Frontiers in Flood Research / Le point de la recherche sur les crues
(IAHS Publ. 305, 2006).

1

Trends in river floods: why is there no clear signal in observations?

CECILIA SVENSSON[1]**, JAMIE HANNAFORD**[1]**,
ZBIGNIEW W. KUNDZEWICZ**[2,3] **& TERRY J. MARSH**[1]

1 *Centre for Ecology and Hydrology, Wallingford, Oxfordshire OX10 8BB, UK*
  csve@ceh.ac.uk
2 *Research Centre of Agricultural and Forest Environment, Polish Academy of Sciences,
  Bukowska 19, 60-809 Poznań, Poland*
3 *Potsdam Institute for Climate Impact Research, Telegrafenberg, D-14412 Potsdam, Germany*

Abstract Floods are of great concern in many areas of the world, with the last decade seeing major fluvial flood events in, for example, Asia, Europe and North America. This has focused attention on whether or not these are a result of a changing climate. River flows calculated from outputs from global climate models often suggest that high river flows will increase in a warmer, future climate. However, the future projections are not necessarily in tune with the records collected so far—the observational evidence is more ambiguous. A recent study of trends in long time series of annual maximum river flows at 195 gauging stations worldwide suggests that the majority of these flow records (70%) do not exhibit any statistically significant trends. Trends in the remaining records are almost evenly split between having a positive and a negative direction. This paper discusses factors that influence the results of trend estimates of floods, and that contribute to the general lack of compelling observational evidence of any long-term increase in extreme river flows. Recent results of trend analysis of observed floods are outlined. Expected impacts of indirect anthropogenic climate change are discussed, and a summary is given of the direct impact of man's influence on river flows in terms of catchment and river management. Different methodologies to detect trends are briefly outlined, and examples are given of how the choice of method can interact with climatological features to result in different estimates of trend. The examples illustrate the effects of using different types of flow indices and different periods of record. The effects on trend estimates of decadal-scale oscillations that have been shown to occur in many river flow records are discussed. Oscillations compound the problem of untangling trends from normal climatic variability as the cycles of the underlying climatic phenomena (e.g. the North Atlantic Oscillation) may also be predicted to change in a greenhouse gas-induced warmer climate. Initiatives to compile networks of pristine catchments with long river flow records are welcomed as a means of keeping scientific objectivity at the forefront of studies of change detection, an area of research riddled by uncertainty and speculation.
Key words catchment management; climate change; flood; trend analysis

Tendances dans les crues de rivières: pourquoi n'y a-t-il pas de signal clair dans les observations?

Résumé Les crues sont à la source de grandes inquiétudes dans de nombreuses régions du Monde, la dernière décennie ayant connu des événements de crue très importants par exemple en Asie, en Europe ou en Amérique du Nord. Cela a soulevé la question de savoir s'il s'agissait ou non d'une conséquence d'un changement climatique. Les données simulées de débits de rivières issues des

modèles climatiques planétaires suggèrent souvent que les forts débits augmenteraient dans un climat futur plus chaud. Ces projections ne sont cependant pas nécessairement en accord avec les données mesurées jusqu'à maintenant et ce que l'on tire de l'observation est plus ambigu. Une étude récente des tendances dans de longues séries de maximums annuels de débits de rivières portant sur 195 stations de jaugeage à travers le Monde laisse supposer que la majorité des ces enregistrements (70%) ne présentent aucune tendance statistiquement significative. Les tendances des autres enregistrements se partagent presque également entre croissance et décroissance. Le présent article discutera de l'impact direct de l'homme sur le débit des rivières en termes de gestion des rivières et d'atténuation des crues et de ses impacts indirects, comme le changement climatique anthropique. Il examinera également les facteurs qui pourraient contribuer à expliquer le défaut général de preuves convaincantes d'une quelconque augmentation à long terme de la puissance des crues fluviales. On insistera sur l'importance d'utiliser de longues séries chronologiques pour l'analyse de tendance, et on présentera des exemples utilisant de longues séries de débits de rivières britanniques allant jusqu'en 2004. Plus précisément, on discutera des effets sur la détection de tendances des oscillations d'échelle décennale existant dans de nombreux enregistrements. Ces oscillations compliquent le problème de la distinction entre tendance et variabilité climatique normale car les phénomènes climatiques sous-jacents (tels que l'Oscillation Nord Atlantique ou l'Oscillation Australe–El Niño) pourraient également être affectés par un réchauffement climatique du aux gaz à effet de serre.

Mots clefs gestion des rivières; changement climatique; crue; analyse de tendance

INTRODUCTION

The costs of catastrophic weather events worldwide exhibited a 10-fold increase between the 1950s and the 1990s (IPCC, 2001a). However, figures for the United States suggest that the number of deaths from extremes has not grown over the past decades, except for those due to floods and heat waves (Chagnon *et al.*, 2000). The financial losses from flood events raises the question of whether or not there is also an increase in major river discharges, and if so, if these are a result of a changing climate.

Large fluvial flood events in Asia, Europe, Australia and North America during the past 15 years (e.g. Kunkel *et al.*, 1994; Munich Re, 1997; CEH Wallingford/Met Office, 2001; Wang & Plate, 2002; Yeo, 2002; Marsh & Bradford, 2003; Saurí *et al.*, 2003) have received much attention in the media. At the same time, many climate change simulations, where river flows are calculated from output from global climate models, suggest that high river flows will increase in a greenhouse gas-induced warmer future climate (e.g. Nijssen *et al.*, 2001; Reynard *et al.*, 2001; Middelkoop *et al.*, 2001; Milly *et al.*, 2002).

This distressing outlook is compounded by observational evidence suggesting that it is likely that heavy precipitation events have increased at mid- and high northern latitudes (IPCC, 2001b). For example, Klein Tank & Können (2003) found that Europe-average indices of extreme precipitation increased in the period 1946–1999, although the spatial trends are not coherent. Yet, studies of long observational records of river flows do not necessarily support an increase in the occurrence of flood events in the mid- and high northern latitudes (e.g. Kundzewicz *et al.*, 2005). Changes in observed

flood records can be investigated through trend analysis. By using observations rather than model output, uncertainties inherent in the modelling procedure, such as simplifying assumptions and concepts, are avoided. However, using real data involves other problems, chiefly relating to data quality and time series homogeneity, but also to data quantity. Trend analysis requires long records to distinguish climate change-induced trends from climate variability, preferably in excess of about 50 years (Kundzewicz & Robson, 2004). Sometimes, metadata are not available for the records. This results in the trend estimates including not only the possible effect of climate change, but also, for example, of changes in land use and flow attenuation due to reservoirs. Notwithstanding such limitations, river flows represent the integrated response to all the hydrometeorological processes operating throughout a catchment and, as such, provide a more direct assessment of hydrological variability than characterizations based on precipitation—the measurement of which is, in itself, subject to considerable uncertainty.

This paper aims to discuss factors that influence the results of trend estimation for floods, and that contribute to the general lack of compelling observational evidence of any long-term increase in extreme river flows. It starts with an outline of recent results of trend analysis of observed floods with a regional or global scope. This is intended as a background to the discussions of the various issues that follow in the rest of the paper. Firstly, the expected (indirect) impact of anthropogenic climate change is discussed, and secondly a summary is given of the direct impact of man's influence on river flows in terms of catchment and river management. Thirdly, different methodologies to detect trends are briefly outlined, and the three following sections give examples of how the choice of method can interact with climatological features to give different estimates of trend. The examples, mainly from the United Kingdom (UK), illustrate the effects of using different types of flow indices and different periods of record. The effects on trend estimates of decadal-scale oscillations that have been shown to occur in many river flow records are then discussed.

TRENDS IN OBSERVED RIVER FLOODS

Global-, continental- or regional-scale studies of trends in river flows mainly use monthly, seasonal or annual flow data, which are not necessarily indicative of the behaviour of floods, which tend to be of shorter duration. Studies using daily mean flow data are fewer, and regional studies of flood trends have mainly been undertaken for the United States (e.g. Lins & Slack, 1999; Douglas *et al*., 2000), Canada (e.g. Adamowski & Bocci, 2001; Burn & Hag Elnur, 2002) and for different parts of Europe (e.g. Robson *et al*., 1998; Lindström & Bergström, 2003, 2004). The only study with a global scope was carried out by Kundzewicz *et al.* (2005), although relatively few gauges are located outside North America, Europe and Australia. The results of this study are shown in Fig. 1.

A range of artificial influences may contribute to a lack of homogeneous spatial patterns emerging from regional studies of trends in floods. However, the findings of the above studies can be summarized as follows: there is some evidence of decreasing trends in floods mainly in parts of western Canada (Adamowski & Bocci, 2001; Burn & Hag Elnur, 2002; Yue & Wang, 2002; Kundzewicz *et al*., 2005), but these studies
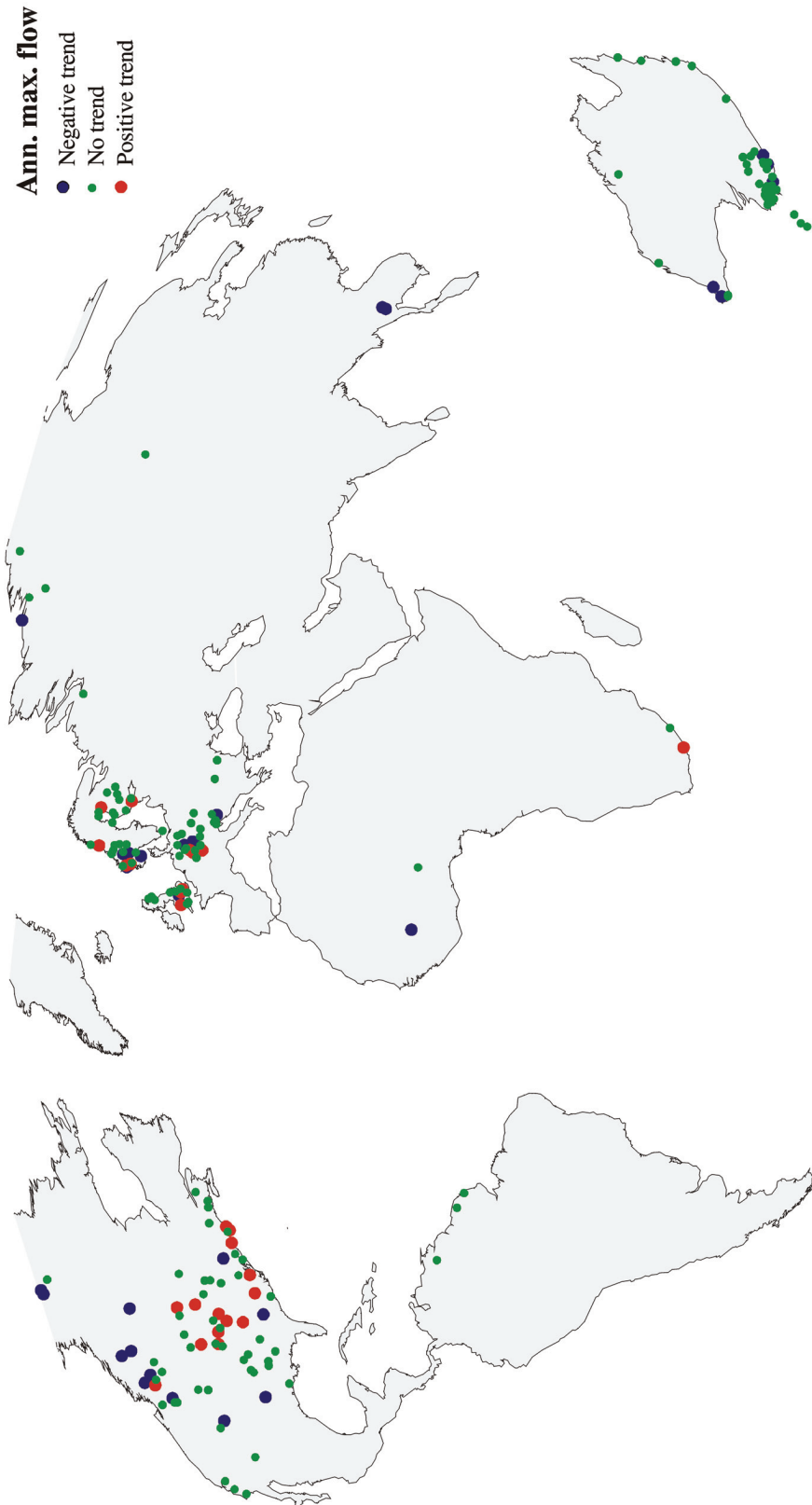
Fig. 1 Trends in annual maximum daily mean river flow at 195 stations across the world, estimated using the Mann-Kendall test. Negative trends are shown as blue dots, and positive trends as red dots. These trends are significant at the 10% level (two-sided test). Adapted from Kundzewicz *et al.*, (2005), based on data from GRDC (2003).

do not show consistent results for the remaining parts of the country. The results for the United States vary from no significant (regional) trends when spatial dependence is taken into account (Douglas *et al.*, 2000) to a small or moderate number of trends of varying direction when flow records are investigated on an individual basis (Lins & Slack, 1999; Kundzewicz *et al.*, 2005). In Europe there is some evidence of significant positive flood trends in northern Scandinavia (Lindström & Bergström, 2003, 2004; Kundzewicz *et al.*, 2005), but no national flood trends could be found in the UK (Robson *et al.*, 1998). There are significant trends at a quarter of the stations in Central Europe (Kundzewicz *et al.*, 2005), but they are of both positive and negative direction. The rest of Europe was not covered by the above studies.

The global study by Kundzewicz *et al.* (2005) uses long time series of annual maximum daily mean river flows at 195 gauging stations (Fig. 1). Their results suggest that the majority of these flow records (70%) do not exhibit any statistically significant trends at the 10% significance level (two-sided test). Trends in the remaining records are almost evenly split between having a positive and a negative direction.

IMPACT OF ANTHROPOGENIC CLIMATE CHANGE

There are two primary factors that determine how human activities change climate: first, the rate of greenhouse gas emissions and other pollutants, and second, the response of the climate to these emissions. The rate of emissions depends on many different assumptions about how the world's population, economy, energy-technology and lifestyles will evolve in the future, and can be summarized in a range of scenarios. The response of the climate under these different potential scenarios can only be explored through climate models (Hulme *et al.*, 2002).

The mechanism whereby an increase in greenhouse gases in the atmosphere would produce global warming is through an increase in downward infrared radiation (Trenberth, 1998). This would not only increase surface temperatures, but also enhance the hydrological cycle as much of the heating at the surface goes into evaporating surface moisture. With higher temperatures in the atmosphere, the water-holding capacity also increases, and together with an increase in evapotranspiration this suggests that the actual atmospheric moisture content would increase. Globally, it therefore seems reasonable that over time there must be an increase in precipitation to balance the enhanced evapotranspiration. However, the processes by which precipitation is altered locally are not well understood. Bearing this in mind, Trenberth (1998) argues further that, in general, the atmospheric moisture increase is likely to result in heavier rainfall and therefore also in an increased flood risk, although locally the impacts of climate change may be different.

In the Arctic region, warming of the permafrost would extend the thaw season and deepen the active layer of water infiltration. The spring melt period should be earlier and possibly stretch over a longer time period. Because a deeper active layer results in increased storage capacity, peak flows associated with both snowmelt and rainfall events would be expected to be similar or lower than at present (Rouse *et al.*, 1997). However, where there are glaciers or permanent ice and snow-packs, increasing melt rates can be expected, at least initially, to increase runoff and high flows (Gwyn Rees, CEH Wallingford, UK, personal communication).

Studying climate change impacts on river flows in Great Britain, Reynard *et al.* (2004) note that increases in the modelled summer temperatures, and corresponding elevated evaporation demands, may result in substantial soil moisture deficits extending through a longer portion of the spring and autumn seasons. The drier soil conditions may have only a limited moderating influence on the more extreme rainfall events but could serve to reduce the length of the flood season.

All modelling exercises involve assumptions and simplifications, and river flows calculated using outputs from climate models are associated with a considerable degree of uncertainty. Although many studies suggest an increase in high-flows in a future, warmer climate, not all of the studies suggest significant changes. For example, Prudhomme *et al.* (2003) conclude that most of the 25 000 Monte Carlo-simulated climate scenarios investigated in their study of six catchments in Great Britain show an increase in both the magnitude and frequency of flood events. However, these changes were generally not greater than the 95% confidence limits. The largest uncertainty was attributed to the type of global climate model used, with the magnitude of changes varying by a factor of up to 9 in northern England and Scotland.

IMPACT OF CATCHMENT AND RIVER MANAGEMENT

Throughout much of the world, man's activities have exercised an increasingly pervasive impact on river flow regimes. Quantifying the net impact on flood generating mechanisms and flood magnitudes remains a major scientific challenge. Engineered diversions for irrigation, public water supply, and power generation can be a major distorting influence on natural flow regimes and also disturb the homogeneity of flood time series. The likely impact of artificial influences on flood magnitude may be very evident, as in the case of flow attenuation due to large flood retention reservoirs, or much more subtle as, for example, when industrial effluent serves to increase water temperatures such that particular reaches are less vulnerable to ice-jam flooding.

At the global scale, more than 40% of the total exploitable runoff is estimated to be captured, temporarily, in surface reservoirs (Postel *et al.*, 1996). Reservoir storage—including controlled washland and flood plain storage—will systematically moderate flood magnitudes and introduce step changes or less dramatic inconsistencies into flood time series. At the basin scale, however, the proportion of total runoff represented by available reservoir storage may be very modest and, for extreme events particularly, may reduce flood magnitudes by less than the uncertainty associated with measurements of the peak flow.

At the small catchment scale, any alteration in the pattern of agricultural production or land management can influence flood generating processes and modify flood frequency and/or magnitude (Boardman, 1995). These influences are often greatly attenuated as catchment areas increase and considerable uncertainty remains concerning the net affect at the basin scale. Agricultural drainage can have contrasting impacts on flood frequency depending on the drainage technique, soil type and planting patterns (Robinson, 1989; Iritz *et al.*, 1994). Deforestation may increase flood risk (e.g. by reducing water storage in the soil profile or the canopy) but a major European study (Robinson *et al.*, 2003) found that, specific combinations of tree and soil type aside, changes in forest cover would be likely to have a relatively small effect

on peak flows. Similarly, using case studies across the globe, Calder *et al.* (2004) concluded that the impact of forest management on flooding—at the basin scale—is often overstated.

Urbanization, which increases the proportion of impermeable surfaces in a catchment and restricts flood plain storage, is probably the most significant impact of land-use change on flood risk. This is particularly true where development covers a highly permeable catchment. The increased catchment responsiveness makes urban flow regimes more vulnerable to intense convective storms. However, balancing ponds, sustainable urban drainage systems and other flood alleviation measures may be expected to play an increasing role in moderating the effect of urbanization, at least in relation to moderate flood events.

The River Thames, which drains a catchment of around 10 000 km^2 in southern England, has been subject to considerable land-use change over the last millennium (Sheail, 1988). Since the instigation of routine flow measurement at Teddington in 1883, agricultural practices have changed substantially and urbanization—including significant flood plain development—has increased considerably. The time series of annual gauged maxima exhibits no trend over the 124-year record. However, when allowance is made for the 10-fold increase in abstractions upstream of Teddington to meet London's increasing water needs, a positive (but non-significant) trend is evident. Some counter-vailing artificial influences may be at play, but the Thames flood record suggests that the land-use change signal is weak in relation to flood magnitude. In terms of flood frequency, river management has certainly had a significant impact on the Thames. Channel re-alignments, dredging and weir improvements have increased the channel capacity such that bankfull discharges are more than 40% greater than in the 1930s. Accordingly, overbank flows have declined in frequency (Crooks, 1994; Marsh *et al.*, 2005).

A study of a sub-set of the stations used in the global study undertaken by Kundzewicz *et al.* (2005) (Fig. 1) suggests that although no metadata were available, the surmised impacts of reservoirs and other human-induced changes to the catchments appear to manifest themselves in a more systematic manner in trends in low flow series than in flood series. About half of the 21 stations in the sub-set showed significant increasing trends in the low-flow series (Svensson *et al.*, 2005), whereas significant trends in the high-flow indices were fewer and of varying direction.

Although many artificial influences have only a modest impact on the homogeneity of flood time series, it will be clear that the detection and interpretation of climate-driven trends requires a focus on those rivers where artificial disturbances have only minimal or very minor influence. The decline in monitoring networks in many parts of the world (Vörösmarty, 2002), together with an associated favouring of gauging stations meeting operational rather than strategic water management information needs, underlines the need to enhance global capabilities to detect and attribute river flow regime changes. This is an urgent requirement given the limited agreement between observational evidence of changes in flood magnitude (e.g. Kundzewicz *et al.*, 2005) and climate change scenario-based assessments. The World Meteorological Organization's Commission for Hydrology initiative to collate a worldwide database of river flow series from pristine catchments is welcomed as it will reduce the uncertainties associated with direct human impacts on the river flow when assessing changes to the flow regime.

IMPACT OF METHODOLOGY

Availability of long time series of quality-controlled data is the backbone of any attempt to detect and study climate change signatures in hydrological records. Careful selection of which stations to use in a study is essential, especially since the process of river flow may result from integration of several factors, such as precipitation, snowmelt, catchment storage, evaporation, and human impacts in the drainage basin and the river. Flow data should ideally be taken from rivers with pristine, or near pristine, regimes. Also a judicious selection of methodology is important, since application of different methodologies to the same original data set may result in different trend estimates. There may be differences in the way a "flood" is defined, in the methods to estimate the actual trends and in the way to estimate significance.

What constitutes a "flood"?

Different definitions can be used to establish what constitutes a flood in the context of change detection studies. Instantaneous peak flows can be used, or means calculated over various durations. A commonly used index is the annual maximum daily mean river flow, that is, the largest daily mean flow that occurs in each year. However, in several years the annual maximum daily flow may be of such modest magnitude that it cannot really be called a flood. Therefore, another option to choose is a flood index series including all independent events which exceed a threshold, so that the series contains a certain number of events per year *on average*. In the latter approach such a data set, called the peak-over-threshold (POT) series (also known as the partial duration series), may contain more than one entry from one year and none from another year (when the threshold is not exceeded). There can be a homogeneity problem with long POT series, because the various people extracting the peaks throughout the period of record (from paper graphs, and more recently digitally) may have applied the independence criteria slightly differently.

Methods to estimate trends and significance

There are many ways of testing for change in long time series of hydrological data (cf. Kundzewicz & Robson, 2004). It is necessary to select a statistical test (more than one is good practice), i.e. a test statistic and a method for evaluating significance levels. This selection depends on the properties of the data. For normally-distributed data, slope-based tests (like linear regression) work well, but such methods are not applicable e.g. for the strongly skewed data, which are common in hydrology. Outliers may even reverse the slope when using linear regression compared with using a distribution-free test (e.g. Svensson *et al.*, 2005).

   If the assumptions made in a test are not fulfilled by the data, then the test results can be invalid, in the sense that there may be large errors when applying theoretical formulae for significance levels. For example, if observations are assumed to be independent when in fact they are serially correlated, significance levels calculated by theoretical formulae, beyond their legitimate applicability, may be considerably higher than in reality.

A group of approaches called distribution-free (non-parametric, e.g. rank-based, such as Mann-Kendall) methods do not require any assumptions about the form of distribution that the data derive from. Although they are statistically less powerful, such tests are more suitable to situations of non-normally distributed data.

If the data are not independent and/or not identically distributed (exhibit serial correlation and/or, e.g. seasonality), one can evaluate significance levels by using resampling methods, such as block-permutation or block-bootstrapping (see Kundzewicz & Robson, 2004).

Spatial studies

When studying spatial data, one can follow either a univariate approach (testing for changes in series at individual sites and then performing regionalization), or a multivariate (regional) approach, where regional time series (for pre-defined, climatologically homogeneous, regions) are tested for changes.

The majority of studies of change detection in river flow assume that the data are spatially independent. However, some of the more recent studies take into account spatial dependence through the application of "field" significance, i.e. looking at a region and comparing the number of observed significant trends with the number expected within the region. Using a field significance rather than significance for the individual sites is recommended for regional studies when large amounts of spatially-distributed records are available. The presence of spatial correlation affects the ability of a test to assess the field significance of trends over the network. When spatial dependence is taken into account, the number of significant regional trends may be lower as compared to the approach without consideration of spatial correlation (cf. Douglas *et al.*, 2000; Yue *et al.*, 2003). Existence of spatial correlation, which is not accounted for, may inflate the results of change detection.

ANNUAL MAXIMUM SERIES *vs* PEAK-OVER-THRESHOLD SERIES

Svensson *et al.* (2005) investigated trends in 21 river flow records with a global spread. Three flood magnitude indices and two flood count indices were used. The annual maximum daily mean flow series was extracted, as were POT series of daily mean flow with on average 1 and 3 events occurring per year. POT series are often used because they are considered to include more information than the annual maximum series, allowing the true temporal pattern of flood occurrence to be better represented. The use of POT series also means that an estimate can be obtained of whether the *number* of floods occurring each year is increasing or decreasing. Svensson *et al.* (2005) found that trends in the three magnitude and the two count series were not necessarily correlated. That is, although trends in flood magnitude and flood count were often of the same direction, this was not always the case.

Svensson *et al.* (2005) compared the estimated trends in the annual maximum series with trends in the POT magnitude series with on average one event per year. They found a larger number of significant trends in the annual maximum series than in

the POT series, which was attributed to the way the POT series is derived. A more significant trend may occur in the annual maximum series than in the POT magnitude series when a series of low peaks occur at the beginning or end of a time series with trend. These peaks may be too low to be selected for the POT analysis, whereas one per year will be included in the annual maximum series, sometimes resulting in a steeper slope and/or longer series. For example, compare the annual maximum and POT magnitude time series plots for the Krka at Podbocje in Slovenia (Fig. 2). For this river, the higher threshold of the POT series means that several of the small annual maxima towards the end of the record are not included in the POT series, resulting in a smaller slope of the regression line as well as a shorter period of observations, and hence a lower significance of the trend. The difference in significance between the annual maximum and the POT series suggests that it may be more useful to incorporate a larger amount of data into the trend analysis in some other way than through a simple peak-over-threshold approach. For example, a fixed number of independent peaks (more than one) per year can be selected.
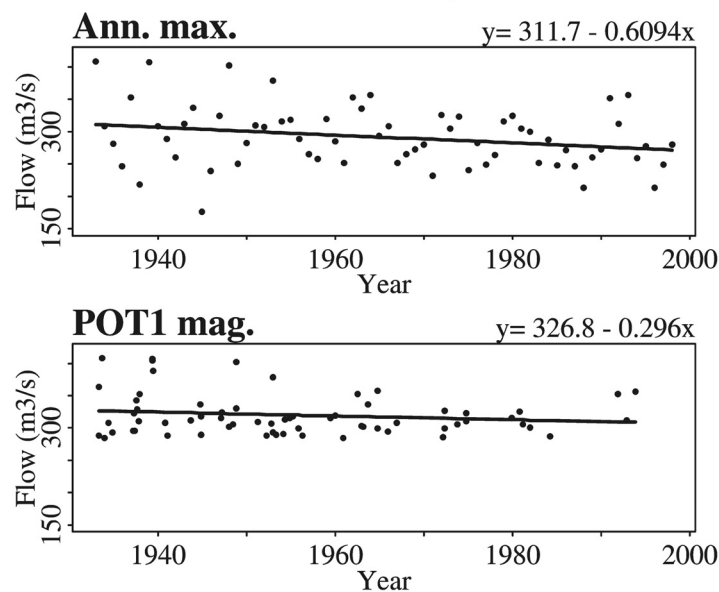

Fig. 2 Observations and linear regression trends in the annual maximum daily mean river flow series (Ann. max.) and the peak-over-threshold magnitude series with on average 1 event per year (POT1 mag.) for the River Krka at Podbocje in Slovenia. Adapted from Svensson *et al.* (2005), based on data from GRDC (2003).

TRENDS IN RUNOFF AND EXTREMES

The impact of increasing temperature and changing rainfall patterns on river flow regimes is often complex. This is a reflection of the interplay of evaporation losses, soil moisture conditions, catchment geology, land use and river and catchment management strategies to moderate drought and flood risk. In addition, snow and ice cover (and melt rates) can also influence the homogeneity of flood time series. The

interaction of all these factors will vary between climatic zones and the net impact may affect flood generating mechanisms responsible for catastrophic events differently to those which cause normal spate conditions. Consequently, there can be no general expectation that, in a warmer world, changes in runoff, for example, will be paralleled by corresponding changes in the frequency and magnitude of major flood events.

In the UK, and across large parts of Europe, the last 30 years have witnessed an overall increase in rainfall with a tendency for wetter winters and drier summers. For England and Wales, the time series of winter (December–February) rainfall exhibits wide variations about the long-term mean but has increased significantly since the 1920s, and the average over the 10 years prior to 2004 is the highest in a series from 1766. There is also evidence that rainfall has become more intense in winter over the 1961–1995 period (Osborn *et al.*, 2000). Studies undertaken using a benchmark network of catchments—where the impact of artificial influences on the flow regime is very limited and hydrometric performance in the flood range is good (Bradford & Marsh, 2003)—indicates that runoff has also increased significantly over the last 30–40 years in many maritime northern and western UK catchments (Hannaford & Marsh, 2006a). This spatial pattern has also been identified in the annual maximum 30-day mean flow and in the persistence of flows exceeding Q10 (i.e. the flow that is exceeded 10% of the time). An increasing trend in high flows is also noted for some southern catchments where the trend is influenced by the extremely wet winter of 2000/2001 at the end of the series (Hannaford & Marsh, 2006b). Significant trends were also observed in annual maximum flows (instantaneous peaks), but these were less widespread, particularly for northern catchments (Fig. 3). This contrast has some parallels with work which has identified increases in heavier rainfall over longer durations, as opposed to 1-day maxima, in some northern and western areas (Fowler & Kilsby, 2003).

Historically, snowmelt and frozen ground were important factors in many major UK flood events (Potter, 1978; Griffiths, 1983) but rising temperatures have substantially reduced their contemporary influence. In the English Lowlands snow is now a very minor component of total precipitation and the last major snowmelt flood on the Thames was in March 1947; at the Teddington gauging station, this peak magnitude has not been approached since. Historical evidence confirms that frozen ground and/or snowmelt were primary causative factors of extensive flooding prior to the 20th century, including the very damaging Thames events in 1829, 1809, 1774 and 1593 (Marsh, 2004). In this context global warming has been beneficial. Similarly, in many polar and temperate rivers where ice jams were a common flood generating mechanism during the Little Ice Age, their role diminished markedly through the 20th century, contributing to declines in winter flood frequency (e.g. on the Elbe and Oder; Mudelsee *et al.*, 2003). The flood record for the River Vltava at Prague (Fig. 4), which extends back to 1830, confirms the long-term decline in winter flood magnitudes (although flood mitigation measures will have been a factor). The catastrophic flooding on the Vltava in 2002 (CHMI, 2003) resulted from extreme August rainfall. This may constitute an early signal of an increasing central European vulnerability to exceptional extreme summer rainfall events but, as yet, there is little evidence for a long-term trend in summer flood magnitudes.
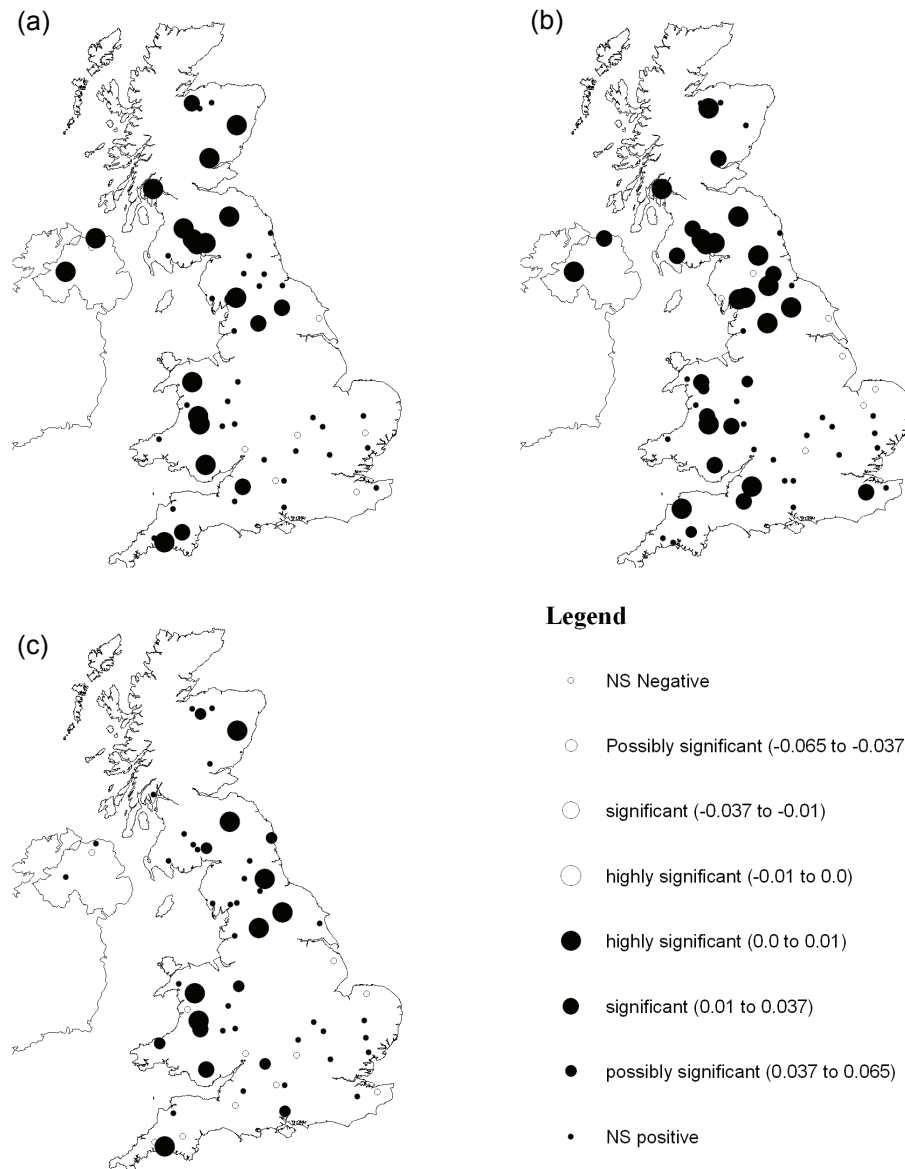
Fig. 3 Comparison between results of trend tests for: (a) annual runoff, (b) annual maximum 30-day mean flow, and (c) annual maximum instantaneous flow, for the UK benchmark network over the 1968–2002 period. Closed circles show positive trends, open circles negative trends, with significance levels shown in the legend. Adapted from Hannaford *et al.* (2005) and Hannaford & Marsh (2006b).

IMPACT OF DECADAL SCALE OSCILLATIONS

Trends in longer-duration maxima, such as the annual maximum 30-day mean flow, may be a manifestation of decadal-scale variations in the predominant storm track. High river flow during a 30-day period will most likely be caused by the passage of several rain-bearing systems, rather than being the response to a single event. Trends may be less visible in the annual maximum daily mean flow series because changes in single-event rainfall totals and rainfall intensities may be less pronounced than changes in the frequency of storm occurrence.
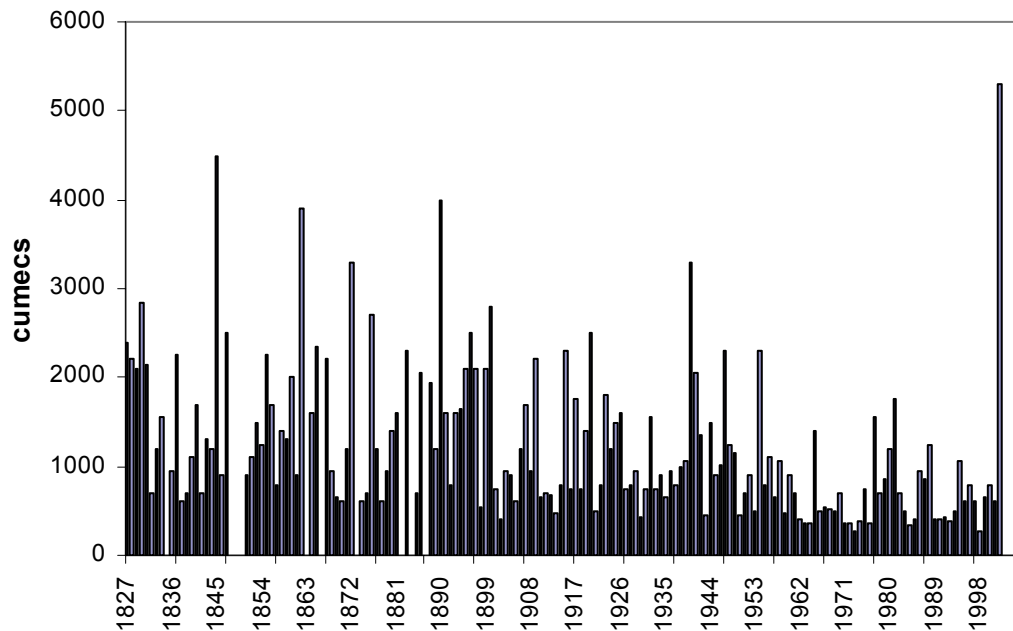
Fig. 4 Annual maximum instantaneous flows for the River Vltava at Prague. Data from the Czech Hydrological and Meteorological Institute, cf. CHMI (2003).

The NAO index (the difference in sea level pressure between the subtropical North Atlantic high and the Icelandic low) indicates the preferred storm track over the North Atlantic into Europe, with positive NAO indices generally being associated with storms tracking in a northeasterly direction towards Iceland and the Norwegian Sea. During the negative mode, storm tracks are more variable, with some storms moving into northwest Europe and others tracking further south, into the Mediterranean (Barry & Carleton, 2001). Consequently, northern parts of Europe exhibit positive correlations between winter river flow and the NAO index, and southern areas show a negative correlation (Shorthouse & Arnell, 1997). From the 1940s to the 1960s, the NAO index exhibited a downward trend, which was followed by a sharp reversal during the next three decades (Hurrell & van Loon, 1997). Any climatic variable related to the NAO is therefore also likely to exhibit trend. From a global perspective, the El Niño Southern Oscillation (ENSO) has an even more widespread impact. Although biennial and four-to-six-year ENSO periodicities are often detected (e.g. Barry & Carleton, 2001), the period 1870 to 1930 also shows longer-period oscillations including a 35-year cycle (Brassington, 1996). It has been suggested that many rivers experience multi-decadal variability (Pekárová *et al.*, 2003). Regardless of the cause of these river flow fluctuations, the length of the cycles involved means that the results of trend analysis will be very sensitive to the length and period of flow record investigated.

The increasing trends in river flows in northern and western areas of the UK reported in the previous section (Fig. 3) are consistent with a shift towards the positive phase of the NAO during the last three decades of the 20th century. Strong correlations between winter rainfall (Wilby *et al.*, 1997), winter runoff (Hannaford *et al.*, 2005) and indicators of winter high-flows—e.g. prevalence of days higher than Q10—(Hannaford & Marsh, 2006b) have been identified in the maritime northern and western catchments where significant high flow trends have been observed.
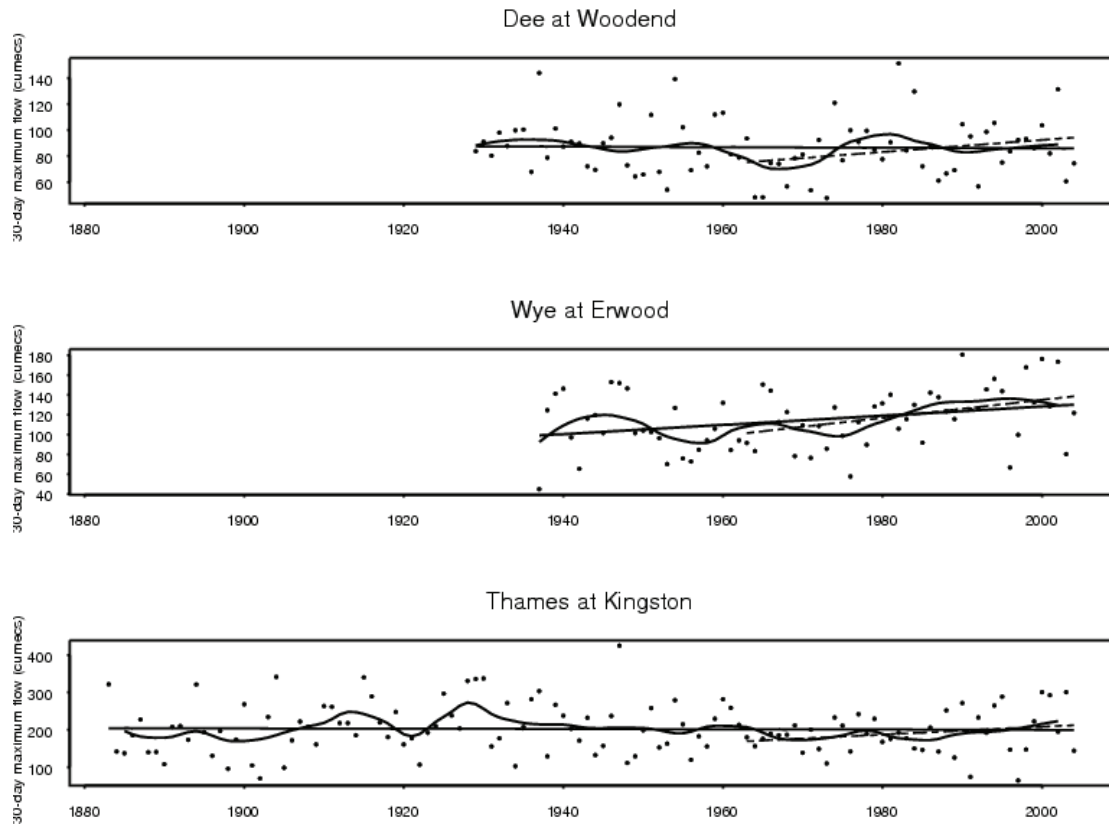
Fig. 5 Time series plots for annual maximum 30-day mean flow for three long hydrometric records from the UK, contrasting linear trends fitted to 1963–2004 (broken line) period, with period-of-record (solid line). Locally-weighted regression curves are also shown. Based on data from the UK National River Flow Archive: www.nwl.ac.uk/ih/nrfa/index.htm.

Consequently, these reported high-flow trends may reflect multi-decadal variability driven by changes in atmospheric circulation patterns; longer-term trends may not display such a pronounced increase. This is illustrated in the time series of annual maximum 30-day mean flows illustrated in Fig. 5. For all three catchments, the shorter record (1963–2004) shows a steeper trend. This is pronounced for the Wye in upland Wales and the Dee in northern Scotland, which are influenced by the NAO. For these catchments, correlations between winter runoff and winter NAO index are 0.5 and 0.23, respectively. The lower correlation for the Dee reflects the more easterly aspect of this catchment, which makes it less exposed to NAO influences. The plot for the Thames, the longest continuous flow record in the UK, illustrates general stability—with marked multi-decadal fluctuations about a relatively stable mean—over a 121-year period.

Natural variability alone is unlikely to be responsible for all of the observed increase in high river flows. The NAO itself is predicted to shift towards its positive phase in a future, warmer climate (Gillett *et al.*, 2002). Thus, in shorter records it becomes very difficult to disentangle trends due to naturally occurring climatic oscillations and the effects of anthropogenically induced climate change. Areas influenced by the ENSO face a similar problem as the ENSO is expected to shift towards its El

Niño phase in the future (Timmermann *et al.*, 1999). In addition to shifts in the mean, changes in inter-annual variance may also be important manifestations of climatic change. For example, Jain *et al.* (2005) report increasing variance in streamflow in catchments in western North America in the post-1970 period, and associate this with changes in atmospheric circulation patterns.

The difficulties involved in attributing causes of change in short records suggest that longer time series should be used. Whereas this is advisable for any trend test, it should be borne in mind that a correct identification of climate change may still not be possible. A change related to a recently altered climate may not be detectable by a statistical trend test as it would only affect the very last part of a long time series. This will be particularly complex if natural variability is high, as variability has a major impact on the detectability of trends, particularly if the trends are weak (Radziejewski & Kundzewicz, 2004). Whilst long records are clearly desirable, there are typically very few long, homogenous records on which to base long-term trend analyses, as noted for the global data sets compiled by Kundzewicz *et al.* (2005). River flow records are generally much shorter than those for rainfall. For example, the UK flow gauging network was largely commissioned in the 1960s and 1970s (Lees, 1987). Broadly speaking, this was a quiescent period for flood events. By contrast, the five years ending in 2002 were, taken together, the wettest on record for the UK and substantial flooding was common. Given the contrasting hydrological character of the early and late years in the study period (1963–2004), and the changes seen in the NAO over this period, a significant tendency for increasing high flows is unsurprising. This highlights the need to balance observations from dedicated networks such as the UK benchmark network, which have sufficient network density to characterize recent variability, with long records where available, to put recent trends into a wider historical context.

CONCLUSIONS

River flows derived from climate change simulations under the assumption of a greenhouse gas-induced warmer future, suggest that high river flows may be expected to increase. However, so far, observational evidence of river floods is more ambiguous. Regional and global studies of trend analysis of high flows generally do not exhibit convincing and spatially coherent patterns of increases in flood magnitude. This does not necessarily mean that there will not be an increase in the future; there may be several different reasons why trends in long-term records are not yet detectable, or not displaying spatial coherence.

Catchment and river management varies from catchment to catchment, and may alter a river's flow regime. For example, an increasing number of reservoirs becoming operational in a catchment over time may counteract any expected increase in fluvial floods due to anthropogenic climate change. However, the surmised impacts of reservoirs and other human-induced changes to the catchments appear to manifest themselves in a more systematic manner in trends in low flow series than in flood series.

The application of different methodologies to the same original data set may result in different trend estimates. There may be differences in the way a "flood" is defined, in the methods to estimate the actual trends and in the way to estimate significance.

The impact on river flow regimes of increasing temperature and changing rainfall patterns is often complex and the use of different flood indices is likely to result in different estimates of trend. There can be no general expectation that, in a warmer world, changes in runoff, for example, will be paralleled by corresponding changes in the frequency and magnitude of major flood events.

Many rivers experience multi-decadal variability. The duration of the fluctuations involved means that the results of trend analysis will be very sensitive to the length and period of flow record investigated. For example, river flows in areas influenced by the North Atlantic Oscillation (NAO) are likely to have experienced increasing trends over the past three or four decades, reflecting the multi-decadal variability of this atmospheric circulation pattern. Longer-term trends may not display such a pronounced increase. The issue is complicated by the NAO itself being predicted to shift towards its positive phase in a future, warmer climate. Thus, in shorter records it becomes very difficult to disentangle trends due to naturally occurring climatic oscillations and the effects of anthropogenically induced climate change. Areas influenced by the ENSO face a similar problem as the ENSO is expected to shift towards its El Niño phase in the future.

It should be borne in mind that even with long records, a correct identification of climate change may still not be possible. A change related to a recently altered climate may not be detectable by a statistical trend test as it would only affect the very last part of a long time series. This will be particularly complex if natural variability (including shorter-term variability) is high, as variability has a major impact on the detectability of trends, particularly if the trends are weak.

Long, quality controlled, data records are the backbone of any attempt to detect changes in hydrological time series. Ideally, data should be taken from catchments where human impact on the flow regime is minimal. The World Meteorological Organization's Commission for Hydrology initiative to collate a worldwide database of river flow series from pristine catchments is welcomed as a contribution to keeping scientific objectivity at the forefront of an area of research riddled by uncertainty and speculation. The discrepancy between results from climate modelling studies and from trend analysis of observed river flows also suggest that a greater focus is needed on reconciling model-based outputs with the variability captured by monitoring programmes around the world.

REFERENCES

Adamowski, K. & Bocci, C. (2001) Geostatistical regional trend detection in river flow data. *Hydrol. Processes* **15**, 3331–3341.

Barry, R. G. & Carleton, A. M. (2001) *Synoptic and Dynamic Climatology.* Routledge, London, UK.

Boardman, J. (1995) Damage to property by runoff from agricultural land, South Downs, southern England, 1976–93. *Geogr. J.* **161**, 177–191.

Bradford, R. B. & Marsh, T. J. (2003) Defining a network of natural benchmark catchments for the UK. *ICE Water & Maritime Eng.* **156**(2), 109–116.

Brassington, G. B. (1996) The modal evolution of the Southern Oscillation. *J. Climate* **10**(5), 1021–1034.

Burn, D. H. & Hag Elnur, M. A. (2002) Detection of hydrologic trends and variability. *J. Hydrol.* **255**, 107–122.

Calder, I. R., Amezaga, J., Aylward, B., Bosch, J., Fuller, L., Gallop, K., Gosain, A., Hope, R., Jewitt, G., Miranda, M., Porras, I. & Wilson, V. (2004) Forest and water policies – the need to reconcile public and science perceptions. *Geologica Acta* **2**(2), 157–166. FRP R8171.

CEH Wallingford/Met Office (2001) To what degree can the October/November 2000 flood events be attributed to climate change? Technical report to Defra, Project FD2304, March 2001. CEH Wallingford, UK.

Changnon, S. A., Pielke, R. A. Jr, Changnon, D., Sylves, R. T. & Pulwarty, R. (2000) Human factors explain the increased losses from weather and climate extremes. *Bull. Am. Met. Soc.* **81**(3), 437–442.

CHMI (2003) Summary report on: Hydrometeorological situation during the August 2002 floods. Czech Hydrological and Meteorological Institute, Prague, Czech Republic.

Crooks, S. M. (1994) Changing flood peak levels on the River Thames. *Proc. Inst. Civ. Engrs Water, Maritime & Energy* **106**, 267–279.

Douglas, E. M., Vogel, R. M. & Kroll, C. N. (2000) Trends in floods and low flows in the United States: impact of spatial correlation. *J. Hydrol.* **240**, 90–105.

Fowler, H. J. & Kilsby, C. G. (2003) A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000. *Int. J. Climatol.* **23**, 1313–1334.

Gillett, N. P., Graf, H. F. & Osborn, T. J. (2002) Climate change and the North Atlantic Oscillation. In: *The North Atlantic Oscillation – Climatic Significance and Environmental Impact* (ed. by J. W. Hurrell, Y. Kushnir, G. Otterson & M. Visbeck), 193–209. AGU Monograph 134, American Geophysical Union.

GRDC (2003) Dataset of 195 river discharge time series from the Global Runoff Data Centre, 56002 Koblenz, Germany http://grdc.bafg.de.

Griffiths, P. P. (1983) *A chronology of Thames Floods*, 2nd edition. Thames Water Authority, Water Resources Report no. 73. Thames Water Authority, UK.

Hannaford, J. & Marsh, T. J. (2006a) An assessment of runoff and low flow trends in a network of undisturbed catchments in the UK. *Int. J. Climatol.* (in press).

Hannaford, J. & Marsh, T. J. (2006b) An assessment of trends in annual maxima and high flow persistence using a network of undisturbed catchments in the UK. *Int. J. Climatol.* (submitted).

Hannaford, J., Marsh, T. J. & Laize, C.R. (2005) An assessment of runoff trends in natural catchments in the Celtic regions of North West Europe. In: Proceedings of the fourth Inter-Celtic Colloquium on Hydrology and Management of Water Resources, Guimaraes, Portugal (ed. by J. P. Lobo Ferreira & J. M. P. Vieira). http://www.aprh.pt/celtico/TEXT/papers.html.

Hulme, M., Jenkins, G. J., Lu, X., Turnpenny, J. R., Mitchell, T. D., Jones, R. G., Lowe, J., Murphy, J. M., Hassell, D., Boorman, P., McDonald, R. & Hill, S. (2002) *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report*. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

Hurrell, J. W. & van Loon, H. (1997) Decadal variations in climate associated with the North Atlantic oscillation. *Climatic Change* **36**, 301–326.

Iritz, L. B., Johansson, B. & Lundin, L. (1994) Impacts of forest drainage on floods. *Hydrol. Sci. J.* **39**, 637-661.

IPCC (Intergovernmental Panel on Climate Change) (2001a) Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change) (2001b) Climate Change 2001: Synthesis Report. Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.

Jain, S., Hoerling, M. & Eischeid, J. (2005) Decreasing reliability and increasing synchroneity of Western North American streamflow. *J. Climate* **18**, 613–618.

Klein Tank, A. M. G. & Können, G. P. (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. *J. Climate* **16**(22), 3665–3680.

Kundzewicz, Z. W., Graczyk, D., Maurer, T., Pińskwar, I., Radziejewski, M., Svensson, C. & Szwed, M. (2005) Trend detection in river flow series: 1. Annual maximum flow. *Hydrol. Sci. J.* **50**(5), 797–810.

Kundzewicz, Z. W. & Robson, A. (2004) Change detection in hydrological records – a review of the methodology. *Hydrol. Sci. J.* **49**(1), 7–19.

Kunkel, K. E., Changnon, S. A. & Angel, J. R. (1994) Climatic aspects of the 1993 upper Mississippi river basin flood. *Bull. Am. Met. Soc.* **75**(5), 811–822.

Lees, M. L. (1987) Inland water surveying in the United Kingdom. In: *1985 Yearbook, Hydrological Data UK Series*, 35–48. Institute of Hydrology, Wallingford, UK.

Lindström, G. & Bergström, S. (2003) Long-term variation in runoff and temperature in Sweden. In: *Water Resources Systems – Water Availability and Global Change* (ed. by S. Franks, G. Blöschl, M. Kumagai, K. Musiake & D. Rosbjerg), 86–92. IAHS Publ. 280. IAHS Press, Wallingford, UK.

Lindström, G. & Bergström, S. (2004) Runoff trends in Sweden 1807-2002. *Hydrol. Sci. J.* **49**(1), 69–83.

Lins, H. F. & Slack, J. R. (1999) Streamflow trends in the United States. *Geophys. Res. Lett.* **26**(2), 227–230.

Marsh, T. J. (2004) The January 2003 flood on the Thames. *Weather* **59**(3), 59–62.

Marsh, T. J. & Bradford, R. B. (2003) The floods of August 2002 in central Europe. *Weather* **58**, 168.

Marsh, T. J., Greenfield, B. J. & Hannaford, J. A. (2005) The River Thames flood of November 1894 – a reappraisal of the maximum flow. *ICE Water Management* **158**, 103–110.

Middelkoop, H., Daamen, K., Gellens D., Grabs, W., Kwadijk, J. C. J., Lang, H., Parmet, B. W. A. H., Schädler, B., Schulla, J. & Wilke, K. (2001) Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic Change* **49**, 105–128.

Milly, P. C. D., Wetherald, R. T., Dunne, K. A. & Delworth, T. L. (2002) Increasing risk of great floods in a changing climate. *Nature* **415**, 514–517.

Mudelsee, M., Börngen, M., Tetzlaff, G. & Grünewald, U. (2003) No upward trend in the occurrence of extreme floods in central Europe. *Nature* **425**, 166–169.

Munich Re (1997) *Flooding and Insurance*. Munich Re, Munich, Germany.

Nijssen, B., O'Donnell, G. M., Hamlet, A. F. & Lettenmaier, D. P. (2001) Hydrologic sensitivity of global rivers to climate change. *Climatic Change* **50**, 143–175.

Osborn, T. J., Hulme, M., Jones, P. D. & Basnett, T. A. (2000) Observed trends in the daily intensity of United Kingdom precipitation. *Int. J. Climatol.* **20**, 347–364.

Pekárová, P., Miklánek, P. & Pekár, J. (2003) Spatial and temporal runoff oscillation analysis of the main rivers of the world during the 19th–20th centuries. *J. Hydrol.* **274**, 62–79.

Postel, S. L., Daily, G. C. & Ehrlich, P. R. (1996) Human appropriation of renewable fresh water. *Science* **271**, 785–788.

Potter, H. A. (1978) *The Use of Historical Records for the Augmentation of Hydrological Data*. Institute of Hydrology Report no. 46. Institute of Hydrology, Wallingford, UK.

Prudhomme, C., Jakob, D. & Svensson, C. (2003) Uncertainty and climate change impact on the flood regime of small UK catchments. *J. Hydrol.* **277**, 1–23.

Radziejewski, M. & Kundzewicz, Z. W. (2004) Detectability of changes in hydrological records. *Hydrol. Sci. J.* **49**, 39–51.

Reynard, N. S., Crooks, S. M. & Kay, A.L. (2004) Impact of climate change on flood flows in river catchments. Report to the UK Department for Environment, Food and Rural Affairs and the Environment Agency, Project W5B-032 final report. CEH-Wallingford, March 2004.

Reynard, N. S., Prudhomme, C. & Crooks, S. M. (2001) The flood characteristics of large U.K. rivers: potential effects of changing climate and land use. *Climatic Change* **48**, 343–359.

Robinson, M. (1989) Small catchment studies of man's impact on flood flows: Agricultural drainage and forestry. In: *FRIENDS in Hydrology* (ed. by L. Roald, K. Nordseth & K. A. Hassel), 299–308. IASH Publ. 187. IAHS Press, Wallingford, UK.

Robinson, M., Cognard-Plancq, A.-L., Cosandey, C., David, J., Durand, P., Führer, H.-W., Hall, R., Hendriques, M. O., Marc, V., McCarthy, R., McDonnell, M., Martin, C., Nisbet, T., O'Dea, P., Rodgers, M. & Zollner, A. (2003) Studies of the impact of forestry on extreme flows: a European perspective. *Forest Ecol. Manage.* **186**, 85–97.

Robson, A. J., Jones, T. K., Reed, D. W. & Bayliss, A. C. (1998) A study of national trend and variation in UK floods. *Int. J. Climatol.* **18**, 165–182.

Rouse, W. R., Douglas, M. V., Hecky, R. E., Hershey, A. E., Kling, G. W., Lesack, L., March, P., McDonald, M., Nicholson, B. J., Roulet, N. T. & Smol, J. P. (1997) Effects of climate change on the freshwaters of Arctic and Subarctic North America. *Hydrol. Processes* **11**(8), 873–902.

Saurí, D., Milego, R., Canalís, A., Ripoll, A. & Kleeschulte, S. (2003) Mapping the impacts of recent natural disasters and technological accidents in Europe. Environmental issue report no. 35, European Environment Agency, Copenhagen, Denmark.

Sheail, J. (1988) River regulation in the United Kingdom: an historical perspective. *Regulated Rivers: Research & Management* **2**, 221–232.

Shorthouse, C. A. & Arnell, N. W. (1997) Spatial and temporal variability in European river flows and the North Altantic oscillation. In: *FRIEND '97 – Regional Hydrology: Concepts and Models for Sustainable Water Resource Management* (ed. by A. Gustard *et al*.) (Proc. Postojna, Slovenia, conference, Sept-Oct 1997), 77–85. IAHS Publ. 246. IAHS Press, Wallingford, UK.

Svensson, C., Kundzewicz, Z. W. & Maurer, T. (2005) Trend detection in river flow series: 2. Flood and low-flow index series. *Hydrol. Sci. J.* **50**(5), 811–824.

Timmermann, A., Oberhuber, J., Bacher, A., Esch, M., Latif, M. & Roeckner, E. (1999) Increased El Niño frequency in a climate model forced by future greenhouse warming. *Nature* **398**, 694–697.

Trenberth, K. E. (1998) Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change. *Climatic Change* **39**, 667–694.

Vörösmarty, C. J. (2002) Global water assessment and potential contributions from Earth Systems Science. *Aquat. Sci.* **64**, 328–351.

Wang, Z.-Y. & Plate, E. J. (2002) Recent flood disasters in China. *Proc. Inst. Civil Engnrs Water & Maritime Engineering* **154**(3), 177–188.

Wilby, R. L., O'Hare, G. & Barnsley, N. (1997) The North Atlantic Oscillation and British Isles climate variability, 1865–1996. *Weather* **52**, 266–275.

Yeo, S. W. (2002) Flooding in Australia: a review of events in 1998. *Natural Hazards* **25**(2), 177–191.

Yue, S., Pilon, P. & Phinney, B. (2003) Canadian streamflow trend detection: impacts of serial and cross-correlation. *Hydrol. Sci. J.* **48**(1), 51–64.

Yue, S. & Wang, C. Y. (2002) Regional streamflow trend detection with consideration of both temporal and spatial correlation. *Int. J. Climatol.* **22**, 933–946.