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Stochastic assessment of Phien generalized reservoir storage–yield–probability models using global runoff data records

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SUMMARY

This study has carried out an assessment of Phien generalised storage–yield–probability (S–Y–P) models using recorded runoff data of six global rivers that were carefully selected such that they satisfy the criteria specified for the models. Using stochastic hydrology, 2000 replicates of the historic records were generated and used to drive the sequent peak algorithm (SPA) for estimating capacity of hypothetical reservoirs at the respective sites. The resulting ensembles of reservoir capacity estimates were then analysed to determine the mean, standard deviation and quantiles, which were then compared with corresponding estimates produced by the Phien models. The results showed that Phien models produced a mix of significant under- and over-predictions of the mean and standard deviation of capacity, with the under-prediction situations occurring as the level of development reduces. On the other hand, consistent over-prediction was obtained for full regulation for all the rivers analysed. The biases in the reservoir capacity quantiles were equally high, implying that the limitations of the Phien models affect the entire distribution function of reservoir capacity. Due to very high values of these errors, it is recommended that the Phien relationships should be avoided for reservoir planning.

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1. Introduction

The determination of reservoir capacity to meet the demand with an acceptable level of satisfaction (or reliability) is an age-old problem and there currently exist many techniques for accomplishing this task as documented by McMahon and Adeloye (2005), Adeloye (2012). Most of these techniques such as behaviour simulation, the mass curve and the sequent peak algorithm are sequential, involving the analysis of time-series runoff data at the reservoir site (Adeloye, 2012). Such sequential techniques are generally preferred because they automatically take into account the effect of runoff characteristics-mean, coefficient of variation (CV = mean/standard deviation), serial dependence, skewness-on capacity estimates. However, sequential methods are sometimes infeasible, e.g. when the site is ungauged or the available record is too short that using them will result in significant uncertainty in the estimated capacity (Adeloye, 1990, 1996), or unwarranted, e.g. during preliminary analysis to screen potential reservoir sites. For these situations, generalised storage–yield–probability (S–Y–P) relationships offer a way out and there are numerous examples of such applications as recently reviewed by Kuria and Vogel (2015). Generalised relationships relate the storage capacity to the demand and runoff summary statistics, most of which can be indirectly estimated from easily measureable catchment characteristics (see Adeloye et al., 2003), thus making them applicable to ungauged or poorly gauged catchments.

Several generalised storage–yield relationships have been reported in the literature including Vogel and Stedinger (1987), Burchberger and Maidement (1989), Bayazit and Bulu (1991), Adeloye et al. (2003), Bayazit and Onoz (2000), Phien (1993), Silva and Portela, 2012, Kuria and Vogel (2015) and McMahon et al. (2007a). Apart from few exceptions that used recorded data (e.g. McMahon et al., 2007a; Adeloye et al., 2003), a common feature of most of the existing generalised relationships is that they have been developed using runoff data sampled stochastically, i.e. a distribution hypothesis of the runoff is first assumed, then plausible statistics of the runoff (mean, CV, and serial dependence) are assumed and used to generate large replicates of runoff data for typical record lengths commonly encountered in practice. Capacity estimates are then obtained by routing the runoff record through a hypothetical reservoir using a suitable reservoir planning technique such as the sequent peak algorithm, SPA (see Loucks et al., 1981). The resulting capacity estimates are then summarised in terms of the mean and standard deviation of reservoir capacity, two of the three statistical parameters required to fully specify

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Nomenclature

Symbols

c	shape parameter of Gamma distribution
D_t	volumetric demand in period t
K_a	volumetric reservoir capacity estimated by SPA
K_t	cumulative sequential deficit at the beginning of year t
m	drift
n	length of data records (years)
N	number of replicates for stochastically generated data
P	cumulative probability (%)
Q_t	annual runoff for year t (annual reservoir inflow)
t	time period (years)
V	scaled capacity (dimensionless)
V^*	standardised storage capacity
V_P	quantiles for scaled storage capacity
$V_P{}^*$	quantiles for standardised storage capacity
Z_g	gamma standard variate
Z_n	standard normal variate
Z_p	standard normal variate for probability p
α	demand ratio
β	scale parameter of Gamma distribution
γ	skewness
$\gamma_Q{}'$	serial-dependent adjusted skew coefficient
γ_Q	skew coefficient of annual runoff
μ	mean
μ_Q	mean annual runoff
μ_v	mean of scaled capacity
ρ	serial correlation
σ^2	variance
σ_g	standard error of the gamma skew
σ_Q	standard deviation of the annual runoff
σ_v	standard deviation of scaled capacity

the 3-parameter log-normal distribution often assumed for reservoir capacity (Vogel and Stedinger, 1987; Bayazit and Bulu, 1991).

To produce the generalised models, the mean capacity and standard deviation of capacity are independently related to the demand and runoff characteristics usually through regression. The resulting calibrated regression relationships can then provide estimates of the mean, standard deviation and ultimately quantiles of reservoir capacity without the need for Monte Carlo simulation. This would be a welcome development if estimates of the quantiles and other reservoir statistics provided by these generalised models compare favourably with similar estimates obtained using Monte Carlo simulation analyses with observed runoff data. However, very few attempts have been made to assess the performance of the existing generalised models using observed runoff data and because of this, there is very little guidance on the bias of the commonly used generalised methods. However, having this information is necessary if the models are to engender confidence in their adoption for reservoir capacity planning analyses.

McMahon et al. (2007b) analysed a large number of global runoff records to assess the performance of some of the existing generalised relationships, including Phien's, and is one of only few studies as far as we are aware that have undertaken this task. However, the study was limited in that it used single historic records and was thus limited to the mean capacity estimate, which is not sufficient for fully specifying the probability distribution function of capacity and hence obtaining the quantile estimates. Nonetheless, they found significant biases with both the Vogel–Stedinger (V–S) and Phien models in predicting the mean of capacity. Additionally, their treatment of the Phien models did not fully satisfy the criteria specified in the original development of the models, especially that relating to the distribution hypothesis for the annual runoff which was that the annual runoff should have a gamma distribution. For example, although they tried to establish that some of the data records followed the gamma distribution using L-moments diagrams, such a "global" goodness-of-fit approach falls short of establishing that each of the records behaved as gamma. Finally, McMahon et al. (2007b) only examined one of the four Phien models (the one which will be referred to later on in this paper as the generic-model); there is therefore no guidance on the remaining three models.

The assessment carried out by Adeloye et al. (2010) focused on the Vogel–Stedinger (V–S) generalised storage–yield model within a Monte Carlo framework and using runoff of three global rivers. They found that the V–S model significantly over-estimates the reservoir capacity especially at high demands where the bias can be as much as 140%. The V–S model assumes that the annual runoff exhibits a normal/log-normal distribution; consequently it is not straightforward to infer the bias of generalised models of gamma-inflow-fed reservoirs from the V–S situation.

As implied above, the Phien (1993) models are unique in that unlike other generalised approaches that assume that the annual runoff is normally or log-normally distributed, the runoff is assumed to be distributed as gamma in the development of the Phien models. As noted by McMahon et al. (2007c,d), many world rivers cannot justifiably be modelled using the normal distribution and the gamma is a more plausible distribution hypothesis to use in such situations. It is therefore important that a complete assessment of the Phien models is carried out and reported.

The aim of this work therefore is to carry out independent assessment of the Phien (1993) models using runoff records that meet the gamma distribution hypothesis. The associated tasks include:

i. Assembling rivers annual runoff data records that exhibit gamma distribution and estimating their summary statistics. As will be seen later, six such records were assembled and used in the study.

Table 1
Details of Phien (1993) models.

Model number	m (see Eq. (8))	Mean of scaled capacity (μ_V)	Standard deviation of scaled capacity (σ_V)
1	0.0 (full regulation)	$0.97n^{0.59}\left[\frac{(1+\rho)}{(1-\rho)}\right]^{0.42}$	$0.69n^{0.55}\left[\frac{(1+\rho)}{(1-\rho)}\right]^{0.52}$
2	0.25	$0.67n^{0.41}\left[\frac{(1+\rho)}{(1-\rho)}\right]^{0.5}$	$0.85n^{0.16}\left[\frac{(1+\rho)}{(1-\rho)}\right]^{0.89}$
3	0.5	$0.18n^{0.4}\left[\frac{(1+\rho)}{(1-\rho)}\right]^{0.67}$	$0.24n^{0.07}\left[\frac{(1+\rho)}{(1-\rho)}\right]^{1.15}$
4	Generic (m-independent)	$1.467n^{0.466}\left[\frac{(1+\rho)}{(1-\rho)}\right]^{0.531}\left[\frac{(1-m)}{(1+m)}\right]^{2.047}$	$1.787n^{0.243}\left[\frac{(1+\rho)}{(1-\rho)}\right]^{0.855}\left[\frac{(1-m)}{(1+m)}\right]^{2.198}$

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