The Thames flood series: a lack of trend in flood magnitude and a decline in maximum levels

Terry Marsh and Catherine L. Harvey

ABSTRACT

The flow series for the River Thames near its tidal limit is one of the most studied in the world. Its length and completeness, and the richness of the historical information which augments the formal flow record, ensures that the series is of immense value. However, the variability in flood magnitude and frequency that it captures needs to be interpreted with caution. The homogeneity of the time series is influenced by a wide range of factors, including changes in the hydrometric capability of the gauging station and the impact of differing water, river and land management practices on the flow regime. Nevertheless, both the daily flow series and the record of lock levels provide some reassuring signals regarding the resilience of the Thames to fluvial flood risk in a warming world. Since routine flow measurement began in 1883, the Thames basin has seen a substantial rise in air temperature and a tendency for both winter rainfall and annual runoff to increase. There is no trend in fluvial flood magnitude however, partly reflecting a decline in snowmelt contributions to major floods and annual maximum lock levels show a significant decline, reflecting a highly sustained programme of river management.

Key words | climate change, floods, hydrometeorological trends, river engineering

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INTRODUCTION

A series of major flood episodes in the early years of the 21st century (European Environment Agency 2005) has fuelled speculation that flood risk in Europe is increasing because of global warming. In the UK, increasing trends in both annual runoff and the prevalence of high flows have been identified over periods of 30 and 40 years ending in 2004 (Werritty 2002; Hannaford & Marsh 2008). However, when longer periods (>60 years) are examined there is only limited evidence of long-term trends in annual peak flows (Centre for Ecology & Hydrology and Met Office 2001; Robson 2002; Marsh & Hannaford 2007) and some historical evidence of higher magnitude and more frequent flooding prior to the 20th century (Beven 1993; Macdonald 2006; Clark 2007).

This study examines trends in the annual maximum flow series for the Thames at Teddington which, beginning in 1883, has the longest continuous flow record in the UK. A substantially longer historical perspective is provided by flood marks which, although often incomplete, extend back four centuries or more (Griffiths 1983) as well as a considerable volume of documentary evidence relating to historical flood events. Much of the latter, often qualitative in nature, has been assembled in the British Hydrological Society's Chronology of British Hydrological Events (Black & Law 2004). This evidence contributes, in particular, to understanding how the relative importance of different flood-generating mechanisms (especially snowmelt) may have changed over time.

Flooding results from high river levels rather than flows directly, and water levels reflect the hydraulic characteristics of the channel (and floodplain) as well as the magnitude of the river flow. Quantifying the multiplicity of factors impacting on flood levels in the lower Thames is exceptionally difficult, but the systematic recording of lock levels (with records often exceeding 100 years) provides a valuable index of their net effect and allows a

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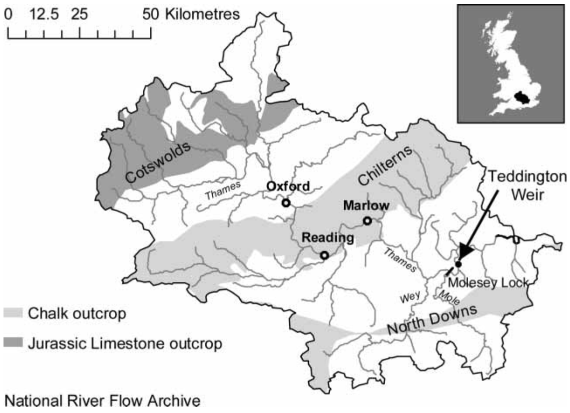
broad assessment of the benefits of river management programmes to be made.

In this paper, statistical analyses of a range of long hydrometeorological time series are provided to identify trends and assess their contribution to change (or a lack of change) in fluvial flood magnitude and frequency in the Teddington reach.

THE THAMES CATCHMENT AND FLOW REGIME

The River Thames drains the largest basin in the UK (see Figure 1); the catchment area above Teddington Weir is 9,948 km^2. Over the 1971–2000 period the average annual rainfall was 717 mm; this was distributed relatively evenly through the year but with a slight tendency to a late autumn/early winter maximum. On average, around 460 mm is lost to evaporation (Marsh & Hannaford 2008), approximately 80% of which occurs during the summer half year (April–September). The evaporation losses impose a marked seasonality on the flow regime; the average January flow at Teddington is four times that of August.

Rainfall patterns in the Thames basin vary substantially over the medium and longer term. For example, 20th century winters were wetter and summers drier than in the 19th century (Marsh *et al.* 2007). However, in relation to flood risk, the frequency of exceptional rainfall totals is of greater significance. Annual daily rainfall maxima are concentrated within the June–October period (Wilby *et al.* 2008) but substantial soil moisture deficits usually greatly reduce the runoff from the summer and early autumn storms. Correspondingly, flood events in the lower Thames are rare during the April–October period. Of a total of 66 events in the 1883–2009 period with daily naturalized flows $>350\ \mathrm{m^3\ s^{-1}}$, only two (in June 1903 and Sept 1968) have occurred in this time frame whereas three-quarters were recorded during the winter (December–February).



National River Flow Archive

Figure 1 | Location map.

The Thames catchment is topographically subdued but geologically diverse with permeable strata underlying around 45% of the catchment (see Figure 1). In flow regime terms there is a particular contrast between groundwater-fed streams draining the chalk (e.g. the Chilterns and North Downs) and Jurassic limestone (Cotswolds) hills and the much more responsive rivers draining the impermeable clay vales. Small water-supply and agricultural reservoirs and urban retention ponds have a local influence on flow regimes but there are no large gravity-fed reservoirs in the catchment to help attenuate flood peaks. However, the geological structure of the Thames Basin provides significant benefit in terms of flood risk in the lower Thames. Commonly, the flood peaks from rapid runoff tributaries draining the impermeable parts of the lower basin (e.g. the Wey and Mole) are seen at Teddington before peaks from the upper and middle parts of the catchment. Flood risk would be greater if these two peaks were more synchronous.

Teddington Weir is on the western outskirts of London, the runoff from which constitutes only a very minor component of the Teddington flow. Land use and land management in the catchment have undergone major historical and more recent changes, but a broad distinction may be drawn between the rural headwaters and increasing urbanization in the lower catchment. Recent population growth has been concentrated in a number of urban and suburban centres in the middle reaches of the river (e.g. Reading and Oxford). This growth has often been accompanied by significant encroachment on the floodplain.

Flow measurement at Teddington/Kingston

Teddington Weir dates from 1811 but the extant hydrometric record begins in 1883. The weir was designed primarily to maintain levels for navigation purposes. The complex barrage of gates and sluices, which has undergone many structural changes in the last 120 years (Anon 1986), has many hydrometric limitations (Mander 1978). Hydraulic formulae – recommended by Sir John Hawkshaw in 1875 (Hunt 1921) – were initially used to calibrate Teddington Weir and some current meter gaugings were undertaken in 1892/93. Although a minor adaptation was made to the Teddington Weir rating (Allard 1937), the gaugings broadly endorsed the hydraulic calibration at low and medium flows. However, the hydrometric performance of Teddington Weir in the flood range was acknowledged to have been poor (McClean 1936). As a consequence, flows in excess of 85 $m^3 s^{-1}$ were generally computed using stage-discharge relations based on tail-water levels; the latter were routinely recorded twice a day at low tide (the incoming tide commonly causes a short-term reversal of flow in the Teddington reach; Mander 1978).

In 1977, the commissioning of an ultrasonic gauging station at Kingston 1 km upstream of Teddington Weir (Child 1979) allowed high flows to be measured with much greater accuracy; the ultrasonic gauge was upgraded to a multi-path configuration in 1983. A comprehensive current metering programme to confirm the ultrasonic calibration endorsed the existing high-flow rating (Mountain 1980), which covered the period from 1951 when a major refurbishment of Teddington Weir was completed. Correspondingly, the post-1951 flow data are both more reliable and more homogeneous than the earlier time series. Knowledge gained from the operation of the ultrasonic station reinforced longstanding doubts about the accuracy of the flows associated with some of the earlier floods on the Thames (most notably the extreme 1894 peak). To address this particular issue a joint study was undertaken to critically review the November 1894 flows by the Centre for Ecology & Hydrology and the Environment Agency, using rainfall–runoff modelling techniques. The analyses strongly supported the need for a reduction in the archived peak flow and a revised maximum gauged flow of 800 $m^3 s^{-1}$ was adopted: a deliberately rounded figure to avoid any implication of spurious precision (Marsh *et al.* 2005).

Because instantaneous peak flows are not available for the greater part of the Teddington record, the water-year (October–September) maximum series (A_{max}) is necessarily based on daily mean flows. The uncertainties associated with the measurement of flood flows prior to 1951, particularly in the early record when only a relatively modest proportion of the more exceptional peak flows would have been contained within bank, implies that a systematic overestimation of the highest discharges cannot be discounted. In addition, the pre-1951 daily flows, derived from two level readings a day, will not have a closely comparable precision with contemporary flows (based on 15-min data). The size and diversity of the Thames catchment means that within-day flow variations at Teddington are normally muted, but an indication of the potential errors involved is provided by the differences between the daily average flows and the associated 15-min maximum flows available since the commissioning of the multi-path ultrasonic gauging station at Kingston. For flood events with peaks >350 $m^3 s^{-1}$, the average difference is 5.9% (with a maximum of 11.1%).

A further and rare characteristic of the Teddington A_{max} series is that it comprises naturalized rather than gauged flows. The former take account of the major abstractions for London's water supply in the lower reaches of the Thames above the gauging station. Contemporary abstractions are well monitored, and can exceed 50 $m^3 s^{-1}$ (compared to a median A_{max} of 318 $m^3 s^{-1}$). There is more uncertainty associated with the early abstraction rates but they were systematically logged and the average over the first 10 years of the Teddington series was <5 $m^3 s^{-1}$ (Littlewood & Marsh 1996). With peak abstractions rates now an order of magnitude greater than in the 1880s, a failure to adjust the gauged flows to accommodate the changes in abstraction rates would, in itself, introduce a tendency for the annual maximum series to decrease.

Major flood events

Extreme events are by their nature both rare and unevenly distributed over time. Figure 2 plots A_{max} for Teddington from 1883, which also shows the locally weighted regression smoothing curve (LOESS) (Cleveland 1979); this provides a guide to fluctuations within the 1883–2009 period (dashes are used to indicate the greater uncertainty associated with the smoothing curve at the beginning and end of the series). The series includes 11 events exceeding 500 $m^3 s^{-1}$. Eight occurred before 1930 and were accompanied by extensive floodplain inundations, but there have been none since November 1974. The subsequent period has

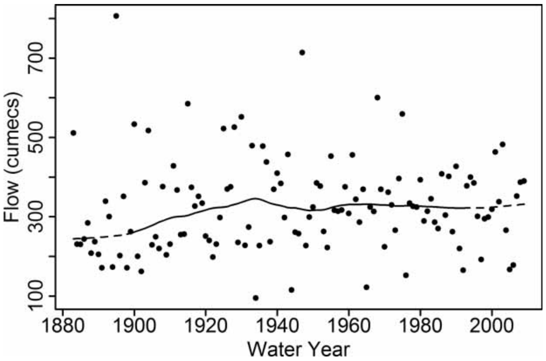


Figure 2 | $A_{\max}$ (naturalized) flows for Teddington.

been notable for the lack of major events; no peaks approached the exceptional magnitude of the 1894, 1947 and 1968 floods.

Since routine flow measurement started at Teddington, the peak levels reported for the 1894 flood are generally the highest on record throughout the lower Thames. Several earlier flood events achieved appreciably higher maximum levels, however. The 1821 peak was '10 inches higher' (0.254 m) and the 1809 peak was 'a foot higher' (0.305 m) in the lower Thames, and at Hampton (3 km upstream of Teddington) the 1774 event was higher by 'about a foot' (Symons & Chatterton 1895). The higher peak levels associated with these pre-1894 events is confirmed by other historical peak flood marks in the middle reaches of the Thames (Griffiths 1983).

Flood-generating mechanisms

The two outstanding events in the Teddington flow series (1894 and 1947) exemplify the two primary flood-generating mechanisms in the lower Thames. In November 1894, flooding resulted from sustained heavy rainfall over a 4-day period (totalling around 120 mm) falling on an already saturated catchment (Symons & Chatterton 1895). By contrast, the March 1947 flood followed the second-coldest winter in the 20th century which left snow accumulations of 50–100 cm across much of the country by early March. The passage of a warm front on the 12th (with rainfall of around 20 mm) triggered a rapid snowmelt over still-frozen ground (Howorth *et al.* 1948). This resulted in the most extensive flooding across England and Wales in the 20th century (Marsh & Hannaford 2007) with widespread and sustained floodplain inundations throughout the Thames basin.

The relative contribution of the main flood-generating mechanisms has changed over time, which has important implications for flood risk in a warming world. Snowmelt (sometimes over frozen ground) was a more common mechanism in major flood events prior to the 1960s and was a contributory factor to many major historical floods, including those of 1809, 1774 and 1768. Although supporting evidence is very limited, an extreme example of a snowmelt flood was recorded by Sydney Gillingham in 1593 (Griffiths 1983). After an exceptionally cold winter, snow accumulations in Oxford were remarkable and a rapid thaw triggered flood levels which were noted as '13 feet [4 m] over Christchurch Meadows'. Many perished in the flooding and the pestilence that followed. It is expected that the thaw would have been general throughout the Thames basin; this flood would therefore have been one of the most outstanding on record.

Rising winter temperatures have seen snowmelt decline as an aggravating factor in relation to flood risk in the Thames basin. Similarly, ice-jam floods (often associated with increased backwater from weirs whose performance was compromised by ice accumulations) also became increasingly rare through the 20th century. In the context of flood risk in the Thames basin, global warming has therefore had some clear beneficial impacts. Kay *et al.* (2006) suggest also that drier soil conditions, particularly in the spring and autumn, may restrict the length of the flood season and consequently reduce flood risk.

Changing hydraulic characteristics of the Thames

The relationship between river levels and flows has been influenced by human activities over many centuries. As a consequence, historical peak levels in many rivers cannot provide a complete and direct comparison with contemporary flood levels. Generally, river management has increased conveyance (albeit unevenly) over time and, for any given flood flow, historical levels may well have been higher than those in the modern era. Correspondingly, the floodplain inundations would have been more extensive.

River and catchment management in the Thames basin has a long history (Ackroyd 2008). In the Middle Ages, the construction of weirs (mostly for milling, fisheries or navigational purposes) tended to exacerbate flood risk. By the 19th century, extensive land drainage in the Thames basin began to have a considerable impact on the flow regime (Robinson 1990); the Rev. J. C. Clutterbuck noted that the time-to-peak in the middle reaches had decreased substantially (Denton 1862). A further extensive land drainage programme (with associated river improvements) was implemented during World War II to help increase food production.

The capacity of the Teddington reach in the late 19th century is uncertain but Andrews (1962) reported that 'for many years' bankfull at Teddington corresponded to a flow of 4,500 mgd (million gallons per day) (237 $m^3 s^{-1}$). Subsequently, river management (including channel-reprofiling and re-alignment and improvements in weir design) has had a very significant moderating impact on flood risk. The 1930 Land Drainage Act and the 1947 flood provided major stimuli to increase the conveyance of the lower Thames (Environment Agency 2009). In relation to the former, Stock (1947) asserted that river engineering, generally increasing the cross-sectional area and slope (and reducing the roughness) of the channel, together with improvements in weir design were intended to increase the channel capacity to 8,000 mgd (415 $m^3 s^{-1}$) by 1935.

It is unclear whether this increased conveyance was fully achieved. The limited channel and weir maintenance during World War II (when Teddington Weir itself suffered structural damage) may have reduced the carrying capacity of the lower Thames. Following the 1947 flood, a strategic dredging programme was initiated to lower the bed of the river between Reading and Teddington by a foot (0.305 m) while the capacity of many of the weirs was further increased (Environment Agency 2009).

Quantifying the net effect of the many factors which influence channel conveyance in the lower Thames is outside the scope of this paper. However, an indication of the overall impact of successive channel improvement (and flood alleviation) programmes is provided by th|e January 2003 flood. Significant floodplain inundations did occur within the Thames catchment (Environment Agency 2008) but in the Teddington reach a peak daily gauged flow of 461 $m^3 s^{-1}$ was accommodated with no local overspill (Marsh 2004). The implications of this improved conveyance are considered further in the discussion.

HYDROMETEOROLOGICAL TIME SERIES FOR THE THAMES CATCHMENT

This section reviews the observational evidence for trends in flood magnitude and frequency in the lower Thames using a range of relevant hydrometeorological variables, most extending over more than 100 years. To provide a necessary backcloth for the trend analyses, the provenance of each time series is outlined below.

Temperature (CET)

Annual mean temperatures derived from the Central England Temperature (CET) series (Manley 1974) are used here as a surrogate for long-term temperature changes in the Thames basin over the 1883–2009 period. Mean temperatures exhibit considerable inter-decadal variability but the overall increase in the CET (around 1.2 °C) represents a historically rapid rise in temperature over the period for which measured flows are available for Teddington.

Annual 3-day rainfall maxima (R_{max})

The lower Thames is particularly vulnerable to notable (multi-day) rainfall events during sustained wet periods (Crooks 1994), especially when catchment soils are close to saturation. In this study, annual 3-day rainfall maxima are used to index changes in the magnitude of high-flow-generating rainfall in the Thames catchment (see Figure 3). The plot is based on accumulations derived from the daily catchment rainfall series developed by Thames Conservancy (Bowen 1960) and now maintained by the Environment Agency. The daily totals are the mean of 12 well-distributed

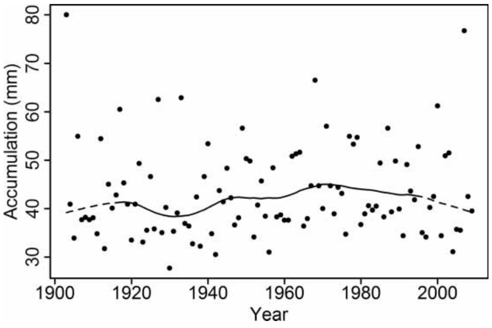


Figure 3 | Annual maximum 3-day rainfall totals for the Thames catchment.

standard raingauges; inevitably, however, there have been a number of site changes since the series was instigated (Chambers 1969).

Conventionally, 'rainfall' implies total precipitation (including sleet and snow) and it is expected, but not fully verifiable, that guidelines on the measurement of precipitation established by the British Rainfall Organisation (Burt 2010) and subsequently adopted by the Met Office (Meteorological Office 1989) have been followed. The modest systematic undercatch of standard raingauges (Rodda 1967) can become significant when snowfall is a substantial component of the total precipitation.

The catchment rainfall series for the Thames begins in 1904 but Figure 3 also incorporates estimates of an extreme rainfall episode in June 1903. During this event, moderate-intensity rainfall fell continuously for 50–70 h (over 13–15 June) across large parts of the catchment; the estimated 3-day rainfall accumulation (80 mm) is based on the maps and tabulations featured in British Rainfall 1903 (Mill 1904).

Annual frequency of 3-day catchment rainfall >30 mm

A 30 mm threshold for catchment-wide 3-day rainfall totals is adopted here to allow sufficient events to be identified for temporal changes in the annual frequency of notable (but not necessarily high-flow-generating) rainfall events to be examined.

Annual naturalized runoff (runoff)

Annual naturalized runoff totals for Teddington are computed using daily flows stored on the UK National River Flow Archive.

Q_5 flows at Teddington (Q_5 nat)

Annual naturalized Q_5 (the flow exceeded 5% of the time in each year) is a commonly used index of high flows; the naturalized Q_5 series for Teddington is shown in Figure 4.

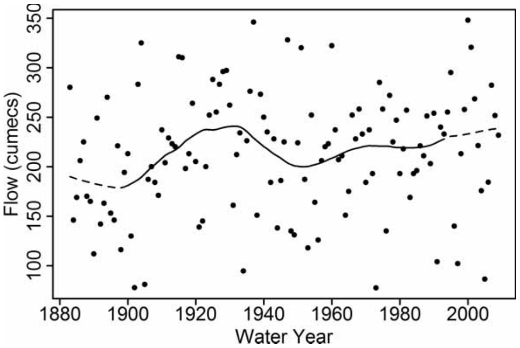


Figure 4 | Annual Q_5 (naturalized) for the Thames at Teddington.

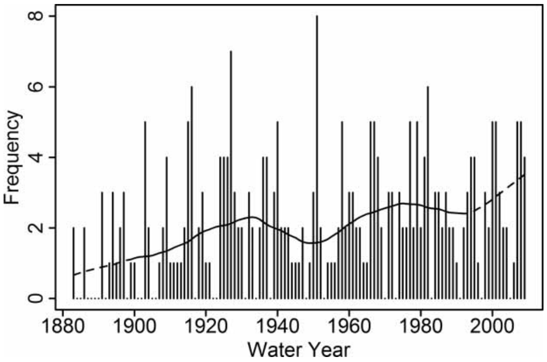


Figure 5 | Annual frequency of flows >250 $m^3 s^{-1}$ at Teddington.

Annual frequency of flow events >250 $m^3 s^{-1}$

In relation to flood risk, both the magnitude and frequency of notably high flows are of importance. Figure 5 shows the annual frequency of independent events with peak daily naturalized flows exceeding 250 $m^3 s^{-1}$ (a relatively modest threshold to allow high flow frequency to be examined).

A_{max}

The highest daily mean flow in each water-year. In this study, both the gauged maximum and the naturalized maximum (illustrated in Figure 2) have been analyzed.

Lock levels (L_{max})

Headwater and tailwater levels at the navigation locks throughout the Thames are routinely recorded at 3-h intervals during the day. All peak levels above a chosen threshold (typically around bankfull) were abstracted to provide a peak-over-threshold (POT) series (Crooks 1994). This current study uses the 1904–2009 series of annual maximum headwater levels (taken from the POT series and updated by the Environment Agency) for Molesey Lock, which is at the upstream end of the Teddington reach and is unaffected by all but the most extreme tides.

The headwater levels are shown in Figure 6 (there are 12 years, spread throughout the series, for which no headwater level exceeded the chosen threshold). It is probable that the outstanding nature of the 1894 peak level partly reflects substantial backwater due to debris accumulation at Molesey Weir (Marsh *et al*. 2005); debris (and ice-jams) will also, on occasions, have influenced other levels in the series.

Trend analyses

Identifying convincing hydrological trends is a complex challenge, not least because of the natural variability in rainfall and river flow patterns, the influence of multi-decadal climatic variations and a range of data homogeneity issues associated with many hydrometric time series (Svensson *et al*. 2006; Wilby *et al*. 2008).

With regard to indexing changes in flood risk in the lower Thames, the most pertinent data limitation concerns the uncertainty associated with flood magnitudes prior to the refurbishment of Teddington Weir in 1951. Correspondingly, the trend analyses incorporate split record components (1883–1951 and 1952–2009) as well as the full time series.

METHODOLOGY AND RESULTS

The World Meteorological Organisation (WMO) guidelines for hydrological trend analysis (Kundzewicz & Robson 2000) recommend the use of several indicators of trend. In this study, two methods were employed to assess the various time series for trends: (1) the Mann–Kendall (MK) test (Kendall 1975), which is a widely-used, non-parametric, rank-based test, and (2) the least-squares linear regression, testing the gradient of the regression line.

Permutation re-sampling was applied to assess the significance levels of the slope estimate; it is a particularly robust method for hydrological time series (Kundzewicz & Robson 2004). The approach involves the generation of a large number of sample time series by randomly re-ordering the observed values. The trend test statistic (e.g. the regression slope) is calculated for each of the re-samples. These are then ranked and if the slope estimated from the original statistic falls outside the 5–95 percentile range of the re-sampled slope values, the slope is considered significant at the 95% level. For those time series exhibiting significant autocorrelations (i.e. the temperature, annual frequency of floods $>250\,\mathrm{m}^3\,\mathrm{s}^{-1}$ and runoff series), a block re-sampling approach was applied.

The results of the MK trend tests for the nine time series are given in Table 1; the sign and significance of any trend is indicated by the number of + or – symbols. Note that the linear regression analyses differed only in that the $A_{\max}$ trends were not significant over any period and the Q_5 trend was not significant in the full record analysis.

The analyses found no trend in any of the hydrometeorological series over the post-1951 period. Over the full record, the expected very significant increase in temperature was confirmed but there is no compelling long-term trend in either the 3-day annual rainfall maxima or the frequency of 3-day catchment rainfall totals exceeding 30 mm. A significant increase in annual naturalized runoff and a modest tendency to increase in the naturalized $A_{\max}$ is evident over the 1883–2009 period. This reflects, in particular, depressed runoff rates prior to 1910 (see below). The annual frequency of daily naturalized flows greater than $250\,\mathrm{m}^3\,\mathrm{s}^{-1}$ shows a very significant increase over the full record; a less significant increase is evident for Q_5.

The results presented in Table 1 index long-term trends but do not capture the substantial multi-decadal variability and persistence that characterize many hydrometeorological time series. LOESS curves have therefore been used to illustrate variability within the full span of the time series featured in Figures 2–6. Recent studies (e.g. Wilby *et al*.

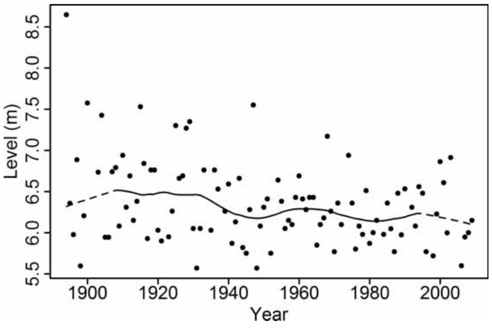


Figure 6 | Annual maximum headwater levels at Molesey Lock.

Table 1 | Results of the Mann–Kendall trend test

	Temp	Rainfall		Flow					
Dataset	**Annual mean CET**	**3-day R_{max}**	**Frequency of 3-day totals >30 mm**	**Annual runoff (nat)**	**Annual Q_5 (nat)**	**Frequency of events >250 $m^3 s^{-1}$**	**A_{max} (gauged)**	**A_{max} (nat)**	**Lock levels L_{max}**
Full record	+++	•	•	++	+	+++	•	+	−−−
Pre-1952	+++	•	•	•	++	++	+	+	•
Post-1951	+++	•	•	•	•	•	•	•	•

Key to symbols: • indicates that no significant trend was found; +, ++, +++ and −, −−, −−− indicate that trends were significant at the 10, 5 and 1% levels, respectively.

2008; Khaliq *et al.* 2009) have highlighted the sensitivity of significance testing to short- or long-term persistence. Where such persistence manifests itself as particularly flood-rich or flood-poor episodes near the beginning or end of a hydrological time series, the impact on the overall trend can be marked.

In relation to the Thames, singularly persistent drought conditions with a notably low frequency of floods are a defining feature of the pre-1910 Teddington record. Intense drought conditions began in 1887 and, notwithstanding some exceptionally wet interludes, runoff rates generally remained relatively depressed until around 1910. One consequence of this 'long drought' (Burt & Shahgedanova 1998; Cole & Marsh 2006) is that trends in the Teddington hydrometric record are generally more evident in the early half of the record.

The impact of the drought can also be seen by examining changes in the significance of any trends as data are removed (or added) to the series under review (Wilby 2006). Here, and using the A_{max} series as an example, the Mann–Kendall test was applied to the full record of 1883–2009 (127 years), then to 1884–2009 and so on up to 1980–2009. Figure 7 illustrates the dependency of the trends on the chosen start year for six of the time series under review. A steep decline in significance of the trends associated with the three river flow series (A_{max}, runoff and Q_5) is evident as the years of the 'long drought' are omitted from the analysis.

Two compelling trends may be identified in Figure 7. Most exceptionally, the increase in temperature over the 1883–2009 period exhibits a very significant (<1%) trend whatever start year is used. The decline in annual

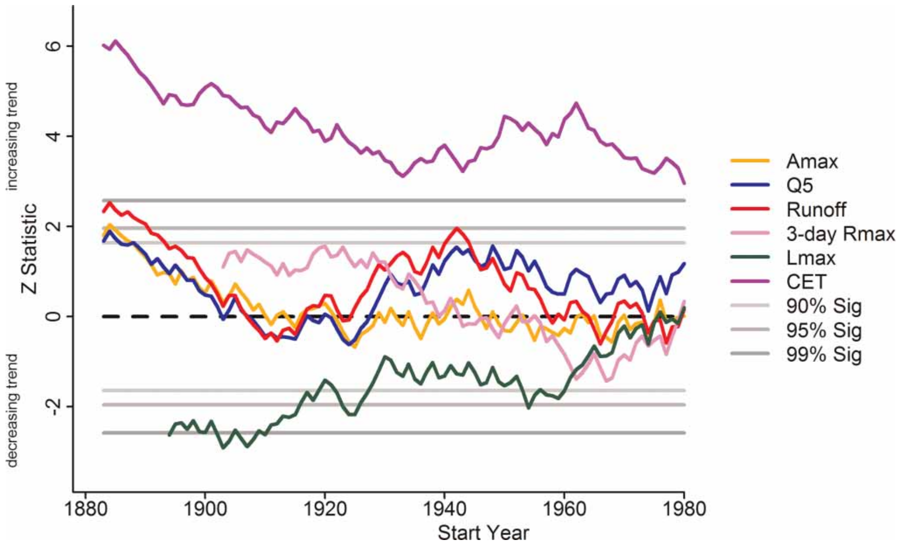


Figure 7 | Variation in the significance of trends in hydrometeorological time series with decreasing record length. The *Z* statistic (the number of standard deviations above or below the sample mean) is a measure of the significance of the trend. Increasing trends plot above the line and decreasing trends below.

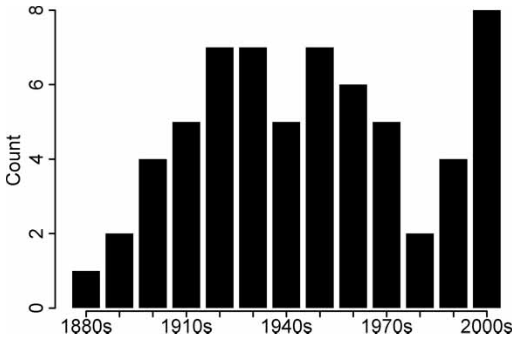


Figure 8 | Decadal count of flow events exceeding >350 $m^3 s^{-1}$ at Teddington.

maximum lock levels (1894–2009) is also very significant for most start years prior to the mid-1920s, and a negative tendency then continues until the end of the major river engineering programme in the late 1950s. The trend in the R_{max} series of 3-day rainfall totals (1904–2009) approaches significance (positive) over timespans beginning before 1920 but not thereafter. In the context of flood risk, any compelling trend in A_{max} would have important implications for flood alleviation strategies. Figure 7 however shows no discernible trend in A_{max} over the 100 years since the end of the long drought.

The importance of a combination of an overall decline in maximum lock levels and the absence of trend in A_{max} is illustrated in Figure 8. It shows decadal counts of events where the maximum daily naturalized flows exceeded 350 $m^3 s^{-1}$, a flow which would have resulted in overbank flows throughout the greater part of the Teddington flow record. The highest frequency is for the decade beginning in 2000 but, given the sensitivity of the analysis to the flow threshold used and the large inter-decadal variability, any statistical inferences should be drawn with caution. Importantly, however, none of the events during the 2000–2009 period produced any appreciable fluvial flooding in the Teddington reach. This is largely a consequence of the improved conveyance in the lower Thames implied by Figure 6.

DISCUSSION

There is considerable evidence that human-induced global warming will impact on river flow regimes (Huntingdon 2006). Several climate modelling studies have predicted that exceptional rainfall events are likely to become more frequent in the UK (Huntingford *et al*. 2003), particularly during the winter. Worldwide climate modelling studies also suggest an increase in rainfall intensities, particularly at middle and high latitudes (IPCC 2007). If realized, such predictions would have major implications for flood risk management and engineering design. However, current assessments of potential future impacts in the UK display large spatial variability and are subject to considerable uncertainties (Prudhomme *et al*. 2003; Wilby *et al*. 2008).

The existence of flood-rich and flood-poor periods has been demonstrated in lengthy UK flood time series (Robson 2002), and a number of studies have identified increases in winter rainfall, annual runoff and flood frequency for parts of the UK over various timespans since 1960 (Black 1996; Werritty 2002; Dixon *et al*. 2006; Hannaford & Marsh 2008). However, for policy development and the design of flood mitigation strategies, the rate of any changes in flood-generating rainfall and fluvial flood magnitude are of primary importance.

Observational evidence from the Thames indicates that, while temporal variability in runoff patterns has been substantial and positive trends exist for some flood-related variables (e.g. Q_5 frequency), there has been no significant change in A_{max} over the full span of the instrumented flood record at Teddington.

In addition, no significant change was identified in the magnitude of 3-day R_{max} or the frequency of 3-day accumulations >30 mm. If a higher 3-day rainfall threshold of 50 mm is adopted, 25 events in the Thames catchment rainfall series can be identified; these are distributed throughout the record with the highest decadal frequencies in the 1960s (5) and 2000s (4). All except five of these major rainfall events occurred in the second half of the year with August and October registering the highest frequency. The soil moisture conditions associated with this seasonal distribution meant that few of the >50 mm rainfall accumulations produced exceptionally high flows; flows at Teddington exceeded 400 $m^3 s^{-1}$ for only two of the events. In a study examining flood-generating rainfall for the Thames catchment above Marlow, Crooks (1994) found a significant decrease in rainfall intensities between the 1892–1940 and 1941–1990 periods. This may be a contributory factor to the relatively low frequency of exceptional flows in the latter half of the Thames record.

While improved mechanisms for indexing historical floods according to their primary generating mechanisms are being developed (Macdonald 2011), the absence of comprehensive snowfall and snowmelt-flood chronologies for the Thames is a barrier to quantifying the decline of snowmelt as a contributory factor in relation to flood risk. Flows exceeding 330 $m^3 s^{-1}$ at Teddington in early 2010 provided a reminder that snowmelt can still impart a significant contribution to flows in the lower Thames (Anon 2010); such circumstances have however been rare since the winter of 1981/82 when snow accumulations reached 26 cm at Heathrow in December (Eden 2008). The paucity of snowmelt events over the last 30 years and the expectation that winter temperatures will continue to rise (UKCP09 2009) suggests that their frequency will continue to decline.

The incorporation of lock level data as well as river flows in the trend analysis has allowed the major impact of river management on fluvial flood risk in the lower Thames to be examined. Headwater lock levels are normally more susceptible to the operation of weir gates than tailwater levels but, for the great majority of the annual maxima featured in Figure 6, Molesey Weir would have been fully drawn (all gates open to maximise conveyance). Corroboration of the general pattern of lock levels featured in Figure 6 is provided by a study of the tailwater series for Molesey undertaken as part of a study of peak lock levels throughout the Thames (Crooks 1994); the general pattern closely replicates that in Figure 6.

Since 1930, a major, sustained and costly programme of river engineering has produced a very substantial increase in the channel capacity of the lower Thames. The Teddington reach is now able to contain flows of around 1.5 Q_{med}; a flow which would have triggered very extensive flooding 100 years ago. While not investigated in this study, an associated reduction in flood risk may derive from the river improvement programmes in some of the lower tributaries (e.g. the Wey and Mole). This would be expected to extend the time lag between the flood peaks associated with rapid runoff from the impermeable lower basin and the flow peaks deriving from the slower-responding upper catchment.

The climatological, geological and land use characteristics of the Thames basin are broadly typical of catchments in the English lowlands but differ appreciably from those in western and northern Britain. Research capitalizing on the recently-released UK Climate Projections (UKCP09 2009) suggests that the heterogeneity of the UK may be reflected in spatially variable catchment responses to climate change (Bell *et al*. 2009). This implies the need for caution when generalizing from the evidence presented in this study. In addition, the large spatial and temporal irregularity associated with exceptional flood events implies that trends (or the lack of them) in individual long records may not be representative. Nonetheless, the lack of long-term trend in the Teddington A_{max} series is consistent with the lack of trend characterizing most lengthy UK flood series (Robson 2002; Marsh & Hannaford 2007).

The very significant decline in maximum lock levels associated with improvements in river management in the lower Thames demonstrates a clear moderation in flood risk at Teddington. It is however essential to emphasize that the impact of flood events, when they occur, has not declined. Continuing floodplain development and urban growth has contributed to the rapidly rising economic costs of notable flood events. The dangers of inappropriate floodplain development have long been recognized and attempts to ensure that natural storage function of the floodplain is not unduly compromised are central to most flood alleviation strategies. Such provision (together with other flood alleviation measures, improved forecasting capabilities and increased alertness of those exposed to flood risk) provides the opportunity to increase resilience to the real and continuing threat of flooding, even in the absence of global warming.

CONCLUSIONS

Naturalized runoff for the Thames at Teddington over the 2000–2009 period was 20% above the 1884–1999 average and the frequency of flows exceeding 350 $m^3 s^{-1}$ was the highest decadal total on record. Such hydrological indices may have contributed to a perception that fluvial flood magnitude and frequency is increasing in a warming world.

This study has found no evidence of a significant increase in water-year maximum daily mean flows or of an increase in the frequency of flood-generating rainfall over the 128-year Teddington series. Notably, none of the hydrometeorological series under review exhibits a positive trend over the post-1951 period. This suggests an insensitivity of flood magnitude to temperature increases. Evidence from historical flood chronologies strongly suggest that this is, in part, a consequence of the decline in snowmelt as an exacerbating factor in relation to major flood events. Furthermore, the statistical analyses strongly support the supposition that flood levels in the Teddington reach have declined relative to the first half of the Thames record. This is a direct reflection of the river management and flood alleviation measures implemented throughout much of the last 100 years.

At this time, when river flow regimes are expected to be undergoing change, long hydrometric time series assume a particular importance. They are a pre-requisite for the identification, quantification and interpretation of hydrological trends which, in turn, provide an essential foundation for the development of robust future flood alleviation strategies. Maximising the completeness and quality of lengthy river flow series requires a continuing commitment to the highest hydrometric and data stewardship standards.

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