Trends and changes in historical annual streamflow volumes and peak discharges of rivers in the world

Francis H.S. Chiew and Thomas A. McMahon
Department of Civil and Environmental Engineering, University of Melbourne, Australia

Abstract It is likely that increasing concentration of greenhouse gases will lead to higher temperatures and changes in precipitation patterns and other climatic variables. These changes can in turn impact on streamflow hydrology and thus the management of land and water resources. In this paper, five statistical tests are applied to the annual streamflow volumes and peak discharges of 142 rivers throughout the world to investigate whether statistically significant trends or changes in means can be detected in the historical streamflow series. The rivers are located mostly in North America, Europe and east Australia, have at least 50 years of data and drainage areas larger than 1,000 km^2. The analyses indicate that although trends and changes are detected by some of the statistical tests at several locations, except for certain parts of North America, they are not consistently observed throughout specific regions. It can be concluded that there is no clear evidence yet of climate change in the annual streamflow volumes and peak discharges of rivers in the world. However, it should be noted that the detection of trend is difficult because of the short period of record, high inter-annual variability, lag between increased concentration of greenhouse gases and the climatic variables affecting streamflow and land use changes masking the data.

1. INTRODUCTION

It is likely that the increasing concentration of greenhouse gases will lead to higher temperatures and changes in precipitation patterns and other climatic variables (see Houghton *et al.*, 1990). Although relating past climate to changes in the concentration of greenhouse gases is central to the detection problem, it is difficult to detect trends in historical data because of the large variability and the relatively short period of instrumental record (see Chiew *et al.*, 1993). Nevertheless, analyses of temperature records by various researchers (see Jones *et al.*, 1986; Ellsaesser *et al.*, 1986; and Wigley *et al.*, 1986) have indicated that the mean global surface air temperature has increased by 0.5°C since the beginning of this century.

Although the mean global surface air temperature is the most commonly used indicator of the state of the climate system, trends in other climatic variables such as precipitation, sea-level, snow, ice cover and water vapour, have also been studied. In particular changes in precipitation are important as they directly influence society. It is difficult to evaluate changes in historical precipitation because of its high inter-annual variability and high spatial variability (see McQuirk, 1982; Elliot and Reid, 1984; and Barnett, 1985). In addition, regional changes in precipitation differ markedly from the global mean which is one reason why most studies on precipitation changes are carried out over regional scales.

This paper investigates whether statistically significant trends and changes in means can be detected in the annual streamflow volumes and peak discharges of 142 rivers throughout the world. The rivers have at least 50 years of record and drainage areas larger than 1000 km^2. Five statistical tests are applied to the historical data.

This study of trends in streamflow is useful for three main reasons. First, changes in streamflow are usually amplified in runoff (see Chiew *et al.*, 1985), and therefore it should be easier to detect climate change in runoff than in rainfall (although the inter-annual variability of runoff is generally higher than the variability of rainfall). Second, streamflow data integrates some of the spatial variability within the catchment. As such, a single streamflow gauging station may provide as much information as rainfall time series from several rainfall stations in the catchment. Third, a study of changes in runoff is important because runoff influences directly the management of land and water resources.

2. STREAMFLOW DATA

The annual flow volumes and peak discharges are selected from the global streamflow dataset of McMahon *et al.* (1992). In preparing the dataset, efforts were taken by McMahon *et al.* (1992) to ensure that the data are for unregulated flow conditions. Only stations with at least 50 years of record and drainage areas larger than 1,000 km^2 are used. Altogether, 120 annual streamflow series and 83 annual peak discharge series are analysed (see Figures 1 and 2 for locations of stations). Although all six major continents are represented, most of the data come from North America, Europe and east Australia.

The records generally extend from the beginning of this century to the 1970s or early 1980s. The record lengths for both the flow volumes and peak discharges vary from 50 to 162 years with an average length of 68 years (a median of 61 years). The catchment areas range from 1,000 to 8,000,000 km^2 with an average area of 225,000 km^2 (a median of 16,000 km^2).

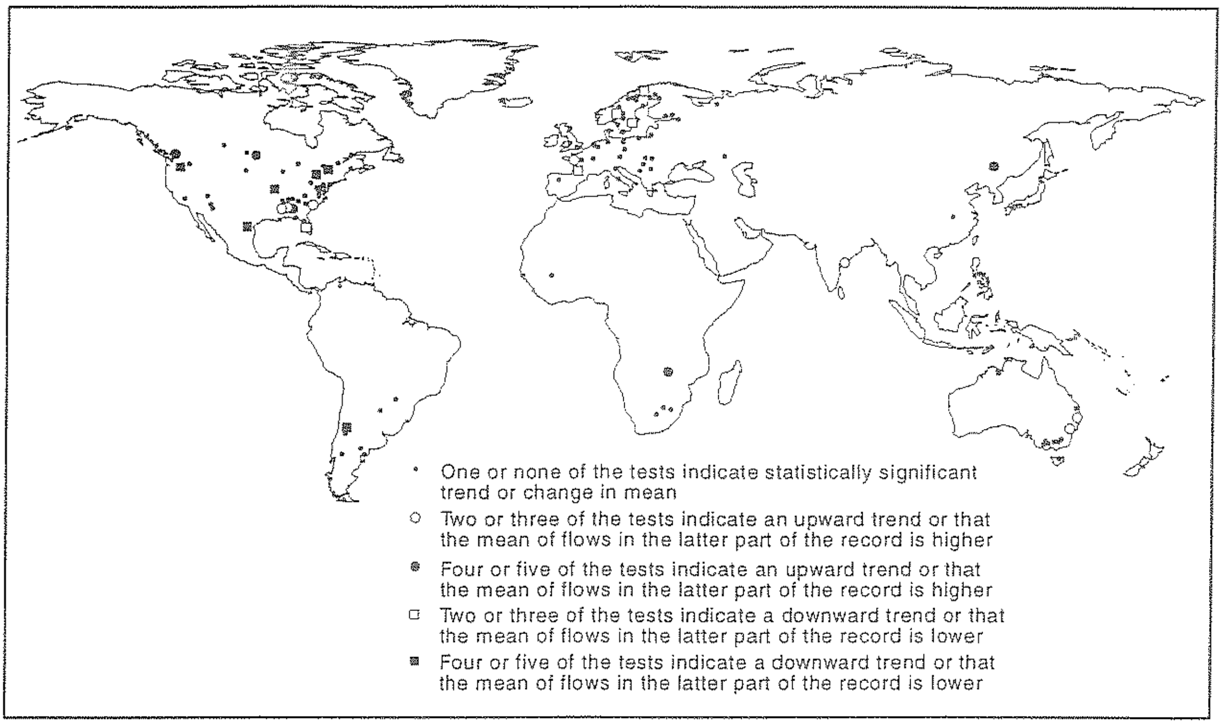

Figure 1 Locations of streamflow gauging stations and summary of statistical analyses of annual streamflow volumes

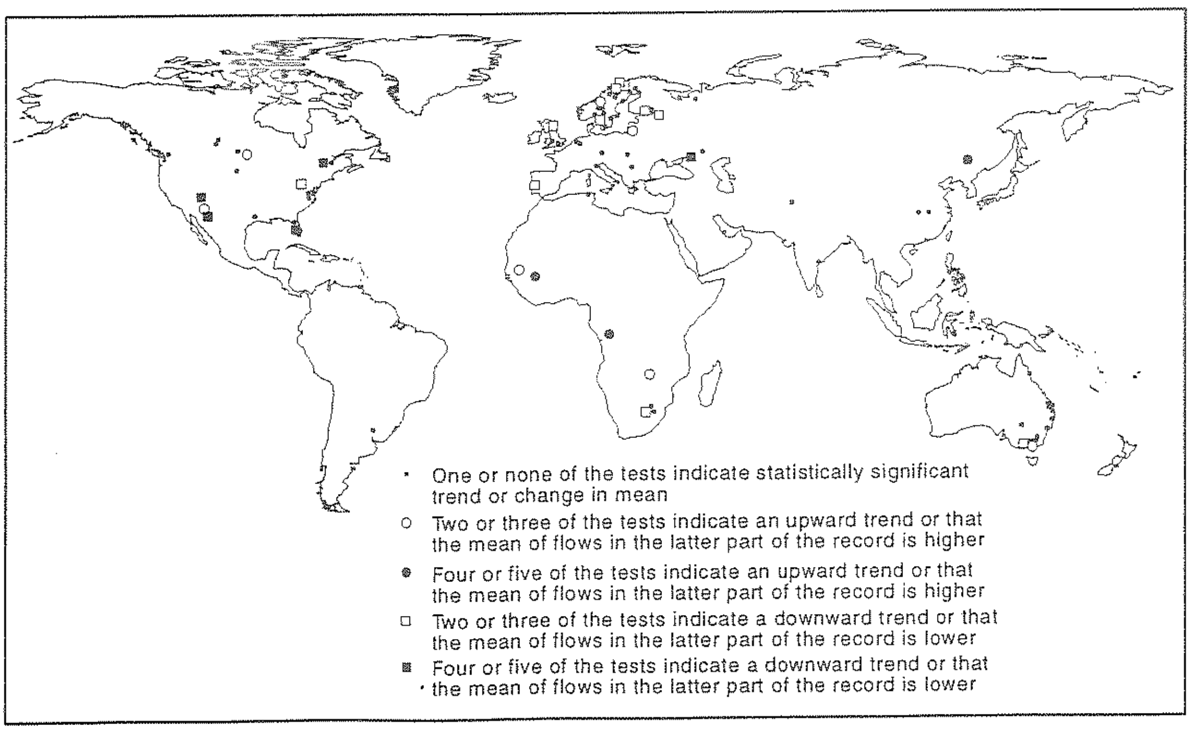

Figure 2 Locations of streamflow gauging stations and summary of statistical analyses of annual peak discharges

3. STATISTICAL TESTS

Five statistical tests are used - Mann (Kendall, 1970), Cumulative Deviation (Buishand, 1982), Worsley Likelihood Ratio (Worsley, 1969), Distribution-Free CUSUM (McGilchrist and Woodyer, 1975) and Kruskal-Wallis (Sneyers, 1975). The Mann statistic tests whether there is a statistically significant trend and indicates the general direction of change (upwards or downwards). The Cumulative Deviation, Worsley Likelihood Ratio and Distribution-Free CUSUM tests locate a change point, test whether the means in the two parts of the dataset are statistically different, and indicate which of the two means is higher. The Kruskal-Wallis statistic tests whether flows in any period (a 10-year sub-period is used here) are significantly different from flows at other times.

The Mann, Distribution-Free CUSUM and Kruskal-Wallis are non-parametric tests, where the calculation of the test statistic is based on the ranks and not the actual values of the records. The reliability of these three statistical tests therefore does not depend on the underlying distribution of the observations. The Cumulative Deviation and Worsley Likelihood Ratio however, assume that the observations are independent and normally distributed, although these tests can still be applied when there are slight departures from normality. The Mann, Cumulative Deviation, Worsley Likelihood Ratio and Kruskal-Wallis tests are recommended by the World Meteorological Organisation (1988) as procedures for detecting trend or change in long hydrological time series.

4. ANALYSES AND RESULTS

The five statistical tests are applied to the annual streamflow volume and peak discharge series. A 5% critical value for two-sided probability is used. The statistics therefore test the null hypothesis H_0 that the observations are randomly ordered versus a trend or change in mean, as opposed to the one-sided probability which tests against either an increase or decrease in the data sequence.

The streamflow series from each station is analysed separately because there is insufficient data to consider average global runoff or average runoff over homogeneous regions. In order to make some general observations, Figures 1 and 2 illustrate locations where 'two or three' or 'four or five' of the statistical tests show significant trends or changes in the means of annual streamflow volumes and peak discharges respectively. Figures 3 and 4 show randomly selected examples of the annual time series of streamflow volumes and peak discharges respectively where one to five of the tests show significant trends or changes.

It is not the intention of this study to rigorously analyse the data or to investigate data from individual stations in detail. The use of a more sophisticated approach is not appropriate as one would be simply trying to read too much into the limited data. Nevertheless, in general, it is difficult to identify trends from the time series plots where fewer than four of the five tests detect statistically significant trends or changes in means. However, where more than three tests show statistically significant trends, the trends can usually be seen in the time series plots (see also Figures 3 and 4).

5. DISCUSSION

The analyses indicate that trends and changes in the means of the annual series (of both the streamflow volumes and peak discharges) are detected at the 5% level of significance by more than one statistical test at about 25% of the stations and by at least four tests at 10% of the stations.

Analyses using the very limited data in Africa and Asia detected positive trends (i.e., flows have been increasing or mean of flows in the latter part of record is higher than that in the earlier part of record) in the peak discharges of three stations in west Africa and streamflow volume of one station in north-east China. In North America, negative trends in both the streamflow volumes and peak discharges are detected (usually by three or four tests) at many stations in the north-east (close to the border of U.S.A. and Canada) and several stations in south-west U.S.A., and positive trends in streamflow volumes are observed for some stations in south-east U.S.A.

In Europe, trends are detected by more than one statistical test (generally only two or three) in less than 10% of the streamflow volume series of 48 locations and about 30% of the peak discharge series of 36 locations. The trends, where observed, are generally negative. In east Australia, trends in streamflow volumes and peak discharges are detected by more than one statistical test at only about 15% of the 21 stations analysed. There is also generally no significant trends observed in the limited data from South America.

The trends and changes in the means at the 5% level of significance are detected by only some of the statistical tests at several sites, and except for certain parts of North America, they are not consistently observed throughout particular regions. In addition, the trends may have resulted from changes in the physical catchment characteristics (although the flows are purported to be for unregulated flow conditions). In any case, if flow conditions have altered as a result of climate change, they should be consistently detected by most of the statistical tests over specific regions. The results from the analyses thus suggest that there is no evidence yet of climate change in the annual streamflow volumes and peak discharges of rivers in the world.

6. SUMMARY AND CONCLUSIONS

Five statistical tests are applied to the annual series of streamflow volumes and peak discharges of 142 rivers throughout the world to investigate whether statistically significant trends or changes in means can be detected in the historical record. The rivers are located mostly in North America, Europe and east Australia and have at least 50 years of data and drainage areas larger than 1,000 km^2.

Trends and changes in mean flows at the 5% level of significance are detected by some of the tests for several locations. However, statistically significant trends are detected by four or five tests at only 10% of the stations. In any case, except for certain parts of North America, the trends are not consistently observed over specific regions. It can therefore be concluded that there is no clear evidence yet of climate change in the annual streamflow volumes and peak discharges of rivers in the world.

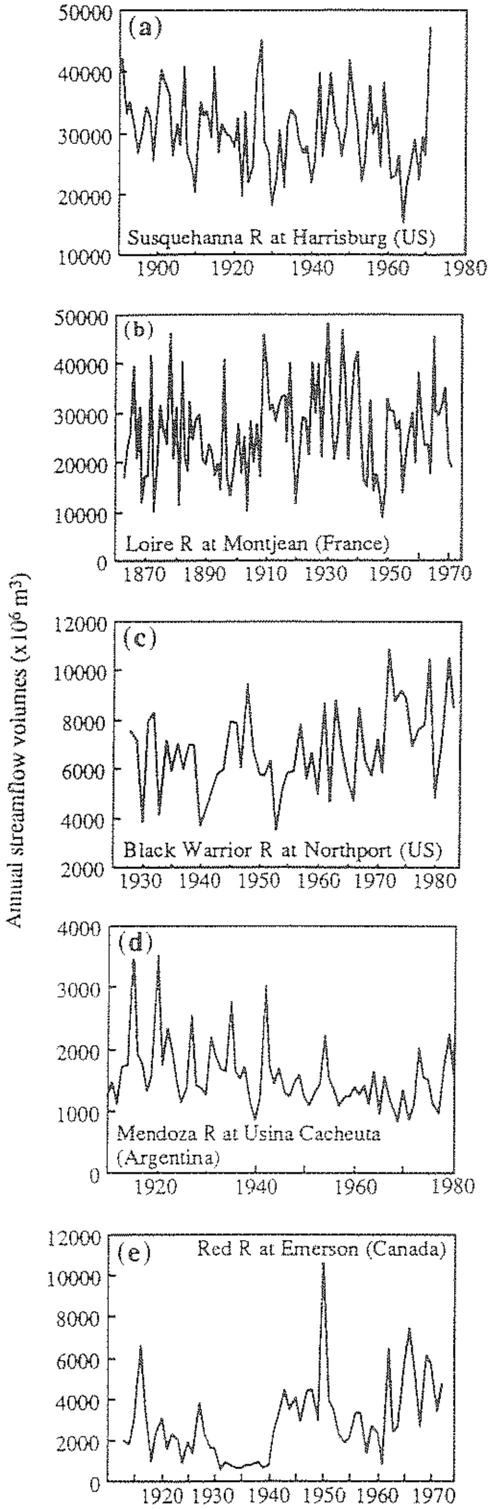

Figure 3 Randomly selected examples of annual series of streamflow volumes where statistically significant trends and/or changes in means (at the 5% level of significance) are detected by (a) one, (b) two, (c) three, (d) four and (e) five statistical tests

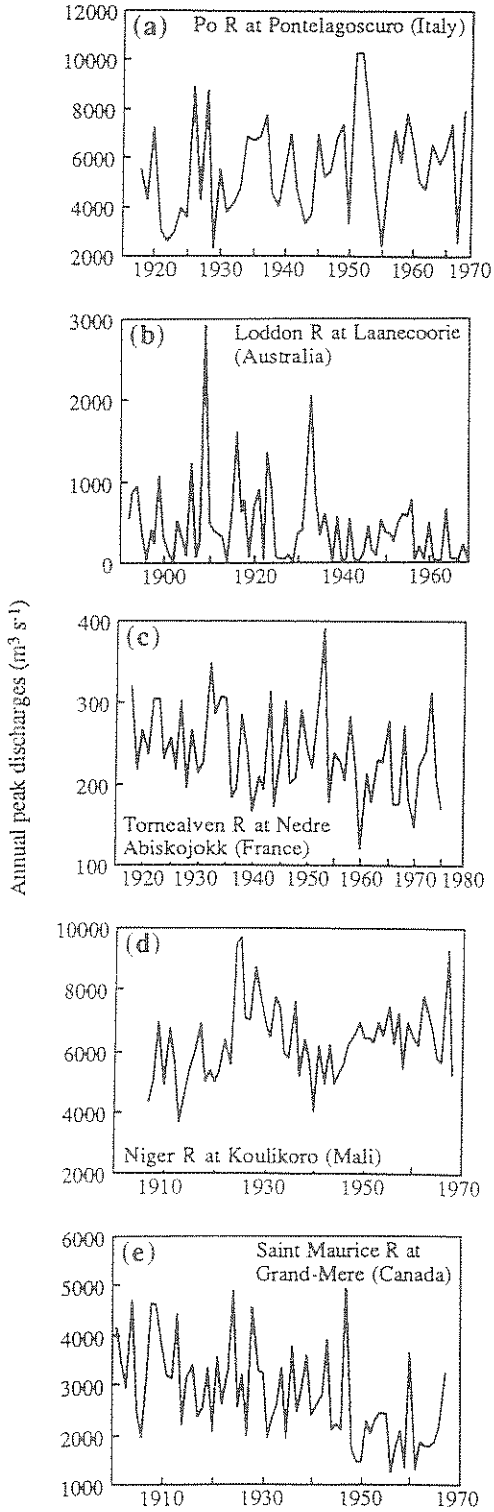

Figure 4 Randomly selected examples of annual series of peak discharges where statistically significant trends and/or changes in means (at the 5% level of significance) are detected by (a) one, (b) two, (c) three, (d) four and (e) five statistical tests

However, it should be noted that the detection of trend or change is difficult because of the short period of instrumental record, high inter-annual variability and lag between increased concentration of greenhouse gases and the climatic variables affecting streamflow.

7. ACKNOWLEDGEMENTS

This is part of a project funded by the National Greenhouse Advisory Committee through the Australian Greenhouse Research Grants Scheme. The authors would like to thank Mr Nishanta Kamaladasa for his assistance in some of the statistical analyses.

8. REFERENCES

Barnett, T.P., Long-term Changes in Precipitation Patterns, in *Detecting the Climatic Effects of Increasing Carbon Dioxide*, edited by M.C. MacCracken and F.M. Luther, pp. 149-162, Carbon Dioxide Research Division, U.S. Dept. of Energy, National Technical Information Service, Springfield, Report DOE/ER-0235, 1985.

Buishand, T.A., Some methods for testing the homogeneity of rainfall records, *J. Hydrol., 58* , 11-27, 1982.

Chiew, F.H.S., and McMahon, T.A., Detection of trend or change in annual flow in Australia rivers, *Int. J. Climatol., 13*, 643-653, 1993.

Chiew, F.H.S., Whetton, P.J., McMahon, T.A., and Pittock, A.B., Simulation of the impacts of climate change on runoff and soil moisture in Australia catchments, *J. Hydrol., 167*, 121-147, 1995.

Elliott, W P., and Reid, R.K., A climatological estimate of precipitation for the world ocean, *J. Clim. Appl. Meterol., 23*, 434-439, 1984.

Ellsaesser, H.W., MacCracken, M.C., Walton, J.J., and Grotch, S.L., Global climatic trends as revealed by the recorded data, *Rev. Geophys., 24*, 745-792, 1986.

Houghton, J.T., Jenkins, G.J., and Ephraums, J.J. (Editors), *Climate Change - The IPCC Scientific Assessment*, Report prepared for the IPCC Working Group 1, Cambridge University Press, 364 pp., New York, 1990.

Jones, P.D., Raper, S.C.B., Bradley, R.S., Diaz, H.F., Kelly, P.M., and Wigley, T.M.L., Northern hemisphere surface air temperature variations 1851-1984, *J. Clim. Appl. Meteorol., 25*, 161-179, 1986.

Jones, P.D., Raper, S.C.B., and Wigley, T.M.L., Southern hemisphere surface air temperature variations 1851-1984, *J. Clim. Appl. Meteorol., 25*, 1213-1230, 1986.

Kendall, M.G., *Rank Correlation Methods*, 4th Edition, Griffin, 202 pp., London, 1970.

McGilchrist, C.A., and Woodyer, K.D., Note on a distribution-free CUSUM technique, *Technometrics, 17*, 321-325, 1975.

McMahon, T.A., Finlayson, B.L., Haines, A.T., and Srikanthan, R., *Global Runoff - Continental Comparisons of Annual Flows and Peak Discharges*, Catena Paperback, 166 pp., Cremlingen-Destedt, Germany, 1992.

McQuirk, J.P., A century of precipitation variability along the Pacific coast of the North America and its impact, *Clim. Change, 4*, 41-56, 1982.

Sneyers, R., *Sur L'analyse Statistique Des Series D'observations*, WMO Technical Note 143, World Meteorological Organisation, 192 pp., Geneva, 1975.

Wigley, T.M.L., Jones, P.D., and Kelly, P.M., Empirical Climate Studies, in *The Greenhouse Effect, Climate Change and Ecosystems*, edited by B. Bolin, B.R. Doos, J. Jager and R.A. Warrick, pp. 271-322, SCOPE 29, John Wiley, Chichester, 1986.

World Meteorological Organisation, *Analysing Long Time Series of Hydrological Data With Respect to Climate Variability*, 12 pp., WCAP-3, WMO/TD, 1980.

Worsley, K.J., On the likelihood ratio test for a shift in location of normal populations, *J. Am. Stat. Assoc., 74*, 365-367, 1979.