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Water supply sensitivity to climate change: An R package for implementing reservoir storage analysis in global and regional impact studies

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ABSTRACT

Whilst there are numerous global and regional studies of climate impacts on water resources, relatively few authors have incorporated reservoir storage into their earth system models. Consequently, such studies are unlikely to provide coherent estimates of how changes in climate might affect water supplies globally. This short communication describes an R package, named *reservoir*, which has been designed for rapid and easy routing of runoff data through storage. The package comprises tools for capacity design, release policy optimisation and performance analysis—allowing users to specify realistic reservoirs and then assess performance in terms of meeting water delivery targets. We demonstrate some of the capabilities of *reservoir* using 271 runoff records from the Global Runoff Data Centre. The package is freely available through the Comprehensive R Archive Network (CRAN).

Software availability

Name of software: *reservoir*
Version: 1.0
Developers: S.W.D. Turner and S. Galelli
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Year first available: 2015
Available from: The Comprehensive R Archive Network (CRAN) (https://cran.r-project.org/web/packages/reservoir); development versions available on GitHub (https://github.com/swd-turner/reservoir).

1. Introduction

Global and regional studies of climate impacts on water resources are seen as part of a critical endeavour towards understanding and preparing for global environmental change. Typically, these studies are based on modelled runoff. For instance, one might propagate climate scenarios through hydrological models to simulate runoff, which is then used to infer impacts on water availability in the broadest sense (e.g., Milly et al., 2005; Jun et al., 2011; Hagemann et al., 2013; Yang et al., 2013; van Vliet et al., 2013; Schewe et al., 2014). One limit to this approach is that water users rarely rely on natural, uninterrupted runoff to meet their water needs—reservoirs play a vital role in most of the world's large river systems (Nilsson et al., 2005) and are instrumental in sustaining water supplies for municipal, industrial, agricultural and environmental purposes. The regulation of runoff by engineered water storage reservoirs must therefore be modelled in order to study the effects of climate change on global water supplies.

One way of tackling this problem is to use a global dataset of reservoirs (ICOLD, 2009; Lehner et al., 2011) and then model the storage dynamics using stylised operating rules tailored to each reservoir's primary function (Nazemi and Wheater, 2015). This approach has been followed in a handful of studies to estimate global and regional impacts of water resources management practices on river discharge (e.g., Haddeland et al., 2006; Hanasaki et al., 2006, 2008; Döll et al., 2009; Haddeland et al., 2014). These studies have advanced the field of earth systems modelling, demonstrating the importance of incorporating reservoir storage in global and regional impact assessments. A further useful development would be to apply the operating methods used widely by

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practicing engineers and then assess performance in terms of water supply to consumers (as opposed to focussing on impacts on downstream discharge or the water cycle more broadly). To help the field advance toward this goal, we present a software package that draws together some of the well-established methods of reservoir storage analysis. The package, named *reservoir*, allows users to design realistic, single-storage systems that can be simulated to evaluate water supply performance in terms of meeting water delivery targets (Turner and Galelli, 2015).

2. Software characteristics and capabilities

2.1. Software environment

We sought to make the software easy to obtain, use and manipulate, so as to expose it to a large community of potential users. We use the statistical computing environment 'R', which runs on all major platforms and is freely-available under the GNU General Public Licence (R Core Team, 2015). Many hydrologists use R because its libraries (packages developed by the R user community) hold thousands of functions for implementing a wide range of statistical techniques. There are also various packages and add-ons designed specifically for hydrological and water management applications (Thyer et al., 2011; Joseph and Guillaume, 2013; Reichert et al., 2013; Zambrano-Bigiarini and Rojas, 2013; Andrews et al., 2011; Fuka et al., 2014; Srivastav and Simonovic, 2014; Wu et al., 2014; Horsburgh and Reeder, 2014; Zambrano-Bigiarini, 2014; Mehrotra et al., 2015; Metcalfe et al., 2015; Whateley et al., 2015). Since *reservoir* is available on CRAN, it can be downloaded and installed directly from the R console using the one-line command install.packages("reservoir").

2.2. Package basics

Version 1.0 of *reservoir* comprises six functions for reservoir analysis, which can be divided into three main categories: capacity design, release policy design and performance analysis (Table 1). A seventh function estimates the Hurst coefficient of a runoff time series. The capacity design functions could be used in instances where users wish to specify realistic, stylised reservoir models based on inflow and demand data. If actual reservoir data are available, then they can be set up as inputs for running policy design and performance analysis functions across multiple sites. In addition to reservoir and demand data, all functions require as input a single vector or time series of runoff data, which is assumed to represent the natural inflow to the reservoir. These data must be in the format of inflow totals for each time step (e.g., Mm^3/month) rather than as average flow rates (e.g., m^3/s). Any desired temporal resolution and time series length can be handled, although a minimum of 30 years of continuous observations is recommended to capture interannual streamflow variability. We anticipate that users of our software would either apply their own hydrological models to compute runoff (which would then be fed into our functions) or use baseline and/or projected runoff scenarios from global runoff data sets. Full details of data and parameter inputs for each function can be found in the documentation accompanying the package. Underlying algorithms can be displayed on screen by entering the relevant function name into the R console.

The reservoir analysis functions apply basic mass balance (Eq. (1)) to simulate storage behaviour:

$$S_{t+1} = S_t + Q_t - R_t \quad \text{s.t. } 0 \leqslant S \leqslant S_{cap} \tag{1}$$

where S_t, Q_t and R_t represent the volume of water held in storage, the inflow and the controlled release at time step t. S_{cap} is the storage capacity of the reservoir. Evaporation can be accommodated by subtracting from the inflow time series, so that Q_t becomes the effective inflow (runoff minus evaporation and other losses). This approach allows the analyst to capture the varying role played by evaporation across different climates.

2.3. Capacity design

The package offers two capacity design functions, named *Rippl* and *storage*. The Rippl function returns the minimum storage required to meet specified water demands without allowing supply shortfall (occurring when the reservoir empties) when fed by the recorded inflow time series (Rippl, 1883). The resulting design capacity is known as the 'no-fail storage,' which is found computationally using the sequent peak algorithm (Thomas Jr and Burden, 1963).

The *storage* function offers a more nuanced approach to capacity design, basing the design on both the desired yield and target reliability of supply. The yield is the maximum demand that the system can meet without violating the reliability criterion, and can be modelled as either a constant demand or by assigning an interannual demand profile—useful for representing summer urban water demand peaks or crop water demands, for instance. We use the time-based reliability, which is the ratio of non-fail periods to total number of periods in the simulation (McMahon et al., 2006). The design storage is computed iteratively using the bisection method, which converges on the target reliability by varying the modelled storage capacity (users may specify a maximum number of iterations to reduce computational time if required). Setting the reliability to 1 will return the no-fail storage (as determined by the Rippl function), although the Rippl function remains useful for situations where rapid determination of the no-fail storage is desired.

Both the *Rippl* and *storage* functions allow the user to double-cycle the inflow time series, which avoids bias in cases where the

Table 1
Functions of *reservoir*.

Category	Function	Purpose	Notable features
Capacity design	Rippl	Determine no-fail storage capacity for specified demand time series.	Double-cycle option; constant or time-varying release target.
	storage	Determine storage capacity for specified time-based reliability and yield target.	Double-cycle option; interannaul demand profile option.
Release policy design	dp	Determine the optimal sequence of releases to minimise a penalty cost function based on water supply deficit	Flexible supply deficit penalty cost function; optional reporting of reliability, resilience and vulnerability
	sdp	Estimate the optimal policy look-up array (based on storage, inflow and within-year time period).	Inflow persistence embedded; flexible supply deficit penalty cost function; optional policy simulation.
Performance analysis	yield	Determine the yield for specified reservoir capacity and time-based reliability.	Double-cycle option; interannual demand profile option
	rrv	Determine reliability, resilience and vulnerability for a specified reservoir capacity and target release.	Standard operating policy or optimised releases; annual, time-based and volumetric reliability measures.
_	Hurst	Estimate the Hurst coefficient of an annualised streamflow record.	