TRENDS IN HYDROLOGICAL INTENSIFICATION IN THE UK:
Implications for flood risk management

Nevil QUINN and Michael HORSWELL

CENTRE FOR FLOODS, COMMUNITIES AND RESILIENCE
Department of Geography and Environmental Management
University of the West of England
Bristol, United Kingdom

University of the West of England BRISTOL

1. INTRODUCTION

Recent reviews suggest that despite unequivocal evidence for warming in the 20th century, evidence for any compelling, long term increase in the magnitude or frequency of fluvial flooding in the UK is sparse (Hannaford & Hall 2012, Wilby 2013). This apparent 'conceptual controversy' has already been noted for both Europe (Brázdil *et al*. 2006) and also the UK (Wilby *et al*. 2008). Trend analysis is confounded by both the relatively short UK data sets (mostly post-1970), and the fact that the start of gauging coincided with a relatively flood-poor period (≈1965-1975), as opposed to a relatively flood-rich period towards the end of the record (1998 -2000). Where significant positive trends were found in earlier studies, they were considered either evidence of climate variability linked to atmospheric drivers (e.g. North Atlantic Oscillation) and/or simply an artefact of the start and end of the measuring periods (Robson 2002, Hannaford & Marsh 2008). In stark contrast, modelling of future climates and hydrological response generally suggests increasing flood magnitude and frequency (Bell *et al*. 2012, Kay & Jones 2012). Is this 'conceptual controversy' still apparent? How do we reconcile these views from an engineering practice and design perspective? The purpose of this paper is:

- to update analyses of trend magnitude and frequency in the UK based on gauged flow data
- to analyse for trends in modelled flows based on climate change models for representative UK catchments
- to consider whether the Richards-Baker Index may provide a useful indication of hydrological intensification
- to consider the implications of these findings in relation to engineering design and practice in the UK.

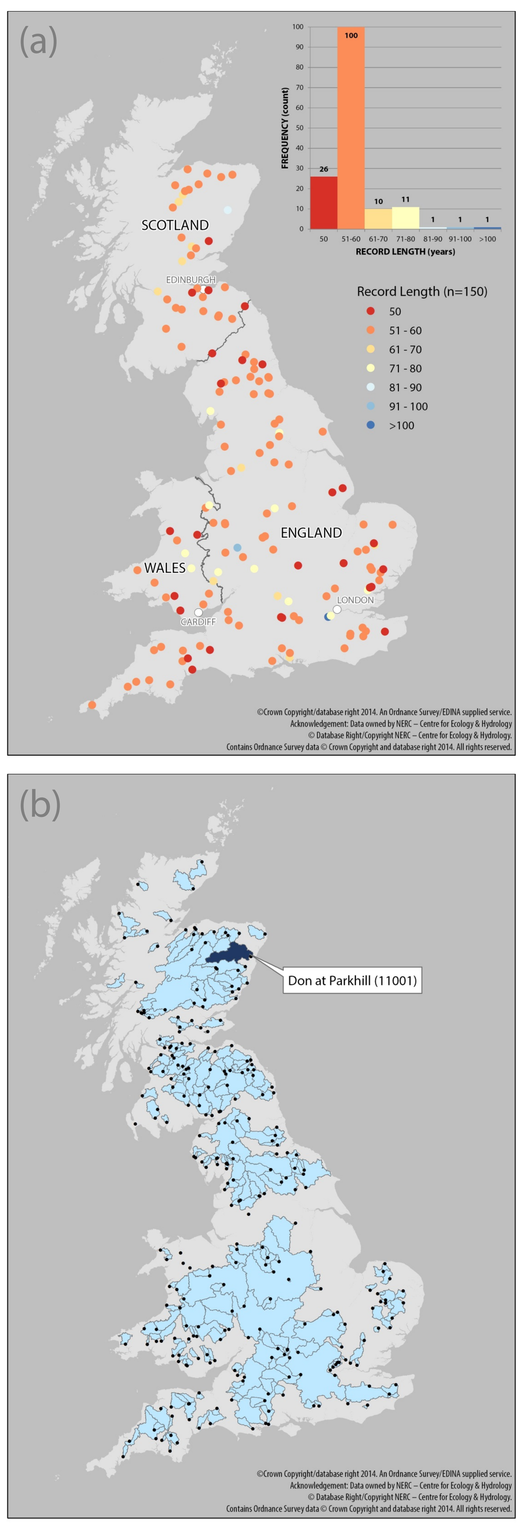

Figure 1: (a) Location of the 150 stations used in the analysis of observed flood peaks and (b) location of the 274 catchments used in the analysis of modelled flows

2. METHODOLOGY

Analysis of observed data – stations with at least 50 years of high-quality data (as defined by their suitability for calculation of QMED and use in pooling for flood frequency estimation in the UK), were selected (Fig. 1a). Both water year annual maxima (AMAX)(150 stations) and peaks-over-threshold (POT) (floods/year)(148 stations) time series were obtained from the UK National River Flow Archive (http://www.ceh.ac.uk/data/nrfa/) and analysed for trend using the Mann-Kendall test (Kendall 1975).

Analysis of modelled flows - '*Future Flows*' comprises an 11-member ensemble of equally probable hydrological outcomes using a nationally consistent method based on the Medium emission scenario (A1B), and the Hadley Centre's HadRM3-PPE-UK climate projections (Prudhomme *et al*. 2013). The ensemble members represent the range of uncertainty in the climate modelling. Daily mean simulated flow is available for 281 representative catchments in the UK, covering the period 1951 to 2098, constituting the best nationally consistent expression of potential flows over the medium to long term (146 water years).

The water year annual maximum of the modelled daily mean flow (M-AMAX) was abstracted for each of 11 ensemble members and 274 catchments (Fig. 1b). The seasonal Richards-Baker Flashiness Index (RBI) (Baker *et al*. 2004) was calculated based on daily mean flow for all ensemble members. The RBI is a good indicator of hydrological intensification because it integrates several flow regime characteristics (e.g. rate of change of flow, peak magnitude, peak frequency). The concept of flashiness is also broadly and intuitively understood. All time series were and analyzed for trend using the Mann-Kendall test.

Further analysis – one catchment showing a high number of significant upward trends was selected for further investigation (11001 Don at Parkhill, shaded dark blue in Fig. 1b). For each ensemble member, the annual maximum was split into two periods (1951-2024 and 2025-2098).

To assess the practical implications for design flood estimation at this station, flood frequencies for typical recurrence intervals were calculated for both periods using the Generalised Logistic distribution and L-moments fitting in HydroTools (Wallingford HydroSolutions). To establish the earliest date by which a statistically significant positive trend attributable to climate change would be detected, Mann-Kendall tests were undertaken iteratively from 30 years of simulated data, increasing the record by one year until a sustained positive trend was recorded.

3. RESULTS

3.1 Trends in observed flood peaks

- ✓ Only 23% of the 150 stations show significant positive trends in the magnitude of AMAX. These stations tend to be in the north of England and south west central England. The three stations with the longest record (>80yrs) do not show a significant trend (Fig 2a).
- ✓ A slightly higher proportion of stations (34%) show a significant trend in POT frequency, principally to the north of the UK and south west Wales (Fig 2b).

3.2 Trends in modelled high flows

- ✓ Of the 3014 simulations (274 catchments, 11 ensemble members) only a small proportion (6%) showed a decreasing trend in M-AMAX, although none were significant (at even p<0.1) (Fig 3a).
- ✓ A majority of simulations (62%) showed a significant increasing trend (p<0.05), 40% of which were at a higher level of significance (p<0.01) (Fig. 3a).
- ✓ Trends were more evident for some ensemble members (e.g. Q4 and Q9) than for others (e.g. Q3) (Fig. 3b). Only one ensemble member (Q3) showed significant trends in less than half of stations.

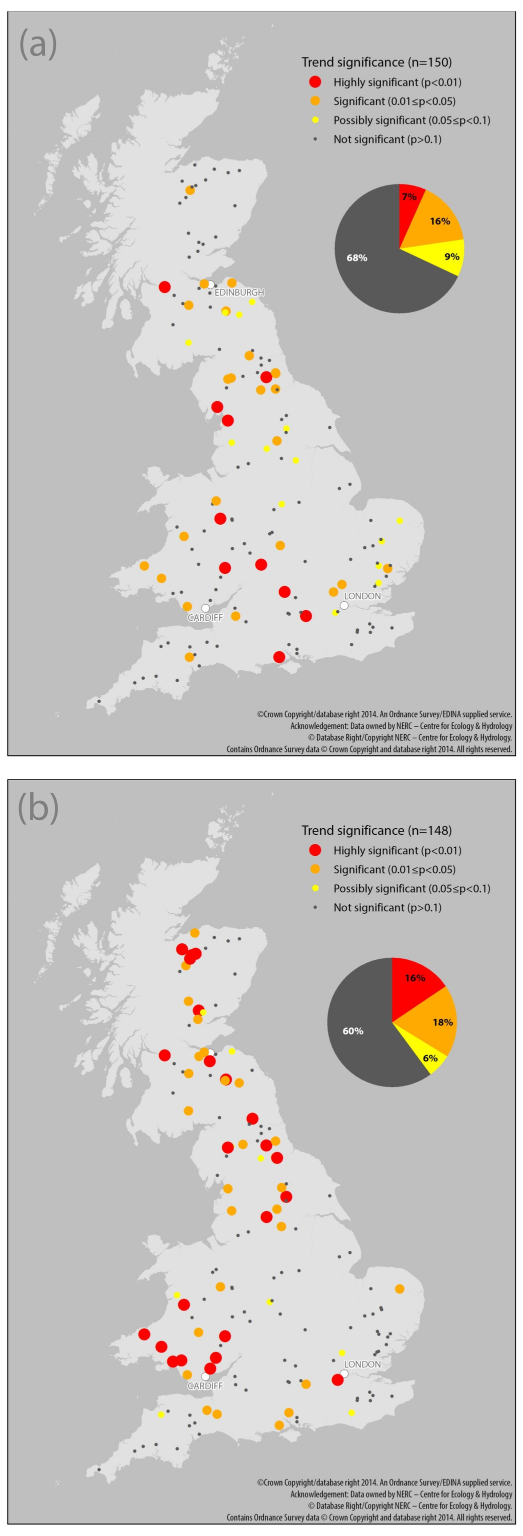

Figure 2: Trend analysis of (a) observed annual maximum series and (b) of peaks-over-threshold frequency (counts/year)

- ✓ Trends in M-AMAX show a clear geographic pattern, with a high proportion of significant trends being reported in the south and south west of England, west Wales, north west England and north east of Scotland (Fig. 3a). East Anglia, the Midlands and south west Scotland show the lowest occurrence of positive trends.
- ✓ 59% of simulations showed a significant increase in winter flashiness (Fig. 3c), in contrast to spring where very few trends are evident (Fig. 3d). In summer, significant decreasing trends dominate (Fig. 3e).

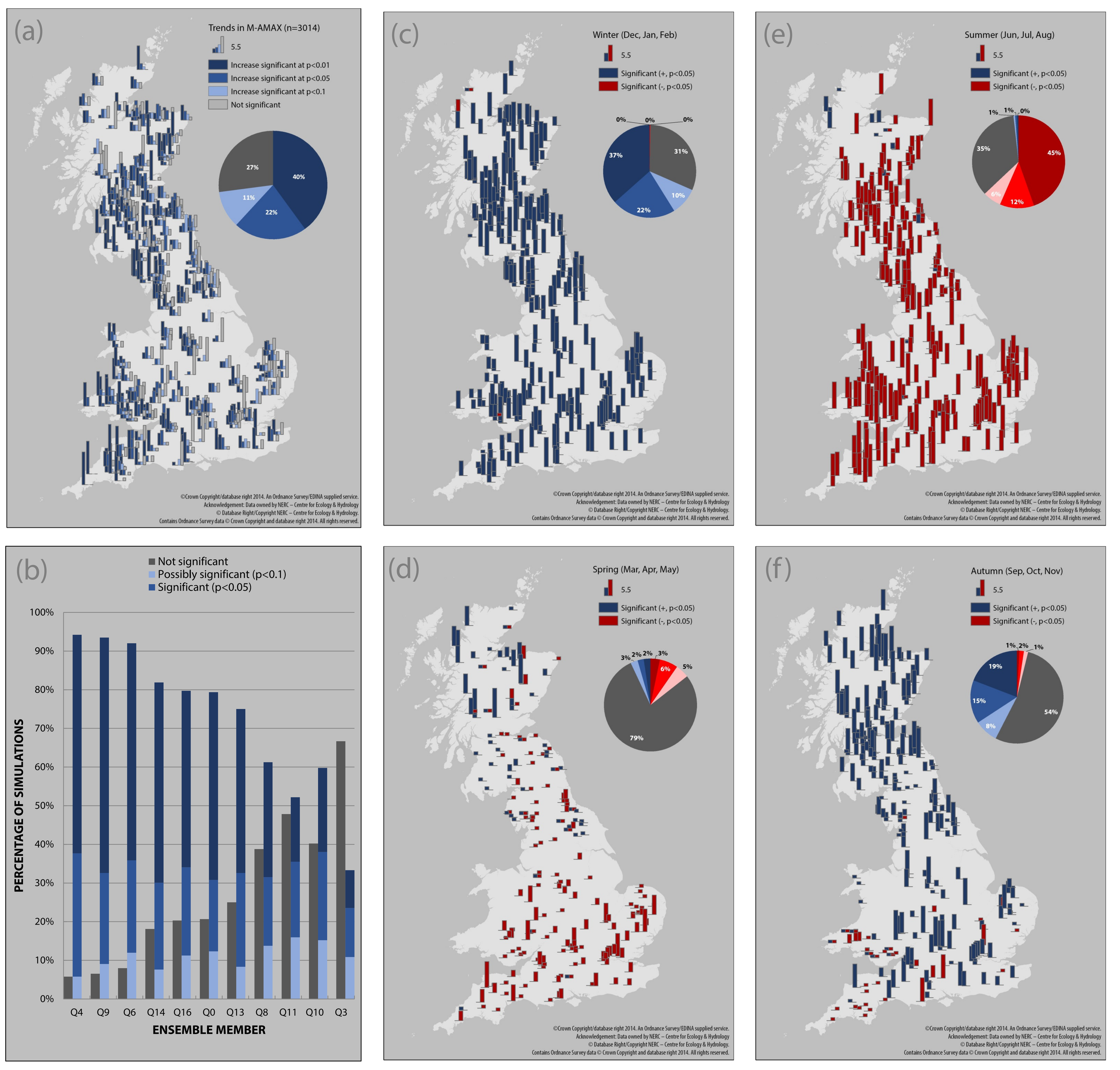

Figure 3: (a) Spatial distribution of trends in M-AMAX and (b) distribution of trends in M-AMAX per ensemble member. Number of ensemble members per station showing trends in the RBI for (c) winter, (d) spring, (e) summer, and (f) autumn.

3.3 Implications for flood risk management and design estimation practice

- ✓ Mann-Kendall trend tests on the observed AMAX and POT frequency for the Don at Parkhill (1969/70 to 2005/06, 37 years) do not show a significant positive trend.
- ✓ Based on modelled daily mean (M-AMAX), the earliest that a significant positive trend could be detected is 2023(72 years of data) (Q11 and Q4), with other ensemble members showing longer times to detection (Fig. 4a). Two ensemble members did not show significant trends over the length of the modelled time series (148 years).
- ✓ Nevertheless, the magnitude of the 1 in 100 event rises from an average across ensemble members of 251m^3/s (1951-2025) to 315m^3/s (2026-2098) (25%) (Fig. 4b). Figure 4c shows the range in flood magnitude increases, between the two time periods, across all ensemble members for different recurrence intervals.
- ✓ Increases for the 1 in 100 event averaged 26% across the ensemble members, but 3 scenarios showed higher increases in the range 40 to 49%. In contrast, earlier estimates suggested a 20 to 30% increase in the 1 in 100 year event in north east Scotland by the 2080s (Price & McKenna 2003).
- ✓ For the 1:200 event one ensemble member showed a 58% increase. This is much higher than the current SEPA guidance suggesting a +20% climate change factor for the 1 in 200 year event in north east Scotland (SEPA 2014).

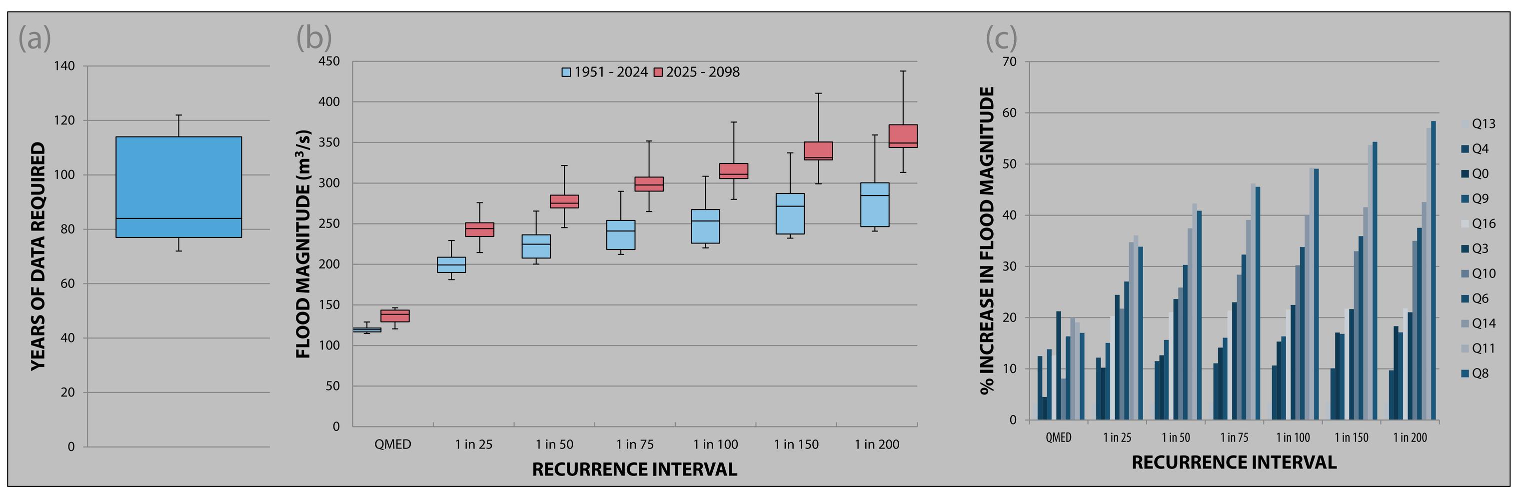

Figure 4: (a) Number of years of data required to detect a statistically significant trend for the Don at Parkhill (11001), (b) the variation in flood magnitude across all ensemble members calculated for two periods for different recurrence intervals , and (c) corresponding percentage increase for each ensemble member.

4. CONCLUSIONS

- ➢ Using the M-AMAX as a proxy, *Future Flows* data suggest a statistically significant and widespread trend of increasing flood magnitude for the period (1951-2098) in the south, west, and north east of the UK. Similarly, the Richards-Baker Index shows a regional increase in hydrological intensification, particularly in winter.
- ➢ However, less than a third of stations with more than 50 years of observed record show statistically significant positive trends in flood magnitude or frequency. This does not mean that UK catchments are resilient to climate change; in their derived flood index, Wilby and Quinn (2013) shown that since 1871, four of the six most severe flood episodes have occurred in the last 30 years. The reason for the low proportion of trends is because 50 years is an insufficient record length for trend detection in the UK, given the strength of the trend relative to climate variability.
- ➢ In the Don at Parkhill catchment at least 72 years would be required to show positive trends in M-AMAX, and 92 years to show trends across more than half of ensemble members. By the time these trends can be statistically confirmed, design flood magnitudes for the same recurrence interval will already be noticeably higher.
- ➢ Furthermore, current guidance on climate change factors in design practice (e.g. +20%) may be underestimates for some UK regions.
- ➢ This paper demonstrates a way of analyzing national data to contextualize local catchment scale impacts of climate change, incorporating uncertainty in climate modelling.

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