

Storage–Yield–Reliability Relationships for Hypothetical Water-Supply Reservoirs in Six French Catchments Using Sequent Peak Analysis and Stochastic Streamflow Generation

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Abstract: Reservoir capacity is often sized from the historical inflow record alone, even though a single record is one realisation of an uncertain process. This study quantified storage–yield–reliability (S–Y–R) relationships for hypothetical water-supply reservoirs at six French gauging stations with contrasting regimes (CAMELS-FR data, monthly flows 1999–2018). Required storage was computed with the sequent peak algorithm (SPA) for draft ratios $\alpha = 0.3$ – 0.9 of the mean annual flow (MAF) and for uniform (D1) and summer-peaking (D2) demands. Performance was evaluated by behaviour simulation using time-based reliability, resilience, vulnerability and a sustainability index. Three generators produced 1000 synthetic 20-year sequences per site: a log-space Thomas–Fiering (TF) model, an annual block bootstrap (BB) and an annual lognormal AR(1) model disaggregated by the method of fragments (AF). All generators reproduced the monthly means within 5%. Only AF preserved the lag-one autocorrelation of annual flows, which was high for the groundwater-fed Loing ($r = 0.43$). For $\alpha = 0.7$ and D1, the historical SPA storage ranged from 0.27 to 0.62 MAF, and the storage for 99% time-based reliability ranged from 0.23 to 0.68 MAF (AF). At the Loing, AF required 81% more storage than TF and BB for 99% reliability at $\alpha = 0.7$, showing that ignoring interannual persistence underestimates over-year storage. The summer-peaking demand increased the required storage by 12–34% at the five rain-fed sites but reduced it at the snowmelt-fed Ubaye. Reservoirs sized on the historical record achieved a mean reliability of 0.987–0.997 on the AF sequences, but the probability of no failure in a new 20-year period was only 0.42–0.81, with resilience of 0.22–0.46. The Gould–Dincer normal approximation deviated from the simulated median storage by factors of 0.54–11.9. Stochastic S–Y–R analysis with a generator that preserves annual persistence is recommended for sizing reservoirs from short records.

Keywords: Reservoir storage, Sequent peak algorithm, Reliability, Resilience, Vulnerability, Stochastic streamflow generation

1. Introduction

Surface reservoirs regulate the temporal variability of river flows so that a demand can be met during dry periods. The storage needed to supply a given yield depends on the magnitude, seasonality and persistence of inflows. It also depends on the level of performance that the operator is willing to accept (McMahon and Adeloye, 2005). Because the historical record is a single realisation of an uncertain process, a reservoir sized on that record alone can fail more often than expected when the future sequence differs from the past (Vogel and Stedinger, 1987; McMahon et al., 2007).

The sequent peak algorithm (SPA) of Thomas and Burden (1963) is the standard method for estimating the storage that meets a demand without failure over a given inflow sequence. Behaviour (simulation) analysis complements the SPA by routing inflows through a reservoir of given capacity and evaluating its performance. Hashimoto et al. (1982) introduced three performance criteria: reliability (how often the system fails), resilience (how quickly it recovers) and vulnerability (how severe failures are). These criteria are now widely used in water-resources planning (Kjeldsen and Rosbjerg, 2004; McMahon et al., 2006), and Sandoval-Solis et al. (2011) combined them into a sustainability index. Different estimators of these criteria can give different conclusions, so their

definitions must be stated explicitly (Kjeldsen and Rosbjerg, 2004).

Stochastic streamflow generation provides many equally likely inflow sequences and therefore a distribution of required storage and performance for each design (Stedinger and Taylor, 1982; Srikanthan and McMahon, 2001). Seasonal autoregressive models such as the Thomas–Fiering model (Thomas and Fiering, 1962) preserve monthly means, variances and month-to-month correlation, but they do not explicitly preserve persistence at the annual scale. Non-parametric resampling (Lall and Sharma, 1996) keeps the observed distributions but cannot produce values outside the record. Annual models disaggregated to months by the method of fragments preserve annual persistence, which controls over-year storage (Srikanthan and McMahon, 2001). Analytical approximations such as the Gould–Dincer family relate over-year storage, yield and reliability to the coefficient of variation and serial correlation of annual flows (Vogel and McMahon, 1996; Vogel and Bolognese, 1995). Global analyses have shown large regional differences in these relationships (McMahon et al., 2007; Kuria and Vogel, 2015).

France has diverse flow regimes, from oceanic and pluvial to Alpine nival and Mediterranean, within a small area (Delaigue et al., 2025). It also experienced severe droughts during the last two decades (Vidal et al., 2010). The CAMELS-FR dataset provides quality-

controlled flow and climate series for hundreds of catchments and allows a transparent, reproducible comparison of reservoir behaviour under contrasting regimes.

The objective of this study was to quantify S–Y–R relationships for hypothetical water-supply reservoirs at six French catchments. The specific aims were to (i) compute historical storage–yield curves for uniform and seasonal demands with the SPA; (ii) compare three synthetic streamflow generators and their effect on required storage; (iii) derive storage–yield–reliability curves and evaluate the reliability, resilience and vulnerability of reservoirs sized on the historical record; and (iv) assess the Gould–Dincer normal approximation against simulation.

2. Materials and Methods

2.1. Study Sites and Data

Six gauging stations were taken from the CAMELS-FR dataset as distributed with the airGRdatasets package (Delaigue et al., 2024, 2025). They cover mid-mountain rain–snow (Bruche), lowland karstic (Meuse), groundwater-dominated sedimentary (Loing), oceanic pluvial (Odette), Alpine nival (Ubaye) and Mediterranean pre-Alpine (Esteron) regimes (Figure 1; Table 1). Daily discharge was converted to monthly runoff depth (mm) from months with at least 20 valid days, and then to volume (hm³) using the catchment area. The analysis

period was January 1999 to December 2018 (20 years, 240 months).

One month at the Ubaye (November 2009) and four at the Esteron (September–October 2004 and June–July 2014) had fewer than 20 valid days. These gaps (0.4% and 1.7% of the record) were filled by a log-linear regression, fitted separately for each calendar month, of monthly flow on the previous month's flow and the current month's precipitation. The other four records were complete.

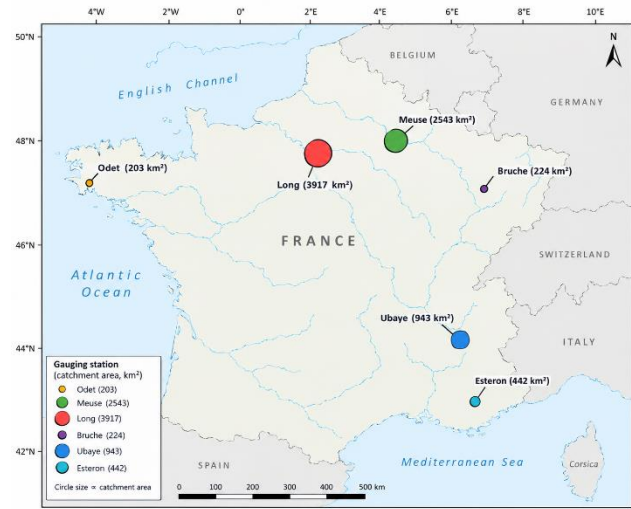


Figure 1. Location of the six gauging stations; symbol size is proportional to catchment area

Table 1. Characteristics of the catchments and inflow statistics (1999–2018)

Site	Station code	Area (km ²)	Median elev. (m)	P (mm yr ⁻¹)	Q (mm yr ⁻¹)	Runoff coeff.	MAF (hm ³)	C _v	r ₁	Max/min month	Max/min monthly ratio	Min 12-mo flow / MAF	m (α = 0.7)
Bruche	A273011002	224	603	1244	769	0.62	172	0.24	0.11	Jan/Aug	1.91/0.36	0.60	1.27
Meuse	B222001001	2543	351	954	366	0.38	932	0.34	0.19	Jan/Sep	2.27/0.19	0.44	0.88
Loing	F439000101	3917	137	754	166	0.22	651	0.38	0.43	Jan/Sep	1.70/0.40	0.50	0.80
Odette	J421191001	203	140	1297	722	0.56	147	0.26	0.21	Jan/Sep	2.34/0.18	0.51	1.17
Ubaye	X045401001	943	2128	998	648	0.65	611	0.22	0.25	May/Feb	2.76/0.34	0.56	1.37
Esteron	Y643401001	442	900	1072	445	0.41	197	0.40	0.20	Nov/Aug	1.80/0.29	0.31	0.76

MAF = mean annual flow volume; C_v and r₁ = coefficient of variation and lag-one autocorrelation of annual (calendar-year) flows; monthly ratio = mean monthly flow divided by MAF/12; m = (1 – α)/C_v is the standardised net inflow (Vogel and Bolognese, 1995).

2.2. Demand Scenarios

Demand was expressed as a draft ratio α, the annual demand divided by MAF, with α = 0.3, 0.4, ..., 0.9. Two monthly patterns were used. Pattern D1 is a uniform demand of α·MAF/12 in every month, typical of municipal supply. Pattern D2 is a summer-peaking demand representing combined municipal and irrigation use, with monthly fractions of 0.05 (January–March), 0.07 (April), 0.10 (May), 0.13 (June), 0.15 (July), 0.14 (August), 0.10 (September), 0.07 (October), 0.05 (November) and 0.04 (December) of the annual demand (Figure 2). Evaporation from the reservoir surface, environmental flows and sediment were not considered, so the results refer to active storage under idealised conditions.

2.3. Sequent Peak Algorithm

For inflow Q_t and demand D_t, the SPA computes the cumulative deficit K_t and the required storage K_a (Thomas and Burden, 1963):

$$K_t = \max(0, K_{t-1} + D_t - Q_t), \quad K_0 = 0 \quad (1)$$

$$K_a = \max_t K_t \quad (2)$$

The record was cycled twice so that a critical period running across the end of the record was captured. K_a is the smallest active storage that meets the demand in every month of the sequence (no-failure storage). All storages are expressed as fractions of MAF.

2.4. Behaviour Simulation and Performance Indices

For a reservoir of capacity K, the storage S_t, release R_t and spill were computed month by month with the continuity equation, starting from a full reservoir:

$$R_t = \min(D_t, S_{t-1} + Q_t) \quad (3)$$

$$S_t = \min(K, S_{t-1} + Q_t - R_t) \quad (4)$$

A month was a failure if $R_t < D_t$. With N_f failure months in N months, the time-based reliability R_t , volumetric reliability R_v , resilience Res and vulnerability Vul were defined as (Hashimoto et al., 1982; McMahon et al., 2006):

$$R_t = 1 - \frac{N_f}{N}, \quad R_v = \frac{\sum_t R_t}{\sum_t D_t} \quad (5)$$

$$Res = \frac{N_{fs}}{N_f}, \quad Vul = \frac{1}{M} \sum_{j=1}^M \max_{t \in j} \frac{D_t - R_t}{D_t} \quad (6)$$

where N_{fs} is the number of transitions from a failure month to a success month and M is the number of failure events (continuous runs of failure months). Vulnerability is the mean of the largest relative monthly shortfall in each event. The sustainability index of Sandoval-Solis et al. (2011) combines the three criteria:

$$SI = [R_t \cdot Res \cdot (1 - Vul)]^{1/3} \quad (7)$$

For the synthetic ensembles, R_t and R_v were averaged over the sequences, and Res and Vul were pooled by summing transitions, failures and events over all sequences. In addition, the probability P_{nf} that a sequence of 20 years contains no failure was computed as the fraction of failure-free sequences. The vectorised simulation code was checked against a direct scalar implementation, and both gave identical indices.

2.5. Synthetic Streamflow Generation

Three generators were used, each producing 1000 sequences of 20 years (240 months), the length of the observed record. Using sequences of the same length as the record isolates the effect of sampling variability on design (Vogel and Stedinger, 1987).

Thomas–Fiering (TF). The log-transformed flows $y = \ln Q$ were modelled by the seasonal lag-one model of Thomas and Fiering (1962):

$$y_{m+1} = \mu_{m+1} + \rho_m \frac{\sigma_{m+1}}{\sigma_m} (y_m - \mu_m) + \sigma_{m+1} \sqrt{1 - \rho_m^2} \varepsilon \quad (8)$$

where μ_m and σ_m are the mean and standard deviation of y in month m , ρ_m is the correlation between months m and $m + 1$ and ε is a standard normal deviate. A five-year warm-up was discarded.

Annual block bootstrap (BB). Complete calendar years of the observed record were resampled with replacement. This non-parametric scheme preserves the within-year sequence and the marginal distribution but not the correlation between years, and it cannot produce a year drier than the driest observed year.

Annual AR(1) with method of fragments (AF). Annual flows were generated with a lognormal lag-one autoregressive model whose mean, standard deviation and lag-one correlation were estimated from the logarithms of the observed annual flows:

$$z_i = \rho z_{i-1} + \sqrt{1 - \rho^2} \varepsilon_i, \quad A_i = \exp(\mu_A + \sigma_A z_i) \quad (9)$$

Each synthetic annual flow A_i was then disaggregated into months with the fragments (monthly flows divided by the annual flow) of an observed year chosen at random among the three years with the closest annual flow (Srikanthan and McMahon, 2001). A 20-year warm-up was discarded.

The generators were checked by comparing the monthly means, standard deviations, skewness and lag-one correlations, and the annual coefficient of variation and lag-one correlation, of the synthetic sequences with those of the record (Stedinger and Taylor, 1982).

2.6. Gould–Dincer Normal Approximation

For over-year reservoirs fed by AR(1) normal annual inflows, the Gould–Dincer normal (GDN) approximation gives the storage needed for an annual reliability $1 - p$ (Vogel and McMahon, 1996; McMahon et al., 2007):

$$\frac{K_p}{MAF} = \frac{z_p^2 C_v^2}{4(1-\alpha)} \cdot \frac{1+\rho}{1-\rho} \quad (10)$$

where z_p is the standard normal variate (1.645 for $p = 0.05$), and C_v and ρ are the coefficient of variation and lag-one correlation of annual flows. The approximation ignores within-year storage. It was compared with the median SPA storage of the AF ensemble.

2.7. Experimental Design

For each site, demand pattern and draft ratio, the SPA storage was computed for the record and for every synthetic sequence. Behaviour simulation was then run for 71 capacities between 0 and 3 MAF (logarithmically spaced above 0.005 MAF). The capacity giving a pooled time-based reliability of 0.90, 0.95 and 0.99 was found by linear interpolation, which gave the S–Y–R curves. Finally, a reservoir with the historical no-failure storage for $\alpha = 0.7$ was simulated with the synthetic sequences to measure how a design based on the record would perform under other plausible sequences. The analysis was coded in Python (NumPy, SciPy and pandas).

3. Results and Discussion

3.1. Inflow Characteristics

Mean annual runoff ranged from 166 mm at the Loing to 769 mm at the Bruche, and MAF ranged from 147 hm³ (Odet) to 932 hm³ (Meuse) (Table 1). Four catchments had a winter maximum and a late-summer minimum. The Ubaye peaked in May with snowmelt (2.76 times the mean monthly flow) and reached its minimum in February, and the Esteron peaked in November with autumn rainfall (Figure 2). Seasonality was strongest at the Odet and Meuse, where the mean September flow was only 0.18 and 0.19 of the mean monthly flow.

Annual flows were most variable at the Esteron ($C_v = 0.40$) and Loing (0.38) and least variable at the Ubaye (0.22) and Bruche (0.24). The Loing, fed by the chalk and limestone aquifers of the Paris Basin, had a strong lag-one autocorrelation of annual flows ($r_1 = 0.43$); at the other sites r_1 ranged from 0.11 to 0.25. The driest 12-month period delivered only 0.31 MAF at the Esteron

and 0.44 MAF at the Meuse. With $\alpha = 0.7$, the standardised net inflow m was below 1 at the Esteron, Loing and Meuse (0.76–0.88). According to Vogel and

Bolognese (1995), such systems are dominated by over-year storage and recover slowly from failure.

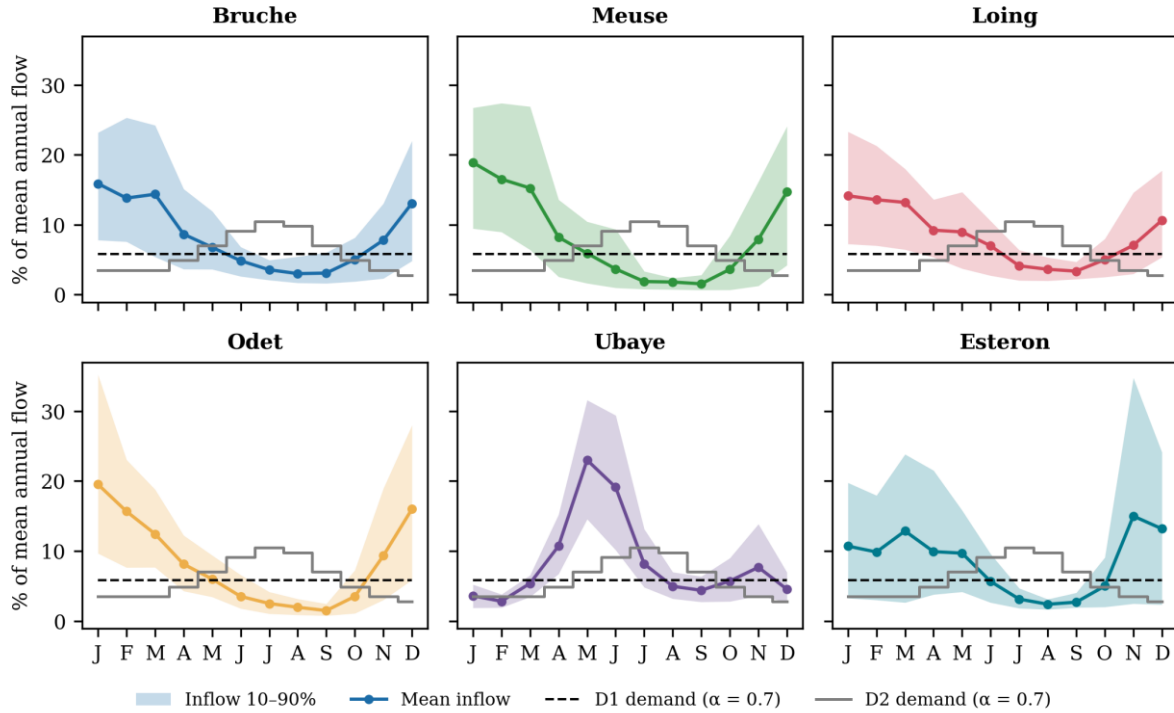


Figure 2. Monthly inflow regimes (mean and 10–90% range, as % of MAF) and the two demand patterns for $\alpha = 0.7$

3.2. Validation of the Streamflow Generators

Table 2. Reproduction of observed statistics by the generators (mean of 1000 synthetic 20-year sequences)

Site	Gen.	Monthly mean error (%)	Monthly SD error (%)	Monthly skew obs/syn	Monthly r_1 obs/syn	Annual mean error (%)	Annual C_v obs/syn	Annual r_1 obs/syn
Bruche	TF	1.5	13.4	1.21/1.18	0.43/0.49	+1.7	0.24/0.27	0.10/0.01
	BB	0.2	4.5	1.21/1.08	0.43/0.40	+0.1	0.24/0.23	0.10/-0.04
	AF	2.5	6.3	1.21/1.13	0.43/0.41	+0.4	0.24/0.25	0.10/-0.01
Meuse	TF	3.6	20.7	1.74/1.51	0.45/0.57	+2.4	0.34/0.37	0.18/0.04
	BB	0.3	6.1	1.74/1.41	0.45/0.44	-0.0	0.34/0.33	0.18/-0.06
	AF	2.3	7.9	1.74/1.47	0.45/0.45	+0.9	0.34/0.34	0.18/0.02
Loing	TF	1.4	13.6	1.54/1.12	0.64/0.69	-0.4	0.38/0.32	0.42/0.08
	BB	0.4	5.7	1.54/1.20	0.64/0.61	+0.2	0.38/0.36	0.42/-0.06
	AF	2.2	6.5	1.54/1.21	0.64/0.62	-0.1	0.38/0.36	0.42/0.31
Odet	TF	1.5	8.8	1.06/1.19	0.60/0.61	+1.4	0.26/0.30	0.21/0.09
	BB	0.3	3.6	1.06/0.93	0.60/0.56	+0.3	0.26/0.25	0.21/-0.04
	AF	1.7	2.6	1.06/1.03	0.60/0.57	+0.4	0.26/0.27	0.21/0.05
Ubaye	TF	0.6	8.1	0.96/0.89	0.58/0.61	+0.3	0.22/0.22	0.24/0.01
	BB	0.2	5.2	0.96/0.75	0.58/0.53	-0.1	0.22/0.21	0.24/-0.05
	AF	2.0	8.9	0.96/0.71	0.58/0.55	-0.1	0.22/0.22	0.24/0.18
Esteron	TF	2.8	18.1	1.43/1.39	0.53/0.57	+4.0	0.40/0.46	0.20/0.05
	BB	0.3	4.9	1.43/1.19	0.53/0.50	-0.1	0.40/0.38	0.20/-0.06
	AF	4.1	5.9	1.43/1.38	0.53/0.54	+1.4	0.40/0.45	0.20/0.01

Errors are mean absolute relative errors over the 12 months (mean and SD) or relative errors of annual means; skewness and r_1 are averaged over the 12 months. TF = Thomas–Fiering; BB = annual block bootstrap; AF = annual AR(1) with fragments.

All generators reproduced the monthly means with mean absolute errors of at most 4.1% and the annual mean within 4.1% (Table 2; Figure 3). The TF model, fitted in log space, overestimated the monthly standard deviations by 8–21% on average, most at the Meuse and Esteron, where the monthly flows were most skewed. It

also slightly overestimated the month-to-month correlation. The BB and AF generators, which reuse observed within-year patterns, reproduced the monthly standard deviations within 9%. Both, however, broke the December–January correlation, because consecutive

synthetic years come from different observed years (Figure 3).

The generators differed most in annual persistence. The TF model gave annual lag-one correlations of 0.01–0.09, much lower than observed. This is because persistence carried from month to month decays within a year. The BB generator gave slightly negative values, which is the small-sample bias of an uncorrelated series.

Only AF retained substantial annual persistence at the Loing (0.31 against 0.42 observed) and Ubaye (0.18 against 0.24). At the other sites, the lag-one correlation of the log-transformed annual flows used by the model (0.05–0.14) was lower than that of the untransformed flows (0.11–0.21), so the synthetic annual persistence was lower as well.

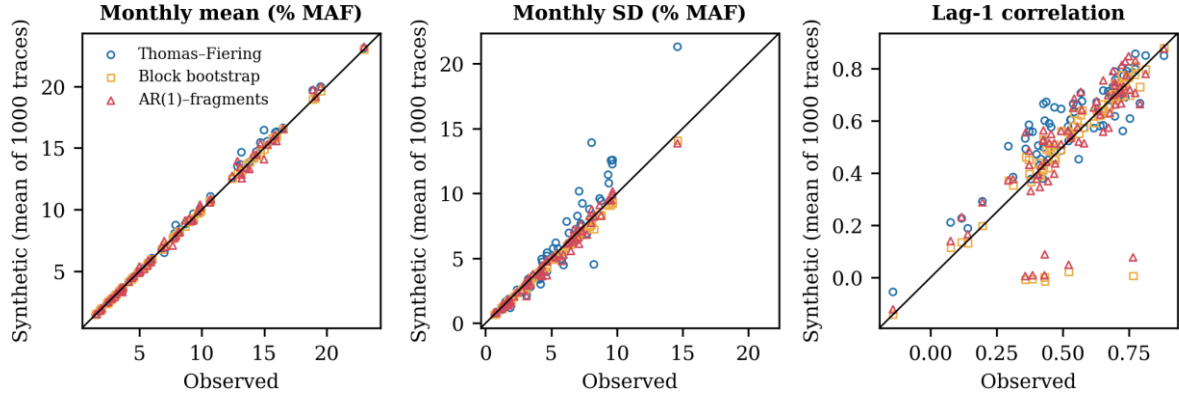


Figure 3. Observed versus synthetic monthly means, standard deviations and lag-one correlations (72 site-month values per generator)

3.3. Storage–Yield Relationships

Table 3. No-failure (SPA) storage as a fraction of MAF: historical record and synthetic ensembles (median and 10–90% range)

Site	α	Historical D1	TF D1	BB D1	AF D1	$P(K_{AF} \leq K_{hist})$	GDN ($p = 0.05$)	Historical D2
Bruche	0.5	0.13	0.14 (0.11–0.17)	0.13 (0.11–0.13)	0.13 (0.11–0.14)	0.37	0.09	0.20
	0.7	0.27	0.29 (0.23–0.40)	0.27 (0.24–0.37)	0.27 (0.23–0.37)	0.49	0.16	0.36
	0.9	0.63	0.75 (0.50–1.24)	0.70 (0.50–1.13)	0.70 (0.49–1.17)	0.36	0.47	0.72
Meuse	0.5	0.25	0.24 (0.20–0.31)	0.25 (0.20–0.25)	0.24 (0.19–0.29)	0.55	0.23	0.32
	0.7	0.43	0.52 (0.37–0.75)	0.48 (0.38–0.60)	0.47 (0.36–0.69)	0.40	0.38	0.51
	0.9	1.13	1.20 (0.78–2.03)	1.07 (0.71–1.83)	1.09 (0.69–2.03)	0.54	1.15	1.26
Loing	0.5	0.15	0.14 (0.10–0.19)	0.15 (0.10–0.15)	0.14 (0.09–0.24)	0.56	0.48	0.23
	0.7	0.62	0.36 (0.25–0.56)	0.36 (0.26–0.53)	0.45 (0.22–0.94)	0.70	0.81	0.72
	0.9	2.17	1.01 (0.60–1.95)	1.01 (0.63–1.87)	1.44 (0.64–3.85)	0.71	2.42	2.31
Odet	0.5	0.21	0.18 (0.16–0.23)	0.21 (0.15–0.21)	0.20 (0.16–0.23)	0.63	0.14	0.28
	0.7	0.40	0.40 (0.29–0.59)	0.35 (0.32–0.49)	0.35 (0.31–0.52)	0.66	0.23	0.51
	0.9	1.03	1.01 (0.65–1.76)	0.81 (0.56–1.29)	0.87 (0.58–1.45)	0.67	0.68	1.19
Ubaye	0.5	0.15	0.12 (0.09–0.16)	0.12 (0.08–0.15)	0.11 (0.07–0.15)	0.93	0.11	0.12
	0.7	0.29	0.26 (0.21–0.33)	0.26 (0.21–0.30)	0.26 (0.20–0.34)	0.80	0.18	0.26
	0.9	1.00	0.64 (0.45–1.02)	0.59 (0.42–0.96)	0.70 (0.43–1.34)	0.78	0.55	0.95
Esteron	0.5	0.20	0.20 (0.13–0.31)	0.21 (0.13–0.33)	0.19 (0.12–0.31)	0.53	0.32	0.28
	0.7	0.60	0.55 (0.36–0.89)	0.53 (0.33–0.87)	0.54 (0.33–0.92)	0.61	0.53	0.67
	0.9	1.54	1.40 (0.84–2.65)	1.23 (0.75–2.38)	1.41 (0.80–2.85)	0.58	1.60	1.65

GDN = Gould–Dincer normal approximation (over-year storage only). $P(K_{AF} \leq K_{hist})$ = fraction of AF sequences whose SPA storage does not exceed the historical value.

Required storage increased non-linearly with draft ratio at all sites (Table 3; Figure 4). For the uniform demand, the historical SPA storage rose from 0.02–0.11 MAF at $\alpha = 0.3$ to 0.63–2.17 MAF at $\alpha = 0.9$. At low draft ratios, storage was governed by the within-year deficit of the driest summer. At high draft ratios, deficits accumulated over several years. The critical periods for $\alpha = 0.7$ lasted 9 months at the Bruche (2003–04 to 2003–

12) and Ubaye, 17–19 months at the Meuse and Odet (2016–07 to 2017–11), 45 months at the Esteron (2004–04 to 2007–12) and 90 months at the Loing (2004–06 to 2011–11). Both long critical periods began in 2004 and spanned several consecutive dry years; multi-year droughts of this kind are a recurrent feature of French hydroclimate (Vidal et al., 2010).

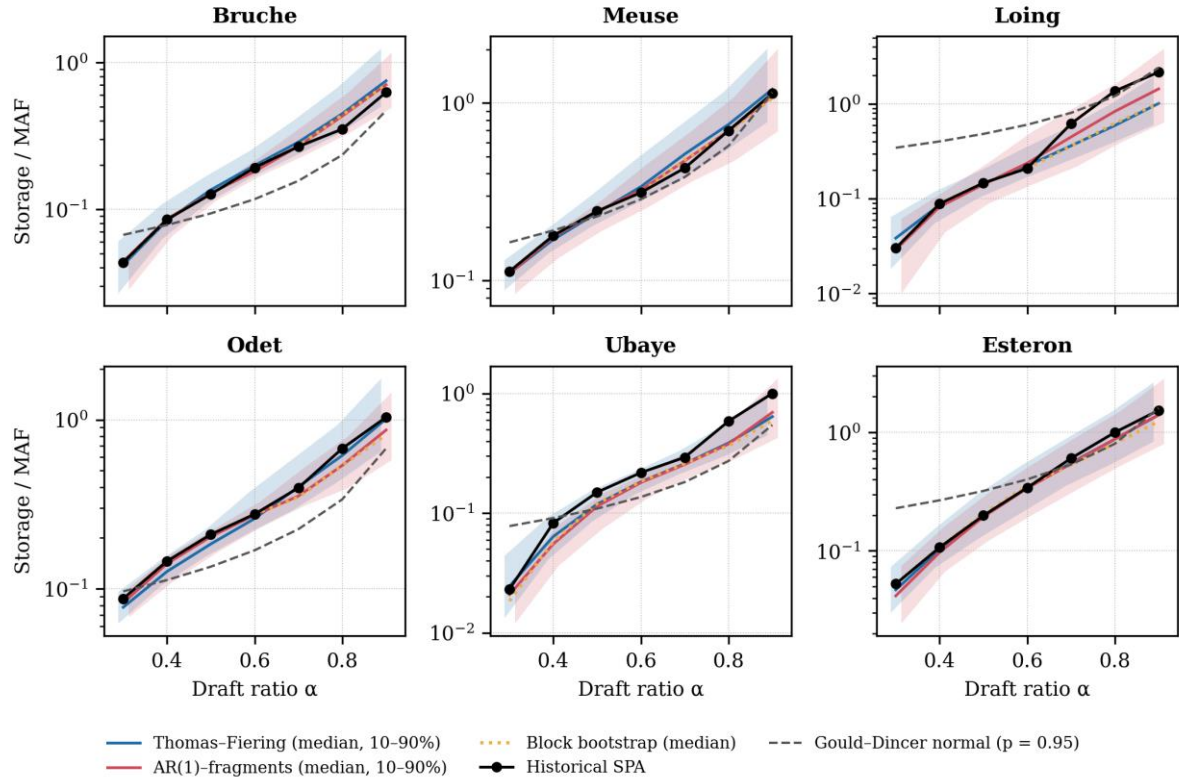


Figure 4. Storage–yield curves for the uniform demand (D1): historical SPA storage, synthetic medians and 10–90% ranges, and the Gould–Dincer normal approximation

The synthetic ensembles showed wide sampling variability. For the AF generator, the ratio of the 90th to the 10th percentile of SPA storage was 1.2–6.1, and it increased with α . The historical storage generally lay near the middle of the synthetic distributions (Figure 7). The exceptions were the Loing and Ubaye at high draft ratios, where the record contained an unusually severe critical period: the historical storage for $\alpha = 0.8$ at the Loing exceeded 98% of the TF and 98% of the BB sequences, but only 80% of the AF sequences. The AF sequences reproduce the multi-year dry spells that the other two generators miss. At four sites, no BB sequence required more storage than the record for $\alpha \leq 0.4$ (non-exceedance probability of 1.00), because within-year storage in a resampled sequence cannot be larger than that of the driest observed year.

The TF and AF medians were within about $\pm 20\%$ of each other at five sites, but the TF median was only 0.70 of the AF median at the Loing for $\alpha = 0.9$. The GDN approximation, which considers only over-year storage,

was a poor predictor of SPA storage. It overestimated storage at $\alpha = 0.3$ at all sites, most at the Loing (ratio 11.9), where the large $(1 + \rho)/(1 - \rho)$ factor applies even when the demand can be met within a year. For $\alpha \geq 0.5$ it underestimated storage at the strongly seasonal Bruche, Odet and Ubaye, where within-year storage dominates. The ratio of GDN to the AF median ranged from 0.54 to 11.9 over all cases and was 0.54–1.68 for $\alpha \geq 0.8$. This agrees with its intended use for over-year systems (Vogel and McMahon, 1996; McMahon et al., 2007).

The summer-peaking demand D2 increased the historical storage at the five rain-fed catchments by 12–34% for $\alpha = 0.7$, because the demand peak coincides with the flow minimum (Table 3). At the Ubaye, D2 reduced the storage by 12%, because the snowmelt peak in May–July supplies the summer demand directly. The relative effect of the demand pattern was largest at low draft ratios, where within-year storage dominates.

3.4. Storage–Yield–Reliability Curves

Table 4. Storage (fraction of MAF) required for pooled time-based reliabilities of 0.90, 0.95 and 0.99

Site	α	AF D1 0.90	AF D1 0.95	AF D1 0.99	AF D2 0.90	AF D2 0.95	AF D2 0.99	TF D1 0.99	BB D1 0.99
Bruche	0.5	0.06	0.09	0.12	0.14	0.17	0.19	0.12	0.11
	0.7	0.16	0.20	0.26	0.26	0.31	0.35	0.27	0.26
	0.9	0.31	0.42	0.77	0.43	0.52	0.88	0.85	0.77
Meuse	0.5	0.13	0.17	0.23	0.21	0.25	0.30	0.22	0.22
	0.7	0.24	0.29	0.47	0.35	0.41	0.56	0.51	0.44
	0.9	0.43	0.67	1.32	0.55	0.78	1.42	1.42	1.24
Loing	0.5	0.04	0.07	0.14	0.11	0.15	0.22	0.13	0.11
	0.7	0.15	0.26	0.68	0.24	0.32	0.72	0.39	0.36
	0.9	0.68	1.25	2.39	0.60	1.14	2.35	1.34	1.31
Odet	0.5	0.10	0.13	0.18	0.18	0.22	0.27	0.17	0.18

	0.7	0.19	0.24	0.34	0.30	0.37	0.45	0.39	0.34
	0.9	0.35	0.51	0.98	0.48	0.64	1.10	1.19	0.84
Ubaye	0.5	0.03	0.05	0.10	0.03	0.06	0.10	0.10	0.10
	0.7	0.11	0.15	0.23	0.12	0.16	0.22	0.24	0.23
	0.9	0.28	0.42	0.89	0.30	0.46	0.94	0.69	0.64
Esteron	0.5	0.07	0.10	0.20	0.14	0.17	0.24	0.20	0.22
	0.7	0.23	0.34	0.66	0.29	0.38	0.70	0.63	0.62
	0.9	0.67	1.06	1.99	0.66	1.03	1.98	1.88	1.60

Accepting occasional failures reduced the required storage considerably (Table 4; Figure 5). For $\alpha = 0.7$ and D1, the AF storage for 99% reliability was 0.23–0.68 MAF, and for 95% reliability it was 0.15–0.34 MAF, i.e. 38–78% of the 99% value. A 99% time-based reliability still allows about one failure month in eight years. Even so, the 99% storage exceeded the historical no-failure

storage at the Meuse, Loing and Esteron (by 8–9%), whereas it was smaller at the Bruche, Odet and Ubaye. For the former three catchments, the historical record is therefore not a conservative basis for design. The storage needed for a given reliability rose steeply with α . At the Esteron, the most variable catchment, 99% reliability required 0.20 MAF at $\alpha = 0.5$ and 1.99 MAF at $\alpha = 0.9$.

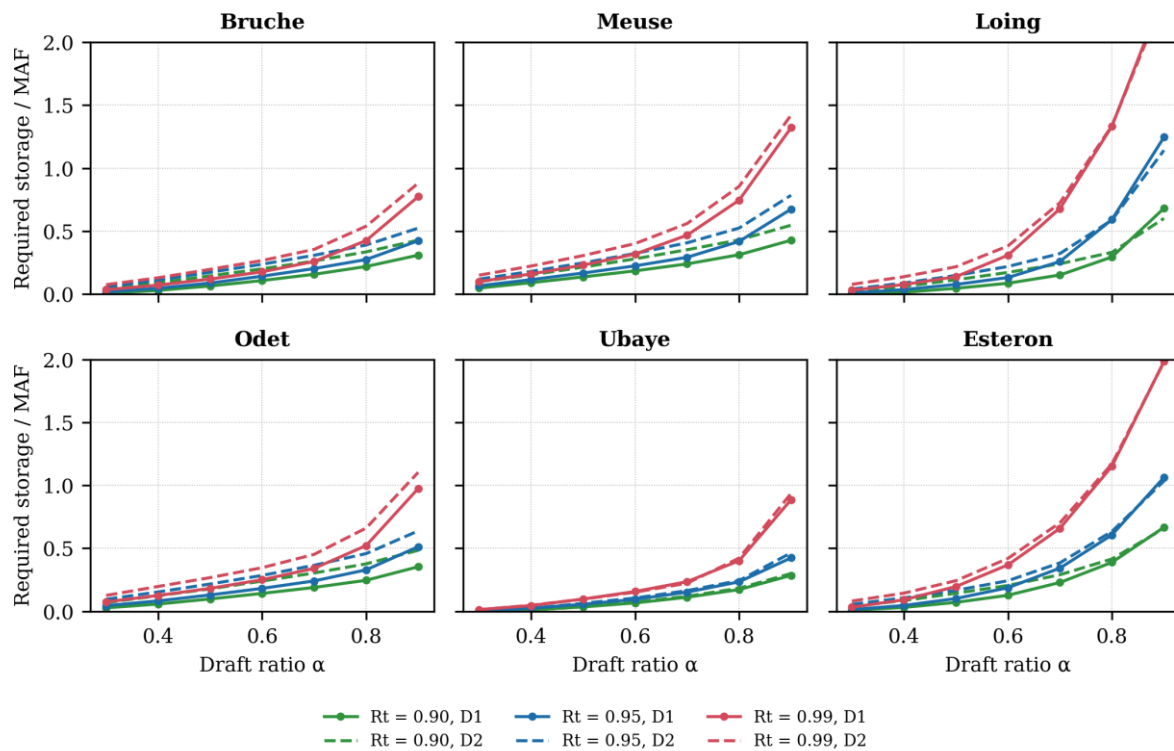


Figure 5. Storage–yield–reliability curves from the AF ensembles for the uniform (D1, solid) and summer-peaking (D2, dashed) demands

The choice of generator mattered most where annual persistence was high. At the Loing, the AF generator required 0.68 MAF for 99% reliability at $\alpha = 0.7$, compared with 0.39 MAF for TF and 0.36 MAF for BB, an increase of 81%. At $\alpha = 0.9$ the increase was 81% (2.39 MAF). A smaller increase was found at the Ubaye for $\alpha = 0.9$ (0.89 against 0.69 and 0.64 MAF). At the other four sites, where annual persistence was weak, the

three generators gave similar curves; TF gave slightly larger storages at the Bruche, Meuse and Odet because it inflated the monthly variance. These results confirm that preserving persistence at the annual scale is essential when over-year storage is needed (Srikanthan and McMahon, 2001; Vogel and McMahon, 1996).

3.5. Performance of Reservoirs Sized on the Historical Record

Table 5. Performance of reservoirs with the historical no-failure storage ($\alpha = 0.7$, D1) under 1000 synthetic 20-year sequences

Site	K/MAF	Gen.	R_t	R_t 5th pct.	R_v	Res	Vul	SI	P_{nf}
Bruche	0.27	TF	0.989	0.963	0.996	0.43	0.42	0.63	0.35
		BB	0.992	0.971	0.998	0.40	0.36	0.63	0.51
		AF	0.992	0.971	0.997	0.41	0.39	0.63	0.51
Meuse	0.43	TF	0.981	0.938	0.990	0.34	0.64	0.49	0.29
		BB	0.990	0.963	0.995	0.41	0.67	0.51	0.42
		AF	0.987	0.954	0.993	0.35	0.65	0.49	0.42
Loing	0.62	TF	0.999	0.996	1.000	0.28	0.50	0.52	0.95
		BB	0.999	1.000	1.000	0.32	0.47	0.55	0.96
		AF	0.988	0.925	0.994	0.22	0.58	0.45	0.71

Odet	0.40	TF	0.990	0.963	0.995	0.37	0.57	0.54	0.49
		BB	0.996	0.983	0.998	0.47	0.64	0.55	0.68
		AF	0.996	0.979	0.998	0.46	0.60	0.57	0.67
Ubaye	0.29	TF	0.998	0.988	0.999	0.48	0.39	0.66	0.78
		BB	0.999	0.992	1.000	0.52	0.35	0.70	0.88
		AF	0.997	0.983	0.999	0.41	0.40	0.63	0.81
Esteron	0.60	TF	0.988	0.938	0.995	0.26	0.56	0.48	0.63
		BB	0.989	0.941	0.995	0.25	0.54	0.48	0.63
		AF	0.987	0.933	0.994	0.24	0.54	0.48	0.64

R_t , R_v = mean time-based and volumetric reliability; R_i 5th pct. = 5th percentile over sequences; Res, Vul = pooled resilience and vulnerability; SI = sustainability index; P_{nf} = probability of no failure in 20 years.

A reservoir sized to meet the demand without failure over the historical record performed well on average but did not guarantee failure-free operation (Table 5). With the AF sequences and $\alpha = 0.7$, the mean time-based reliability was 0.987–0.997 and the volumetric reliability was 0.993–0.999. However, the probability of passing a new 20-year period without any failure was only 0.42 at the Meuse and 0.51 at the Bruche, and at most 0.81 (Ubaye). In the worst 5% of sequences, reliability fell to 0.925–0.983.

When failures occurred, they were persistent and severe. Resilience was 0.22–0.46, i.e. a failure month

was followed by another failure month in 54–78% of cases. The mean maximum shortfall per event was 39–65% of the monthly demand. The Loing and Esteron had the lowest resilience, consistent with their low standardised net inflow ($m < 1$) and long critical periods (Vogel and Bolognese, 1995). The sustainability index was 0.45–0.63, highest at the Bruche and Ubaye. At the Loing, the AF sequences gave a much lower probability of no failure (0.71) than the TF (0.95) and BB (0.96) sequences. A generator without annual persistence would therefore suggest that the historical design is almost fail-safe when it is not.

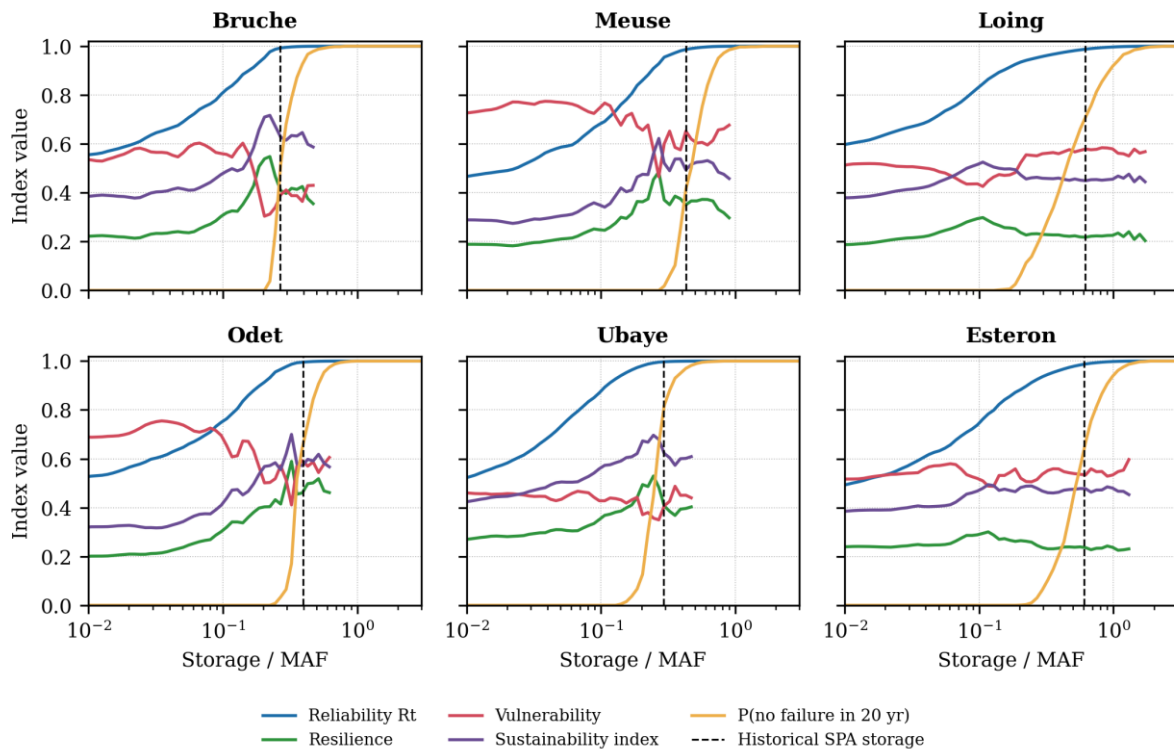


Figure 6. Performance indices versus storage for $\alpha = 0.7$ and D1 (AF ensembles); resilience, vulnerability and SI are shown only where the ensemble contains at least 50 failure months

Figure 6 shows how the indices change with capacity. Time-based reliability increased smoothly with storage, whereas the probability of no failure rose from zero to one over a narrow range around the historical storage. Resilience and vulnerability changed comparatively little over most of the storage range. Adding storage therefore mainly reduced the number of

failures rather than their severity. This behaviour is typical of reservoirs operated with the standard operating policy, which releases the full demand until the reservoir is empty. Hedging rules that ration supply at low storage can reduce vulnerability at the cost of more frequent small shortfalls (McMahon et al., 2006; Adeloje et al., 2001).

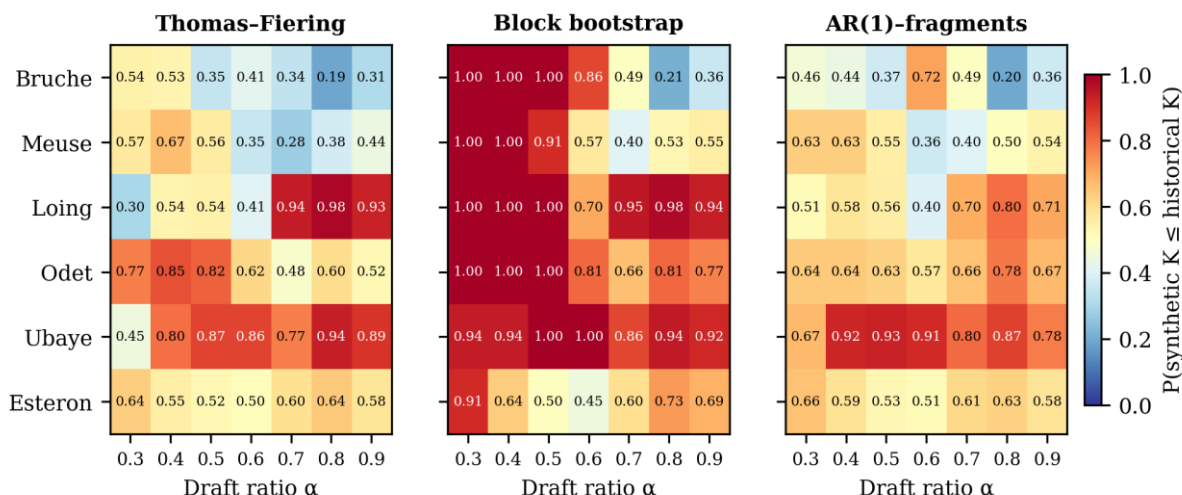


Figure 7. Non-exceedance probability of the historical SPA storage within each synthetic ensemble (D1)

3.6. Implications and Limitations

The results have three practical implications. First, sizing a reservoir on a single 20-year record gives a design whose failure-free performance in the next 20 years is far from certain, even when its long-run reliability is high. Stochastic S–Y–R curves make this risk explicit and allow the designer to choose storage for a stated reliability (McMahon and Adedoye, 2005). Second, the generator must preserve the statistics that control the design. Seasonal monthly models are adequate where within-year storage dominates, but annual persistence must be modelled in groundwater-fed or semi-arid catchments where over-year storage dominates (Hurst, 1951; Srikanthan and McMahon, 2001). Third, simple over-year approximations such as GDN should be restricted to high draft ratios.

The study has limitations. The 20-year record gives uncertain estimates of annual persistence and skewness, so the synthetic ensembles also inherit parameter uncertainty that was not propagated. Reservoir evaporation, environmental flows, operating rules and climate change were not considered, although they can change reliability considerably (Fowler et al., 2003). The reservoirs are hypothetical, and a real project would require site-specific topography and demand data. Future work could use longer records or regional information to constrain persistence, propagate parameter uncertainty and include climate projections and hedging policies.

4. Conclusions

Storage–yield–reliability relationships were derived for hypothetical reservoirs at six French catchments using the sequent peak algorithm, behaviour simulation and three stochastic generators. The main conclusions are:

(1) The historical no-failure storage for $\alpha = 0.7$ ranged from 0.27 to 0.62 MAF. The largest values occurred in the groundwater-fed Loing and

Mediterranean Esteron catchments, which had multi-year critical periods.

(2) All generators reproduced the monthly means, but only the annual AR(1)–fragments model preserved annual persistence. At the Loing, it increased the storage for 99% reliability by 81% ($\alpha = 0.7$) and 81% ($\alpha = 0.9$) relative to the Thomas–Fiering and bootstrap models.

(3) A summer-peaking demand increased storage by 12–34% in rain-fed catchments but reduced it in the snowmelt-fed Ubaye.

(4) Reservoirs sized on the historical record had high mean reliability (0.987–0.997), but only a 0.42–0.81 probability of no failure in a new 20-year period, with low resilience (0.22–0.46) and high vulnerability (0.39–0.65).

(5) The Gould–Dincer normal approximation was unreliable at low and moderate draft ratios and should be limited to over-year systems. Stochastic S–Y–R analysis with persistence-preserving generators is recommended for reservoir planning from short records.

Data Availability Statement

The streamflow and climate data are openly available in the CAMELS-FR dataset (<https://doi.org/10.57745/WH7FJR>) and the airGRdatasets R package (<https://CRAN.R-project.org/package=airGRdatasets>). Scripts are available from the corresponding author on request.

Conflict of Interest

The authors declare no conflict of interest.

References

- Adedoye, A.J., Montaseri, M., & Garman, C. (2001). Curing the misbehavior of reservoir capacity statistics by controlling shortfall during failures using the modified sequent peak algorithm. *Water Resources Research*, 37(1), 73–82. <https://doi.org/10.1029/2000WR900237>
- Delaigue, O., Guimarães, G.M., Brigode, P., Génot, B., Perrin, C., & Andréassian, V. (2024). CAMELS-FR dataset, V1. Recherche Data Gouv. <https://doi.org/10.57745/WH7FJR>

- Delaigue, O., Guimarães, G.M., Brigode, P., Génot, B., Perrin, C., Soubeyroux, J.-M., Janet, B., Addor, N., & Andréassian, V. (2025). CAMELS-FR dataset: a large-sample hydroclimatic dataset for France to explore hydrological diversity and support model benchmarking. *Earth System Science Data*, 17, 1461–1479. <https://doi.org/10.5194/essd-17-1461-2025>
- Fowler, H.J., Kilsby, C.G., & O’Connell, P.E. (2003). Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system. *Water Resources Research*, 39(8), 1222. <https://doi.org/10.1029/2002WR001778>
- Hashimoto, T., Stedinger, J.R., & Loucks, D.P. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resources Research*, 18(1), 14–20. <https://doi.org/10.1029/WR018i001p00014>
- Hurst, H.E. (1951). Long-term storage capacity of reservoirs. *Transactions of the American Society of Civil Engineers*, 116, 770–799.
- Kjeldsen, T.R., & Rosbjerg, D. (2004). Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems. *Hydrological Sciences Journal*, 49(5), 755–767. <https://doi.org/10.1623/hysj.49.5.755.55136>
- Kuria, F.W., & Vogel, R.M. (2015). Global storage-reliability-yield relationships for water supply reservoirs. *Water Resources Management*, 29(5), 1591–1605. <https://doi.org/10.1007/s11269-014-0896-4>
- Lall, U., & Sharma, A. (1996). A nearest neighbor bootstrap for resampling hydrologic time series. *Water Resources Research*, 32(3), 679–693. <https://doi.org/10.1029/95WR02966>
- McMahon, T.A., & Adeloye, A.J. (2005). *Water Resources Yield*. Water Resources Publications, Littleton, Colorado.
- McMahon, T.A., Adeloye, A.J., & Zhou, S.L. (2006). Understanding performance measures of reservoirs. *Journal of Hydrology*, 324(1–4), 359–382.
- McMahon, T.A., Pegram, G.G.S., Vogel, R.M., & Peel, M.C. (2007). Revisiting reservoir storage–yield relationships using a global streamflow database. *Advances in Water Resources*, 30(8), 1858–1872. <https://doi.org/10.1016/j.advwatres.2007.02.003>
- Sandoval-Solis, S., McKinney, D.C., & Loucks, D.P. (2011). Sustainability index for water resources planning and management. *Journal of Water Resources Planning and Management*, 137(5), 381–390. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000134](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000134)
- Srikanthan, R., & McMahon, T.A. (2001). Stochastic generation of annual, monthly and daily climate data: A review. *Hydrology and Earth System Sciences*, 5(4), 653–670. <https://doi.org/10.5194/hess-5-653-2001>
- Stedinger, J.R., & Taylor, M.R. (1982). Synthetic streamflow generation: 1. Model verification and validation. *Water Resources Research*, 18(4), 909–918. <https://doi.org/10.1029/WR018i004p00909>
- Thomas, H.A., & Burden, R.P. (1963). *Operations Research in Water Quality Management*. Harvard Water Resources Group, Cambridge, Massachusetts.
- Thomas, H.A., & Fiering, M.B. (1962). Mathematical synthesis of streamflow sequences for the analysis of river basins by simulation. In: Maass, A., et al. (Eds.), *Design of Water Resource Systems*, Harvard University Press, Cambridge, Massachusetts, 459–493.
- Vidal, J.-P., Martin, E., Franchistéguy, L., Habets, F., Soubeyroux, J.-M., Blanchard, M., & Baillon, M. (2010). Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite. *Hydrology and Earth System Sciences*, 14, 459–478. <https://doi.org/10.5194/hess-14-459-2010>
- Vogel, R.M., & Bolognese, R.A. (1995). Storage-reliability-resilience-yield relations for over-year water supply systems. *Water Resources Research*, 31(3), 645–654. <https://doi.org/10.1029/94WR02814>
- Vogel, R.M., & McMahon, T.A. (1996). Approximate reliability and resilience indices of over-year reservoirs fed by AR(1) gamma and normal flows. *Hydrological Sciences Journal*, 41(1), 75–96. <https://doi.org/10.1080/02626669609491480>
- Vogel, R.M., & Stedinger, J.R. (1987). Generalized storage-reliability-yield relationships. *Journal of Hydrology*, 89(3–4), 303–327. [https://doi.org/10.1016/0022-1694\(87\)90184-3](https://doi.org/10.1016/0022-1694(87)90184-3)