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Global streamflows — Part 3: Country and climate zone characteristics

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Summary This is the final paper in a series of three dealing with global hydrology based on a world-wide historical data set of monthly and annual streamflow records. In this paper hypothetical reservoir capacity estimates and reservoir-yield performance characteristics are compared between countries and between climate zones. The comparison for each characteristic is based mainly on its median value. For the comparison based on countries, the median value for 17 countries was based on at least 10 rivers, and for a further 19 countries on at least three rivers within the country. For the 30 Köppen climate zones, 13 zones had at least 10 rivers and a further seven zones were represented by at least three rivers. Some conclusions include: rivers in the Sahel region of Africa exhibit larger inter-decadal variances compared with those for other global rivers; the observation that western Canadian rivers display longer run lengths than expected from an AR(1) model may be due to the influence of the Pacific Decadal Oscillation; between countries, storage resilience is strongly positively related to reliability, and dimensionless vulnerability is strongly negatively related to reliability; and, finally, rivers in countries that exhibit low resilience tend to show high dimensionless vulnerability. It was also observed for several rivers in Finland and Sudan, that large natural lakes, not unexpectedly, increase streamflow auto-correlation and thereby reduce a reservoir's ability to recover quickly following a major deficit.

Introduction

This is the third and final paper in a series dealing with analysis of a global data set of monthly and annual historical

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streamflows. The first paper (McMahon et al., 2007c) describes the data briefly and discusses the unregulated characteristics of 1221 river flows including the probability density function of their annual flows, related statistical parameters, auto-correlation, persistence and low flow run characteristics. The second paper (McMahon et al., 2007d) concentrates on global summaries of hypothetical reservoir storage—yield performance of 729 rivers that have 25 years or more of continuous streamflow data. (In that paper a hypothetical reservoir is one in which the capacity is dependent only on inflow characteristics, target draft and a performance measure like reliability. Practical issues including evaporation losses and operational losses are not considered.)

The purpose of this paper is threefold. Firstly, to establish a baseline analysis that can be used to assess climate change impacts (e.g. $2 \times$ present CO_2) of surface hydrologic characteristics sampled by country or climate. Secondly, to develop empirical equations that can be used to estimate both firm yield and steady state yield and to compute reservoir capacity for a range of practical conditions that are experienced globally. In this paper, we define firm yield as the target draft that can be met during the historical period for a given no-failure reliability and steady state yield is the target draft that can be met for a given reliability. We adopted the traditional Sequent Peak Algorithm (SPA) and the Behaviour Analysis along with Extended Deficit Analysis (EDA) to compute these different yield estimates. The third purpose is to assess the inter-country and inter-climate zone variations of hypothetical reservoir sizes and their performance under common demand conditions.

The authors are unaware of any papers or reports that address the characteristics of annual streamflow (other than mean annual runoff and variability — see for example Dettinger and Diaz, 2000), reservoir capacity estimates or reservoir performance from an inter-country or inter-climate zone point of view. However, there are individual countries in which a range of assessments have been made.

In this paper, we address country and climate zone streamflow and reservoir performance characteristics as exhibited in the variations of the hydrologic characteristics of the global data set. Following this introduction we describe the data that are used in this study. Next, the methods used in the analyses are outlined. In '' Results and discussion'', the results are presented and discussed under the headings: annual flow statistics, persistence, runs below the median, hypothetical reservoir capacity estimates and reservoir storage—yield performance. Finally, we list some conclusions.

Data

The global data set consists of 1221 unregulated rivers with 10 years or more, and a subset of 729 rivers with 25 years or more, of continuous historical annual and monthly flows. Fig. 1 shows the locations of rivers with 10—24 years of data and those with 25 or more years. The 25+ data set is a satisfactory representation of rivers covering the whole data set. It is noted that the rivers are reasonably distributed globally, although there are some regions (for example, arid regions — Mediterranean North Africa, the Middle East, South Western Africa, central Australia and tropical regions — central America, Indonesia, non-coastal Brazil, Peru, Bolivia, Ecuador) with little or no data.

The data set was initially collated by the first author during the 1980s and details were reported several years later (McMahon et al., 1992), with subsequent additions and revisions to the data set since that time (Peel et al., 2001, 2004a). Considerable effort has gone into ensuring the data are free of errors, are not impacted by major water withdrawals from the streams and the flow values are not affected by reservoirs upstream.

To introduce the data set, Table 1 (which will be referred to frequently in the sequel because it contains many of the statistics of interest in reservoir storage) is a listing by continent and by country of the properties of the river flow records used herein. Included in the table are records that have annual data for at least three rivers (column 2). We note the median length of those included (column 3), which are limited to continuous historical data with 25 or more

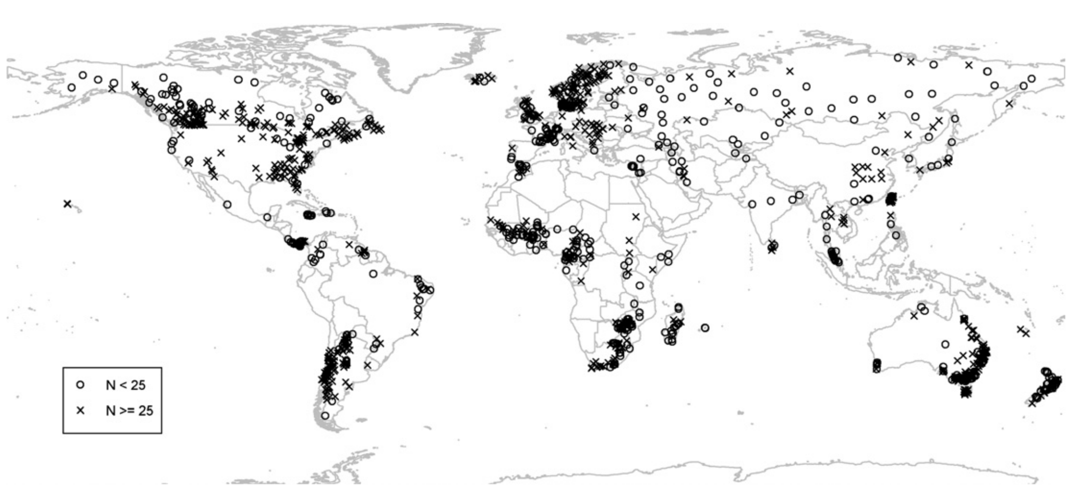

Figure 1 Location of 1221 rivers in the global data set showing separately rivers with less than 25 years and those 729 rivers with 25 years or more of historical annual and monthly flows.

Table 1 Characteristics of rivers with 25 years or more of annual streamflows by country

Country (1)	No. of rivers (2)	Median length of historical data (years) (3)	Median catchment area (km^2) (4)	Median MAR (mm) (5)	Median annual Cv (6)	Median annual γ (7)	Median annual ρ (8)
Asia							
China	11	37	329,700	237	0.36	0.97	0.19
		(32–79)	(41,400–1,488,000)	(62–525)	(0.14–0.56)	(0.025–1.24)	(−0.046–0.30)
Iran	3	25	10,230	377	0.48	1.16	0.19
Japan	3	25	898	982	0.27	0.56	0.25
Russia	11	51	305,000	178	0.18	0.40	0.19
		(40–90)	(36,900–2,440,000)	(103–543)	(0.11–0.35)	(0.00–0.83)	(0.052–0.43)
Sri Lanka	3	34	1189	1745	0.22	0.12	−0.034
Taiwan	18	34	237	232	0.30	0.39	−0.023
		(30–37)	(111–435)	(165–270)	(0.27–0.38)	(0.10–1.13)	(−0.27–0.069)
Thailand	6	32	146,500	188	0.23	0.68	−0.0073
Australia							
Australia	114	36.5	548	236	0.68	1.12	0.10
		(27–68)	(52–7150)	(43.6–1434)	(0.26–1.22)	(0.28–2.28)	(−0.12–0.33)
Europe							
Denmark	31	39	131	281	0.28	0.62	0.098
		(31–51)	(35–680)	(176–557)	(0.12–0.43)	(0.26–1.11)	(−0.053–0.34)
Finland	3	64	50,820	305	0.21	0.20	0.40
France	4	26	94	204	0.50	0.36	0.20
Hungary	6	52	6003	200	0.39	0.71	0.25
Iceland	6	43	3168	1568	0.12	0.31	0.36
Italy	4	56	29,290	613	0.26	1.06	0.11
Norway	21	53	470	1009	0.19	0.23	0.071
		(36–73)	(18.5–3636)	(495–2951)	(0.17–0.25)	(−0.10–0.62)	(−0.008–0.21)
Slovakia	4	59	816	488	0.27	0.54	−0.015
Sweden	46	52	1138	462	0.23	0.40	0.11
		(36–66)	(262–8580)	(242–803)	(0.15–0.37)	(−0.11–0.69)	(−0.028–0.30)
United Kingdom	16	33	691	696	0.22	0.28	0.0023
		(27–49)	(370–1460)	(194–959)	(0.16–0.47)	(0.04–0.59)	(−0.18–0.093)
North Africa							
Burkina Faso	4	32	28,570	45	0.40	0.17	0.56
Cameroon	12	26	11,260	462	0.17	0.15	0.24
		(25–31)	(2280–76,000)	(345–981)	(0.15–0.28)	(−0.33–0.52)	(−0.025–0.38)
Mali	7	38	127,000	130	0.47	0.14	0.75
Morocco	5	29	6190	105	0.61	1.08	0.42
Senegal	3	62	230,000	97	0.33	−0.045	0.30
Sudan	3	70	450,000	73	0.31	1.22	0.75
North America							
Canada	124	37	2005	465	0.21	0.37	0.14
		(29–68)	(205–85,700)	(68.4–1081)	(0.14–0.48)	(−0.19–1.01)	(−0.13–0.35)
Jamaica	3	26	158	1056	0.20	0.041	0.013
Panama	18	28	310	2417	0.24	0.40	−0.037
		(26–34)	(136–1337)	(1523–3765)	(0.18–0.31)	(−0.07–0.83)	(−0.15–0.039)
United States	50	54	2266	390	0.37	0.49	0.18
		(44–68)	(466–29,707)	(101–632)	(0.25–0.66)	(0.03–1.41)	(0.030–0.35)
South Africa							
Madagascar	3	29	4151	767	0.27	0.93	−0.072
Rep South Africa	26	36	663	33.9	0.83	1.73	0.057
		(29–40)	(67.3–4310)	(6.0–374)	(0.48–1.03)	(0.87–2.47)	(−0.19–0.21)
Zimbabwe	16	30	373	95.5	1.00	1.58	0.15
		(27–53)	(218–1217)	(55–155)	(0.76–1.19)	(1.29–2.30)	(−0.046–0.23)
South America							
Argentina	51	39	4150	172	0.41	1.07	0.17
		(29–61)	(460–31,900)	(30–919)	(0.21–0.67)	(−0.05–3.05)	(−0.057–0.48)
Brazil	7	35	55,080	208	0.32	0.63	0.22
Chile	35	40	1054	1057	0.34	0.64	−0.019
		(40–41)	(326–5323)	(42–2402)	(0.27–0.96)	(−0.30–2.47)	(−0.18–0.33)

Table 1 (*continued*)

Country (1)	No. of rivers (2)	Median length of historical data (years) (3)	Median catchment area (km^2) (4)	Median MAR (mm) (5)	Median annual Cv (6)	Median annual γ (7)	Median annual ρ (8)
Guyana	4	32	28,000	1006	0.28	0.18	0.42
South Pacific							
New Zealand	14	30 (26–32)	531 (89–1557)	1191 (648–2217)	0.21 (0.16–0.33)	0.17 (−0.34–0.93)	0.075 (−0.21–0.25)

Note: 10th and 90th percentile values are in parenthesis.

years in length, together with their equivalent catchment areas (in km^2 in column 4). For both statistics the 10 and 90 percentile values are given in parentheses. In the data set, we note that there are only four countries, namely Russia, Norway, Sweden and United States, which have a median data length of 50 or more years for 10 or more rivers. A further 11 countries have at least 10 rivers with a median length of 30 or more years of continuous historical flow data. In total, there are streamflow data for rivers from 60 countries.

Table 2 Description of Köppen climate classification

Köppen zone	Description of climate
Af	Tropical, rainforest
Am	Tropical, monsoon
Aw	Tropical, savanna
BWh	Arid, desert hot
BWk	Arid, desert cold
BSh	Arid, steppe hot
BSk	Arid, steppe cold
Csa	Temperate, dry and hot summer
Csb	Temperate, dry and warm summer
Csc	Temperate, dry and cold summer
Cwa	Temperate, dry winter and hot summer
Cwb	Temperate, dry winter and warm summer
Cwc	Temperate, dry winter and cold summer
Cfa	Temperate, without dry season and hot summer
Cfb	Temperate, without dry season and warm summer
Cfc	Temperate, without dry season and cold summer
Dsa	Cold, dry and hot summer
Dsb	Cold, dry and warm summer
Dsc	Cold, dry and cool summer
Dsd	Cold, dry summer and very cold winter
Dwa	Cold, dry winter and hot summer
Dwb	Cold, dry winter and warm summer
Dwc	Cold, dry winter and cool summer
Dwd	Cold, dry winter and very cold winter
Dfa	Cold, without dry season and hot summer
Dfb	Cold, without dry season and warm summer
Dfc	Cold, without dry season and cool summer
Dfd	Cold, without dry season and very cold winter
ET	Polar, tundra
ETH	Polar, tundra (due to high elevation)

Table 3 Number of rivers located within each major climate zone

A Tropical	B Arid	C Temperate	D Cold	E Polar
76	82	303	255	6

Most of the results of the analyses described in Section ''Results and discussion'' are based on 25 or more years of data. Departures from this are noted as appropriate. In addition, we record which type of time series is used because unbroken sequences of both monthly and annual flow data are available.

The rivers have been stratified (Peel et al., 2004a) using the Köppen climate classification system (Köppen, 1936), which is a widely used and accepted climate classification system (a summary of the climate zones is given in Table 2). Of the 30 climate zones world-wide, 20 zones have streamflow data for at least three global rivers located within each zone. At the more general climate classification level (first letter of the climate zone), there are sufficient numbers of rivers for four of the five classes (listed in Table 3) to be confident of any generalizations that follow.

Analyses

Three groups of analyses were performed on each river. The first consisted of computing the standard statistics of the annual flows — mean (μ), coefficient of variation (Cv), coefficient of skewness (γ) and the lag-one serial correlation coefficient (ρ). Standard product-moment statistics were adopted here.

In addition to examining ρ, we analyze persistence through Empirical Mode Decomposition (EMD) (introduced by Huang et al., 1998) to examine the proportion of variance in the historical time series of annual streamflows from the global data set due to inter-decadal fluctuations. Details of EMD analysis are given in Part 1 (McMahon et al., 2007c) but suffice to say that it allows one to decompose a time series (in this paper annual flows are used) into a set of independent intrinsic mode functions (IMFs) and a residual that summed together reproduce the original time series. For a river each IMF has an average time period and associated variance. Readers are referred to Fig. 12 in McMahon et al. (2007c) which shows an example of the individual components (IMFs and residual) for a specific river.

Runs analysis is also a part of the first group of analyses. In this paper, we consider only the low flow series defined as the deviations of the flows below the median annual flow. For each river we compute the frequency of run lengths below the median, run magnitude and run severity. Details are given in Part 1 (McMahon et al., 2007c).

The second group of analyses addresses hypothetical reservoir storage—yield relationships based on the Extended Deficit Analysis (Pegram, 2000; McMahon and Adeloye, 2005), SPA (Thomas and Burden, 1963) and the behaviour (simulation) analysis. EDA is a relatively new technique that allows one to estimate for a river the storage required to provide a given draft (from a hypothetical semi-infinite reservoir) at a given level of reliability. In this paper, the EDA analysis is based on the annual streamflow series. The procedure used in this analysis is a modified version of the published technique. Details of the adopted changes are described in McMahon et al. (2007a).

The traditional Sequent Peak Algorithm is the automated version of the Rippl mass curve procedure and is widely used globally to estimate reservoir capacity (Rippl, 1883). It computes, using historical streamflows, the firm yield which is the yield that can be met over a particular planning period with a specified no-failure reliability. The behaviour procedure is also included in this analysis as it is used in countries that determine yield with a given level of reliability.

The third group of analyses deals with the performance of a hypothetical reservoir located on each of the global rivers. Three metrics are computed to define performance. These are monthly time reliability, resilience and dimensionless vulnerability; the latter two are also based on monthly flows. Computational details are presented in Part 2 (McMahon et al., 2007d). The three metrics as used in this paper can be explained as follows. Monthly time reliability is the probability that a reservoir will be able to meet the target demand in any month within the simulation period, usually equal to the length of the historical record (McMahon and Adeloye, 2005). Resilience is a measure of how quickly a reservoir will recover from emptiness and, in this analysis, we have adopted the Hashimoto et al. (1982) equation. And finally, vulnerability measures the severity of a failure and, in this paper, it is expressed non-dimensionally by dividing the shortfall or deficit by the target demand during the failure period. Again, we adopt the Hashimoto et al. (1982) definition although we observe that Kaczmarek et al. (1996) note there is no generally accepted definition of water supply vulnerability.

Results and discussion

The results of the analyses are presented as a series of tables and figures. Tables 1, 5, 7 and 9 are based on the results summarized by country whereas Tables 4, 6, 8 and 10 relate the results to the Köppen climate zones. The figures show the streamflow characteristics and reservoir performance characteristics mainly on world maps.

Annual flow statistics

As already noted where it was introduced in Section ''Data'', Table 1 sets out some key hydrologic features about the rivers classified by country. To elaborate, the rivers cover a very wide range hydrologically, with median values of mean annual runoff varying from a minimum of 34 mm in South Africa to 2417 mm in Panama. Other high annual runoffs are exhibited by the Sri Lankan rivers (1745 mm per year) and Iceland rivers (1568 mm). In addition to the rivers in South Africa, those in Burkina Faso also have low runoffs (45 mm per year).

The spatial distribution of the annual coefficient of variation (Cv) is presented in Fig. 2 and summarized in Table 1. In the table we observe the large range of Cv values varying from a median value of 0.12 in Iceland to 1.0 in Zimbabwe. Except for Morocco (median annual Cv = 0.61), Australia (0.68), South Africa (0.83) and Zimbabwe (1.0), the annual Cv of all other countries is <0.6. Other than Iceland, countries with median annual Cv's $\leqslant$0.2 include Cameroon (0.17), Russia (0.18), Norway (0.19) and Jamaica (0.20). It is interesting to note that 10% of the rivers sampled in Australia, South Africa and Zimbabwe have annual Cv's >1.0, respectively. Also, some countries' river records with median Cv values in the range 0.3 to $\sim$0.4 exhibit large Cv's among their upper 10 percentile; the following countries have 10% of records with Cv's greater than 0.6: United States (0.66), Argentina (0.67) and Chile (0.96). These countries all experience a wide range of climatic zones, with rivers exhibiting high Cv's located in arid regions (southwestern USA and near latitude 30°S in Argentina and Chile, Fig. 2).

Based on the Köppen classification, the annual Cv (Table 4) exhibits a similar range of median values as that shown by country from 0.12 for ET to 1.01 for BSh. The variation in median value of Cv across the general climate zones reveals that interannual variability is greatest in the Arid zone (0.79), followed by the Temperate (0.39), Tropical (0.27), Cold (0.23) and Polar zone (0.12). The country median and percentile range results for Cv, shown in Table 1, are largely due to the spatial distribution of climate zones within those countries.

Drift (m) is the standardized net inflow to a reservoir and is defined as

$$m = \frac{1-\alpha}{\mathrm{Cv}} \tag{1}$$

where α is the standardized draft expressed as the ratio of mean annual flow. (In the analysis discussed in Section ''Runs below the median'' we use $\alpha = 0.75$.) Low values of drift imply relatively large reservoir capacities (with carryover storage from one year to the following) or, alternatively, relatively low yields.

Fig. 2 shows the spatial distribution of Cv globally and, for a constant α, may be interpreted as a plot of the reciprocal of m. Thus in terms of drift, the figure highlights the relatively low m values (high values of annual Cv) along eastern Australia, South Africa and Zimbabwe and the northern region of Chile. There are also low m values in northeast Brazil and north central Argentina. For $\alpha = 0.75$, values of m greater than 1.0 are observed in Scandinavia, northern Russia,

Table 4 Characteristics of rivers with 25 years or more of annual streamflows by Köppen climate

Köppen zone (1)	No. of rivers (2)	Median length of historical data (years) (3)	Median catchment area (km^2) (4)	Median MAR (mm) (5)	Median annual Cv (6)	Median annual γ (7)	Median annual ρ (8)
Af	32	28 (25–56)	576 (122–8026)	1874 (966–3318)	0.26 (0.17–0.34)	0.33 (−0.25–1.00)	−0.0047 (−0.21–0.30)
Am	4	33	10,370	1268	0.22	0.42	0.34
Aw	40	31 (25–63)	40,120 (337–510,800)	230 (50–1180)	0.29 (0.14–0.72)	0.40 (−0.16–1.26)	0.28 (−0.034–0.70)
BWk	22	40 (29–60)	3930 (597–25,000)	56 (11–255)	0.76 (0.43–1.08)	1.80 (1.06–2.78)	0.17 (−0.023–0.42)
BSh	26	38 (29–62)	45,450 (492–281,600)	81 (6.0–105)	1.01 (0.28–1.40)	1.56 (−0.058–2.52)	0.27 (−0.035–0.72)
BSk	34	40 (28–68)	3975 (460–29,710)	69 (7.9–377)	0.64 (0.29–1.58)	1.42 (0.51–4.50)	0.058 (−0.19–0.27)
Csa	12	30 (26–61)	811 (1.92–17,250)	165 (27–459)	0.58 (0.40–0.99)	1.05 (0.30–1.65)	0.36 (0.14–0.78)
Csb	42	40 (29–42)	866 (224–4968)	1063 (172–2402)	0.30 (0.19–0.56)	0.24 (−0.13–1.13)	−0.026 (−0.18–0.17)
Cwa	31	38 (28–51)	1030 (161–40,000)	233 (31–549)	0.40 (0.30–0.82)	0.82 (0.15–1.68)	0.17 (−0.087–0.45)
Cwb	17	30 (26–51)	1036 (231–8190)	80 (29–225)	0.80 (0.40–0.99)	1.57 (1.13–2.47)	0.10 (−0.089–0.21)
Cfa	87	42 (29–60)	1660 (160–42,030)	371 (100–646)	0.39 (0.25–0.98)	0.68 (0.011–1.94)	0.20 (−0.043–0.36)
Cfb	114	35 (26–62)	444 (39–32,890)	531 (106–1788)	0.35 (0.18–0.80)	0.65 (0.041–1.60)	0.068 (−0.14–0.29)
Dsb	3	49	2160	284	0.19	0.40	0.14
Dwa	3	42	44,100	96	0.56	1.24	0.30
Dwb	3	32	43,200	46	0.18	1.13	0.018
Dwc	3	51	1,630,000	165	0.22	−0.003	0.43
Dfa	3	58	29,940	267	0.38	0.43	0.12
Dfb	164	44 (33–70)	1225 (120–38,800)	375 (158–939)	0.25 (0.15–0.41)	0.39 (−0.10–1.03)	0.14 (−0.11–0.34)
Dfc	76	38 (29–69)	2873 (340–74,600)	442 (134–1009)	0.19 (0.15–0.35)	0.41 (−0.15–0.89)	0.12 (−0.051–0.40)
ET	6	43	3168	1568	0.12	0.31	0.36

coastal Canada, Cameroon, Iceland and New Zealand; we note that $m > 1$ is a rough indicator of reservoirs exhibiting within year storage characteristics, or in other words, a tendency to spill annually.

McMahon et al. (2007b) show through a sensitivity analysis that the effect on individual reservoir's storage of the four main streamflow statistics confirms that the influential ones are mean and standard deviation, while effects of skew and serial correlation are orders of magnitude lower. Nevertheless, McMahon et al. (2007c) demonstrate that the majority of the world data set of streamflow records are best modeled by a Gamma probability distribution function, hence our interest in skewness in this context. A unique property of the Gamma distribution is that the skewness coefficient is exactly twice the coefficient of variation.

In Table 1, the statistics for the coefficient of skewness (γ) show that several countries have median $\gamma > 1$ including South Africa (1.73), Zimbabwe (1.58), Sudan (1.22), Iran (1.16), Australia (1.12), Morocco (1.08), Argentina (1.07) and Italy (1.06). The variation of skewness across the broad climate classes (Table 4) is Tropical (0.37), Arid (1.57), Temperate (0.68), Cold (0.41) and Polar (0.31). In more detail, within the D (Cold) zone, γ varies from −0.003 (Dwc) to

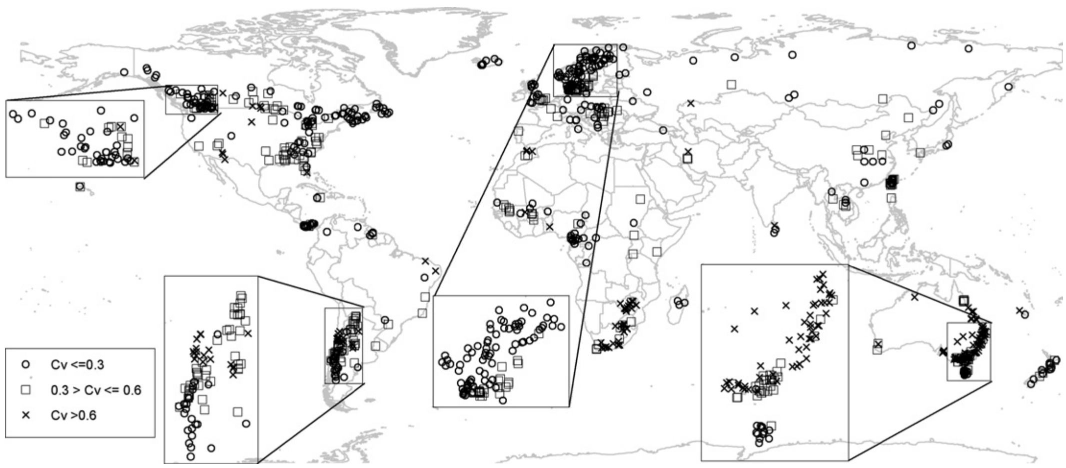

Figure 2 Global distribution of the coefficient of variation of annual streamflows.

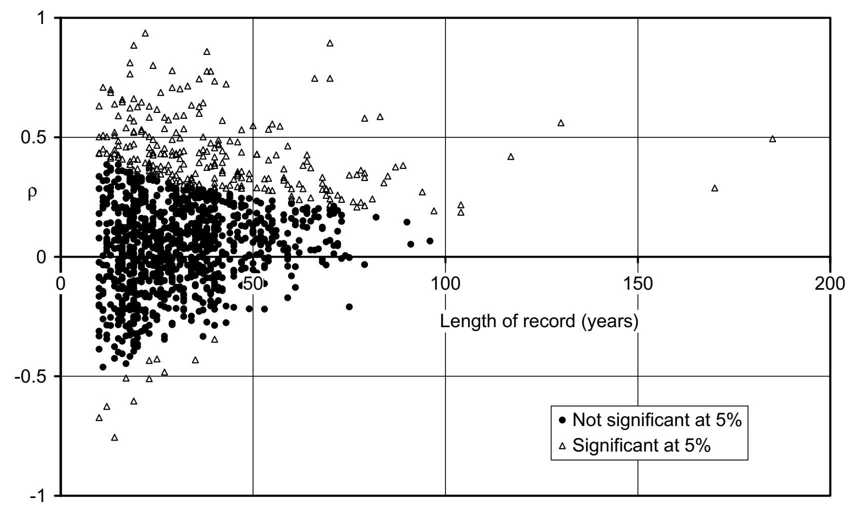

Figure 3 Plot showing annual lag-one serial correlation and length of historical streamflow data.

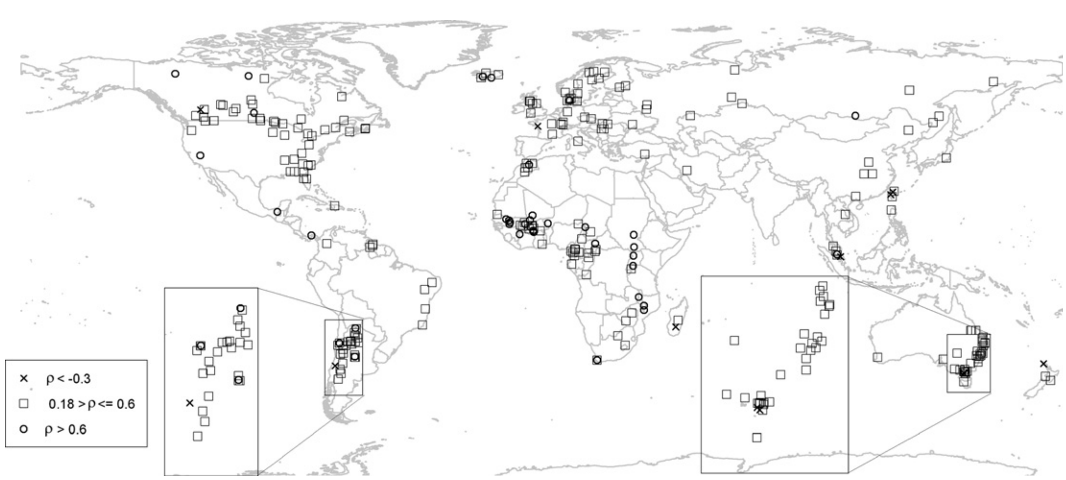

Figure 4 Location of rivers with lag-one serial correlation values that are statistically significant at the 5% level.

1.24 (Dwa). It is noted that across the broad climate classes, these five γ values and the equivalent Cv values for the five climate classes are strongly related, as indicated by the following regression relationship: $\gamma = 2.10\text{Cv} - 0.11$, (with $R^2 = 98\%$, $p = 0.001$ based on weighted least squares). The observation that $\gamma \sim 2\text{Cv}$ as demonstrated by the grouped data is consistent with our conclusion in Paper 1 (McMahon et al., 2007c) that annual flows tend to follow a Gamma probability distribution function.

The range of annual lag-one serial correlation coefficients (ρ) is also listed in Table 1 and the values are plotted against record length in Fig. 3. The data in the figure are based on all rivers in the global data set. Of the 1221 rivers, 260 (21.3%) are statistically significant from zero at the 5% level of significance. The test adopted is from Yevjevich (1972, Eqs. (2.22) and (2.23)) which is a good approximation for independent non-normal variables. The locations of the statistically significant rivers are shown in Fig. 4. Except for a group of rivers in Africa (Sahel) that have values of $\rho > 0.6$, no dominant pattern appears. The average magnitude of the statistically significant auto-correlations (absolute values) is 0.44.

It is likely that some of the variability in estimators of the statistics reported in this section is due to sampling. This issue will be examined in a detailed follow up study.

Persistence

Empirical Mode Decomposition (EMD, Huang et al., 1998) was applied to all streamflow stations with at least 30 years of consecutive data to quantify the proportion of variation in the annual streamflow time series due to fluctuations at intra- and inter-decadal time scales. Fluctuations within a time series are automatically and adaptively selected from the time series using the EMD algorithm, resulting in a decomposition of the time series into a set of independent intrinsic mode functions (IMFs) and a residual (trend). When the IMFs and residual are summed together they form the original time series. At each station the average period of each resultant IMF was calculated. IMFs with an average period $\leqslant$10 years were summed to form an intra-decadal component, while the remaining IMFs and residual were summed to form an inter-decadal component. Details of the EMD methodology used in this analysis are available in Peel et al. (2005) and Peel and McMahon (2006) and, more generally, in Huang et al. (1998).

The percentage of the total variance due to the intra- and inter-decadal components was estimated at each station. In Table 5, the percentage of total variance due to each component is presented for countries with three or more rivers. The average proportion of total variance explained by the intra-decadal component is 71% for all stations. Clearly intra-decadal fluctuations are the dominant feature for annual streamflow around the world. The most notable exceptions to the average for the intra-decadal component are countries in the Sahel region of Northern Africa, where the inter-decadal component is dominant. The likely cause of the Sahel results is the reduction in rainfall in this region, and therefore reduced streamflow, during the 1960s (Nicholson, 1980), which is captured in the residual trend of the EMD analysis and increases the percentage of the total variance due to the inter-decadal component. This is particularly evident in Fig. 5 where the percentage of the total variance due to the intra-decadal component is mapped. The high proportion of total variance explained by the inter-decadal component in the Sahel being associated with high values of annual lag-one serial correlation coefficient (previous section) is consistent with the relationship observed between these two variables in McMahon et al. (2007c, Fig. 13).

The influence of the inter-decadal changes in the Sahel region is also apparent when the proportion of total

Table 5 Percentage of total variance due to intra- and inter-decadal components for rivers with 30 years or more of annual streamflow by country, after the analysis by Empirical Mode Decomposition

Country (1)	No. of stations (2)	Intra-decadal (%) (3)	Inter-decadal (%) (4)
Asia			
China	10	66.6	33.4
Russia	11	67.0	33.0
Taiwan	16	73.9	26.1
Thailand	4	75.4	24.6
Australia			
Australia	93	69.5	30.5
Europe			
Slovakia	4	83.3	16.7
Denmark	29	73.8	26.2
Finland	3	68.5	31.5
Hungary	6	70.3	29.7
Iceland	4	65.2	34.8
Italy	3	61.3	38.7
Norway	21	76.6	23.4
Sweden	44	78.7	21.3
United Kingdom	11	74.7	25.3
North Africa			
Burkina Faso	3	46.4	53.6
Mali	6	21.3	78.7
Senegal	3	48.3	51.7
Sudan	3	48.3	51.7
North America			
Canada	108	72.2	27.8
Panama	4	85.0	15.0
United States	49	69.5	30.5
South Africa			
Rep South Africa	21	69.5	30.5
Zimbabwe	9	63.0	37.0
South America			
Argentina	43	69.5	30.5
Brazil	6	59.2	40.8
Chile	35	74.7	25.3
Guyana	3	62.7	37.3
South Pacific			
New Zealand	7	74.7	25.3

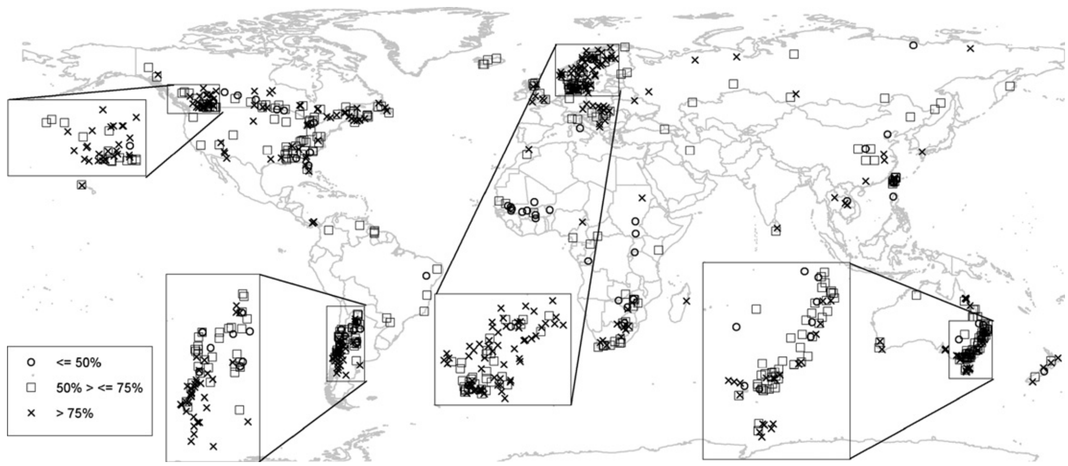

Figure 5 Global distribution of the percentage of inter-decadal variance compared with the total variance for rivers with 30 or more years of annual streamflows.

variance at each station is stratified by Köppen climate type (Table 6). Sahel stations are largely found in tropical Aw and arid BSh climate types and these two climate types display the highest (48.6% and 46.8%, respectively) proportion of total variance for the inter-decadal component in Table 6.

Runs below the median

The previous lag-one serial correlation (ρ) and EMD based persistence analyses are indicative of the run length behaviour of a time series. However, a more complete metric of run length behaviour is the run length skewness (g) (Peel et al., 2004b), which summarizes the shape of the frequency distribution of run lengths in a time series. This metric was calculated for each river for all run lengths below the median. To assess whether the run length behaviour at each river is significantly different from an AR(1) model, a 90% confidence interval for g was calculated for each river based on formulas given in Peel et al. (2004b) that require values of record length and ρ. As an indication of the form that this test takes, we here repeat a diagram from that paper in Fig. 6. It shows the two-dimensional 90% confidence zone (for any specific ρ, a one-dimensional confidence interval) calculated by simulation of AR(1) sequences of various lengths and ρ — this figure summarizes 40,040 simulations of sequences of length 64. Readers interested in further details of the test are referred to Peel et al. (2004b).

Table 6 Percentage of total variance due to intra- and inter-decadal components for rivers with 30 years or more of annual streamflow by Köppen climate, after the analysis by Empirical Mode Decomposition

Köppen class (1)	No. of stations (2)	Intra-decadal (%) (3)	Inter-decadal (%) (4)
Af	14	76.3	23.7
Aw	23	51.4	48.6
BWk	19	65.8	34.2
BSh	21	53.2	46.8
BSk	30	73.3	26.7
Csa	6	69.6	30.4
Csb	37	81.1	18.9
Cwa	29	64.3	35.7
Cwb	9	64.8	35.2
Cfa	78	68.8	31.2
Cfb	84	72.4	27.6
Dwa	3	58.5	41.5
Dwc	3	63.2	36.8
Dfa	3	67.2	32.8
Dfb	153	73.3	26.7
Dfc	67	76.3	23.7
ET	4	65.2	34.8

In Table 7, the run length results are presented for countries with three or more rivers. The number (and percentage) of rivers in each country displaying run lengths below, within or above the 90% confidence interval (CI) are listed. The percentage of rivers in each category was tested using Chi-square at the 5% level of significance for countries with 20 or more rivers to determine if their run length behaviour was significantly different from the AR(1) model. Of the nine countries with 20 or more rivers only Australia and Sweden showed run lengths not significantly different from an AR(1) model. Norway, Canada, the United States, South Africa and Argentina all showed significantly more rivers with longer run lengths than expected from the AR(1) model, while Denmark and Chile showed significantly less rivers outside the 90% CI than expected for an AR(1) model. These individual country results are not inconsistent with the observation in Paper 1 (McMahon et al., 2007c) that the AR(1) model adequately represents the range of lag-one serial correlation observed world-wide.

To obtain the spatial detail summarized in Table 7, those rivers where the run length frequency distribution skewness metric lies outside the confidence interval were noted. The spatial distribution of whether a river has shorter (below the 90% CI) or longer (above the 90% CI) run lengths than expected for an AR(1) model is shown in Fig. 7. Of the five countries with statistically significant numbers of longer run length stations, those in Argentina are found in the northern and central regions, in Canada, along the western mountains and in Norway, the United States and South Afri-

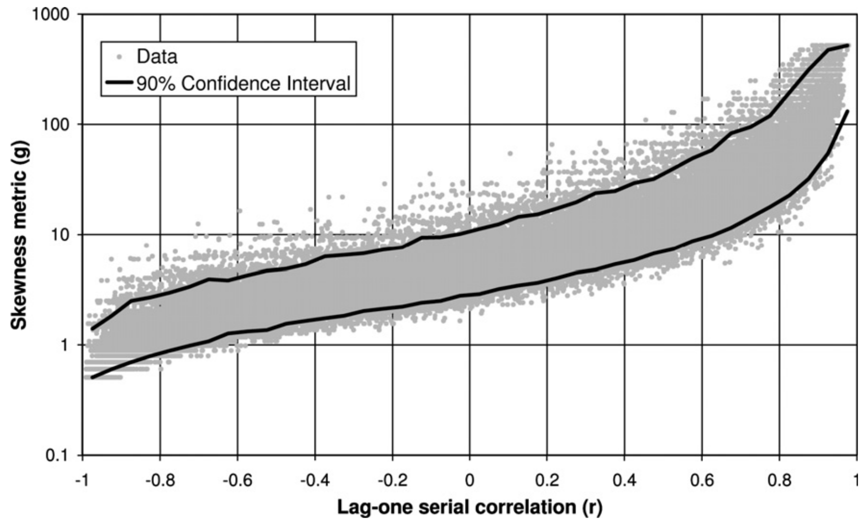

Figure 6 Simulated values of run length skewness metric *g* and lag-one serial correlation for 40,040 samples of size 64, with 90% confidence interval (adapted from Peel et al., 2004b).

ca, they are widely dispersed. The tendency of western Canadian rivers to display longer run lengths than expected from an AR(1) model maybe due to the influence of the Pacific Decadal Oscillation (PDO, Mantua et al., 1997).

In Table 8, the run length results are presented for those Köppen zones containing three or more rivers. Like the country analysis in Table 7 the number (and percentage) of rivers in each Köppen zone displaying a different distribution of run lengths than expected for an AR(1) model are shown. Again the percentage of rivers in each category was tested using Chi-square, at the 5% level of significance, for zones with 20 or more rivers to determine if the run length behaviour was significantly different from the AR(1) model. Of the 11 zones with 20 or more rivers, six zones (tropical Af, arid BSk, temperate Cwa, Cfa and cold Dfb, Dfc) had significantly more stations with longer run lengths than expected from an AR(1) model. Three zones (arid BWk and temperate Csb and Cfb) showed run lengths which are not significantly different from an AR(1) model. In tropical Aw, rivers displayed significantly longer and shorter runs than expected and in arid BSh the rivers showed significantly shorter run lengths than expected from an AR(1) model. Referring again to Fig. 7, the spatial distribution of significantly shorter or longer run lengths for individual rivers, the Aw result (significant number of shorter and longer stations) reveals an interesting pattern. The Aw rivers with significantly shorter runs are grouped in central Africa, while the rivers with longer runs are in West Africa. Why this is the case is presently unknown, but requires further investigation. The other Köppen zone results (Table 8) did not display any consistent spatial patterns (Fig. 7).

Hypothetical reservoir capacity estimates

We carried out reservoir storage—yield analysis using three techniques — two well-known procedures, SPA and Behaviour Analysis, and a relatively new procedure, EDA. The three techniques were applied to a hypothetical storage located on each of the 729 rivers in the data set with 25 or more years of data. Monthly time series were used for SPA and Behaviour Analysis and annual data were used for EDA. In each case we assumed a target draft or yield from the reservoir of 75% of the mean annual inflow. In the Behaviour Analysis, capacity was required to meet the target draft 95% of time on a monthly basis and 1 in 100 years recurrence interval was adopted for EDA. The capacity estimates to meet the relevant conditions are expressed as ratios of the mean annual inflow. These three methods are carefully compared in McMahon et al. (2007a,b), where it is noted that EDA, SPA and Behaviour Analysis (BA) all give comparative storage values, but that they have individual limitations. For a common withdrawal rate, EDA needs a long enough record to produce at least two annual deficits; SPA does not link reliability to the storage calculated; BA is an iterative procedure to find the critical storage associated with a given reliability, which requires either a long record or a low failure risk. The result is that their values which appear in Tables 9 and 10 are not intended to be compared across the tables but down the tables.

Tables 9 and 10 and Fig. 8 detail the results of reservoir storage—yield analyses. Values of EDA are presented in Table 9, column 4 for the same global rivers as listed in Table 1. However, because there is a restriction in the application of EDA as noted above, column 4 in Table 9 includes the number of rivers used in the EDA analysis. Countries exhibiting the major deficits (>1) are Zimbabwe 4.58, Mali 4.27, Morocco 2.86, South Africa 2.14, Burkina Faso 2.00, Australia 1.88, Iran 1.27 and France 1.20. France appears to be the odd country out in this group but we note it has a median annual Cv of 0.49, much larger than Cv's in other European countries.

Column 4, Table 10 lists the EDA values of storage required as a ratio to mean annual flow, by Köppen zone. The values range from 4.6 for BSh (arid, steppe hot) to 0.18 for Dfc (cold, without dry season and cool summer). No statistics are available for ET (polar, tundra) either because the records are too short to give at least two deficits or because the 'reservoirs' would continuously spill. This observation is reinforced by the SPA and Behaviour values which would suggest that this region would require smaller

Table 7 Runs below the median for rivers with 25 years or more of annual streamflow by country

Country (1)	No. of stations (2)	Shorter[a] (%) (3)	Normal[a] (%) (4)	Longer[a] (%) (5)
Asia				
China	11	0 (0.0)	9 (81.8)	2 (18.2)
Iran	3	0	1	2
Japan	3	0	2	1
Russia	11	0 (0.0)	11 (100.0)	0 (0.0)
Sri Lanka	3	0	3	0
Taiwan	18	0 (0.0)	16 (88.9)	2 (11.1)
Thailand	6	0	6	0
Australia				
Australia	114	11 (9.7)	95 (83.3)	8 (7.0)
Europe				
Slovakia	4	0	3	1
Denmark	31	0 (0.0)	30 (96.8)	1 (3.2)
Finland	3	0	3	0
France	4	0	3	1
Hungary	6	0	5	1
Iceland	6	0	4	2
Italy	4	0	4	0
Norway	21	0 (0.0)	18 (85.7)	3 (14.3)
Sweden	46	1 (2.2)	42 (91.3)	3 (6.5)
United Kingdom	16	0 (0.0)	14 (87.5)	2 (12.5)
North Africa				
Burkina Faso	4	0	3	1
Cameroon	12	1 (8.3)	10 (83.3)	1 (8.3)
Mali	7	1	4	2
Morocco	5	0	3	2
Senegal	3	0	3	0
Sudan	3	2	1	0
North America				
Canada	124	**0 (0.0)**	**108 (87.1)**	**16 (12.9)**
Jamaica	3	0	3	0
Panama	18	1 (5.6)	13 (72.2)	4 (22.2)
United States	50	**1 (2.0)**	**43 (86.0)**	**6 (12.0)**
South Africa				
Madagascar	3	0	3	0
Rep South Africa	26	1 (3.9)	22 (84.6)	3 (11.5)
Zimbabwe	16	1 (6.3)	11 (68.7)	4 (25.0)
South America				
Argentina	51	**1 (2.0)**	**42 (82.3)**	**8 (15.7)**
Brazil	7	0	6	1
Chile	35	0 (0.0)	34 (97.1)	1 (2.9)
Guyana	4	0	3	1
South Pacific				
New Zealand	14	0 (0.0)	14 (100.0)	0 (0.0)

[a] Number (percentage) of rivers with values of g less than (Shorter), within (Normal) or above (Longer) the AR(1) 90% confidence interval. Percentages are given only for countries where there are 10 or more rivers. Values in bold indicate the percentages for a country are significantly different from the expected values of 5%, 90% and 5% at the 5% level of significance using a Chi-square test (only applied to countries with 50 or more rivers).

storages than even Dfc. On the other hand, in contrast to the very high value for Cwb, zone Cwa (temperate, dry winter and hot summer) exhibits a lower median value. This is due to most Cwb stations being located in Argentina, South Africa and Zimbabwe (generally large storages required), while in the Cwa zone the same three countries are represented along with China and Taiwan. Overall, however, as expected, the B (arid) climates show the largest storage requirements and cold climates show the smallest.

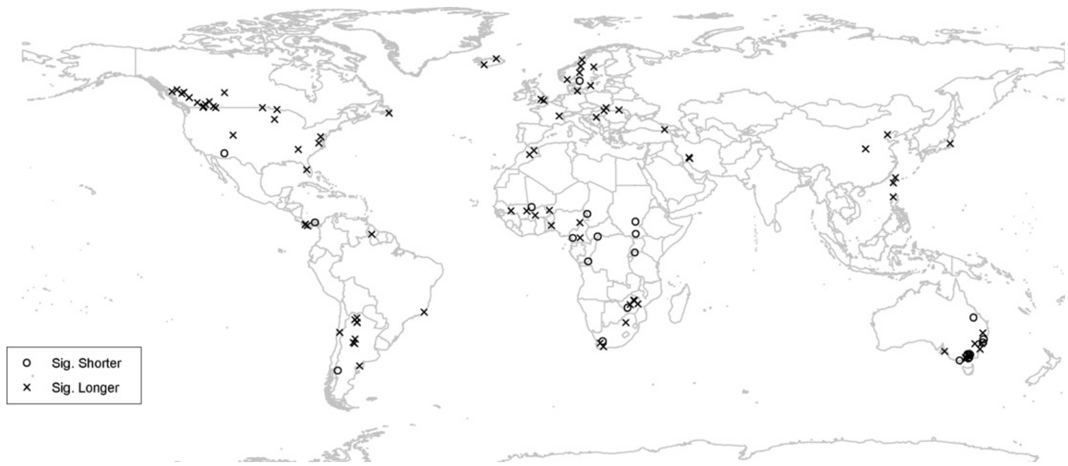

Figure 7 Global distribution of rivers that have shorter or longer run lengths than expected for an AR(1) model.

Table 8 Runs below the median for rivers with 25 years or more of annual streamflow by Köppen climate

Köppen class (1)	No. of stations (2)	Shorter[a] (%) (3)	Normal[a] (%) (4)	Longer[a] (%) (5)
Af	32	2 (6.3)	26 (81.2)	4 (12.5)
Am	4	0	3	1
Aw	40	6 (15.0)	27 (67.5)	7 (17.5)
BWk	22	1 (4.5)	20 (90.9)	1 (4.5)
BSh	26	3 (11.5)	22 (84.6)	1 (3.9)
BSk	34	1 (2.9)	26 (76.5)	7 (20.6)
Csa	12	0 (0.0)	9 (75.0)	3 (25.0)
Csb	42	1 (2.4)	40 (95.2)	1 (2.4)
Cwa	31	0 (0.0)	24 (77.4)	7 (22.6)
Cwb	17	0 (0.0)	13 (76.5)	4 (23.5)
Cfa	87	**1 (1.1)**	**78 (89.7)**	**8 (9.2)**
Cfb	114	9 (7.9)	95 (83.3)	10 (8.8)
Dsb	3	0	3	0
Dwa	3	0	2	1
Dwb	3	0	3	0
Dwc	3	0	3	0
Dfa	3	0	2	1
Dfb	164	**1 (0.6)**	**144 (87.8)**	**19 (11.6)**
Dfc	76	**0 (0.0)**	**67 (88.2)**	**9 (11.8)**
ET	6	0	4	2

[a] Number (percentage) of rivers with values of g less than (Shorter), within (Normal) or above (Longer) the AR(1) 90% confidence interval. Percentages are given only for Köppen zones where there are 10 or more rivers. Values in bold indicate the percentages for a Köppen zone are significantly different from the expected values of 5%, 90% and 5% at the 5% level of significance using a Chi-square test (only applied to zones with 50 or more rivers).

SPA values as ratios of mean annual flow are listed in Table 9, column 5. Four countries exhibit median SPA values >2 — Zimbabwe (4.00), Mali (3.59), South Africa (2.43) and Morocco (2.25) and a further five have values $>1 \times \mu$ — Australia (1.95), Burkina Faso (1.66), France (1.20), Senegal (1.14) and Iran (1.07). It is reassuring to note that the same nine countries rank as the countries with the largest reservoir capacity requirements based on a Behaviour Analysis (Table 9, column 6). (The behaviour estimates are for 95% monthly reliability, and so the estimates will tend to be smaller than the SPA values.)

The spatial distribution of the SPA values (Fig. 8) as a ratio of the mean annual flow is very similar to the EDA results (figure not included). Fig. 8 shows that as a whole Europe exhibits low reservoir need, with France being an exception. Coastal northeastern and northwestern North America exhibit low to medium reservoir requirements, with higher values appearing in the central and southern regions of Canada and the United States. South America generally shows low to medium deficits with the exception of the central regions of Chile and Argentina. In Africa the required reservoir capacities are low in equatorial Cameroon, while they are high in the Sahel region, Morocco, Zimbabwe and South Africa. Deficits are high on mainland Australia and low in Tasmania and New Zealand.

Table 9 Median values of reservoir capacity estimates (as ratios of mean annual flow) and performance measures for 75% targeted draft by country

Country (1)	No. of rivers (2)	Annual Cv (3)	EDA (4)	SPA (5)	Behave (6)	Monthly rel. (7)	Monthly resil. (8)	Monthly dim. vul. (9)
Asia								
China	11	0.36	0.48 (10)[b]	0.57	0.27	0.69	0.25	0.60
			(0.12–2.32)[a]	(0.25–2.11)	(0.15–1.35)	(0.58–0.79)	(0.17–0.35)	(0.42–0.76)
Iran	3	0.47	1.27	1.07	0.48	0.73	0.21	0.49
Japan	3	0.27	0.28	0.38	0.17	0.84	0.44	0.37
Russia	11	0.18	0.21 (7)	0.56	0.27	0.64	0.24	0.85
				(0.28–0.85)	(0.22–0.44)	(0.52–0.70)	(0.17–0.27)	(0.64–0.96)
Sri Lanka	3	0.22	0.26	0.36	0.20	0.76	0.32	0.61
Taiwan	18	0.30	0.37	0.56	0.30	0.63	0.25	0.62
			(0.18–0.59)	(0.36–0.99)	(0.23–0.54)	(0.47–0.74)	(0.16–0.33)	(0.50–0.92)
Thailand	6	0.23	0.42 (4)	0.49	0.31	0.59	0.21	0.77
Australia								
Australia	114	0.68	1.88 (113)	1.95	1.19	0.51	0.18	0.82
			(0.35–5.07)	(0.46–4.92)	(0.20–3.34)	(0.33–0.77)	(0.12–0.33)	(0.59–0.95)
Europe								
Denmark	31	0.28	0.37 (26)	0.50	0.23	0.75	0.26	0.51
			(0.17–0.83)	(0.07–0.94)	(0.02–0.52)	(0.58–0.996)	(0.20–0.42)	(0.00–0.86)
Finland	3	0.21	0.41	0.77	0.21	0.87	0.12	0.38
France	4	0.49	1.20	1.20	0.59	0.66	0.23	0.69
Hungary	6	0.39	0.67	0.85	0.39	0.73	0.25	0.54
Iceland	6	0.12	ns	0.10	0.035	0.99	0.64	0.16
Italy	4	0.26	0.30	0.39	0.13	0.91	0.31	0.33
Norway	21	0.19	0.19 (20)	0.41	0.24	0.70	0.31	0.69
			(0.12–0.30)	(0.30–0.68)	(0.16–0.34)	(0.58–0.85)	(0.20–0.45)	(0.54–0.88)
Slovakia	4	0.27	0.30	0.47	0.21	0.80	0.30	0.50
Sweden	46	0.23	0.19 (40)	0.45	0.27	0.70	0.26	0.64
			(0.09–0.64)	(0.29–0.81)	(0.19–0.38)	(0.62–0.82)	(0.22–0.34)	(0.87–0.58)
United Kingdom	16	0.22	0.36 (15)	0.45	0.20	0.78	0.33	0.53
			(0.13–0.99)	(0.23–1.30)	(0.11–0.61)	(0.63–0.91)	(0.20–0.50)	(0.43–0.71)
North Africa								
Burkina Faso	4	0.40	2.00 (3)	1.66	0.66	0.59	0.20	0.73
Cameroon	12	0.17	0.19 (6)	0.30	0.20	0.72	0.28	0.57
				(0.20–0.45)	(0.11–0.27)	(0.61–0.86)	(0.22–0.48)	(0.28–0.90)
Mali	7	0.47	4.27 (5)	3.59	2.52	0.49	0.17	0.95

Morocco	5	0.61	2.86	2.25	1.38	0.56	0.19	0.55
Senegal	3	0.33	0.74	1.14	0.48	0.48	0.16	0.98
Sudan	3	0.31	0.64 (2)	0.87	0.46	0.82	0.14	0.27
North America								
Canada	124	0.21	0.32 (100) (0.10—1.62)	0.46 (0.28—1.41)	0.27 (0.16—0.81)	0.67 (0.51—0.83)	0.24 (0.17—0.40)	0.65 (0.47—0.82)
Jamaica	3	0.20	0.20	0.35	0.22	0.75	0.34	0.58
Panama	18	0.24	0.27 (13) (0.12—0.60)	0.36 (0.12—0.56)	0.22 (0.08—0.32)	0.76 (0.68—0.95)	0.34 (0.27—0.46)	0.58 (0.25—0.71)
United States	50	0.37	0.76 (49) (0.36—2.02)	0.88 (0.59—2.13)	0.42 (0.21—1.17)	0.65 (0.54—0.80)	0.24 (0.17—0.31)	0.69 (0.45—0.85)
South Africa								
Madagascar	3	0.27	0.34 (1)	0.33	0.18	0.76	0.30	0.54
Rep South Africa	26	0.83	2.14 (25) (0.60—3.81)	2.43 (0.79—3.76)	1.50 (0.46—2.46)	0.47 (0.34—0.71)	0.18 (0.14—0.24)	0.85 (0.58—0.90)
Zimbabwe	16	1.00	4.58 (3.43—7.03)	4.00 (2.96—5.63)	3.02 (2.09—4.69)	0.40 (0.31—0.50)	0.12 (0.11—0.15)	0.89 (0.75—0.97)
South America								
Argentina	51	0.41	0.73 (49) (0.25—2.75)	0.82 (0.31—2.97)	0.37 (0.12—1.61)	0.66 (0.52—0.90)	0.22 (0.14—0.40)	0.53 (0.31—0.80)
Brazil	7	0.33	0.88	0.83	0.40	0.80	0.25	0.50
Chile	35	0.34	0.64 (33) (0.28—2.95)	0.77 (0.46—3.38)	0.31 (0.19—2.25)	0.69 (0.52—0.81)	0.25 (0.07—0.35)	0.56 (0.38—0.79)
Guyana	4	0.28	0.69	0.78	0.31	0.73	0.28	0.57
South Pacific								
New Zealand	14	0.21	0.32 (9)	0.30 (0.14—0.42)	0.15 (0.07—0.23)	0.87 (0.79—0.96)	0.43 (0.25—0.57)	0.45 (0.23—0.53)

EDA is deficit for 1 in 100-year recurrence.
Behave is behaviour storage estimates for 95% monthly time reliability.
rel. is reliability.
resil. is resilience.
dim. vul. is dimensionless vulnerability.
ns, no solution.
[a] Values in parenthesis are 10th and 90th percentiles.
[b] Value in parenthesis indicate the number of rivers for which a solution was available.

Table 10 Median values of reservoir capacity estimates (as ratios of mean annual flow) and performance measures for 75% targeted draft by Köppen climate

Köppen zone (1)	No. of rivers (2)	Annual Cv (3)	EDA (4)	SPA (5)	Behave (6)	Monthly rel. (7)	Monthly resil. (8)	Monthly dim. vul. (9)
Af	32	0.26	0.35 (25)[#] (0.13–0.70)[a]	0.39 (0.16–0.74)	0.23 (0.083–0.37)	0.75 (0.64–0.93)	0.31 (0.23–0.47)	0.60 (0.32–0.71)
Am	4	0.22	0.49 (3)	0.46	0.18	0.80	0.39	0.47
Aw	40	0.29	0.76 (26) (0.11–4.39)	0.68 (0.20–3.13)	0.38 (0.11–2.23)	0.63 (0.45–0.88)	0.22 (0.14–0.40)	0.73 (0.27–0.97)
BWk	22	0.76	2.46 (20) (1.10–4.39)	2.26 (0.99–3.92)	1.58 (0.60–2.95)	0.58 (0.48–0.75)	0.11 (0.040–0.22)	0.53 (0.40–0.80)
BSh	26	1.01	4.63 (24) (0.82–9.76)	3.94 (5.21–9.15)	2.83 (0.35–7.16)	0.41 (0.27–0.69)	0.12 (0.11–0.22)	0.95 (0.82–0.98)
BSk	34	0.64	1.57 (0.43–4.21)	1.71 (0.58–4.84)	0.97 (0.23–3.14)	0.53 (0.34–0.80)	0.18 (0.13–0.28)	0.75 (0.38–0.90)
Csa	12	0.58	1.80 (11) (0.81–3.81)	2.19 (0.72–3.82)	1.17 (0.64–2.38)	0.55 (0.49–0.89)	0.19 (0.16–0.28)	0.77 (0.36–0.94)
Csb	42	0.30	0.54 (40) (0.19–1.14)	0.63 (0.28–1.71)	0.26 (0.10–0.77)	0.76 (0.51–0.92)	0.28 (0.17–0.40)	0.57 (0.34–0.93)
Cwa	31	0.40	0.69 (0.31–2.80)	0.99 (0.53–2.86)	0.52 (0.27–1.73)	0.58 (0.44–0.69)	0.20 (0.15–0.28)	0.78 (0.58–0.96)
Cwb	17	0.80	3.39 (15) (1.00–4.94)	2.81 (0.65–3.96)	1.91 (0.33–3.10)	0.49 (0.37–0.60)	0.15 (0.12–0.28)	0.84 (0.56–0.95)
Cfa	87	0.39	0.93 (86) (0.24–4.21)	1.14 (0.38–4.43)	0.50 (0.17–3.08)	0.62 (0.41–0.82)	0.23 (0.13–0.34)	0.73 (0.41–0.85)
Cfb	114	0.35	0.61 (106) (0.14–2.75)	0.70 (0.23–2.74)	0.31 (0.12–1.70)	0.70 (0.46–0.89)	0.24 (0.16–0.45)	0.66 (0.41–0.88)
Dsb	3	0.19	0.48 (2)	0.46	0.24	0.72	0.25	0.44
Dwa	3	0.56	2.32	2.11	1.35	0.67	0.25	0.66
Dwb	3	0.18	0.29 (2)	0.57	0.31	0.69	0.22	0.57
Dwc	3	0.22	0.41	0.69	0.27	0.66	0.25	0.88
Dfa	3	0.38	0.51	0.81	0.40	0.71	0.24	0.71
Dfb	164	0.25	0.33 (146) (0.11–0.94)	0.54 (0.28–1.09)	0.28 (0.15–0.55)	0.69 (0.53–0.85)	0.26 (0.18–0.42)	0.60 (0.43–0.79)
Dfc	76	0.19	0.18 (56) (0.10–0.91)	0.41 (0.28–1.12)	0.26 (0.16–0.38)	0.69 (0.58–0.87)	0.25 (0.19–0.34)	0.68 (0.39–0.85)
ET	6	0.12	ns	0.10	0.035	0.99	0.64	0.16

EDA is deficit for 1 in 100-year recurrence.
Behave is behaviour storage estimates for 95% monthly time reliability.
rel. is reliability.
resil. is resilience.
dim. vul. is dimensionless vulnerability.
ns, no solution.
[a] 10th and 90th percentile values are in parenthesis.
[#] Value in parenthesis indicates the number of river for which a solution was available.

Because of the high correlation (98%) between the SPA and behaviour reservoir capacity estimates in Table 9, in examining how capacity need varies with climate we will deal only with SPA estimates (Table 10, column 5). Based on the five broad climate classes, the following median SPA capacity estimates are required to meet the given draft: B (arid) 2.56, C (temperate) 1.22, A (tropical) 0.55, D (cold) 0.54 and E (polar) 0.10. These are consistent with the EDA values. In the C climate zones several classes stand out, especially Cwb and Csa.

Reservoir storage—yield performance

The results of analysis of the three measures of reservoir storage—yield performance — monthly time-based reliability, resilience and dimensionless vulnerability — are set out in Tables 9 and 10, columns 7, 8 and 9, respectively. It needs to be recalled that these metrics are based on a monthly simulation (behaviour) analysis for an initially full hypothetical reservoir of capacity equal to the mean annual inflow and for a 75% targeted draft. The absolute values in the table are not particularly important but rather the relative median values between countries (Table 9) and between climates (Table 10).

It is noted that, because monthly reliability values are constrained between 0 and 1, the range of relative differences in both tables appears less than the range of reservoir capacity estimates discussed above. Furthermore, the relationship between reservoir capacity and reliability is a non-linear one, so that as the reliability approaches zero, the required capacity to supply the draft increases dramatically. The nine countries in rank order having the least reliable reservoirs are: Zimbabwe 0.40, South Africa 0.47, Senegal 0.48, Mali 0.49, Australia 0.51, Morocco 0.56, Burkina Faso 0.59, Thailand 0.59 and Taiwan 0.63. Compared with the SPA list of countries requiring the largest storages, Thailand and Taiwan have replaced France and Iran from that list. For Table 9, columns 5 and 6 it can be observed that based on the Behaviour Analysis relatively smaller storages are required in France and Iran compared with SPA estimates, and hence the reservoirs in those countries would be less likely to fail compared with reservoirs in Thailand and Taiwan.

Of more interest is the relation of reservoir reliability to climate (Table 10, column 7) than reliability to country. Here we observe for the general climate classes, that reservoirs on rivers located in arid climates (B in Table 10) are less reliable than those in the other climates. The reservoir reliability ranking is as follows: reservoirs in arid (B) climate 0.50, temperate (C) 0.66, tropical (A) and cold (D) 0.69 and polar (E) 0.99. These are not inconsistent with the values noted earlier for reservoir capacities based on the Behaviour Analysis. Again, as observed earlier, both Cwb and Csa stand out as being the two sub-classes in the temperate (C) zone that exhibit, in this analysis, reliabilities of reservoir yield which are much lower than the rivers in other temperate classes.

The spatial distribution of monthly reservoir reliability (Fig. 9) shows a pattern that is similar to the distribution of Cv (Fig. 2) and virtually the inverse of the SPA reservoir capacity as a ratio of mean annual flow (Fig. 8).

We turn to the resilience metric, which describes how readily a reservoir will recover following a state of near emptiness. Median values by country and climate are listed in Tables 9 and 10, column 8, respectively. By country, we note that Zimbabwe rivers are least able to recover from low inflows. The ranking of resilience values <0.2 is Zimbabwe 0.12, Finland 0.12, Sudan 0.14, Senegal 0.16, Mali 0.17, South Africa 0.18, Australia 0.18 and Morocco 0.19. From our earlier analysis Finland rivers (there are only three) seem to be misplaced. To explore this, monthly reservoir reliability is plotted against resilience for the global rivers in Fig. 10. The figure shows as expected that there is general relationship between these two variables, so that systems with higher reliability also tend to exhibit higher resilience, though there are exceptions. The median values of two of the three Finnish rivers are examples of such exceptions. An interesting feature of these two Finnish rivers is that natural lakes are upstream of the gauging stations. A check of the location of the other rivers with high reliability and low

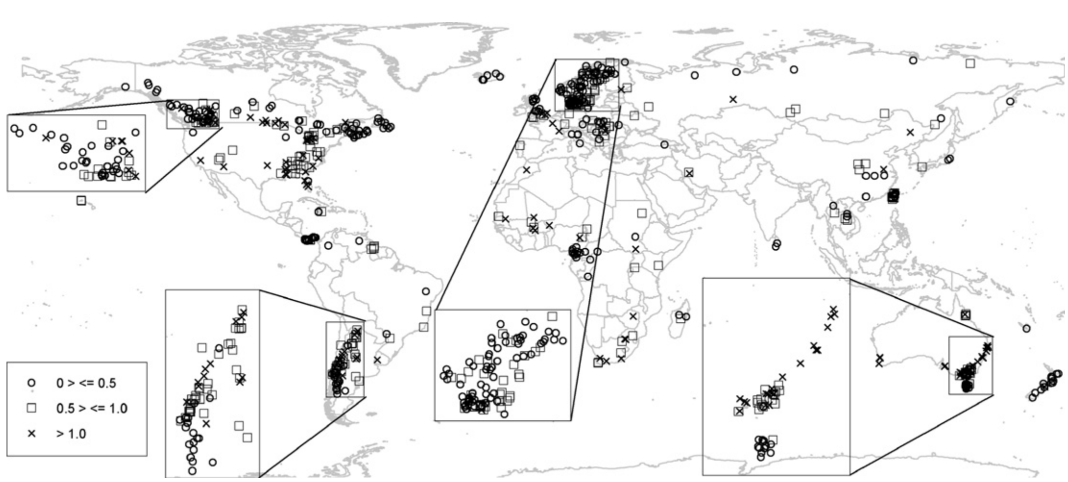

Figure 8 Global distribution of estimated reservoir capacity estimates as ratios of mean annual flow for 75% targeted draft using traditional Sequent Peak Algorithm.

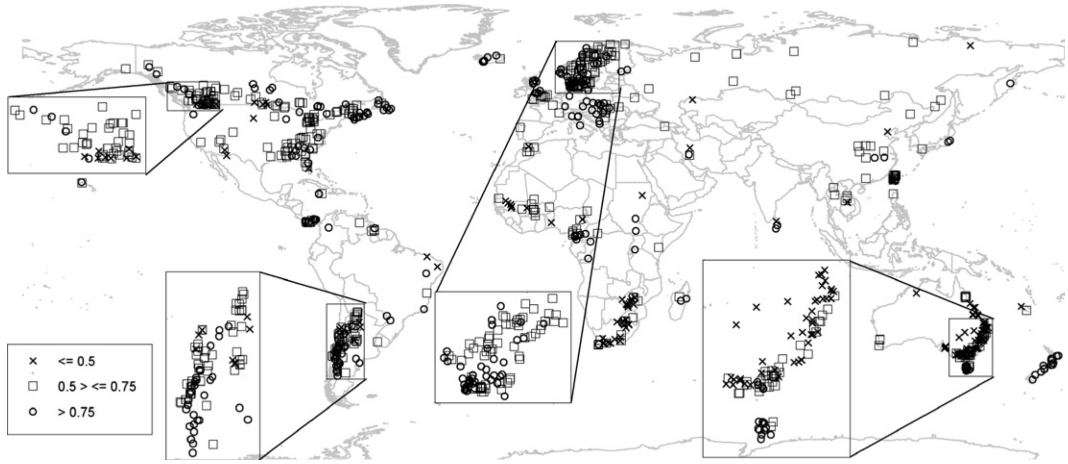

Figure 9 Global distribution of monthly time reliability for storage sizes equal to the mean annual flow and for 75% targeted draft. (Analysis is based on monthly flow sequences with 25 or more years of data.)

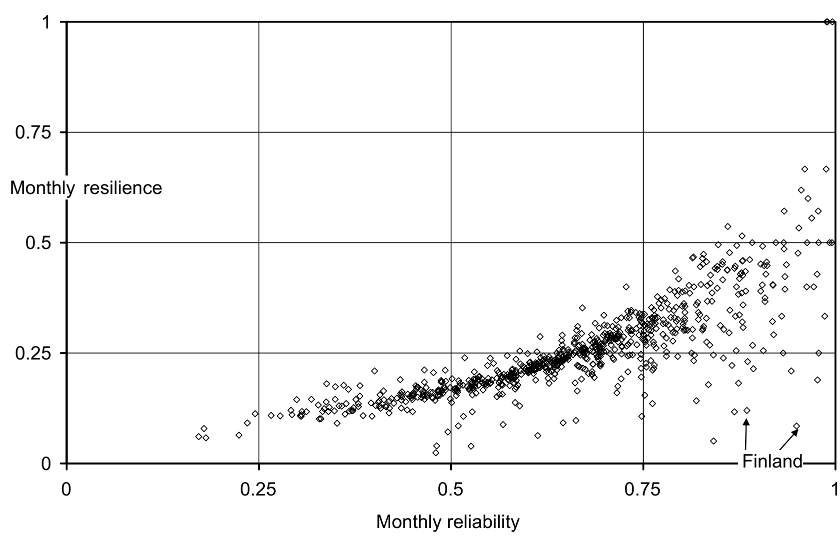

Figure 10 Relationship for the global set of rivers based on monthly inflows between resilience and monthly time reliability for a reservoir of capacity equal to mean annual inflow and 75% target draft.

resilience (lower right corner of Fig. 10) reveals that most of these rivers also have natural lakes upstream. Streamflow downstream of a lake system generally has low interannual variability (high reliability) and high lag-one serial correlation. In terms of resilience, when a reservoir approaches emptiness, inflows with high serial correlation and low variability tend to take longer to recover and, therefore, exhibit low resilience.

The relationship between resilience and climate (Table 10, column 8) is consistent with the storage need and climate. This is confirmed in Fig. 11 in which the median SPA values (reservoir capacity as ratio of mean annual flow) (Table 10, column 5) are plotted against the equivalent resilience values (Table 10, column 8). Clearly, rivers that require relatively large storage reservoirs have low resilience i.e. they will recover very slowly whereas those that are relatively small will respond quickly when emptied.

The spatial distribution of resilience (Fig. 12) appears to be broadly similar to that of reliability (Fig. 9), as expected from the relationship between the two variables (Fig. 10).

The third reservoir performance characteristic is dimensionless vulnerability and measures the severity of a failure in terms of the shortfall in meeting the target draft during a period of failure. Values of dimensionless vulnerability for the global set are summarized by countries and climates in Tables 9 and 10, column 9, respectively. It has been shown elsewhere (McMahon et al., 2006) that for practical purposes dimensionless vulnerability is the complement of resilience for reservoirs exhibiting over-year storage (see, for example, the values for Australia and South Africa in Table 9) and the relationships between the two metrics are examined in the second paper in this series (McMahon et al., 2007d).

Dimensionless vulnerability (DV) by country shows values ranging from 0.16 (shortfalls are not severe) in Iceland to

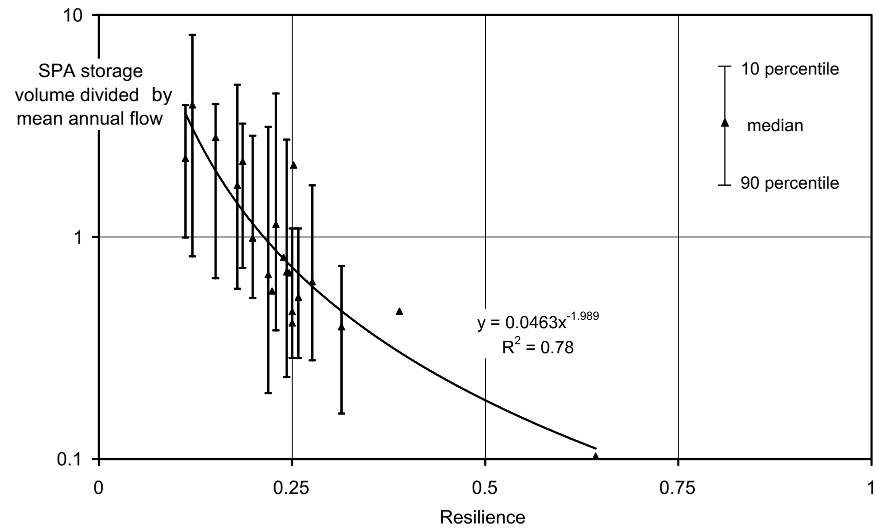

Figure 11 Relationship based on Köppen zones between traditional Sequent Peak Algorithm reservoir capacities (as ratios of mean annual flow) and resilience values using the global set of monthly inflows for 75% target draft. The median values were based on at least three rivers in each zone and at least 10 rivers were used to compute the percentiles.

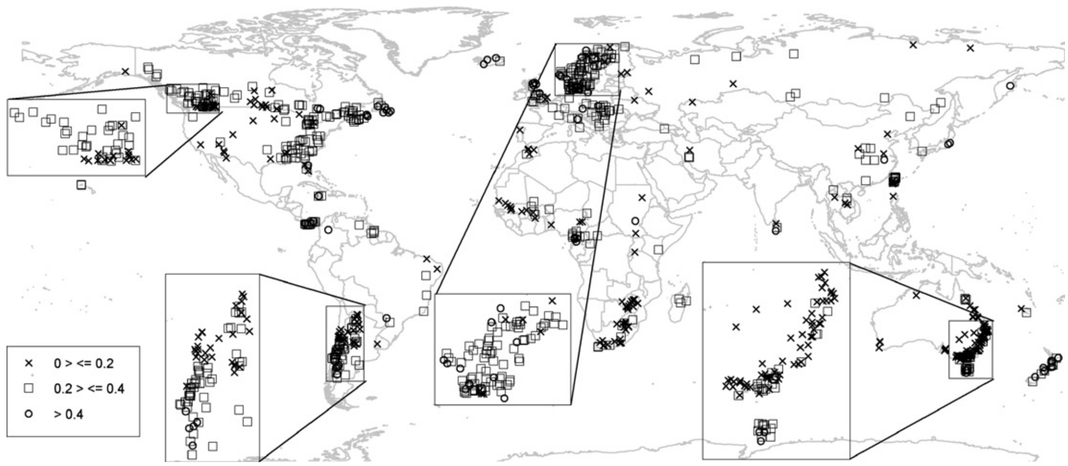

Figure 12 Global distribution of Hashimoto resilience estimates for storages in size equal to mean annual flow and for 75% targeted draft. (Analysis is based on monthly flows.)

0.98 (extreme severity) in Senegal. The countries with the median DV values >0.8 are Senegal 0.98, Mali 0.95, Zimbabwe 0.89, South Africa 0.85, Russia 0.85 and Australia 0.82. Many of the countries that exhibited low resilience also show high dimensionless vulnerability. The exceptions to this observation are Finland and Sudan. Both these countries have rivers with low resilience and low vulnerability, due to the majority of the rivers being fed by natural lakes. The effect of the lakes is to increase the streamflow autocorrelation thereby reducing their ability to recover quickly from a major deficit.

Rivers in the BSh (arid steppe hot) climate zone exhibit the greatest relative shortfall in failing to meet a target draft (DV = 0.95). Two other climate classes (Dwc 0.88 and Cwb 0.84) also have very high dimensionless vulnerability values. It can be seen from Table 10, column 9 that generally rivers in B (arid) climates have the highest DV values. Consistent with an earlier observation, rivers in the E (polar) climates have very small shortfalls. However, it is noteworthy that the rivers in the other three broad climate divisions have similar DV values (C 0.70, A 0.66 and D 0.63). We have not made a plot showing the global variation of DV as it exhibits a similar pattern to the inverse of reliability (Fig. 9).

Conclusions

For most analyses reported in this paper, there were 729 rivers available world-wide that had monthly and annual historical streamflow records with 25 or more years of continuous data. The analyses can be grouped under three headings:

(a) The first group included standard statistical parameters, persistence analysis through Empirical Mode Decomposition and runs length analysis.
(b) The second group addresses reservoir storage—yield relationships through the application of the Extended Deficit Analysis, traditional Sequent Peak Algorithm and Behaviour simulation.
(c) The performance of a hypothetical reservoir on each river was explored through reliability, resilience and vulnerability metrics in the third group of analyses.

The results are summarized by country and climate. The well-known Köppen climate classification was adopted to provide a climate setting for the study.

Based on our analyses, we have identified the following conclusions:

(1) Overall, there appear to be few published papers or reports dealing with comparisons of capacities of hypothetical reservoirs and their performance by country or climate zone.
(2) The rivers cover a wide range of mean annual runoff from a country median of 34 mm in South Africa to 2417 mm in Panama.
(3) The median country variation of annual Cv is also large, varying from Zimbabwe (1.0) to Iceland (0.12). The variation across the major climate zones is Tropical 0.27, Arid 0.79, Temperate 0.39, Cold 0.23 and Polar 0.12.
(4) Of the 1221 rivers in the global data set, 260 have annual auto-correlations that are significantly different from zero at the 5% level of significance.
(5) Based on EMD analysis it was found that rivers in the Sahel region of Africa exhibited larger inter-decadal variances compared with those for other global rivers.
(6) It was observed that Argentina, Canada and the United States showed significantly more rivers with longer run lengths than expected from an AR(1) model. The tendency of western Canadian rivers to display longer run lengths than expected from an AR(1) model maybe due to the influence of the Pacific Decadal Oscillation (PDO, Mantua et al., 1997).
(7) The three methods used to study reservoir capacities — the Extended Deficit Analysis, the Sequent Peak Analysis and the Behaviour Analysis — produced very consistent results. Countries exhibiting high deficits ($>1 \times \mu$) include Zimbabwe 4.58, Mali 4.27, Morocco 2.86, South Africa 2.14, Burkina Faso 2.00, Australia 1.88, Iran 1.27 and France 1.20 using Extended Deficit Analysis.
(8) Large deficits occur across the climate classes — B (arid) $2.56 \times \mu$, C (temperate) $1.22 \times \mu$, A (tropical) $0.55 \times \mu$, D (cold) 0.54 and E (polar) $0.10 \times \mu$. In the C climate Cwb (temperate, dry winter and warm summer) and Csa (temperate, dry and hot summer) stand out as regions with large deficits.
(9) In terms of reliability, the reservoirs located in countries with high capacity requirements also exhibit low reliability for a given reservoir size to mean annual flow. We observe for the general climate classes that rivers located in arid climates are less reliable than those in the other climates.
(10) Between countries, resilience is strongly positively related to reliability ($R^2 = 0.67$, $p < 0.001$); dimensionless vulnerability is strongly negatively related to reliability ($R^2 = 0.81$, $p < 0.001$). Thus the comments regarding reliability are appropriately applicable to resilience and dimensionless vulnerability, except where natural lakes are present, which decreases the observed resilience.

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