT 2.0 was therefore developed based on feedback from stakeholders, particularly from member countries of the Mekong River Commission (MRC), to improve the updating frequency (to weekly) and improve the accuracy of outflow data. This resulted in better decision-making for stakeholder agencies. As a result, RAT 2.0 was the first major operational uptake by a large inter-governmental river agency such as the MRC (Das et al, 2022).

2.2 WHY RAT 3.0?

RAT 3.0 has been developed to expand on the improvements made in the RAT 2.0 framework and apply them on a global scale to achieve RAT's original design goals. The provision of sub-weekly estimates of reservoir outflow can enable the user to gain insight into the operational patterns of dams and their effects on the aquatic environment. RAT 3.0 has been designed to appeal to a broader range of users beyond just government water agencies and large stakeholder communities, using a user-friendly setup that can be installed locally on any Linux machine for any reservoir worldwide. Input requirements have been significantly reduced in RAT 3.0, making it easier for non-hydrology communities such as farmers and fishing communities to install the tool. Wherever possible, familiarity with data and parameters related to hydrologic modelling or remote sensing is not required for the RAT 3.0 user. The open-access, scalable and user-friendly features of RAT 3.0 is designed to nurture a self-sustaining community of users who can actively contribute to the open-source development of the software, leading to further advancements, modifications, and breakthroughs in new frontiers for managing Earth's precious water resources. Figure 2.2 summarizes the technological evolution of RAT from version 1.0 to version 3.0.

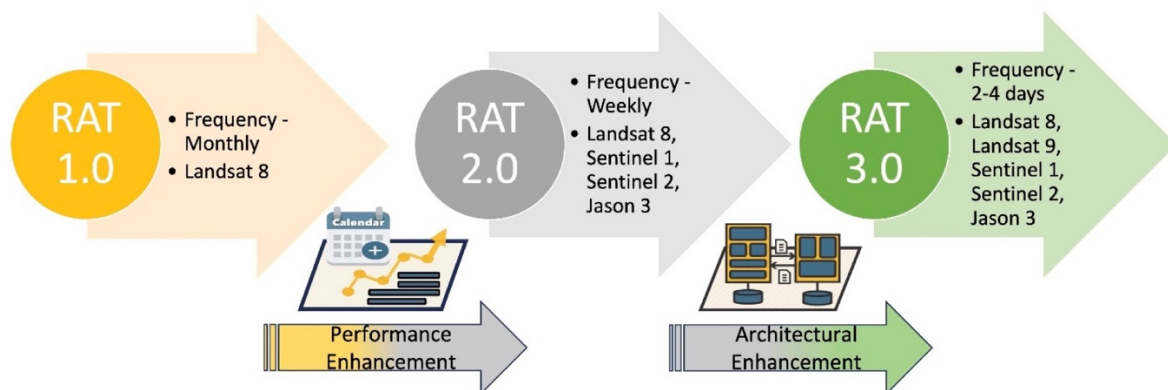


Figure 2.2 Technological Evolution of the RAT software from version 1.0 to 3.0. Names of key satellite missions are mentioned in the second bullet of each version.

2.3 THE FRAMEWORK OF RAT 3.0

The RAT 3.0 framework comprises 14 key steps that need to be executed successfully to complete a RAT installation run (Figure 2.3). While these steps are independent in their execution, some of them may depend on others for input. For example, outflow calculation requires the prior execution of inflow estimation through VIC and its streamflow routing. Hence, users must ensure that any omitted step has already run or that its output does not serve as input for another step. This independent execution of steps is advantageous as it eliminates the need to rerun previously executed steps during debugging or software enhancement exercises. Additionally, users have the flexibility to choose specific steps to execute, allowing them to run just individual steps, such as the surface area time series calculation instead of a complete RAT run. The list of steps is shown in Table 2.1. The workflow diagram in Figure 2.3 summarizes the comprehensive process employed by RAT 3.0, executing the 14 key steps to generate essential reservoir data, including inflow, outflow, storage change, and evaporation.

In Step 1 of RAT 3.0, global meteorological data is downloaded, which includes precipitation, minimum and maximum temperature, and wind speed, for the user-provided duration. The [IMERG Late product](#) (Huffman et al., 2014) is used to retrieve daily precipitation, while temperature and wind speed data are sourced from NOAA NCEP/Climate Prediction Center (Kalnay et al., 1996). The data is then scaled, aligned, and clipped to the region of interest. In Step 2, all the meteorological data is combined into a single NetCDF file in the format required by MetSim (Bennett et al., 2020) for input. The spatial resolution of the data remains fixed at 0.0625° for the entirety of the RAT run. Additionally, Step 3 generates region-specific parameter files for MetSim if not supplied by the user.

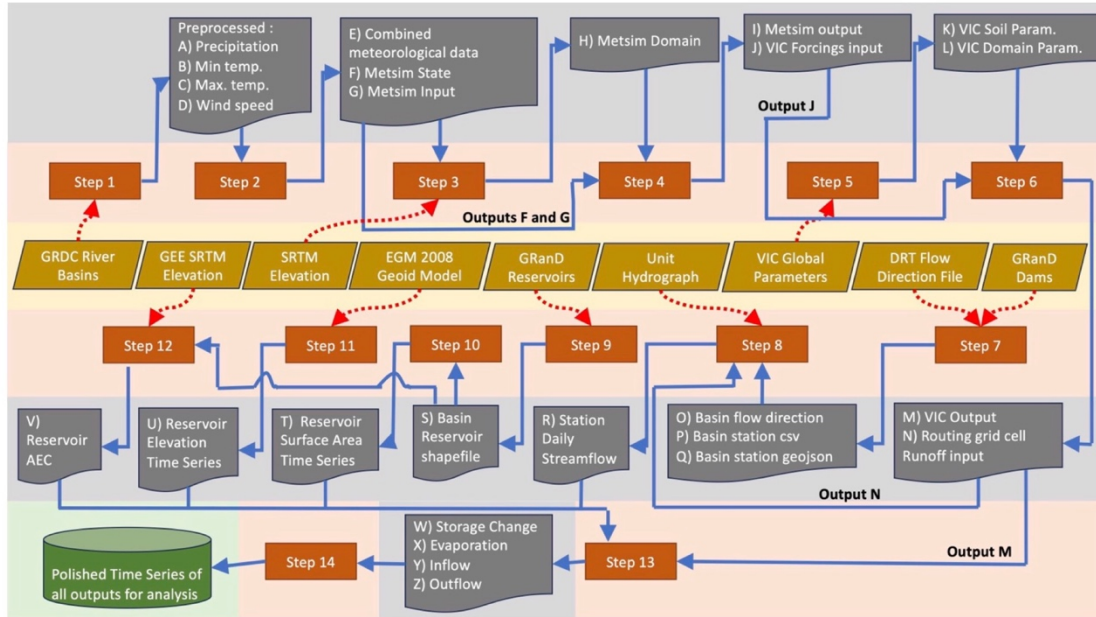


Figure 2.3 Workflow of RAT 3.0 with all the different steps listed in Table 2.1. The yellow layer shows the user inputs, the orange layer shows the flow of different steps or processes, and the grey and green layers show the intermediate and final outputs produced by RAT 3.0, respectively.

After the parameter and input files are prepared for MetSim, Step 4 initiates the MetSim run to produce forcings that are reformatted for input into VIC. If the user has provided parameter files that extend beyond the basin's spatial extent, Step 5 creates VIC's parameter files. Next, in Step 6, VIC generates gridded runoff from the meteorological forcings, which is converted to the format required by the routing model. RAT 3.0 employs the same routing model as RAT 2.0. To prepare for Step 8, parameter files for the routing model are created in Step 7, including the basin's flow direction file and station file, if necessary. Step 8 involves executing the routing model to generate daily, monthly, and yearly streamflow files for each reservoir.

Step 9 of RAT 3.0 involves the creation of a shapefile for the basin's reservoir polygons using a global reservoir shapefile, if available. In Step 10, the TMS-OS algorithm (Das et al., 2022), and

Google Earth Engine (GEE) Python API (Gorelick et al., 2017) are used to produce a surface area time series for each reservoir by efficiently using cloud computing. Step 11 extracts the water level time series for any reservoir that lies on the Jason-3 altimeter track. In Step 12, the area-elevation curve for each reservoir is generated using a digital elevation model, unless provided by the user. Step 13 first calculates the daily inflow for each reservoir using the streamflow files created in Step 8 by the routing model. The storage change time series for each reservoir is then estimated using its surface area/water level time series and area-elevation curve, implementing the trapezoidal rule. The Penman equation of Penman (1948) is then used to estimate the water loss from a reservoir in terms of evaporation. Lastly, Step 13 implements the mass-balance approach to estimate outflow from the reservoirs. Finally, all outputs of the RAT 3.0 are prepared as separate time series CSV files for each reservoir in Step 14.

Table 2.1 List of step numbers and their functions executed by RAT 3.0

Step Number	Step Name
1	Downloading and Pre-processing of meteorological data
2	Pre-processing of data and preparation of MetSim Input
3	Preparation of MetSim Parameter Files
4	Running MetSim & preparation of VIC input
5	Preparation of VIC Parameter Files
6	Running of VIC and preparation of Routing input
7	Preparation of Routing Parameter Files
8	Running Routing
9	Preparation of parameter files for Surface Area Calculation
10	TMS-OS Surface Area Calculation from GEE
11	Elevation extraction from Altimeter
12	Generating Area Elevation Curves for reservoirs
13	Calculation of Outflow, Evaporation, Storage change and Inflow
14	Conversion of output data to final format as time series

Chapter 3. ADVANCEMENTS IN RAT 3.0

RAT 3.0 introduces several improvements in terms of scalability, robustness, efficiency, ease of use while retaining the power for the user to customize, and improve specific processes in the spirit of open-source software development (Figure 3.1). These advancements are in line with the software design vision to increase the applicability of RAT to diverse fields allied to managed water such as food, energy, fisheries, bio-diversity, drought, recreation etc. One of the most notable improvements in RAT 3.0 is its ability to offer users a global database that can serve as a default configuration. This global database contains input files for VIC global parameters, river basin shapefiles, flow direction and dam geolocation (from GranD) which consequently makes it easier for the first-time user to install RAT 3.0 at a basin of their choice without requiring much customization.

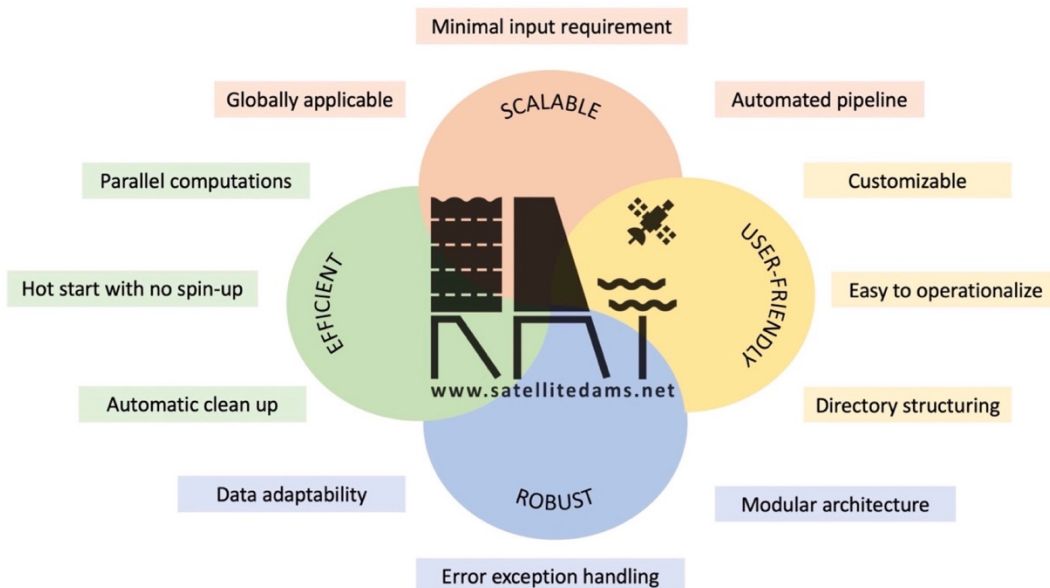


Figure 3.1 Major software design advancements in RAT 3.0

Also, with the introduction of RAT 3.0, we adopt the semantic versioning system (Preston-Werner, 2023) to define the names of future releases. In this system, version numbers adhere to the format "MAJOR.MINOR.PATCH". A MAJOR version is incremented when changes are made that are not backward compatible, a MINOR version is incremented when new features and functionality are added in a backward-compatible manner, and a PATCH version is incremented for backward-compatible bug fixes. This approach ensures clarity and consistency in communicating the nature of each release.

3.1 SCALABILITY

RAT 3.0 operates at the river basin level and can be set up for any river basin worldwide. Users have the flexibility to either select a basin from the global database, allowing RAT 3.0 to automatically set up for the reservoirs within that basin. Alternately, users can provide specific basin geometry and reservoir information for RAT to work with. Moreover, for large-scale analysis, users can select multiple basins simultaneously by utilizing a single configuration file in RAT 3.0. The software also simplifies the creation of region-specific parameter files through automation. The streamlined and automated pipeline of RAT 3.0 allows for global-scale usage, eliminating the need for user dependencies during the process. Notably, RAT 3.0 utilizes a service account to access GEE Python API and converts reservoir geometries into earth-engine objects in real-time. This advancement eliminates the requirement of pre-loading reservoir shapefiles as assets into the user's earth-engine account. This characteristic, in conjunction with RAT 3.0's software architecture featuring modular components and independent stepwise execution, enhances scalability and user-friendliness.

3.2 ROBUSTNESS

RAT 3.0 conducts thorough validation of user input, which is provided via a configuration file, ensuring crucial checks such as the chronological correctness of start and end dates. The software adopts significant improvements in error handling, implementing a two-level log file system. The first log file (level 1) corresponds to the user's RAT execution, providing concise information on the successful execution of each step for each basin, along with any associated errors. The second log file (level 2) corresponds to a basin for which RAT 3.0 has been executed and offers a comprehensive description of the computations and processes undertaken by RAT for that basin. The level-1 log file also provides the authentication status of the earth-engine service account provided by the user.

In managing missing meteorological data within the designated execution period, the resilience of RAT 3.0 should be noted. The version 3.0 software proactively handles potential issues of file corruption resulting from internet connectivity problems during satellite data file downloads. It triggers an automatic re-download process to ensure data integrity. Users also have the flexibility to provide a climatological dataset specific to the basin, empowering RAT 3.0 to identify unphysical precipitation values that are sometimes produced by satellite data algorithms and substitute them with more realistic alternatives.

To guarantee execution stability, RAT 3.0 integrates robust exception-handling mechanisms that prevent the failure of one step from obstructing the progress of subsequent steps. While the level-1 log file records any encountered errors, it may not provide in-depth insights into the underlying cause. Therefore, users are advised to seek support through the RAT discussion forum at <https://github.com/UW-SASWE/RAT/discussions>, where the engaged user and developer community can assist in diagnosing and resolving specific errors. Additionally, RAT 3.0 verifies

the availability of at least one satellite imagery for each reservoir within the desired execution period before initiating computations in GEE, effectively avoiding potential errors thrown by its Python API.

3.3 EFFICIENCY

RAT 3.0 improves computational performance and memory usage. To optimize resource utilization, RAT 3.0 leverages the `dask` Python library (Rocklin, 2015), enabling parallelization of meteorological data downloads and routing model execution for multiple reservoirs. Additionally, it incorporates a smart mechanism to avoid redundant operations by skipping the downloading and processing of files as well as the creation of parameter files that already exist from previous RAT runs. The configuration file of RAT 3.0 has been expanded to include new sections that correspond to the various steps outlined in the 'Framework of RAT 3.0' subsection. This enhancement allows users to selectively choose a subset of these 14 steps, enabling them to reduce the execution time of RAT based on their specific output requirements or to resume the process from a previous checkpoint.

RAT 3.0 offers automatic handling of the spin-up time required by the MetSim and VIC model, while still allowing users to utilize VIC's 'hot start' feature. In the hot start feature, VIC hydrologic model bypasses the spin-up period and initializes the soil parameters using an existing parameter file, which, in the case of RAT 3.0, represents the soil state conditions at the end of the duration of the last RAT execution. This time-saving capability allows users to seamlessly resume the RAT execution from the point where it last ended, unlike RAT 2.0, which required starting from the beginning to ensure an adequate spin-up period for VIC. This hot start feature brings down the computational burden of any operational cron job involving RAT 3.0. It is worth noting that employing VIC's 'hot start' feature necessitates a spin-up time for the routing model, which

varies based on the basin size and the duration required for water to travel from upstream to downstream locations within the basin. RAT 3.0 effectively accounts for this spin-up time to ensure precise and accurate results.

Efficiency in memory usage has been achieved through the elimination of the need to save parameter files for each RAT execution. Moreover, users are offered the convenience of automatically deleting intermediate data while retaining only the final outputs. By default, RAT 3.0 merges newly generated output data with the previously stored results based on the date. However, users have the flexibility to execute RAT 3.0 by replacing the previous outputs, enabling a fresh start when desired.

3.4 EASE OF USE

RAT 3.0 improves user-friendliness, particularly in the realm of data management. A major improvement is the separation of the data directory from the source code directory. Users are no longer required to keep the data directory in the same location as the source code. This separation proves advantageous when users need to store the data directory on a different disk to overcome memory limitations. Furthermore, RAT 3.0 recognizes the extensive generation of intermediate outputs and parameter files before obtaining the final outputs. To streamline file organization and ease navigation, the data directory has undergone restructuring and re-organization. This allows users to effortlessly locate files associated with specific intermediate processes within RAT 3.0, such as MetSim, VIC, and GEE.

This version of RAT also introduces a convenient built-in feature for operationalizing RAT 3.0, allowing users to specify the desired latency. While the typical latency of meteorological data ranges from 1-2 days, it is advised to set a latency of 3 days when operationalizing RAT 3.0. This ensures that RAT 3.0 obtains all the necessary input data from various satellite data servers and

executes smoothly, without encountering any errors. By setting a latency of 3 days, RAT 3.0 will initiate execution from the end of the previous RAT 3.0 run and cover the duration up to three days prior to the current day. This approach guarantees that RAT 3.0 has access to the most up-to-date and reliable input data, providing users with comprehensive results.

The introduction of the global database simplifies the input requirements for utilizing and operationalizing RAT 3.0 for first-time users. The expanded functionality of executing RAT 3.0 for multiple basins or selectively choosing specific tasks (steps) enhances the versatility of RAT. In RAT 3.0, users only need to provide a single configuration file and a secrets file to customize their preferences and provide the necessary credentials. To enhance user visibility and troubleshooting capabilities, RAT 3.0 incorporates two-level logging, enabling users to track the progress of each RAT execution and promptly identify and address any encountered errors or warnings. These combined features significantly reduce the barrier of installation for first-time users, making RAT more accessible to the broader water community.

For additional support and for downloading the RAT 3.0 software, a comprehensive user guide is available on the RAT Global web app, described in the Chapter 5. A dedicated discussion forum (see section 3.2) has been established to foster collaboration among RAT users, facilitating the open exchange of experiences, challenges, and specific use cases.

3.5 GLOBAL DATABASE

While the inclusion of the global database may not be considered a technical advancement specific to RAT 3.0, its presence has brought about a transformative shift in the development of RAT 3.0. Without the global database, the significance of other enhancements in RAT 3.0 would have been diminished. Leveraging various global datasets outlined in Table 2, RAT 3.0 now possesses default inputs that enable the execution of RAT 3.0 for any river basin worldwide for the first-time user.

This approach allows the user to focus more on improving the skill of RAT iteratively once the initial version is quickly set up and made functional.

Table 3.1 Different datasets in the global database used as default inputs by RAT 3.0

S. No.	Dataset Name	Brief Description	Reference
1	GRDC Major River Basins	Shapefile of all the major river basins' polygons in the world.	GRDC, 2020
2	GReND Dams	Shapefile of all the major dams' locations in the world.	Lehner et al., 2011
3	GReND Reservoirs	Shapefile of all the reservoirs' polygons associated with dams in [2].	Lehner et al., 2011
4	DRT Flow Direction	Global raster file providing the flow directions.	Wu et al., 2011, 2012
5	SRTM_30 Elevation	Global elevation raster file providing elevation in meters.	Becker et al., 2009
6	VIC Soil Parameters	Global VIC soil parameter dataset containing separate raster files for each continent in VIC compatible format.	Schaperow et al., 2021
7	VIC Domain Parameters	Global VIC domain parameter dataset containing separate raster files for each continent in VIC compatible format.	Schaperow et al., 2021
8	EGM2008	Geoid model that provides mean sea level in meters everywhere on Earth.	Pavlis et al., 2012

The GRDC river basin shapefile [row 1 of Table 3.1] is utilized to generate a grid of the river basin for calculating inflow using VIC and routing models. In addition, the boundary polygon from this shapefile is also employed to select only those reservoirs and dams from the GReND dam database of Lehner et al. (2011) [rows 2 and 3 of Table 3.1] that lie within the river basin. RAT is then executed for only these dams and calculates inflow, surface area change, evaporation, and outflow. The routing model relies on the flow direction file [row 4 of Table 3.1] to calculate inflow based on gridded runoff data obtained from VIC.

The DEM elevation raster from the Shuttle Radar Topography Mission (SRTM) [row 5 of Table 3.1] is used by RAT to create a domain parameter file required for the execution of MetSim. VIC Soil and Domain Parameter raster files [rows 6 and 7 of Table 3.1] offer global-scale and

high-resolution information, respectively, enabling the creation of input parameter files required by VIC.

Lastly, the EGM2008 geoid model [row 8 of Table 3.1] is used to extract reservoir levels from altimetry data. It is important to note that while these datasets are provided as default inputs for RAT execution, users have the flexibility to override these options according to their preferences and select dam locations that are not in the Grand database. Additionally, if no AEC (area elevation curve) file is provided for a reservoir, the SRTM 30 m digital elevation model available in GEE is used to automatically estimate the AEC for the reservoirs in question (Farr et al., 2007).

Chapter 4. RAT - PYTHON PACKAGE

Rivers, Earth's circulatory system, akin to human arteries, ensure water reaches every corner of the planet. While these river networks are natural, human intervention has led to the construction of dams, which store substantial water volumes in reservoirs for human consumption, such as, domestic water supply, irrigation, and hydropower generation (Jackson et al., 2001). Although dams with the reservoirs behind them, offer benefits, they can also have adverse effects, such as exacerbating downstream droughts, choking the natural flow of sediments and ecological disturbance. Such effects emphasize the necessity for consistent reservoir monitoring (Poff & Hart, 2002). Amidst today's ever-increasing advancing technological landscape, real-time reservoir monitoring through satellite data is now a reality (Bonnema & Hossain, 2017; Eldardiry & Hossain, 2019). Reservoir Assessment Tool (RAT), is a Python package that seamlessly integrates cloud computing, satellite imagery processing, information technology, and hydrological modeling to provide estimation of critical reservoir metrics, encompassing surface area, inflow, outflow, and storage changes.

4.1 STATEMENT OF NEED

The Data regarding inland water quantities that are regulated by dams with reservoirs, hold profound significance, not only for water scientists, but also for diverse fields closely intertwined with water, such as food production, energy generation, and climate modeling. The availability of surface water in a region is no longer solely determined by natural factors like precipitation; human activities, notably dam operations, now exert significant influence over reservoir levels (Adrian et al., 2009). Satellite remote sensing offers a viable means of monitoring these dynamic reservoir conditions. However, most studies and currently available tools are constrained to specific regions

due to challenges in accessing and integrating real-time meteorological data and the complexities associated with implementing hydrological models for inflow estimation (Bonnema et al., 2016; Muala et al., 2014). The intricacies involved in processing satellite imagery to extract water quantity data present an additional hurdle, creating difficulties for the diverse stakeholders as they endeavor to independently apply these techniques within their respective areas of need. This reliance on specialized expertise creates a barrier, hindering broader accessibility to this invaluable information on how dams are regulating surface water.

To lower this barrier and democratize the access to dynamic information on reservoirs operated by dams, we introduce RAT, an open-source Python package. It functions as an all-in-one tool for investigating near real-time reservoir dynamics. This versatile suite effortlessly integrates various functions, including real-time meteorological data retrieval, hydrological modeling, cloud computing for satellite image processing through the Google Earth Engine, and the use of parallel processing for computing reservoir parameters. While other Python packages can measure water body surface areas, they often overlook the potential of cloud computing for satellite image processing, do not integrate distributed physical modeling of the landscape, or are unsuitable for automating workflows (Owusu et al., 2022; Cordeiro et al., 2021). To the best of our knowledge, no other Python package offers such a comprehensive and complete view of dynamic state vector of reservoirs (comprising inflow, outflow, surface area, elevation and evaporation).

RAT is user-friendly and simple to set up, requiring minimal preparation of input parameters for the first-time users. Its automated self-installation design is tailored to make RAT useable even to those with limited knowledge of hydrology or remote sensing. RAT is a comprehensive model offering data on inflow, storage changes, evaporation, outflow dynamic surface area and water

surface elevation of a reservoir. Additionally, by running RAT at a daily operational frequency by utilizing the previous run's state, one can efficiently monitor in real-time reservoir dynamics while minimizing computational burden. These attributes position RAT as a tool for enabling breakthroughs across hydrology-related fields. For detailed information on the architecture of version 3.0 of RAT, which has been instrumental in the development of this Python package, please read the Chapter 3.

4.2 COMMAND LINE FUNCTIONALITY

4.2.1 *Initialization*

RAT relies on models like MetSim, VIC, and routing to estimate inflow through the execution of hydrological models (Bennett et al., 2020; Hamman et al., 2018). While both MetSim and VIC are Python packages, they require separate Python environments for their operation. Additionally, the Fortran script used for routing (Lohmann et al., 1996) must be downloaded and compiled independently. To simplify this process, the CLI (command-line interface) command 'rat init' streamlines RAT's initialization. It accomplishes this by automatically downloading and installing the required Python environments for MetSim and VIC, as well as fetching and compiling the routing scripts. Moreover, it acquires several default parameter files necessary for VIC, MetSim, Routing, or RAT with the option to modify these files as necessary during calibration and validation. This command also offers users the option to download a global database, encompassing multiple global datasets, which can serve as the default values for a newly setup RAT instance. Notably, the initialization of RAT is a one-time requirement following the installation of the RAT conda package.

4.2.2 *Testing*

After RAT is installed and initialized, users can test it using 'rat test' command. This command downloads a test dataset with parameter files for test river basins and expected results. It runs RAT for a test basin selected by user, comparing outputs to expectations across six test cases: inflow, outflow, surface area, storage change, evaporation, and area elevation curve. It also validates user provided credentials.

4.2.3 *Execution*

To run RAT through the command-line interface, you can utilize the 'rat run' command by specifying its configuration file. It also offers users the option to run RAT in an operational mode, which means that RAT will resume from the last state of a previous run, commencing execution from the end date of that prior run. Moreover, executing and operationalizing RAT can also be accomplished through Python scripts for more flexibility and customization.

4.2.4 *Configure*

Given that the RAT configuration file contains numerous parameters, many of which may prove perplexing for beginners while being useful for advanced users, there exists a 'rat configure' command. This command automatically fills in specific parameter values in the configuration file using user-provided options and, when available, the default global database, enhancing convenience and clarity.

4.3 INPUT REQUIREMENTS

At the least, execution of RAT requires a river basin shapefile, point locations of dams (or stations) where to calculate inflow, and a shapefile containing geometry polygons of all reservoirs to track

storage change, evaporation and outflow from the dams (Figure 4.1). For rest of the required parameters, default global database can be used for initial run. These default datasets can then be modified based on calibration using actual observed data to achieve better accuracy.

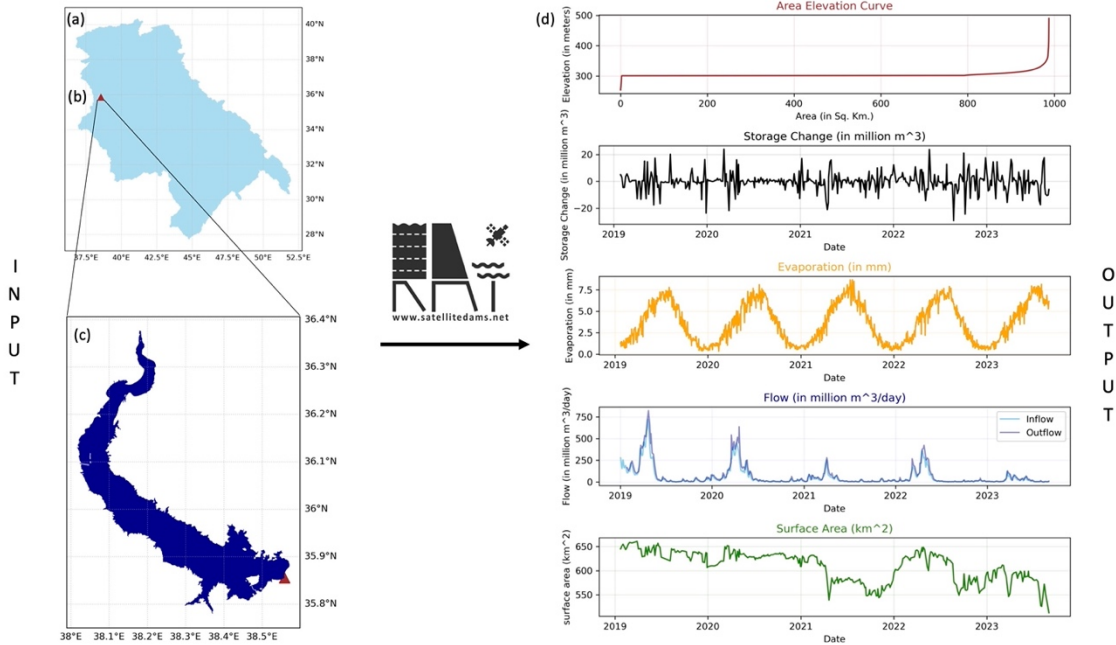


Figure 4.1. RAT python package minimal input requirements are (a) river basin shapefile (example- Tigris-Euphrates River basin), (b) dam location (example- Tabqa dam) and (c) reservoir shapefile (example- Tabqa reservoir) and it will give output (d) area-elevation curve and time series for storage change, evaporation, inflow, outflow and surface area.

4.4 APPLICATIONS AND ONGOING RESEARCH

RAT has the ability to offer a global perspective on reservoir dynamics, revealing insights into how stakeholders manage dams and alter natural river flows. It's already adopted by organizations like the Asian Disaster Preparedness Center and the Mekong River Commission for operational use (Das et al., 2022). It can acquire setting reservoir data in transboundary river basins like Mekong and Tigris-Euphrates where the data is not available due to logistical or political barriers (Hossain et al., 2023). Additionally, RAT has been employed in studying flood tracking in Kerala

(Suresh et al., 2023) and is being utilized to analyze the hydro-thermal history of the Columbia River basin. Ongoing research aims to expand RAT's capabilities, including features related to regulated river inflow, forecasted inflow and improving accuracy of storage change using new satellite missions like SWOT.

4.5 DEVELOPER NOTES

RAT is developed on [GitHub](#) as an open-source package and is available only for Unix based OS to download from [anaconda.org](#). The authors encourage contributions from the community and report issues faced at <https://github.com/UW-SASWE/RAT/issues>. The discussion forum dedicated to support the user community of RAT can be accessed at <https://github.com/UW-SASWE/RAT/discussions>. Complete documentation of the python package is available at <https://rat-satellitedams.readthedocs.io/en/latest/>.

Chapter 5. RAT – THE GLOBAL MODELING PLATFORM

5.1 WEB-APPLICATION

An interactive web application for RAT 3.0 has been developed and can now be accessed at www.satellitedams.net. This platform serves as an informational hub for RAT and provides users with an interactive map to visualize and analyse data from numerous dams worldwide (Figure 5.1). In addition, this global web app offers a comprehensive 'HELP' section where users can access three types of educational and training resources. These are: 1) accessing the source codes from the RAT 3.0 github page; 2) detailed software documentation hosted on ratdocs.io and 3) comprehensive tutorial detailing how to execute each of the 14 key steps for RAT 3.0 installation. Those interested in deepening their understanding of the tool can explore the 'PUBLICATIONS' section to access relevant literature and enhance their knowledge.

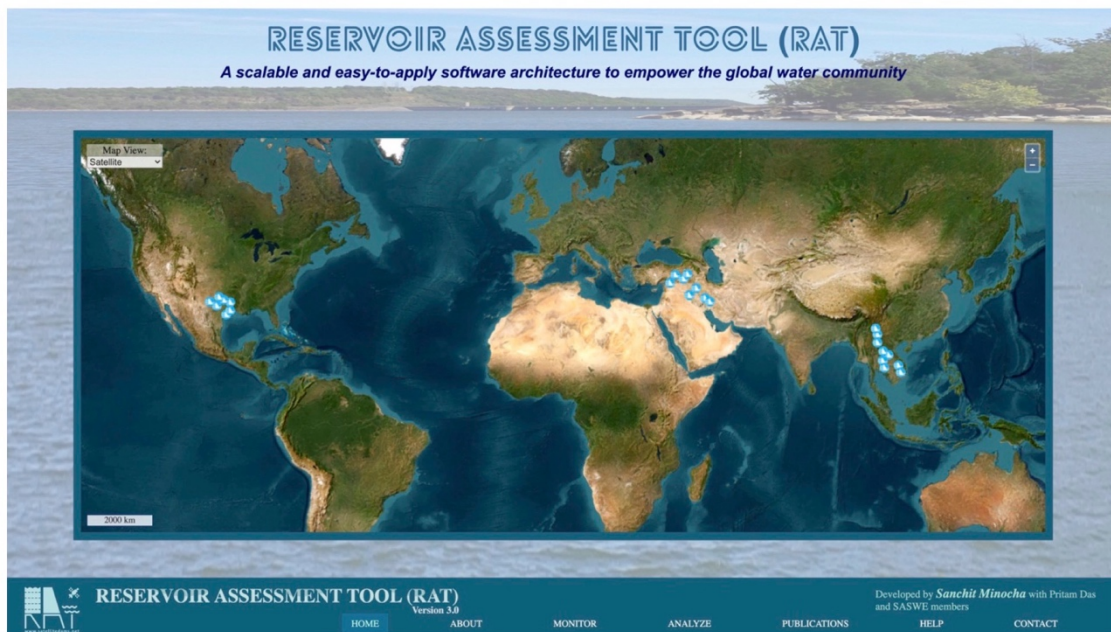


Figure 5.1 Homepage of the front end of the global RAT 3.0's online set up at www.satellitedams.net. On the HELP menu, the RAT 3.0 software can be downloaded as well as other resources such as training and education can be found.

The web application has been carefully developed to cater to a wide range of users, including stakeholders, government officials, and the general public. The key idea was to make it easy for users to access and visualize the dynamic outputs on reservoir state that are routinely generated by University of Washington developers to develop a first-cut understanding. Currently, the tool offers data for reservoirs located in the Texas-Gulf, Mesopotamia, and Southeast Asian river basins, with plans to include information on 1600 major dams worldwide that were originally monitored in RAT 1.0 in the near future. Once the tool becomes operational for most of the world's major reservoirs, users will have access to data (with a 3-day latency) on the dynamic state reservoirs (hindcast and nowcast). We firmly believe that every individual user or entity should have equal access to such information of our managed water resources. By making this data publicly available on the global web app, the developers have contributed their part to mitigating the lack of access to water information in transboundary and ungauged river basins.



Figure 5.2 Advanced visualizer feature to meet the diverse requirements of different entities and stakeholders.

We have implemented an advanced visualizer feature (Figure 5.2) to expand the capabilities of the web application and meet the diverse requirements of different entities and stakeholders. With this feature, users can extract meaningful information without the hassle of downloading the data, allowing for a more streamlined and efficient analysis process.

The advanced visualizer component allows users to conduct in-depth analyses using the reservoir data by plotting multiple axes on a single interactive graph, such as discharge, surface area, and storage change (Figure 5.3). This functionality extends to any two reservoirs globally, providing the flexibility to perform comparative analyses (Figure 5.4, Figure 5.5). For instance, users can compare the outflow of an upstream dam with the inflow of a downstream dam, shedding light on the dynamics between the two. Another scenario may involve plotting the surface area of a reservoir alongside its inflow, allowing users to gain a comprehensive understanding of the relationship between these reservoir state variables.

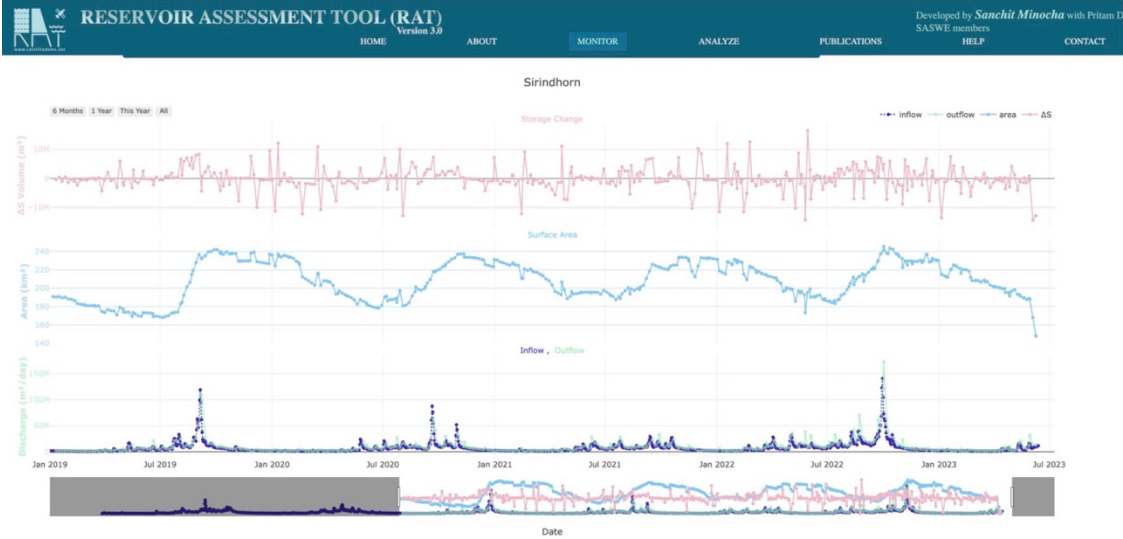


Figure 5.3 Reservoir data for one of the reservoirs ‘Sirindhorn’ (shown in Figure 5.5) in the Mekong River basin produced by RAT 3.0.

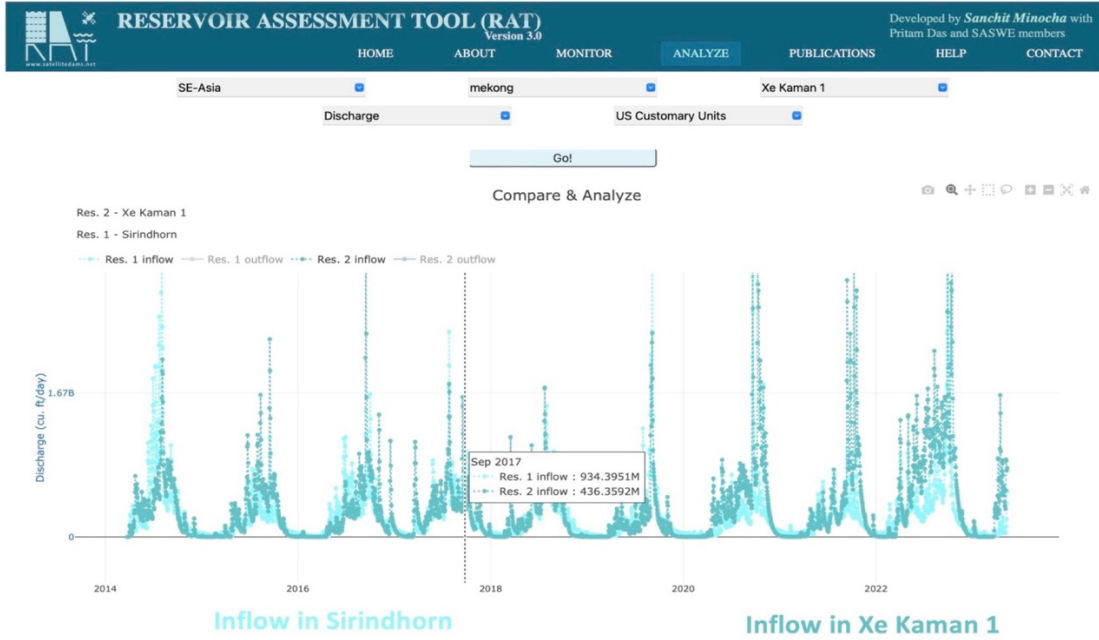


Figure 5.4 Inflow for ‘Sirindhorn’ in the Mekong River basin is compared to another nearby reservoir ‘Xe Kaman 1’ (shown in Figure 5.5) using the advanced visualizer feature.

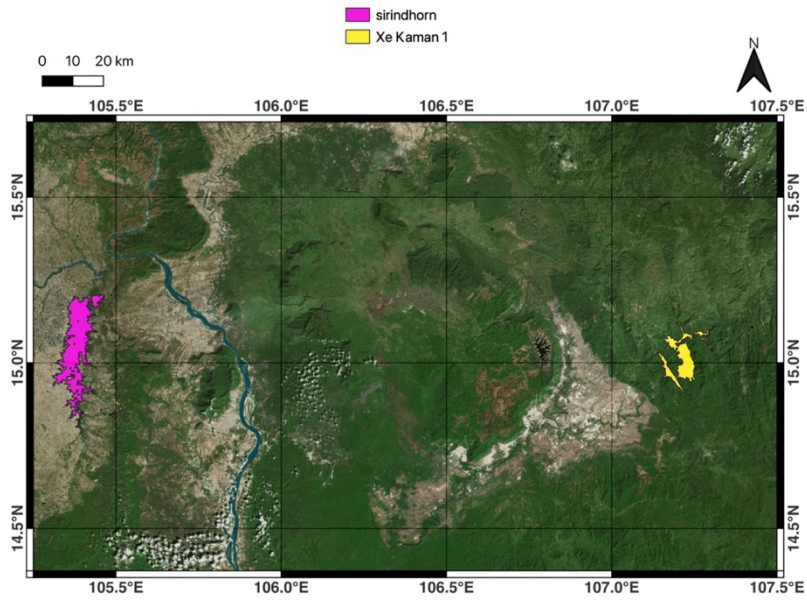


Figure 5.5 Reservoirs Sirindhorn and Xe Kaman 1 shown on the map for comparative analyses of RAT outputs on the global web app of RAT at www.satellitedams.net.

5.2 SOFTWARE DOCUMENTATION

Comprehensive and meticulous documentation is readily available and continually maintained at two URLs: <http://ratdocs.io> and <https://rat-satellitedams.readthedocs.io/>. This documentation serves as a valuable resource for users of the RAT Python package, offering a user-friendly guide for swift and trouble-free installation.

Within this documentation, users will find a wealth of information, including:

- **User Guide:** This guide simplifies the installation process for the RAT Python package, making it quick and accessible.
- **Command Line Interface:** Instructions on how to use command line interface of RAT to initialize and verify the successful installation of the package are provided.
- **Directory Structure:** Details about the directory structure created by RAT, along with guidance on locating data files generated by the RAT tool.
- **Global Datasets:** Descriptions of the global datasets included with RAT for user convenience.
- **Model Architecture:** A comprehensive exploration of the model's architecture is found in the 'Computational Model' section, while the 'Conceptual Model' section elucidates the theoretical model.
- **Configuration Parameters:** Each configuration file parameter is explained, including its necessity, description, and required syntax.
- **Developer Guide:** Easy guide summarizing how to use developer version for new developers who want to contribute towards the improvement and enhancement of the software.

Furthermore, the documentation not only covers the creation and acquisition of various credentials needed for successful RAT execution but also offers guidance on consolidating them into a single 'secrets' file.

This documentation plays a pivotal role in democratizing access to information regarding the dynamic state of reservoirs. Soon, video tutorials will complement the documentation, enabling users to deepen their knowledge and expertise in RAT 3.0. Additionally, a Frequently Asked Questions (FAQs) section will be incorporated to swiftly address common and general issues that users may encounter.

5.3 SOFTWARE SOURCE-CODE

RAT has been developed as an open-source project on GitHub and is freely available to the public. Embracing the principles of open-source and open-science, our aim is to foster and nurture a community of RAT users who can continually enhance the software and incorporate cutting-edge technology into satellite-based reservoir management.

To facilitate collaborative development, we've established a CI/CD (continuous integration-continuous deployment) pipeline using GitHub actions. Developers can plan, edit, debug, and test the source code, then push it for deployment. With each new version release, the Python and Conda RAT packages are automatically updated. Users can effortlessly update their RAT packages to the latest version using Conda commands.

The complete and well-commented software code is freely accessible on GitHub at <https://github.com/UW-SASWE/RAT>. For tracking and managing further RAT development within the open-source framework, users can post issues, suggestions, and feature requests at <https://github.com/UW-SASWE/RAT/issues>. We've also established a discussion forum, accessible at <https://github.com/UW-SASWE/RAT/discussions>, to encourage interaction within

the RAT user community. This forum provides a platform for experienced users and developers to assist beginners and contribute to the sustainability of our community.

Chapter 6. CONCLUSION

In a world where dams continue to be constructed or maintained at a rate faster than they are dismantled, it is important to acknowledge that dams are here to stay in the foreseeable future with their inherent advantages and disadvantages. Our focus here is on mitigating the negative impacts associated with these structures by levelling the playing field of access to information on the dynamic state of the world's reservoirs. Timely understanding of how dams and reservoirs affect natural river flow and other important water parameters is crucial in achieving this goal. Real-time monitoring of reservoirs is also essential for effectively addressing immediate threats such as floods and droughts. RAT 3.0 makes such monitoring possible with satellite remote sensing missions that have emerged as an indispensable vantage for studying reservoir operations and their impact on surrounding areas.

In this thesis, we have described systematically the redesigned software architecture of RAT 3.0. The modular design with 14 self-contained steps makes it possible for a user to execute RAT only for a desired set of tasks. This enhances the user-friendliness of RAT 3.0 and lowers the barrier of entry for the first-time user. Several improvements, like multiple log files, reduction of input requirements, and provision of customization using a config file, have been done to maximize user-friendliness. Error handling has been improved and RAT 3.0 is now more robust when input data is unstable or missing. RAT 3.0 is computationally more efficient by adopting parallelization during downloading and processing meteorological data and the automatic deletion of intermediate files. Finally, RAT 3.0 has been developed with global scalability in mind so that it can be set up for any reservoir system worldwide. Scalability is the most important consideration for developing and nurturing a self-sustaining community of users who can continuously improve such a software in the spirit of open-source development and open science.

RAT 3.0 has already undergone extensive global testing across various basins by multiple users, as illustrated in Figure 6.1, covering a wide range of use cases. Notably, RAT 3.0 has been instrumental in studying flood tracking in mountainous regions characterized by high precipitation and steep terrain, with a specific focus on the 2018 floods in Kerala, India (Suresh et al., 2023). It has been utilized to assess the impact of the Belo Monte Dam on the Xingu River in the Amazon (Hossain et al., 2023) and to compute and compare regulated inflow with natural inflow in the absence of upstream dams in the Tennessee River basin (Das et al., 2023). RAT 3.0 has also provided valuable insights into the effects of dams in the transboundary river basin of Mesopotamia (Hossain et al., 2023). Recently, RAT was upgraded by the Asian Disaster Preparedness Center (ADPC) from version 2.0 to 3.0 for the Mekong River basin with assistance from co-author Pritam Das (see <https://ratmekong-servir.adpc.net/>). This version currently serves as an operational system for the MRC stakeholders. Currently, RAT 3.0 is being employed to analyse the hydro-thermal history of the Columbia River in the Pacific Northwest and upgraded from version 1.0 for the Nile and Indus River basins (Figure 6.1).

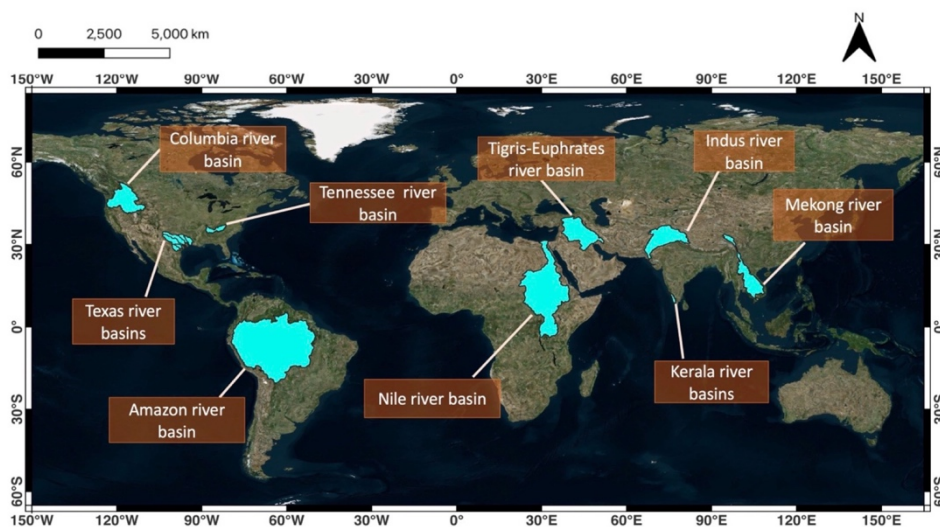


Figure 6.1 River basins where RAT 3.0 has been (or is being) independently installed and tested by users.

RAT 3.0 does not represent the final word on satellite-based reservoir monitoring software development. There will undoubtedly be numerous unforeseen software hurdles or bugs that will emerge as the use of RAT 3.0 expands. New satellite missions will emerge and many current ones may become less relevant, requiring updating of certain components of the software architecture. One such satellite mission is the recently launched Surface Water and Ocean Topography (SWOT) mission that will produce more accurate reservoir storage level, area and change data. Based on simulation studies reported by Bonnema and Hossain (2019), we believe SWOT will “turbocharge” the accuracy and operational efficiency of RAT 3.0 (see also Hossain et al., 2023; 2022). RAT is also purported to be hydrologic model agnostic. In its current architecture RAT 3.0 is not yet streamlined to allow easy swapping of the hydrologic model, select specific satellites and input data streams by the user. These issues will no doubt be addressed in a future and minor upgrade of RAT 3.0. What is important to note is that with the wholesale overhaul of the RAT software architecture in version 3.0, we now have the necessary design spirit of user-friendliness, scalability, open-access and open-sharing embraced to nurture a self-sustaining community of users who can continuously improve satellite-based reservoir monitoring based on grassroots needs of users.

The current applications of RAT 3.0 mark the advent of a new era, where the combined power of high-performance computing, information technology and satellite earth observations enables us to deepen our understanding of dams and their ecological impacts. RAT 3.0 represents the vanguard of this progress, offered to the global community as the first stride towards advancing water resource management practices and bringing them up to speed in the 21st century space age. As water demand continues to escalate, RAT 3.0 equips water resource managers and stakeholders with invaluable insights to make informed decisions and optimize the utilization of scarce water

resources. With RAT 3.0, it is our hope that the deep-seated disparities among nations pertaining to transboundary rivers can be drastically reduced, ushering in a more harmonious world. We believe the day is not far when the transformative power of the open source and collaborative software development spirit of RAT 3.0 will touch the lives of all, ensuring equal access to information on the reservoir's dynamic state.

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