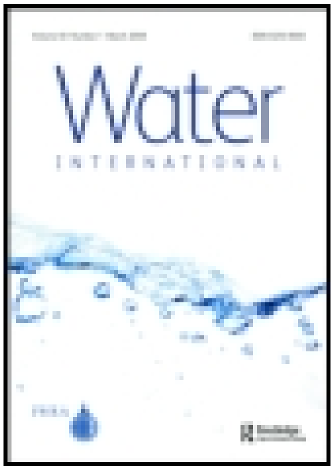

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Climate Change and Trend Detection in Selected Rivers within the Asia-Pacific Region

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Abstract: *Global climate change is currently an issue of great concern. This phenomenon was studied using the runoff of large rivers, which can be considered a regional integrator of the local precipitation occurring in their basins. The long-term stationarity and the possibility of trends in streamflow records stored in the databank of the Global Runoff Data Center (GRDC) at the Federal Institute of Hydrology in Koblenz (Germany) were studied. Runoff records originating from 78 rivers with long monthly runoff series that are geographically distributed throughout the whole Asia-Pacific region were selected for study. For each of the selected rivers, three time series were constructed and analyzed: the mean yearly, and the maximum and minimum monthly discharges. These series were submitted to a two-tier analysis. First, a segmentation procedure developed by Hubert was applied to assess their stationarity. Then the segmented series were submitted to a specialized trend detection software. The results show that about two-thirds of the series have remained stationary and that the monthly minimum runoff exhibited more changing levels (37/78) than the mean (26/78) and maximum (18/78) runoff. Most of the detected changes occurred during the 1960s and 1970s, a period of rapid demographic expansion and urbanization in Asia, when irrigation and other water uses were developed, especially in tropical areas. During the same period and within the area studied, a number of large dams and reservoirs were completed. Since these anthropic interventions could be at the origin of the changes in runoff, there is no regionally consistent evidence supporting global climate change.*

Keywords: *Climate change, trend detection, Asia-Pacific rivers, segmentation, non-parametric tests.*

Introduction

Global climate change is currently an issue of great concern and is often blamed for the occurrence of very low frequency, extreme meteorological events. In this regard, the runoff from large rivers can be considered a regional integrator of the local precipitation occurring in their basins. Folland et al. (1990) and Mann et al. (1999) showed an increase in global temperature variations over the last two decades. IPCC (1996) also concluded that there has been an increase in global mean surface air temperature by between 0.3 and 0.6°C since the late 19th century. These warmer temperatures over the last two decades could imply some changes in the water balance of different parts of the world. Leith and Wakefield (1998) and Zhang et al. (in press) have shown that warmer temperatures have had an effect on the hydrology of streams in Canada. IPCC (1996) also stated that warmer temperatures will lead to more vigorous hydrological cycle, translating into prospects for more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Hence, more investigation must be performed to evaluate the effects of warmer temperatures on hydrology and the availability of an international databank for river runoff constitutes a precious tool that should be exploited for regional analyses.

The Global Runoff Data Center (GRDC) in the German Federal Institute of Hydrology (BfG) at Koblenz (Germany) operates under the auspices of the World Meteorological Organization (WMO). One of its objectives is to collect the discharge time series of the world's rivers, to store them in a unified data bank with a consistent format, and to disseminate this acquired information for scientific use. This exchange of data allows interesting regional syntheses to be made, exploiting information otherwise disseminated at the country level. Such an availability of regional data leads to a better global knowledge of the river regimes (mean values and seasonal distribution of discharges), as well as the availability of surface water resources which constitute an important part of the terrestrial hydrologic cycle.

On the scientific front, this data bank constitutes a major contribution to the water budgets of the world's oceans and to Global Circulation Models (GCM), which are an increasingly important tool for providing a better understanding of the phenomena driving the Earth's climatic environment. In this period of postulated climatic changes and of devastating “El Niño” effects, it provides an unbiased reference against which hypotheses can be statistically tested and assessed.

In a more practical way, water availability constitutes a vital but scarce and dwindling resource for many countries, which limits possibilities for current and future food self-sufficiency. For these mostly tropical and equatorial countries, any change in the long-term availability of water will be fundamentally important for their survival and future well being, both economically and politically.

The purpose of this paper is to investigate the long-time trends of selected Asian and Oceanian river discharges chosen in WMO Regions 2 and 5 by examining and testing whether the eventuality of structural changes (trends) in the discharge data is related to possible modifications either of regional climatic conditions or land and water uses within the river basins. For the purposes of this study, two statistical tools are used: the segmentation procedure (Hubert et al., 1989) and DETECT specialized software (Cluis, 1988; Cluis et al., 1989) for trend detection in time series with characteristics such as non normal distribution, auto-correlation, seasons, outliers, and non-equidistant sampling intervals.

Data Description

The data were directly selected from the GRDC data bank using the GRDC Catalogue Tool software (Version 2.1 for Windows 95-NT). This software allows a researcher to query for data according to specific successive selection criteria such as aggregation frequency (daily or monthly), WMO regions (six continental entities) or subregion numbers (regional entities or watersheds), river name or GRDC station number, country code, range of operational years, and size of river basin.

Once the query file for stations is completed, the GRDC database system extracts the selected data and provides them to the user as an ASCII file. In this case, stations with monthly records from WMO Regions 5 (Oceania-Pacific) and 2 (Asia) were extracted from the GRDC database. A working data set of 78 stations was obtained by using the following criteria as selection guidelines:

- Length of operation: The selected stations present a record of a minimum of 25 years of continuous operation until recent years, with generally less than 5 percent missing data (eight stations were selected with a proportion of missing values greater than 5 percent but smaller than 10 percent).
- Regional representativity: The selected stations should drain large areas, making them representative of their climatic regions and less sensitive to local meteorological events.
- Geographical distribution: The chosen stations are distributed within the whole Asia-Pacific region according to the availability of long time series within the database and their adherence to the selection criteria. They are grouped into five regional geographical subsets to allow possible regionalization of the obtained results. These five subsets are: Oceania-Pacific (19), Southeast Asia (9), Far East Asia (25), Indian Subcontinent (11), and Central Asia (13). The location of the gauging stations is shown in Figure 1 with each station identified by its number from Table 1.

According to GRDC procedures, countries provide their discharge data for storage in the database and are solely responsible for the quality of these data. Lacking information about the quality and homogeneity of the data, the non-parametric trend detection techniques as described and used later in this paper seem to be the most appropriate techniques, even if some detection power is lost in exchange for robustness. On the other hand, very little is known about land and water uses in the water basin areas controlled by the stations; this is also true for historic changes within the river basin, human interventions, derivations or impoundments that might have occurred over the duration of the discharge records. These uncertainties need to be considered in the interpretation of the results obtained in this study, so that conclusion may eventually be derived from these results.

The selected stations within the Asia-Pacific region used for this study are presented in Table 1. The table presents the following information for each river: its GRDC station number, a number for identification on Figure 1, country location code, name of the river and of the related gauging station, longitude and latitude, watershed area, first and last full years of operation, percentage of missing data, and total length of the record in years. The data extracted from the database and used throughout the analysis are the monthly discharges from which yearly values were compounded. The few monthly missing values were first filled in using the long-term monthly mean values. This procedure was generally applied with the exception of cases where such a synthetic value would become a yearly maximum or minimum; in such cases, an interpolated value calculated between successive months was preferred to generate an occasional missing monthly value. Three series of yearly values were then created for analysis:

- A mean yearly series obtained from the 12 monthly values,
- A yearly series of monthly maximum values, abbreviated as maximum monthly series,
- A yearly series of monthly minimum values, abbreviated as minimum monthly series.

The first series should allow the detection of temporal changes in the mean level of the series, and the two last series reflect the change in levels of extreme (high or low) events over time.

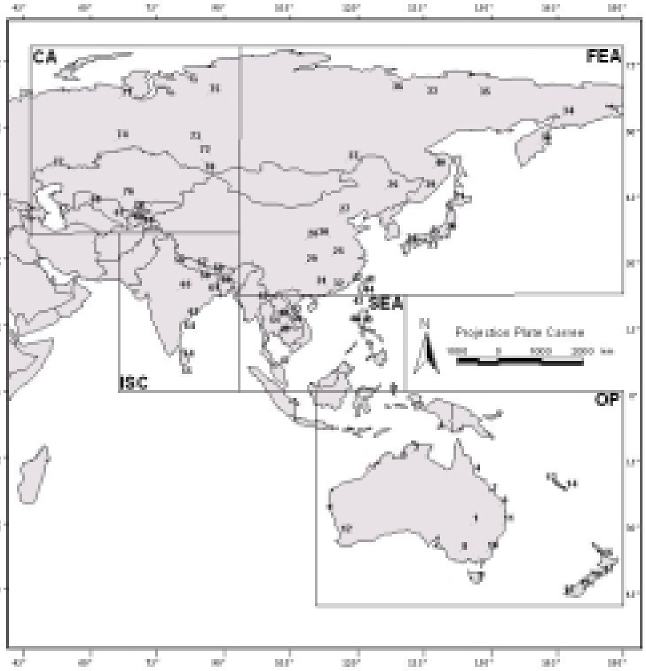

Figure 1. Location of rivers studied in Asia and Oceania. The number representing each river is shown in Table 1. CA = Central Asia; FEA = Far-East Asia; ISC = Indian Subcontinent; SEA = Southeast Asia; and OP = Oceania-Pacific.

Statistical Approach

Hubert's Segmentation Procedure

As a preliminary analysis, a segmentation procedure was applied to yearly series (minimum, mean and maximum). The segmentation procedure was developed by Hubert et al. (1989) and has found many applications, especially for testing for homogeneity and stationarity in the means of West African precipitation and discharge records. In the present study, the segmentation procedure is used to reduce the number of series to be studied by the DETECT software. Without this preliminary step, 234 series would have to be studied by the time-consuming interactive DETECT software.

Essentially, the segmentation procedure determines, for a record of given length, the optimal segmentation of this series into two, three, four, etc., segments of constant levels (stepwise change). The sense of "optimal" here is that the Root Mean Square Error between the measured data and the model (the different levels of each segment) is minimal.

For a series of length n, the number of possible segmentations into m segments $N(n,m)$ can be expressed as the number of possible groupings of $(m - 1)$ objects selected out of a population of $(n - 1)$ objects:

$$N(n,m) = \frac{(n-1)!}{(m-1)!(n-m)!}$$

This number quickly becomes very large and Hubert et al. (1989) have developed an optimization algorithm based on arborescences that avoids testing the bulk of the possible combinations. The search for the optimal segmentation is completed by a constraint applied to the produced segmentations; segments will only be accepted if the means of contiguous segments are significantly different; this can be tested using the contrast concepts introduced by Scheffé (1959) and presented by Dagnelie (1970). The Scheffé test limits the order of the segmentations. Once the optimal segmentation is obtained, the residuals (differences between data values and the local segmentation level) are tested for independence (Wald-Wolfowitz, 1943).

This procedure makes no hypothesis about the distributional or persistence structure of the data. The authors tested the reliability of their procedure using Monte-Carlo simulations on constructed stationary series and found that the Scheffé test on the absence of contrast often falsely rejected the stationarity hypothesis, i.e., over-segmenting the stationary series. In fact, the significance level of the procedure is not related in a simple way to that of the Scheffé test itself. Due to the fact that the procedure has a tendency to over-segment, the procedure has been and can be successfully used as an exploratory analysis to determine which series should be studied in a complete trend detection analysis.

Trend Detection Using the DETECT Software

Most of the classical statistical tests and techniques have been developed with restricting hypotheses of normality and independence. It is well known that real-life data diverge from these theoretical considerations. Most natural resource data exhibit distributions that are not normal and generally positively skewed, and they often simultaneously present all three types of persistence: short-term persistence, annual seasonality and eventually some long-term trends. Furthermore, extreme values (such as outliers) have a determining impact on the results of classical parametric procedures.

To deal with this type of "messy" data, which are more the rule than the exception in nature, classical parametric methods exhibit several weaknesses. Montgomery and Loftis (1987) studied the effects of non-normality, unequal variances, temporal persistence, seasonal fluctuations, and unevenly spaced data on the results obtained using the Student's t-test, and they showed that this test should not be used if the samples have different distributions, unequal variances, or lengths. In addition, seasonal variations or temporal persistence invalidate the results. Helsel (1987) has also shown that parametric procedures are largely influenced by messy data.

Robust techniques (i.e., techniques that give acceptable results, even if the basic theoretical hypotheses are not fully respected) are largely considered as the best available option. Several robust techniques are available, for example M-Estimators (Huber, 1981) and non-parametric tests. In the present study, only non-parametric robust techniques are discussed and used.

Table 1. Characteristics of the Selected Rivers by Area

# on Fig. 1	*River*	*Station*	*Country Code*	*Latitude*	*Longitude*	*Watershed Area*	*Begin Year*	*End Year*	*Percent Missing Data*	*Duration (Years)*
					Oceania-Pacific Area					
1	Darling River	Bourke Town	AU	3009S	14594E	386,000	1944	1993	2.9	49
2	Fitzroy	The Gap	AU	2310S	15010E	135,860	1965	1995	2.5	30
3	Daly	Mount Nancar	AU	1383S	13241E	47,000	1970	1995	3.4	25
4	Herbert River	Ingham	AU	1863S	14613E	8,805	1916	1996	1.4	80
5	Mary River (1)	Mount Bundy	AU	1292S	13165E	5,700	1957	1995	0.6	38
6	Mary River (2)	Miva	AU	2595S	15250E	4,830	1910	1995	0	85
7	Mitchell River	Glenaladale	AU	3775S	14737E	3,900	1938	1987	2.4	49
8	Avoca River	Coonooer	AU	3644S	14330E	2,670	1890	1993	1.3	103
9	Huon River	Frying Pan Creek	AU	4304S	14684E	2,097	1949	1994	0.9	45
10	Murrumbidgee	Mittagang Cross.	AU	3618S	14909E	1,891	1927	1993	1.1	66
11	Nymboida	Nymboida	AU	2998S	15272E	1,660	1909	1993	2.6	84
12	Serpentine	Serpent. Falls	AU	3237S	11601E	769	1911	1992	0.9	81
13	Tipindje	Ouen-Kout	NC	2078S	16499E	247	1956	1984	1.4	28
14	Riviere Des Lacs	Goulet	NC	2223S	16685E	69	1958	1984	0	26
15	Mataura	Gore Hbr	NZ	4610S	16895E	3,465	1961	1993	0	32
16	Motu	Houpoto	NZ	3786S	17765E	1,393	1958	1990	1.7	32
17	Ongarue	Taringamutu	NZ	3886S	17524E	1,075	1963	1994	0	31
18	Hurunui	Mandamus	NZ	4279S	17255E	1,070	1957	1990	4.2	33
19	Ahuriri	Sth Diadem	NZ	4447S	16973E	57	1964	1994	0	30
					Far East Asia Area					
20	Tone	Kurihashi	JP	3613N	13970E	8,588	1938	1986	6.1	48
21	Ishikari	Ishikari-Ohasha	JP	4312N	14153E	12,697	1954	1986	6.3	32
22	Shinano	Ojiya	JP	3730N	13880E	9,719	1965	1988	4.5	23
23	Yodo	Hirakata	JP	3480N	13563E	7,281	1965	1988	4.2	23
24	Chikugo	Senoshita	JP	3353N	13080E	2,315	1965	1988	4.2	23
25	Changjiang	Hankou	CI	3058N	11428E	1,488,036	1865	1986	1.2	121
26	Songhuajiang	Haerbin	CI	4577N	12658E	391,000	1898	1987	4.4	89
27	Yongding	Guanting	CI	4023N	11560E	42,500	1925	1988	6.6	63
28	Jinghe	Zhangjiashan	CI	3463N	10860E	43,200	1933	1986	7.6	53
29	Wujiang	Gongtan	CI	2890N	10835E	58,300	1939	1982	9.1	43
30	Huanghe	Huayuankou	CI	3492N	11365E	730,036	1947	1988	5.2	41
31	Beijiang	Hengshi	CI	2385N	11327E	34,013	1954	1987	1	33
32	Dongjiang	Boluo	CI	2317N	11430E	25,325	1960	1987	0	27
33	Yana	Dzanghky	RS	6967N	13533E	216,000	1938	1984	1.8	46
34	Penzhina	Kamenskoe	RS	6242N	16603E	71,600	1957	1984	3.6	27
35	Indigirka	Vorontsovo	RS	6958N	14735E	305,000	1937	1994	1	57
36	Lena	Kusur	RS	7070N	12765E	2,430,000	1935	1994	0	59
37	Shilka	Sretensk	RS	5225N	11772E	175,000	1897	1985	1.9	88
38	Kamchatka	Kluchi	RS	5643N	16105E	45,600	1931	1984	0.8	53
39	Amur (1)	Khabarovsk	RS	4843N	13505E	1,630,000	1897	1985	0.9	88
40	Amur (2)	Komsomolsk	RS	5063N	13712E	1,730,000	1933	1990	0	57
41	Li-Wu	Lu-Shui	TW	2418N	12150E	435	1960	1993	0	33
42	Yufeng	Dahan	TW	2465N	12118E	335	1964	1989	0	25
43	Sandimen	Ailiao	TW	2270N	12063E	408	1964	1989	0	25
44	Xinfadaqiao	Laonong	TW	2305N	12065E	812	1964	1989	0	25
					Southeast Asia Area					
45	Pampanga	San Agustin	PH	1517N	12078E	6,487	1946	1974	5.7	28
46	Konga	kangay	PH	1808N	12070E	534	1947	1976	6.1	29
47	Kelatan	Guillemard Bridge	MS	577N	10215E	11,900	1950	1986	7.7	37
48	Mekong (1)	Mukdahan	TH	1653N	10473E	391,000	1925	1991	0.4	66
49	Nam Chi	yasothon	TH	1578N	10415E	43,100	1954	1991	0.6	37
50	Nam Mun	Ubon	TH	1522N	10487E	104,000	1956	1991	1.1	35
51	Nan	Sirkit Dam	TH	1777N	10055E	13,300	1956	1988	2.9	32
52	Mekong (2)	Chiang Saen	TH	2027N	10010E	189,000	1961	1991	1	30
53	Mekong (3)	Nakhon Phanom	TH	1740N	10480E	373,000	1962	1991	3.3	29

Table 1. Characteristics of the Selected Rivers by Area (continued)

# on Fig. 1	*River*	*Station*	*Country Code*	*Latitude*	*Longitude*	*Watershed Area*	*Begin Year*	*End Year*	*Percent Missing Data*	*Duration (Years)*
				Indian Subcontinent Area						
54	Mahaweli Ganga	Peradeniya	SB	727N	8058E	1,189	1950	1984	2.8	34
55	Gin Ganga	Agaliya	SB	618N	8020E	681	1928	1989	1.7	61
56	Karnali River	Chisapani	NE	2864N	8129E	42,890	1962	1993	0	31
57	Kali Gandaki (1)	Setibeni	NE	2801N	8360E	6,630	1964	1993	0.3	29
58	Kali Gandaki (2)	Kotagaon Shringe	NE	2775N	8435E	11,400	1964	1985	4.2	21
59	Tamur River	Mulghat	NE	2693N	8733E	5,640	1965	1986	0	21
60	Ganges R. (1)	Harlinge Bridge	BW	2408N	8903E	846,300	1934	1989	2.1	55
61	Ganges R. (2)	Farakka	IN	2500N	8792E	935,000	1949	1985	0	36
62	Sapt Kosi	Barashetra	NE	-	-	-	1947	1978	0	31
63	Godavari	Polavaram	IN	1692N	8178E	299,320	1902	1979	7	77
64	Krishna	Vijayawada	IN	1652N	8062E	251,355	1901	1979	6.3	78
64	Narmada	Jamtara	IN	2302N	7993E	16,576	1949	1974	0.3	25
				Central Asia Area						
66	Amu-Darya	Chatly	UZ	4228N	5970E	450,000	1931	1973	2.1	42
67	Zaravchan	Dupuli	TA	3938N	6777E	10,200	1932	1994	1.3	62
68	Gunt	Khorog	TA	3753N	7152E	13,700	1940	1985	0	45
69	Vakhsh	Tutkaul	TA	3833N	6930E	31,200	1932	1967	1.6	35
70	Biya	Biysk	RS	5252N	8527E	36,900	1895	1985	0	90
71	Ob	Salekhard	RS	6657N	6653E	2,949,998	1930	1994	0	64
72	Tom (1)	Novokuznetsk	RS	5375N	8710E	29,800	1894	1985	0	91
73	Tom (2)	Tomsk	RS	5658N	8487E	57,000	1965	1990	0	25
74	Tura	Tiumen	RS	5715N	6553E	58,500	1896	1985	0	89
75	Yenisei	Igarka	RS	6748N	8650E	2,440,000	1936	1995	0	59
76	Syr-Darya	Tyumen-Aryk	KZ	4405N	6705E	219,000	1930	1984	7	54
77	Ural	Kushum	KZ	5085N	5128E	190,000	1915	1984	4.3	69
78	Naryn	Uch-Kurgan	KG	4117N	7210E	58,400	1933	1990	0	57

Non-parametric techniques are based on the ranks of the data within the sample. As such, they are unaffected by the shape of the distribution and are also robust to outliers, as extreme values are limited to the maximum ranks even if they are very far from the bulk of the data. Although classical non-parametric trend tests such as the Mann-Whitney and the Spearman tests are very useful for the detection of monotonic or stepwise trends, they do not address the problems of temporal persistence and of seasonal fluctuations often found in hydrological data.

The main developments in non-parametric procedures adapted to messy data were obtained during the last 25 years (Lettenmaier, 1976; Hirsch et al., 1982; Hirsch and Slack, 1984) to exploit the water quality data bases resulting from monitoring programs established as a result of environmental concerns; these data bases were the archetype of messy data since they exhibited all characteristics associated to messy data. It was thus quite difficult to answer the very practical question as to whether the state of the environment was improving or deteriorating, which was and still remains, a very pertinent question. In these developments, authors have adapted non-parametric tests to allow for trend detection, without being influenced by other types of short-term interdependence (autocorrelation and seasons).

Non-parametric Tests Adapted to Autocorrelation and Seasonal Dependence

The adapted non-parametric techniques consider two particular types of trends: (1) a stepwise (or jump-in-the-mean) trend where, at some point in time, a sudden change of levels occurs as the result of some intervention; mean levels before and after this date are compared using an adaptation of the Mann-Whitney test, to test if they are significantly different; and (2) a progressive, monotonic evolution of the series level over time. In this case, adaptation of the Spearman's or Kendall's test can be applied, using time as the independent variable.

The statistics of tests for trend include a level or location parameter estimate (mean, median, slope, etc.) and a scale estimate for the level or location estimate (variance, standard deviation, etc.). The scale estimate for the level or location estimate is generally related to the number of observations and to the variance of the sample. The observations in a sample are autocorrelated when successive observations in time are correlated meaning that each observation contains some part of the information already available in the previous and following observations. If the number of autocorrelated samples rises for a fixed and given period, then the sampled observations become more and more autocorrelated and the variance of the mean more and more underestimated. An equivalent number of independent observations, n^*, lower than the actual number of dependent observations, (n), can be defined to obtain an adequate estimate of the variance of the sample mean. Each (dependent) observation has an information content I = n^*/n.

Lettenmaier (1976), using results from Matalas and Langbein (1962), presents the relationship between n and n^* for a general autocorrelation structure and for a simple lag-1 autoregressive Markovian (AR(1)) process. The latter process is important, as most natural processes locally follow a Markovian-type structure reflecting the progressive loss of memory of the phenomenon.

In Table 2, the effective number of independent observations (n^*) is presented for some combinations of lag-1 autocorrelation coefficients r_1 and series lengths n assuming that the underlying process is an AR(1). For example, a series of length 100 and of correlation coefficient of 0.3 is equivalent, for application of trend detection tests, to a series of only 54 independent observations.

Lettenmaier (1976) studied, using Monte-Carlo simulations, the power of Spearman's Rho test against linear monotonic trends, and the power of the Mann-Whitney test against step trends for series presenting an AR(1) persistence structure. This author found that the documented power curves obtained in the case of independent samples were relevant for the dependent sample case if an equivalent number of independent observations n^* was used, instead of the actual length n of the sample.

After this breakthrough, Hirsch et al. (1982) investigated the case of the seasonal fluctuations present in the vast majority of hydrological series. Kendall's test (Lehman and D'Abrera, 1975) is used for each recognized seasonal sub-series, and the resulting statistics were added together. This property was exploited to assess if a global trend was present. Unfortunately this test could not be applied if both persistence and seasonality were simultaneously present in the series. Hirsch and Slack (1984) investigated this last problem. In addition, Van Belle and Hughes (1984), presented a new method for determining if a trend was caused by a particular season.

At this point, a complete set of non-parametric tests for monotonic and stepwise trend detection was available for independent/autocorrelated, seasonal/non-seasonal time series. The decision tree for choosing the appropriate test according to the structure of the series and to the type of trend is presented in Table 3. This set of non-parametric tests is well adapted to the real structure of hydrological data, but as they have been developed only recently, their power has only been partially established (Berryman et al., 1988) and they often rely on Monte-Carlo simulations to validate performances. Nevertheless, Bradley (1968) demonstrated that even under the worst case situations,

Table 2. Effective Number of Independent Observations for Various Combinations of Autocorrelation Coefficients r_1 and Series Lengths n

r_1	n=10	n=25	n=50	n=75	n=100	n=200
0,1	8,4	21	41	62	82	164
0,2	7	17	34	50	67	134
0,3	5,8	14	27	41	54	108
0,4	4,7	11	21	33	43	86
0,5	3,9	8,8	17	25	34	67
0,6	3,1	6,8	13	19	25	50
0,7	2,4	5	9,3	14	18	36
0,8	1,8	3,4	6,1	8,9	12	23
0,9	1,4	2	3,2	4,5	5,8	11
0,95	1,2	1,5	2	2,6	3,2	5,7

the power of non-parametric procedures varied between 85 percent and 96 percent of that of their parametric counterparts. In fact, when tested with a whole range of asymmetrical distributions, their power generally exceeded that of traditional parametric techniques.

To exploit the new, previously described non-parametric tests in a practical way, interactive software has been written (Cluis, 1988; Cluis et al., 1989) and accepted as a Canadian contribution to the HOMS program (module K55.2.01) of the World Meteorological Organization (WMO). This software, written in Fortran 77, is composed of stand-alone modules which are executed in succession, using a series of intermediate data files to transfer interim results downstream from the first modules. It performs the following operations:

- Reading of the input data in an appropriate format; display of the time-series; interactive appraisal and elimination of obvious outliers.
- Analysis of the frequency of sampling; ANOVA on months; interactive grouping of months into seasons and test the equality of the means of the selected seasons (groupings of months).
- Choice of an equi-spaced working interval, seasonal or non-seasonal, with several options for filling-in missing data; analysis of the persistence structure of the working series using significance levels for the sampled autocorrelation coefficient.
- Analysis with inertia graphics (Mass-curves and CUSUM functions, Cluis; 1983; Doerffet et al., 1991) in order to assess the nature of a possible trend (stepwise or monotonic) and also its eventual time of occurrence.

Given the above information, the software performs the trend test adapted to the data, tests the significance of the results and calculates the parametric values pertaining to each segment. The correspondence between the trend model and the data is computed as an RMSE (Root Mean Square Error), which has to be minimized in order to retain the best-fitted alternative. In a single time-series, the

Table 3. Set of Non-parametric Tests for Monotonic and Stepwise Trend Detection Available for Independent/Dependent, Seasonal/Non-Seasonal Time Series

Type of Trend	*Persistence*	*Seasonality*	*Appropriate Test*
Monotonic trend	Markovian persistence	No seasons With seasons	Lettenmaier/Spearman Hirsh and Slack
	No persistence	No seasons With seasons	Spearman/Kendall Kendall seasonal
Stepwise trend	Markovian persistence	No seasons With seasons	Lettenmaier/ Mann-Whitney Hirsch and Slack
	No persistence	No seasons With seasons	Mann-Whitney Kendall seasonal

software may have to be rerun several times if there was more than one change in level during the length of the record or if computing for either monotonic or stepwise structures lead to non-clearly discriminating RMSE. All the choices made by the user are written in a report file for further analysis of the statistical results related to the different options run for the same series.

Results

The results presented here constitute a fraction of the actual work done with the GRDC databank. The reader interested in more detailed results should refer to Cluis (1998).

Hubert's Segmentation Procedure

We used the segmentation software developed and provided by Hubert et al. (1989) and ran it on the three yearly series of interest, i.e., the mean, maximum, and minimum monthly series. It was applied to the discharge data of the selected rivers of the Asia-Pacific region as described in Table 1. For these 234 runs, the significance level of 0.01 for the Scheffé test was used and, in addition, we limited the investigation to a maximum of three segmentations per record.

The summary results are presented in Table 4. Figure 2 presents the results for each station, indicating whether a segmentation is significant for one, two or three of the series (minimum, mean and maximum). Table 4 and Figure 2 show that about 32 percent of the stations (and 60 percent of the series) are not segmented at all during their record periods, and only 22 percent of the stations are segmented for all three series (minimum, mean, and maximum). The least segmented series is the yearly series of monthly maximums, which generally presents the relatively larger standard deviations, followed by the series of yearly means and then by the series of monthly minimums. One can note that, from the three studied yearly series (yearly means, monthly maximum, and monthly minimum), the series of monthly minimums are the most highly truncated into segments. This makes sense, since low flow values are most likely to reflect local anthropic interventions as flow diversions for irrigation purposes take place in the dry season.

Trend Detection Using the DETECT Software

All series that had been segmented by Hubert's procedure were submitted to the specialized non-parametric tests included in the DETECT software (Table 3). As already discussed, this software takes into account the seasonal and/or persistence structures of the series and redirects the treated series towards the adequate adapted test. In fact, these characteristics (reduced seasonal sub-series lengths, effective number of independent observations n^*) are at the root of the recognized over-segmentation properties (falsely rejecting the stationarity hypothesis) of the procedure developed by Hubert et al. (1989).

Table 4. Summary Results, for Each Area, of the Segmentation and Trend Analyses Applied to the ThreeTypes of Series Investigated (mean yearly, monthly maximum, and minimum discharge series)

		Segmentation		*Trend Detection*		
Region	*Type of Series*	*Yes*	*No*	*Down-ward Trend*	*Upward Trend*	*No Trend*
Oceania	mean	4	15	3	1	15
Pacific	maximum	3	16	2	1	16
(19 rivers)	minimum	7	12	2	1	16
Far East	mean	11	14	6	4	15
Asia	maximum	6	19	4	1	20
(25 rivers)	minimum	18	7	5	10	10
Southeast	mean	3	6	3	0	6
Asia	maximum	4	5	3	1	5
(9 rivers)	minimum	8	1	3	4	2
Indian	mean	4	8	3	1	8
Subcontinent	maximum	4	8	1	2	9
(12 rivers)	minimum	5	7	2	2	8
Central Asia	mean	5	8	3	2	8
	maximum	4	9	3	0	10
(13 rivers)	minimum	10	3	2	6	5
Total	mean	27	51	18	8	52
	maximum	21	57	13	5	60
	minimum	48	30	14	23	41

The summary results of trend detection are presented in Table 4 and Figure 3, and specific results for each region are presented in the following sections.

Oceania-Pacific

The results pertaining to each station within the Oceania-Pacific area are presented in Table 5; one can see that four minimum monthly discharge series that had been previously segmented, when revisited by this actual

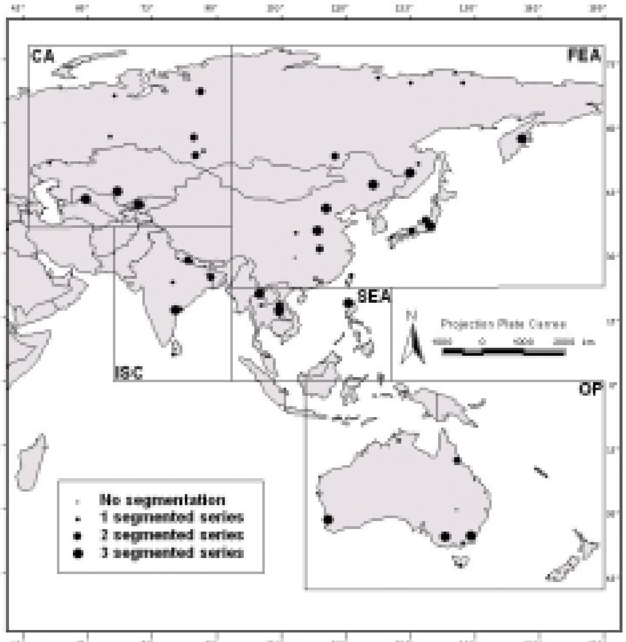

Figure 2. Representation of the segmentation results for all studied rivers. The size of the dots indicates the number of series segmented among the monthly minimum, monthly maximum, and yearly mean series.

step, exhibited no trend (in the mean) after having been submitted to the non-parametric tests. Further investigation of Table 5 and Figure 3 shows that all stations with downward trends showed changes in the 1960s and early 1970s while all stations with upward trends showed changes in the late 1970s, and 1980s. These results suggest that the opposite directions in trends for the Oceania-Pacific area could be time related rather than spatially related if a regional pattern can be deduced for this area. Only two stations showed significant trends in all three series (minimum, mean, and maximum): the Avoca River with upward step trends in 1988 and the Murrumbidgee River with downward step trends in 1961.

Far-East Asia

The results for Far East Asia presented in Table 6 show that three minimum monthly discharge series and one mean monthly series that had been previously segmented exhibited no trend when revisited with the DETECT software. Further investigation of Table 6 and Figure 3 illustrates that all northern stations exhibited upward trends taking place between 1960 and 1985. In the center of the area, a majority of the stations showed downward trends with changes in the 1960s, 1970s, and early 1980s, the main exception being the Songhuajiang River which showed upward step trends in all three series but the changes in mean appeared in the 1930s and 1940s. Finally, three stations in the south of the area show upward step trends in the minimum series with changes in the 1960s and 1970s. These results suggest that the opposite directions in trends for the Far East Asia area could be explained by regional patterns since adjacent rivers tend to produce similar trend patterns. Only three stations showed

Table 5. Trend Detection Analysis Results for the Yearly Mean, the Minimum and Maximum Monthly Discharges in the Oceania-Pacific Area

	Minimum Monthly Discharges				*Mean Yearly Discharges*				*Maximum Monthly Discharges*			
River	*Period*		*Trend Type*	*Period Level**	*Period*		*Trend Type*	*Period Level**	*Period*		*Trend Type*	*Period Level**
Daly	1970	1973	-	8.9	No segmentation identified				No segmentation identified			
	1974	1995	Step	17.9								
Herbert	1916	1996	No trend	5.4	1916	1960	-	113	No segmentation identified			
					1961	1970	Step	76				
					1971	1996	Monotic	171-39				
Mitchell	1938	1987	No trend	2.24	No segmentation identified				No segmentation identified			
Avoca	1890	1987	-	0.19	1890	1895	-	316	1890	1895	-	1240
	1988	1993	Step	5.7	1896	1987	Step	6.4	1896	1987	Step	32.6
					1988	1993	Step	378	1988	1993	Step	2010
Huon	1949	1994	No trend	18.3	No segmentation identified				No segmentation identified			
Murrumbidgee	1927	1960		113	1927	1960		1190	1927	1960		3730
	1961	1993	Step	55	1961	1993	Step	457	1961	1993	Step	1480
Serpentine	1911	1992	No trend	6.2	1911	1970	-	6.2	1911	1970	-	29.1
					1971	1992	Step	0.49	1971	1992	Step	2.19

*For monotonic trends, period level represents the value estimated for the first and last year in the period.

Table 6. Trend Detection Analysis Results for the Yearly Mean, the Minimum and Maximum Monthly Discharges in the Far East Asia Area

	Minimum Monthly Discharges			*Mean Yearly Discharges*			*Maximum Monthly Discharges*		
River	*Period*	*Trend Type*	*Period Level**	*Period*	*Trend Type*	*Period Level**	*Period*	*Trend Type*	*Period Level**
Tone	1938 1947	No trend	94	1938 1960		288	1938 1962		742
	1948 1973		112	1961 1985	Step	222	1963 1985	Step	535
	1974 1985	Step	79						
Shinano	1965 1988	Monotonic	295-207	1965 1988	No trend	530	No segmentation identified		
Yodo	1965 1983		127	1965 1976		316	No segmentation identified		
	1984 1988	Step	86	1977 1988	Step	234			
Chikugo	1965 1974		36	No segmentation identified			No segmentation identified		
	1975 1988	Step	45.3						
Changjiang	1865 1904		6,370	1865 1953		23,700	No segmentation identified		
	1905 1985	Step	7,230	1954 1985	Step	22,300			
Songhuajiang	1898 1946		108	1898 1928		895	1898 1931		2,500
	1947 1987	Step	302	1929 1987	Step	1360	1932 1987	Step	3,580
Yongding	1925 1942	No trend	9.5	1925 1949		39	1925 1962		126
	1943 1970		15.4	1950 1964	Step	50.3	1963 1988	Step	58.6
	1971 1988	Step	9.3	1965 1988	Step	21.1			
Jinghe	1933 1986	No trend	17.2	No segmentation identified			No segmentation identified		
Huanghe	1947 1955		576	1947 1966		1,610	No segmentation identified		
	1956 1988	Step	385	1967 1988	Step	1,260			
Beijang	1954 1969		201	No segmentation identified			No segmentation identified		
	1970 1969	Step	268						
Dongjiang	1960 1973		208	No segmentation identified			No segmentation identified		
	1974 1987	Step	351						
Yana	1938 1984	No trend	0.42	No segmentation identified			No segmentation identified		
Indigirka	1937 1984		7.1	No segmentation identified			No segmentation identified		
	1985 1994	Step	10.2						
Lena	1935 1978		1.1	No segmentation identified			No segmentation identified		
	1979 1994	Step	1.9						
Shilka	1897 1985	No trend	3.63	1898 1982		398	No segmentation identified		
				1984 1095	Step	627			
Kamchatka	1931 1984	Monotonic	323-438	1931 1959		736	1931 1959		1780
				1960 1984	Step	826	1960 1984	Step	1990
Amur (1)	1897 1946		486	1897 1955	No trend	8370	1897 1953	No trend	20800
	1947 1985	Step	765	1956 1985	Monotonic	10600-6640	1954 1985	Monotonic	25300-16900
Amur (2)	1933 1978		877	No segmentation identified			No segmentation identified		
	1979 1990	Step	1660						
Yufeng	No segmentation identified			1964 1967		1110	No segmentation identified		
				1968 1989	Step	1780			
				1964 1989	Monotonic	1430-1980			

*For monotonic trends, period level reprsents the value estimated for the first and last year in the period.

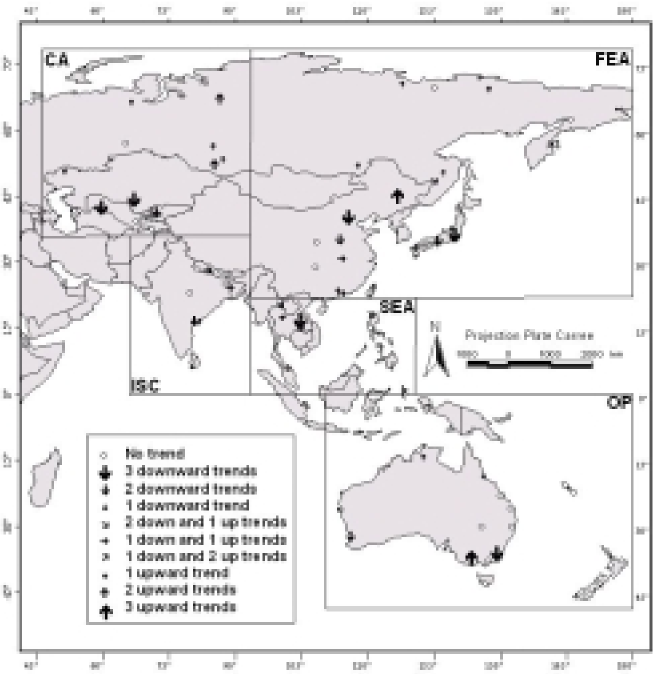

Figure 3. Representation of the trend detection results for all the studied rivers. The size of the arrows indicates the number of series segmented among the monthly minimum, monthly maximum, and yearly mean series. the direction of the arrows indicates The direction of the trend.

significant trends in all three series (minimum, mean, and maximum): the Tone and Yongding Rivers with downward step trends in the 1960s and 1970s, and the Songhuajiang River with upward step trends in 1930s and 1940s.

Southeast Asia

The results for Southeast Asia are presented in Table 7. Only one minimum monthly discharge series that had been previously segmented exhibited no trend when revisited with the DETECT software. Further investigation of Table 7 and Figure 3 shows that all trends take place between 1960 and 1982. In general, the stations showed downward step trends, with almost all exceptions being in minimum monthly discharge series: the Nam Chi, Nam Mun, and Nan Rivers showing upward step trends in the 1960s but no trends in the mean and maximum series, and the Mekong (2) River showing an upward step trend in the 1970s but downward trends in the mean and maximum series. These results suggest that the trends in the South East Asia area could be explained by regional patterns since a vast majority of stations produce similar trend patterns.

Indian Subcontinent

The results for the Indian Subcontinent Area are pre-

Table 7. Trend Detection Analysis Results for the Yearly Mean, the Minimum and Maximum Monthly Discharges in the Southeast Area

	Minimum Monthly Discharges				*Mean Yearly Discharges*				*Maximum Monthly Discharges*			
River	*Period*		*Trend Type*	*Period Level**	*Period*		*Trend Type*	*Period Level**	*Period*		*Trend Type*	*Period Level**
Bonga	1947	1966	Step	1.9	1947	1959	No trend	26.3	1947	1958	No trend	98.6
	1967	1976	Step	0.9	1960	1976	Monotonic	42.8-4.2	1959	1976	Monotonic	163-358
Kelantan	1950	1961		317	No segmentation identified				No segmentation identified			
	1962	1986	Step	231								
Mekong (1)	1925	1950		1550	1925	1966		8350	1925	1973		24400
	1951	1991	Step	1410	1967	1991	Step	7270	1974	1991	Step	20500
Nam Chi	1954	1966		5.83	No segmentation identified				No segmentation identified			
	1967	1991	Step	37.8								
Nam Mun	1956	1966		18.4	No segmentation identified				No segmentation identified			
	1967	1991	Step	62								
Nan	1956	1967		16.5	No segmentation identified				No segmentation identified			
	1968	1988	Step	27.8								
Mekong (2)	1961	1971		764	1961	1971		2950	1961	1971		8080
	1972	1991	Step	839	1972	1991	Step	2600	1972	1991	Step	6400
Mekong (3)	1962	1991	No trend	1440	No segmentation identified				1962	1981		21400
									1982	1991	Step	17800

*For monotonic trends, period level represents the value estimated for the first and last year of the period.

Table 8. Trend Detection Analyses Results for the Yearly Mean, the Minimum and Maximum Monthly Discharges in the Indian Subcontinent

	Minimum Monthly Discharges				*Mean Yearly Discharges*				*Maximum Monthly Discharges*			
River	*Period*		*Trend Type*	*Period Level**	*Period*		*Trend Type*	*Period Level**	*Period*		*Trend Type*	*Period Level**
Gin Ganga	1928	1957	No trend	19.5	No segmentation identified				No segmentation identified			
	1958	1989	Monotonic	26.3-11.3								
Kali Gandaki (1)	1964	1993	Monotonic	31.2-55.7	1964	1976		284	No segmentation identified			
					1977	1993	Step	247				
Kali Gandaki (2)	No segmentation identified				1964	1968		530	No segmentation identified			
					1969	1985	Step	457				
Sapt Kosi	No segmentation identified				1947	1969		1540	1947	1969		4510
					1961	1979	Step	1250	1970	1979	Step	5440
Krishna	1901	1979	No trend	21.7	1901	1960		1780	1901	1960	Monotonic	9590-3960
					1961	1979	Step	1250				
Ganges R. (1)	1934	1974		1950	No segmentation identified				1934	1945		35200
	1975	1989	Step	1130					1946	1989	Step	42500
Godavari	1902	1979	Monotonic	23.7-120	No segmentation identified							
Narmada	No segmentation identified				No segmentation identified				1949	1974	No trend	1730

*For monotonic trends, period level represents the value estimated for the first and last year of the period.

sented in Table 8. Only one minimum monthly discharge and one maximum monthly discharge series that had been previously segmented exhibited no trend according to the nonparametric tests. Further investigation of Table 8 and Figure 3 shows that almost all trends taking place between 1960 and 1975 are downward trends. These results suggest that the trends in the Indian Subcontinent area could be explained by regional patterns since a vast majority of stations produce similar trend patterns and these trend patterns are very similar to those of the adjacent Southeast Asia region.

Central Asia

The results for the Central Asia area are very similar to those observed in the Far East Asia area: The northern stations (between the 55th and 75th parallels) exhibiting upward trends and southern stations (around the 45th parallel) showing downward trends. These results, added to the results of the adjacent Far East Asia area, suggest the presence of a regional trend pattern.

Discussion

Tables 4, 5, 6, 7, 8, and 9 show that about 65 percent of the studied series exhibited no change in their mean, minimum, or maximum levels during their record period. One can also see that the runoff of rivers in Southeast Asia have exhibited decreasing trends with time. For all the regions, it is also clear that minimum monthly runoffs were much more prone to changing levels than the mean and maximum ones. This reflects the fact that even small impoundments constructed for various water uses such as irrigation, municipal or industrial uses can significantly change the levels of the low flows. Conversely, dams and reservoirs can be managed and operated in such a way to guarantee a residual minimal flow in the river at all times, for navigation or ecological purposes.

Also to be noted is the large magnitude of the historical changes in levels demonstrated during the analysis by some Australian rivers. It is also apparent that on the Indian Subcontinent and in Southeast Asia, many rivers have exhibited a steady downward trend starting at the end of the 1960s until now, possibly reflecting increased water use for irrigation, industrialization, or municipal uses. Also, one can clearly appreciate the historical fate of the rivers Amu-Darya and Syr-Darya flowing into the Aral sea, but largely diverted in recent times for widespread irrigation of cotton fields

Table 10 synthesizes, by region, the number of occurrences of shifts in levels by decades, as compounded for all the considered series (mean yearly, maximum monthly, and minimum monthly discharges). It provides the count of series for which levels shifted during a given decade. One can see that most of the changes occurred during the 1960s and 1970s, a period of rapid demographic expansion, and, consequently, of the development of irrigation, especially in tropical regions.

During the same period, a large number of dams and

Table 9. Trend Detection Analysis Results for the Yearly Mean, the Minimum and Maximum Monthly Discharges in Central Asia

	Minimum Monthly Discharges				*Mean Yearly Discharges*				*Maximum Monthly Discharges*			
	Period		*Trend Type*	*Period Level**	*Period*		*Trend Type*	*Period Level**	*Period*		*Trend Type*	*Period Level**
Amu-Darya	1931	1957	Step	516	1931			1520	1931			3540
	1958	1973	Step	180	1958	1973	Step	1150	1961	1973	Step	2730
Biya	1895	1985	Monotonic	46-62	1895	1910		425	No segmentation identified			
					1911	1984	Step	489				
Ob	1930	1994	Monotonic	2530-3970	No segmentation identified				No segmentation identified			
Tom (1)	1894	1985	Monotonic	56.7-80.8	No segmentation identified				No segmentation identified			
Tom (2)	1965	1979		112	No segmentation identified				1965	1990	No trend	4620
	1980	1990	Step	149								
Tura	1896	1985	No trend	24.1	No segmentation identified				No segmentation identified			
Yenisei	1936	1969		3.92	1936	1972		17.7	No segmentation identified			
	1970	1995	Step	6.6	1973	1995	Step	18.6				
Syr-Darya	1930	1964		334	1930	1960		673	1930	1960		1310
	1965	1984	Step	133	1961	1984	Step	384	1961	1984	Step	761
Ural	1915	1953		38	No segmentation identified				No segmentation identified			
	1954	1981	Step	57.4								
Naryn	1933	1990	No trend	136	1933	1970		393	1933	1973		1010
					1971	1990	Step	316	1974	1990	Step	703

*For monotonic trends, period level represents the value estimated for the first and last year of the period.

Table 10. Counts per Decade of the Occurrence of Upward and Downward Trends in Each of the Five Areas

		Decade									
Region	*Trend*	*'00*	*'10*	*'20*	*'30*	*'40*	*'50*	*'60*	*'70*	*'80*	*'90*
Oceania	Downs	2						4	3		
Pacific	Ups								1	3	
Far East	Downs						4	6	3	1	
Asia	Ups	1		1	1	2	1	2	6	2	
Southeast	Downs						2	4	3	1	
Asia	Ups							3	1		
Indian	Downs	1				1	1	2	2		
Subcontinent	Ups	1						2	1	1	
Central	Downs						2	4	2		
Asia	Ups	2	1		1		1		2	1	

reservoirs were completed (Vörösmarty et al., 1997; ICOLD, 1984, 1988), modifying the historical regimes of rivers. This has been the case within the watersheds of some of the larger rivers studied here, such as the Murrumbidgee (1956) and Darling Rivers (1960) in Australia, the Nan River (1972) in Thailand, the Godavari (1976) and Krishna Rivers (1974, 1982, 1984) in India, the Syrdaria (1957, 1965) and Ural Rivers (1958) in Kazakhstan, the Yenisei (1967) and the Ob Rivers (1957) in Russia, the Narin River (1978) in Kirghiztan, and the Beijiang (1973) Dongjiang (1974) and Yellow or Huanghe River (1960 and 1968) in China. Some of these impoundments could be at the origin of the results presented here.

In a future study, it would be interesting to submit the same data set to new statistical analyses in order to assess a possible regional change over time in the internal variability of the runoff series as suggested by some studies on the "El Niño" phenomenon. Such a study could attempt to relate monthly or seasonal runoff values to the lagged values of the Southern Oscillation Index (SOI), whose frequency occurrence of low and high extreme values appears to be closely related to climate change.

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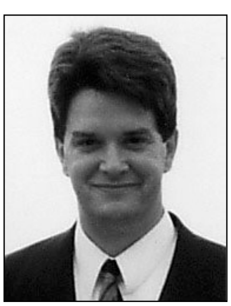

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