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Attribution of detected changes in streamflow using multiple working hypotheses

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Abstract

This paper revisits a widely cited study of the Boyne catchment in the east of Ireland that attributed a change in streamflow during the mid-1970s to increased precipitation linked to a shift in the North Atlantic Oscillation. Using the method of Multiple Working Hypotheses we explore a wider set of potential drivers of hydrological change. Rainfall-runoff models are employed to reconstruct streamflow to isolate the effect of climate taking account of both model structure and parameter uncertainty. The Mann–Kendall test for monotonic trend and Pettitt change point test are applied to explore signatures of change. Different to earlier work, arterial drainage and the simultaneous onset of field drainage in the 1970s and early 1980s were inferred to be the predominant driver of change within the Boyne. There is evidence that a change in precipitation regime is also present, albeit to a lesser extent. This new explanation posits that multiple drivers acting simultaneously were responsible for the observed change. This work highlights the utility of the Multiple Working Hypotheses framework in moving towards more rigorous attribution, which is an important part of managing unfolding impacts on hydrological systems.

1 Introduction

There has been a proliferation of studies assessing changes in observed hydrological series (whether gradual trend, abrupt change or more complex forms) at the catchment scale (e.g. Villarini et al., 2009; Burn et al., 2010; Petrone et al., 2010; Stahl et al., 2010; Hannaford and Buys, 2012; Murphy et al., 2013). While statistical detection of change is an important scientific endeavour, attribution of change is fundamental to developing appropriate management responses and long-term adaptation strategies. In pursuit of evidence-based decision making, water managers need to not only better understand how but why hydrological change is happening. Without rigorous attribution detection studies can be of limited use for planning and could even lead to mal-adaptation, thereby increasing risks to society and the environment, or wasting limited economic resources.

Merz et al. (2012) claim that the majority of studies concerning attribution of statistically detected change fall into the category of "soft" attribution, employing qualitative reasoning and/or correlation based techniques to show consistency between changes detected and typically a single driver (e.g. climatic change). In calling for increased rigour in attribution, Merz et al. (2012) suggest a framework based on proof of consistency, inconsistency and provision of a statement of confidence for "hard" attribution.

Few studies have attempted this challenging task. For example, Jia et al. (2012) employed a fingerprint based method to attribute observed changes in water resource amounts in the Hai catchment, China to local human activity, rather than climate variability. Vorogushyn and Merz (2013) showed that an important contribution to detected increasing trends in observed flood time-series along the Rhine is attributable to extensive river training. Fenicia et al. (2009) used a rainfall-runoff modelling approach to re-examine an anomalous model overestimation in the River Meuse rainfall-runoff behaviour between 1930 and 1965 and hypothesise that land-use and land management changes rather than climate change (as suggested by previous studies) were the likely responsible drivers.

Model-based approaches have been widely used for hydrological change detection and attribution (e.g. Schreider et al., 2002; Andréassian et al., 2003; Seibert and McDonnell, 2010; Gebrehiwot et al., 2013). The creation of a "virtual control catchment" (Andréassian et al., 2003) is possible by calibrating rainfall-runoff models before a known internal disturbance (e.g. forest cover change, urbanisation, river engineering, dam construction) to reconstruct streamflow throughout the period of interest, driven by observed climate inputs as if the internal change had not occurred. The divergence between reconstructed and observed streamflow can then be attributed to an internal disturbance rather than a change in climate, with the premise that the model(s) fully capture catchment behaviour. Use of models to isolate internal disturbances form external climate driven changes can help deciphering the nature of change and therefore contribute to a better understanding of processes of change.

To avoid confirmation bias in attributing change, that is, only assessing information that confirms hypotheses, Merz et al. (2012) suggest that studies should consider other potential drivers. The method of Multiple Working Hypotheses (MWH) offers an established framework in which to develop and test hypotheses of change (Chamberlin, 1890). The MWH method involves the development, prior to the analysis, of several hypotheses that might explain the phenomenon being studied (Chamberlin, 1890). Setting multiple hypotheses prior to conducting analysis increases the likelihood that potential interactions and synergies among hypotheses be uncovered. The method requires an open-minded assessment of known drivers of change, including the possibility that none are correct and that some new explanation may emerge. The application of MWH is an underutilised framework in hydrological research. Only few studies have employed MWH, such as Clark et al. (2011) who advocates MWH in attaining more scientifically defensible and operationally reliable hydrological models.

Following tenets of Chamberlin (1890) and Merz et al. (2012), this paper revisits an earlier study that attributed an abrupt change (change point) in daily streamflow records of the Boyne catchment in the east of Ireland to climatic change (Kiely, 1999). Using flow series derived from the gauging station at Slane Castle for 1941–1995, Kiely (1999) found a statistically significant upward change point (increase in flow after change point) in annual (1978, $p = 0.004$) (Fig. 1) and March (1976, $p = 0.001$) mean flows. Additionally, on a national scale an increase in March, October and annual precipitation was found to occur after 1975, most noticeable in the west of Ireland (Kiely, 1999). The change point in both variables was attributed to a shift in the North Atlantic Oscillation (NAO) resulting in a more positive phase of the NAO index after the mid-1970s, resulting in stronger mid-latitude westerlies, with increased precipitation over Ireland and higher mean annual and March streamflow.

This paper extends the single driver analysis of Kiely (1999) by investigating multiple factors causing change both climate driven and internal within the Boyne catchment.

Using the method of MWH a preliminary assessment of potential drivers for consistency and inconsistency with the observed change point is undertaken based on process understanding, available data and meta-data. From this preliminary assessment, hypotheses about the causes of change are formulated and assessed in more detail. To isolate hypothesised internal and climatic drivers of change, streamflow is reconstructed using a suite of conceptual rainfall-runoff (CRR) models. Statistical tests for evidence of both monotonic trends and change points are employed to explore signatures of change from hypothesised drivers using a comparative analysis between reconstructed and observed streamflow and precipitation. Accordingly, Sect. 2 provides detail on the case study catchment and presents a preliminary assessment of the potential drivers of change within the Boyne using the method of MWH. Section 3 outlines the methods and data used to decipher the nature of change. The results are presented in Sect. 4 and discussed in Sect. 5 in light of advancing more rigorous attribution within the discipline before key conclusions and suggestions for further research are offered in Sect. 6.

2 Study area and hypotheses of hydrological change

2.1 The Boyne catchment

The study area is the Boyne catchment at Slane Castle streamflow gauging station (latitude: 53.706870° N, longitude: 6.562389° W) (Fig. 2). The catchment is located in the east of Ireland with an annual average total precipitation of 897 mm (1952–2009). The catchment has an area of 2460km^2 and a main channel length of 94 km. Topography is predominantly flat to undulating lowland with elevation ranging between 16 m and 338 m. Soil and land-use data were obtained from the Irish Environmental Protection Agency (EPA). Land-use was calculated using the 2006 European Union Coordination of Information on the Environment (CORINE) dataset and consists mainly of agricultural pastures (87 %) with approximately 1.5 % forest and urban area. The catchment is classified as “essentially rural” (FEH, 1999). Over 35 % of the Boyne is comprised of poorly drained soils.

2.2 Overview of potential drivers of hydrological change

Using the method of MWH, possible explanations for the change points detected by Kiely (1999) were derived. Our eleven working hypotheses (WHs) (Table 1) are based on potential internal and climate drivers of change, together with combinations of drivers where potential synergies (WH 10) are apparent. There is also an acceptance that other factors not yet known/accounted for could be contributing to or counteracting change (WH 11). Each WH was subject to an assessment of consistency and inconsistency with the detected change based on previous literature, expert consultation and analysis of available qualitative and quantitative data with potentially important drivers selected for further quantitative analysis as described below.

Some hypotheses of change were relatively straightforward to reject such as WH 2 (Water abstractions/diversions) which is inconsistent with the direction of detected change. Change in Potential Evapotranspiration (PET) (WH 9) was assessed using estimated PET derived for Dublin airport which is the closest synoptic station (38 km south-east of Slane Castle streamflow gauging station) with data covering the period of study. PET was eliminated as no changes were found that are consistent with the detected increase in streamflow. The quality and consistency of hydrometric data at the Slane Castle gauging station was examined through consultation with responsible hydrometric personnel. The station changed ownership from the Irish Electricity Supply Board (ESB) to the Office of Public Works (OPW) on the 25 February 1977, which also coincided with metrication of the measurements. Archived paper streamflow charts before and after 1977 were examined for inconsistencies in measurement and data collection methods along with historical and current rating curves for this station. For the period of record the gauge is deemed of high quality for high and mean flows and fair for low flows according to OPW quality ratings. The station location and measurement method (automatic gauge) have remained the same throughout. Inconsistent/poor quality streamflow data (WH 1) was therefore ruled an unlikely explanation.

WH 3 to 5 (treated water discharges, urbanisation and forest cover and management change) were not selected for further analysis due to their assumed second-order influence. An increase in treated water discharges (WH 3) is known to occur around the mid-1970s from discharge of groundwater from Tara Mines zinc and lead mine 2 km west of the town of Navan into the River Boyne. The contribution to flow is limited to a dilution rate of 1 % (EPA, 2012) hence can be effectively ruled out as having a strong influence on streamflow.

The impact of land-use changes are difficult to assess at the scale of the Boyne catchment. In spite of this, it is a local phenomenon so the impact is assumed to decrease with increasing catchment size (Blöschl et al., 2007). However, it is important to consider the position of land-use change within the catchment as well as total extent of disturbances. The town of Navan (Fig. 2) is the largest in the catchment (9.13km^2 in 2006) and is situated 10 km upstream of the Slane Castle gauging station. While the population of Navan urban area decreased slightly (5.6 %) from 4367 people between 1971 and 1981, the population immediately surrounding the town centre almost doubled from 5907 to 11 136 people during the same period (Meath County Council, 2009). Navan also experienced a similar expansion in population between 1996 and 2002 but streamflow at Slane Castle show no evidence of change during this period. Hence, an increase in population leading to likely urban expansion in the 1970s was deduced not to have had an important influence, although it is acknowledged that the effects of the two periods of urban expansion might be different with regard to their influences on the hydrological system. Forest cover (WH 5) accounts for only ∼ 1.5 % of catchment land-use (in 2006), with change in management practices unlikely to cause a magnitude of change in streamflow consistent with that detected.

2.2.1 Arterial and field drainage

Both WH 6 (arterial drainage) and WH 7, (agricultural land-use and management change) were identified as plausible drivers of change. Arterial drainage (WH 6) has been widely installed in Ireland and involved the artificial widening and deepening of the main river channels and important tributaries to increase their effectiveness in conveying discharge. O'Kelly (1955) noted that following arterial works peak flows were raised to about three times pre-drainage values and that both the time to peak and the duration of flood hydrographs were greatly shortened following implementation in the adjacent Brosna catchment. Similar responses in flood peaks have been reported elsewhere (e.g. Bree and Cunnane, 1979; Bailey and Bree, 1981; Lynn, 1981). Likewise, Wilcock and Wilcock (1995) examined the impacts of arterial drainage on the River Maine in Northern Ireland and found systematic increases in high flows. Similarly, Bhattarai and O'Connor (2004), studying the Brosna catchment with the benefit of additional data, confirm the effects of arterial drainage reported by previous research.

The Boyne catchment has experienced widespread arterial drainage with over 60 % of the river network affected during the period 1969–1986 (FSU, 2013). The Boyne scheme represents the largest investment in arterial drainage in Ireland at a cost of IEP 8.6 m at the time (equivalent of EU 10.9 m without accounting for inflation) and employed 1000 people at peak (OPW arterial drainage archives). Figure 3 shows the extent and timing of completion of arterial drainage works and the cumulative length of network excavated for major watercourses in the catchment based on information derived from hard copy archives from the OPW. Most works on channels were completed between 1977 and 1979 with large increases in the length of channel (km) in which drainage works were completed in 1973, 1977 and when the works at the largest tributary (the Blackwater) and the Boyne main channel were completed in 1983 and 1984 respectively.

The most important agricultural land-use and management change (WH 7) during the late 1970s and early 1980s was the implementation of field drainage. Field drainage involves the installation of pipes and ditches to remove surplus water from waterlogged agricultural lands resulting in reduced transmission time of water to river channels. Little research has been reported in Ireland on the impact of field drainage on hydrological response, however, Burdon (1986) notes that field drainage appreciably increases winter and spring flows (wetter seasons) from drained lands. Drainage measures have been widely implemented in Ireland, under the Land Reclamation Project (1949) then superseded by the Farm Modernisation Scheme (1974) following Ireland's entry to the European Economic Community (EEC).

It is estimated that a large proportion (> 30 %) of the Boyne catchment area has been subjected to field drainage (Burdon, 1986). However, exact figures are not available due to a lack of records on implementation, because the physical work of drainage was undertaken at a local scale by individual farmers. When field and arterial drainage measures were implemented they were intended to work in tandem, with the efficiency of field works reliant on the increased capacity of receiving river channels to convey additional runoff. Due to their close association, WH 6 and WH 7 are henceforth regarded as a single driver of change (drainage) in the further analysis.

2.2.2 Precipitation regime

Kiely (1999) originally linked the observed change point in streamflow in the Boyne to increases in precipitation driven by the NAO. Hence, WH 8 (changes in precipitation) is also included for further analysis. The NAO can be regarded as the dominant mode of natural climate variability in the region (Hurrell and Van Loon, 1997; Wilby et al., 1997) with positive phases of the NAO index associated with increased westerly airflow and positioning of storm tracks over north-west Europe. The NAO influence in winter has subsequently been linked to extreme rainfalls (Maraun et al., 2011), winter runoff (Laizé and Hannah, 2010), high flows (Hannaford and Marsh, 2008), and enhanced orographic rainfall (Burt and Howden, 2013) in the British Isles. Similarly, Leahy and Kiely (2011) report an increase in March and October hourly rainfall in 1975 across Ireland, with a corresponding decrease in July rainfall. These changes are concurrent with a shift in the winter NAO index to a more positive phase. They further note that annual totals and seasonal distributions of rainfall have changed most in the west and northwest of Ireland. Kingston et al. (2006) undertook a comprehensive review of the NAO and hydrological variables and found a positive correlation between winter NAO and streamflow for most of north-west Europe between 1961 and 1990.

3 Methodology

Four favoured hypotheses of change emerge from our preliminary screening of WHs in Sect. 2: drainage (combination of WH 6 and 7); precipitation (WH 8); the combined effects of drainage and precipitation (WH 10); and other unknown factors (WH 11). To obtain a better understanding of the influence of drainage on hydrological behaviour in the Boyne, rainfall-runoff models were used to simulate a control catchment using data before known disturbance. As climate variables (precipitation and PET) are used to force hydrological models, reconstructed streamflow was assumed to isolate the influence of drainage in the observed flows. Statistical tests for both monotonic trend and change points were then employed to explore signatures of change in observed and reconstructed streamflow. The following sections describe the data and each step of the methodology.

3.1 Hydro-climatic data

Meteorological and streamflow data were obtained from Met Éireann (the Irish Meteorological Service) and the OPW respectively. Daily data from three precipitation stations were averaged to produce catchment area precipitation (see Fig. 2, red points and Table 2). Data for Navan and Mullingar were not available post 2003, so data from Warrenstown was used to extend the catchment average to 2009. Raw data for Warrenstown slightly underestimates the 1952–2003 catchment average hence monthly correction factors were applied to Warrenstown from 2004–2009 following the method of Barker et al. (2004). Here, correction factors were calculated for each month by dividing the sum of monthly total precipitation from the 1952–2003 catchment average by the sum of the total monthly precipitation from Warrenstown over the same period (Table 2). These correction factors were then applied to daily Warrenstown data from 2004–2009 and merged with the 1952–2003 catchment average to create an extended catchment precipitation series of 58 yr. Daily streamflow data for the Boyne at Slane Castle (Fig. 2, red triangle) were obtained for the period 1952–2009. Slane Castle is a velocity-area gauging station automated in 1940 with a weir acting as a control. This is one of the longest, highest quality (stable rating) records in Ireland with less than 1 % of the data missing.

3.2 Hydrological modelling

CRR models were employed to reconstruct daily mean flows. Using the pre-drainage period (pre-1970) to train models allows the reconstruction of streamflow free from the effects of drainage. All CRR models are subject to uncertainties stemming from input data, parameter and model structure uncertainty. It is well known that different combinations of plausible parameter sets within a hydrological model structure can simulate the observed flow to a similar extent – the concept of equifinality (Beven and Binley, 1992). The same concept also applies to model structure, with a number of studies highlighting the utility of multi-model ensembles in simulating change in catchments (Butts et al., 2004; Bastola et al., 2011), while Clark et al. (2008) highlight the challenges of identifying appropriate model structures.

To reconstruct streamflow, three structurally different hydrological models were chosen, each of which have been successfully applied to the Boyne before (Murphy et al., 2006, 2011; Bastola et al., 2011, 2012; Hall and Murphy, 2011; Bastola and Murphy, 2013). These comprise HYSIM (Manley, 1978), NAM (Madsen, 2000) and HyMOD (Boyle, 2001). While all three models are lumped, they differ in their complexity as defined by the number of parameters requiring calibration and the way in which they represent the spatial heterogeneity of the catchment. HYSIM and NAM describe catchment hydrology using a group of conceptual elements. HyMOD is a variable contributing area model, with spatial variability modelled using a probability distribution function. All three models employ a single linear reservoir to represent groundwater.

Each model was calibrated using streamflow data prior to widespread drainage and then used to simulate streamflow for the full period 1952–2009. The time periods for calibration and evaluation were 1952–1959 and 1960–1969 respectively, with one year used for model warm up to adjust the storage components within the model. No weights were applied to individual model structures or parameter sets. All models were forced with the catchment average rainfall and PET data described previously. To account for parameter uncertainty Latin Hypercube Sampling (LHS) using a uniform distribution was employed to generate 500 parameter sets for each model structure. Three objective functions were employed to identify behavioural parameter sets that can acceptably simulate the observed pre-drainage flow: the Nash–Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970); Percent Bias (PBIAS) (Gupta et al., 1999); and the Mean Absolute Error (MAE) (Dawson and Wilby, 2001). NSE is a measure of the goodness-of-fit to the 1 : 1 line when the observed flow is plotted against modelled flow (Moriasi et al., 2007). The closer the NSE is to 1, the higher the accuracy of the hydrological model. PBIAS measures the average tendency of the modelled flow series to be larger or smaller than the observed flow expressed as percentage. Positive (negative) PBIAS values mean reconstructed flow over (under)estimated observed flow values. MAE provides the average magnitude of the residuals. Behavioural parameter sets were defined as those achieving $\text{NSE} \geq 0.75$, $\text{PBIAS} \leq |10|$ and $\text{MAE} < \frac{1}{2}$ multiplied by standard deviation of observed streamflow for that period. The selection of these thresholds ensures that unsatisfactory models are not classed as behavioural (Moriasi et al., 2007). Only parameter sets that were found to be behavioural for both calibration and evaluation periods were used for reconstructing flows.

3.3 Trend and change point analysis

3.3.1 Hydrological and precipitation indicators

Observed precipitation, observed streamflow and reconstructed streamflow series were analysed for evidence of monotonic trends and change points. Fifteen hydrological and fifteen precipitation indicators were extracted for the period 1952–2009. These were:

- Annual mean flow (AMF)
- Annual 90th percentile of daily mean flow (Q10)
- Annual Richards–Baker hydrological flashiness index (RB)
- Monthly mean flow, January to December (MMF)
- Total annual precipitation (TAP)
- Annual 90th percentile of daily precipitation totals (P10)
- Annual coefficient of variation (CV) of daily precipitation totals (PCV)
- Total monthly precipitation, January to December (TMP)

The RB index computes catchment response to rainfall, by measuring oscillations in flow relative to total flow and provides a useful characterisation of the way catchments process hydrological inputs into streamflow outputs (Baker et al., 2004). Q10 and P10 are high flow/precipitation indicators defined as the flow/precipitation equalled or exceeded for 10 % of the time (i.e. 90th percentile) during each year in the 1952–2009 period. Hydrological and precipitation indicators were calculated in $m^3\,s^{-1}$ and mm over period of time, respectively, except for the RB index and PCV which are dimensionless. PCV is the standard deviation divided by the mean daily precipitation totals for each year and is used to test for evidence of changing precipitation variability. To aid comparison between hydrological and climatological indicators, as well as with the results obtained by Kiely (1999) all indicators were derived for the calendar year (1 January to 31 December).

3.3.2 Tests for change detection

Evidence for monotonic trends was assessed using the Mann–Kendall test (MK) (Mann, 1945; Kendall, 1975), a non-parametric rank-based method that is widely applied in streamflow (e.g. Hannaford and Marsh, 2008; Villarini et al., 2011b; Murphy et al., 2013) and precipitation (e.g. Villiarini et al., 2011a; Guerreiro et al., 2013) trend studies. The standardized MK statistic (MKZs) follows the standard normal distribution with a mean of zero and variance of one. A positive (negative) value of MKZs indicates an increasing (decreasing) trend. Statistical significance was evaluated with the probability of Type I error set at the 5 % significance level. A two tailed MK test was chosen, hence the null hypothesis of no trend (increasing or decreasing) is rejected when $|\mathrm{MKZs}| > 1.96$.

The Pettitt (1979) statistic was used to identify a single change point and is extensively employed in both hydrological and precipitation change detection studies (e.g. Kiely, 1999; Zhang et al., 2008; Villarini et al., 2011a, b; Gao et al., 2011; Guerreiro et al., 2013). The Pettitt test is non-parametric and relative to other tests is less sensitive to outliers and skewed data (Pettitt, 1979). The null hypothesis (no step change in time-series) against the alternative (an upward or downward change point in a given year) is tested at the 5 % significance level.

Both change detection tests require data to be independent (i.e. free from serial correlation). This is because presence of positive serial correlation increases the likelihood of Type 1 errors or incorrect rejection of a true null hypothesis (Kulkarni and von Storch, 1995). All indicators were, therefore, checked for positive lag-1 serial correlation at the 5 % level using the autocorrelation function (ACF). The existence of a trend influences the correct estimate of serial correlation (Yue et al., 2002). Therefore to avoid the possibility of detecting significant serial correlation, when in fact none may exist, the original time-series were detrended to form a "trend-removed" *residual* series before the ACF was applied. The linear trend, *b*, used to detrend the original time-series was estimated using the robust Theil–Sen approach (TSA; Theil, 1950; Sen, 1968) which is the median of all pairwise slopes in the time-series:

$$b = \text{Median}\left(\frac{X_j - X_i}{j - i}\right) \forall i < j. \tag{1}$$

where X_i and X_j are sequential data values of the time-series in the years i and j. The TSA is more suitable for use with hydro-climatic data compared to linear regression as it is a robust non-parametric method that is less sensitive to outliers (Helsel and Hirsch, 2002).

Pre-whitening was used to remove lag-1 serial correlation from time-series that had statistically significant serial correlation. The conventional pre-whitening approach (Kulkarni and von Storch, 1995) was however found to artificially remove part of the magnitude of the trend hence Yue et al. (2002) proposed a modified Trend Free Pre-Whitening (TFPW) technique. This approach has been used widely to deal with serially correlated data when using the Mann–Kendall (e.g. Yue et al., 2002; Petrow and Merz, 2009) and Pettitt test (e.g. Busuioc and von Storch, 1996; Zhang et al., 2008). Steps involved with the TFPW procedure are described in detail by Yue et al. (2002). To summarise, the trend is first removed, lag-1 positive serial correlation removed, then the trend is added back to the time-series producing a blended TFPW time-series including the original trend but without serial correlation. In this study, trend tests were only applied to the TFPW time-series when significant serial correlation existed; otherwise they were applied to the original time-series.

Hydro-climatic data often violate the strict assumptions required for statistical testing (Cohn and Lins, 2005; Clarke, 2010). To this end, Busuioc and von Storch (1996) recommend that statistical tests are not viewed as strict confirmatory tools when dealing with environmental data. Here, over reliance on statistical significance is reduced by presenting the actual MKZs statistic values and the Pettitt test *p* values to help interpret relative differences between signatures of change in observed and reconstructed indicators, rather than relying entirely on statistical significance relative to arbitrary *p* value thresholds.

4 Results

4.1 Hydrological modelling

Model calibration and evaluation yielded 328 out of 1500 model simulations deemed to be behavioural (HYSIM 151, HyMOD 113 and NAM 64). Figure 4 compares the performance of the three models in simulating daily mean flows during calibration (1952–1959), evaluation (1960–1969) and for the period with known disturbance, post 1970 (1970–2009). During calibration, median NSE values for each model range between 0.82 (NAM) and 0.87 (HYSIM), with the maximum NSE value of 0.92 returned for both HYSIM and HyMOD. Similarly high objective function scores are returned for the evaluation period. However, there is a large reduction in the performance of each model for the post 1970 simulation period, resulting in median NSE scores of all reconstructed flows ranging from 0.72 (NAM) to 0.74 (HYSIM). There are also large differences apparent between the reconstructed and observed PBIAS in the post 1970 period, with differences in the order of 20 %. Similarly, the MAE values show a large increase post 1970 compared with model training periods. There is a strong degree of consistency between the three models used in all simulation periods despite the differences in model structure and complexity. Overall, during the post 1970 period, all reconstructed flows show a large discrepancy compared to the observed flows. This is evident in the lower NSE values, increased PBIAS and higher MAE. The differences in model performance obtained as measured by PBIAS and MAE suggest that the differences between the reconstructed flows and observed flow for the post drainage period are volumetric in nature.

Figure 5 compares time-series of annual flows for observed and reconstructed series. Figure 5a shows close agreement between observed and reconstructed flows for both the calibration and evaluation periods with observed flows well bounded by the simulations. After 1970, annual sums of reconstructed and observed flows start to diverge. Largest divergence occurs from the end of the 1970s onwards, after which none of the simulations can capture the observations. Despite the large deviation, the pattern of inter-annual variability between the observed and reconstructed flows remains similar, again emphasising the volumetric nature of the differences between the reconstructed and observed series. This deviation is also apparent from the cumulative sums plot in Fig. 5b where a point of inflection in the late 1970s becomes noticeable, after which a large deviation in the volume of flows occurs. The cumulative sum of flows for the full observed series is 17.6 % higher than the median of the reconstructed time-series. Under the full range of simulations the cumulative sums underestimation range from 5.5 % to 24.2 % for the reconstructed flow.

Figures 6 and 7 display time-series of monthly sums and their respective cumulative sums for the summer (dry) half year (April–September) and winter (wet) half year (October–March) respectively. Greatest divergence between observed and reconstructed flows is apparent for months within the winter half year. Conversely, within the summer half year only April shows any substantial evidence of divergence. For the remainder of summer months the observed series lies near the centre of the reconstructed flows.

For months within the winter half year, again reconstructed flows show good agreement with observed monthly flow sums for the calibration and evaluation periods (Fig. 7 left). However, for the post drainage period a large divergence is evident, particularly from the cumulative sums plots (Fig. 7 right) where in the majority of months the observed series lies at the very upper bounds or outside of the reconstructed flows. Months showing the largest divergence are December, January and February. The magnitude of divergence in winter half year months highlight their dominant contribution to the divergence evident in the annual observed flow.

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4.2 Trend and change point analysis

In total 15 observed precipitation, 15 observed streamflow and 4920 reconstructed streamflow series (i.e. 15 indicators by 328 reconstructed series) were generated for further analysis for the period 1952–2009. Use of the term "significant" below refers to changes at $p = 0.05$ level.

4.2.1 Serial correlation

When analysing time-series for serial correlation only the observed flow indicators for March and August mean flows show significant positive lag-1 serial correlation. This serial correlation is also reflected in the reconstructed flow series with 81 % and 79 % of reconstructed simulations for March and August mean flow exhibiting serial correlation respectively. Four additional reconstructed indicators have a smaller degree of significant serial correlation, AMF (33 % of the reconstructed series), and to a lesser extent in the RB index (3 %), September (5 %) and June (2 %) mean flow reconstructions. No precipitation indicators were significantly serially correlated. For observed streamflow indicators with significant serial correlation MK and Pettitt tests were applied to both original and TFPW time-series for comparison.

4.2.2 Monotonic trend

Results from the monotonic trend analysis for the period 1952–2009 using the MK test are presented in Fig. 8. There is a large relative difference between the MKZs values obtained from observed and reconstructed series, with observed indicators consistently showing larger MKZs values than reconstructed. Observed AMF shows a significant increasing monotonic trend with the strongest positive MKZs value (3.1) in the analysis. None of the reconstructed AMF time-series or observed annual total precipitation show significant trends. Similarly, observed Q10 shows a significant increasing trend (MKZs 2.6), while P10 shows a non-significant increasing trend (MKZs 0.85).

The median MKZs for reconstructed Q10 is 1.14, with one reconstructed Q10 series showing a significant trend (MKZs 1.97). A near significant increasing trend is found for the observed RB index (MKZs 1.93) with none of the reconstructed data or PCV (MKZs 1.58) exhibiting a significant trend.

All observed monthly mean flow indicators show increasing monotonic trends over the period 1952–2009 with significant trends found for January, March, June and July. When serial correlation is accounted for the strength of trends in March and August reduces. For the reconstructed monthly flow indicators the majority of the series reveal non-significant increasing trends with the exception of September and October which show non-significant decreasing trends. Only in May is there evidence of several significant trends in reconstructed series with 16 % showing significant increasing trends. For reconstructed June mean flows, one model from 328 behavioural simulations shows a significant increasing trend. Observed precipitation did not reveal significant trends in any of the fifteen indicators with the relative strength of trends being much weaker than observed flow for corresponding metrics.

4.2.3 Change point

Results from the Pettitt change point test are presented in Fig. 9 for selected indicators. For all identified change points the time-series increase after the stated change point year. A significant change point is found in 1978 ($p < 0.001$) in observed AMF. Observed TAP and 85 % of reconstructed AMF series reveal non-significant change points also in 1978. For the remaining 15 % of reconstructed AMF series non-significant change points are shown for 1993. Observed annual Q10 also shows a significant upward change point in 1978 ($p = 0.004$) with 61 % of models showing a non-significant change point for the same year, the remaining simulations show non-significant change points in different years. For P10 there is a non-significant ($p = 0.12$) change point in 1977. A significant change point in 1982 ($p = 0.014$) is found for the observed RB index with no significant changes in the reconstructed RB series for that year and several non-significant change points in other parts of the reconstructed series. In addition, there is a non-significant change in PCV in 2002 ($p = 0.098$).

For monthly indicators observed January mean flow shows a non-significant ($p = 0.086$) change point in 1978. 31 % of reconstructed January flows also show non-significant change points for the same year. However, there is a large difference in the strength of changes with reconstructed series having a median p value of 0.558. January precipitation shows a non-significant change point in 1964 ($p = 0.7$). In March, a significant change point is detected in both observed mean flow (TFPW series) ($p = 0.0012$) and total precipitation ($p = 0.044$) in 1975 with 7 % of reconstructed time-series having a change point in 1976. March is the only precipitation indicator found to have a significant change point.

Serial correlation has a large influence on results for March mean flows. Before serial correlation was accounted for the change point in observations occurred one year later in 1976 ($p < 0.001$) while 85 % of reconstructed series showed a significant change point between 1975 and 1977. Despite the large reduction in the number of reconstructed series showing a significant change point after application of TFPW, the relative difference between observed and reconstructed p values around the mid-1970s is the closest of all the indicators shown in Fig. 9. Other statistically significant change points (not shown) occurred in observed monthly mean flow in April (1976), June (1978) and July (1978). For reconstructed April and June mean flows less than 3 % of simulations show significant changes in the same year, with none reproducing a significant change in 1978 for July.

5 Discussion

5.1 Attribution of change in Boyne streamflow

The contribution of climate (WH 8 precipitation) and internal (WH 6 and 7 drainage) drivers to the detected mid-1970s change point in Boyne streamflow were explored.

Reconstructed flows obtained from behavioural simulations from three structurally different CRR models do not show the change point found in observed AMF in 1978 when only climate variability is considered. This discrepancy is particularly evident for high flows (Q10) and during winter months. Additionally, there is no evidence of increasing precipitation for these indicators. Given that reconstructed flows contain precipitation as a key forcing variable it is therefore unlikely that changes in flow observations are entirely driven by a change in precipitation (WH 8). The observed RB index was found to increase post 1982 while the PCV (coefficient of variation of daily precipitation) did not change significantly. Changes in RB index have been previously linked to human disturbance within catchments (e.g. Baker et al., 2004; Holko et al., 2011). An increase in flashiness is consistent with the effects of drainage, where there is an acceleration of the response to rainfall with flood peaks of increased intensity (Lynn, 1981).

However, the influence of precipitation change cannot be completely discounted. A significant (5 % level) change point in 1975 was detected in March in this study for both observed mean flow and precipitation totals, with reconstructed series showing some evidence of a change around the same time. This is further supported by visual inspection of the time-series for observed and reconstructed March mean flows in Fig. 10. The plot shows the median of observed and reconstructed time-series before and after 1975. Evident is the close agreement between series before the change point, while an increase in the median of March mean flows is apparent after 1975 in both observed and reconstructed flows. Of note, however, is the larger change in flow observations which can be interpreted as a combined influence of drainage and precipitation. This is consistent with increased March precipitation after 1975 being magnified by an altered rainfall-runoff response of the catchment following drainage which also increases flashiness.

In light of these findings it is unlikely that observed changes in the flow regime of the Boyne are driven solely by changes in precipitation as a result of a shift in the NAO index from a negative to positive phase in the mid-1970s. While detection of the change point in annual and March observed mean flow by Kiely (1999) is confirmed here, attribution of change is different. We assert that the dominant driver of change is arterial and field drainage (WH 6 and 7). Data on the extent and timing of arterial drainage show that the majority of dredging in major channels was completed between the late 1970s and early 1980s thereby facilitating widespread field drainage. Differences in response between observed and reconstructed flows are consistent with current understanding of the impact of drainage, with largest divergence evident in wetter months. From this analysis it is estimated that the implementation of drainage works increased annual flows by approximately 20 %. However, it is also evident, particularly from the results for March that there are multiple drivers occurring at the same time, both internal and climatic drivers of change, where drainage magnifies the signal of the mid-1970s abrupt change in precipitation. Therefore, in line with WH 10 (multiple drivers/synergetic effects) we postulate that the step change evident in observations is brought about by both drainage and precipitation change, with drainage the predominant factor.

5.2 Confidence in attribution

To qualify this revised attribution of hydrological change a critical examination of uncertainties and assumptions in the methodology is required (after Merz et al., 2012). While the methods used incorporate structural and parametric uncertainties in the application of rainfall-runoff models, our findings are based on the assumption that the simulations reflect the hydrological response of the catchment. Results from model inter-comparison tests (e.g. Reed et al., 2004; Duan et al., 2006) indicate a wide range of simulations when many different model structures are forced with the same input. In this study only when all three models are combined is the full range of observed flows in the pre-drainage series (calibration and evaluation period) captured. This highlights the importance of considering multiple model structures and points to opportunities that might arise from applying generic model structures such as the Framework for Understanding Structural Errors (FUSE; Clark et al., 2008) in detection and attribution studies.

Positive serial correlation has a large influence on the statistical significance of results. There are several ways of dealing with this. We applied pre-whitening (TFPW) before application of statistical tests, but block bootstrapping among others has also been used in other studies (e.g. Önöz and Bayazit, 2012; Murphy et al., 2013). The large reduction in the number of statistically significant change points in reconstructed March mean flows shown above also occurred when block bootstrapping was applied (not shown here). This influence of serial correlation on statistical change detection is particularly important when using reconstructed time-series given the high degree of serial correlation that can be introduced by soil moisture accounting algorithms or "memory" of CRR models (Evin et al., 2013). However of most importance in this approach is the relative difference between the magnitude of statistics derived from observed and reconstructed series, rather than basing conclusions solely on arbitrary p value thresholds.

Due to the possibility of change at all scales within the hydrological system a recognition under the MWH framework is that other currently unknown factors (WH 11) may emerge as important drivers of change given further research. Here, treated water discharges (WH 3), urbanisation (WH 4) and forest cover and management change (WH 5) were considered second order influences based on available data. Although the scale of land-use change, such as urban and forest cover, is modest and unlikely to be influential in a catchment of this size (Blöschl et al., 2007), there is little research that assesses these impacts at the scale of the Boyne catchment. This is due to the lack of controlled conditions in large catchments compared to small experimental watersheds, where the paired catchment approach can be used to examine impacts of land-use changes under controlled conditions (Hewlett, 1982; Brown et al., 2005).

5.3 Towards more rigorous attribution

A detected change in streamflow time-series is the integrated response to all drivers climate and internal, natural and human induced. This makes attribution of hydrological change inherently challenging. Moving towards more rigorous attribution, the use of the MWH framework offers considerable potential as demonstrated here. The goal of the application of MWH has been find dominant drivers of change. Primary in any attribution investigation is to identify if change is climate and/or driven by internal disturbances as management responses to the detected driver will be very different. Here, this was achieved with the aid of hydrological simulation. It was also shown that human disturbance can have larger impacts on the hydrological system than climate at the catchment scale.

Even within this case study, where relatively rich data sources are available in comparison to other catchments, full confidence in attribution cannot be achieved. Our conclusions are founded on an assessment of inconsistency, while hard attribution also requires evidence of consistency (Merz et al., 2012). Data was gathered on precipitation, PET, streamflow, the NAO, land-use, soil types and supplemented with documentary evidence from hydrometric and drainage archives. In pursuing evidence of consistency physically based models could be used to explicitly represent arterial and field drainage systems. However, the value-added by more complex modelling of artificial drainage at the scale of the Boyne is contingent on the availability of detailed data on the timing and location of local channel changes. Improved rigour in attribution requires greater investment in monitoring change in catchments, beyond typical hydrological variables. Hard attribution is more problematic for historic changes where data can be more quantitative in nature.

In agreement with Merz et al. (2012) advancement in attribution is an iterative process where finding weaknesses in established hypotheses of change leads to improved overall understanding of dominant drivers of change. In this study coupled interactions and feedbacks between human and natural components of the catchment system are apparent. For example, the economic imperative for increased agricultural productivity was the main motivation for implementing drainage, facilitated through structural funds available by the accession of Ireland to the EEC. In the face of such complexity the framework of MWH offers a formal and rigorous structure within which to build and refine hypotheses of change.

6 Conclusions

Attributing changes in streamflow, solely to climate drivers, cannot take place without extensive investigation of other human induced catchment disturbances. This paper revisited an attributed change point in observed streamflow in the Boyne (Kiely, 1999) using the framework of MWH. Evidence of consistency and inconsistency with the detected change was systematically examined given a set of credible climatic and internal drivers. Changes in precipitation and a combination of arterial and field drainage, as well as possible synergistic effects were brought forward for further analysis. CRR models were employed to reconstruct streamflow in the absence of drainage while statistical tests were used to detect monotonic trends and change points in reconstructed and observed flows.

Different to earlier work, external climate variability was not the only possible driver of hydrological change. Arterial drainage and the simultaneous onset of field drainage in the 1970s and early 1980s were inferred to be the predominant driver of change within the Boyne. It is the change in wetter winter months that contribute to the large 1978 change point found in annual flows. There is evidence that a change in precipitation regime is also present, albeit to a lesser extent. March mean flow and precipitation totals, observed and reconstructed runoff show a contemporaneous upward change point in 1975. This new explanation posits that multiple drivers acting simultaneously were responsible for the observed change, thereby extending previous interpretations based on shorter hydro-climatic records.

This case study emphasises the amount and range of data types needed for rigorous attribution, especially when substantial human modifications to catchments may be involved. A better understanding of the dominant drivers of change and hence improved attribution was possible with the use of Multiple Working Hypotheses. The main purpose of this framework is to compel the researcher to consider multiple potential drivers of change, thus avoiding confirmation bias in addition to identifying key weakness in current understanding of change within the catchment. The example of such weaknesses here was the limited information and data availability on the impact of urbanisation and forest cover change on hydrological behaviour. These knowledge gaps create opportunities for future research. Attribution of hydrological change is a challenging task but understanding the interplay and co-evolution of human and natural hydrological dynamics (Sivapalan et al., 2012) is essential to the discipline (Montanari et al., 2013). It is of great societal importance that signals of human disturbance and natural and anthropogenic climate change within the hydrological system are detected and properly attributed before management and adaptation plans are assessed and put in place.

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Table 1. The summary of working hypotheses (WHs) for drivers of change in the Boyne catchment. The table provides an overview of potential influence of each WH, information on preliminary assessment of each WH and decision and justification for inclusion/exclusion in further investigation (Roman = not further analysed; Italic = not further analysed but justification based on limited evidence; Bold = warrants further investigation).

Working hypotheses	Potential influence	Additional information	Decision and Justification
1. Inconsistent/poor quality river flow data.	Data values post (pre) mid 1970s artificially higher (lower).	Checks were made to ensure data at Slane Castle gauging station was of good consistent quality. Hydrometric experts responsible for gauge were consulted and archives analysed.	No evidence of inconsistent measurements from consultation with OPW hydrometric division.
2. Water abstractions/ diversions.	Reduction in flow quantity.	Inconsistent with direction of change.	Logical/quantitative assessment.
3. Treated water discharges.	Increased flow quantity.	Potentially consistent with direction of change. Largest known discharge is from pumping groundwater from Tara Mines clear water pond in Navan into surface water of the River Boyne. Discharges limited to a dilution rate of 1 % (EPA, 2012).	*Volume of discharged water from Tara Mines too small to have significant impact. Other possible notable discharges unknown.*
4. Urbanisation.	More flashy rainfall-runoff response.	Potentially consistent with direction of change. ~ 1.5 % of catchment urbanised, essentially rural FEH (1999) definition.	*Urbanisation unlikely important but cannot be completely ruled out.*
5. Forest cover and management change.	Increased flow by reduction of evaporation with declining forest cover.	Potentially consistent with direction of change. ~ 1.5 % of total catchment area is covered in forest.	*Limited area of forest cover. Unlikely to have an important effect but cannot be completely ruled out.*
6. Arterial drainage.	Increase discharge capacity of channel; increasing flood peaks; increased flashiness.	Over 60 % of the Boyne channel network was subject to arterial drainage where the channel bed was deepened and widened (some instances by up to 3 m) between 1969 and 1986.	**Evidence of widespread installation of arterial drainage, merits further analysis.**
7. Agricultural land-use and management change.	Multiple influences. E.g. Drainage of land increases transmission of water to the channel.	Potentially consistent with direction of change. Majority land cover is agricultural pastures (87 %). Government initiatives to install field drainage consistent with timing of change.	**Evidence of widespread installation of field drainage, merits further analysis.**
8. Changes in precipitation.	Increase in precipitation quantity translates into increased river flow.	Consistent with direction of change. The NAO index changed from a negative to positive phase during the mid-1970s.	**Increases in precipitation linked to changes in NAO in the 1970s; well documented in literature.**
9. Changes in Potential Evapotranspiration (PET).	Decrease in PET increases runoff.	Daily PET data was analysed to assess if a decrease occurred that could possibly contribute to the change point.	No change in PET that could explain the Boyne change point.
10. Multiple drivers/ synergetic effects.	Multiple influences, working together or against each other.	Given the integral nature of river flow the potential for synergistic interaction of multiple drivers is high. WH 6, 7 and 8 could all contribute to increase in river flow.	**Potential for interaction between combination of field and arterial drainage and changes in precipitation.**
11. Other drivers.	Unknown.	The identification of other potential driver(s) of change is limited to current knowledge/data availability. Future research may unearth other factors that could further refine hypotheses of change.	*Lack of current knowledge of other potential drivers but cannot be ruled out.*

Table 2. Precipitation stations and correction factors used to obtain catchment average precipitation.

Station No.	Station name				Period				m a.s.l.			
2531	Navan				1952–2003				52			
2922	Mullingar				1952–2003				101			
2931	Warrenstown				1952–2009				90			
Correction	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
factor	1.038	1.039	1.032	1.019	1.018	1.003	1.062	1.001	1.029	1.021	1.031	1.014

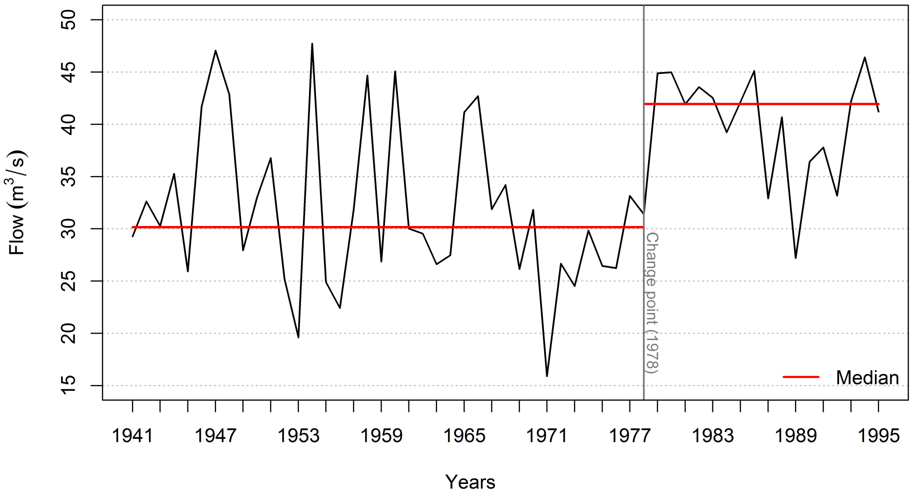

Fig. 1. Observed annual mean flows in the Boyne for 1941–1995. Solid red line is the median of the period before and after the 1978 change point detected by Kiely (1999).

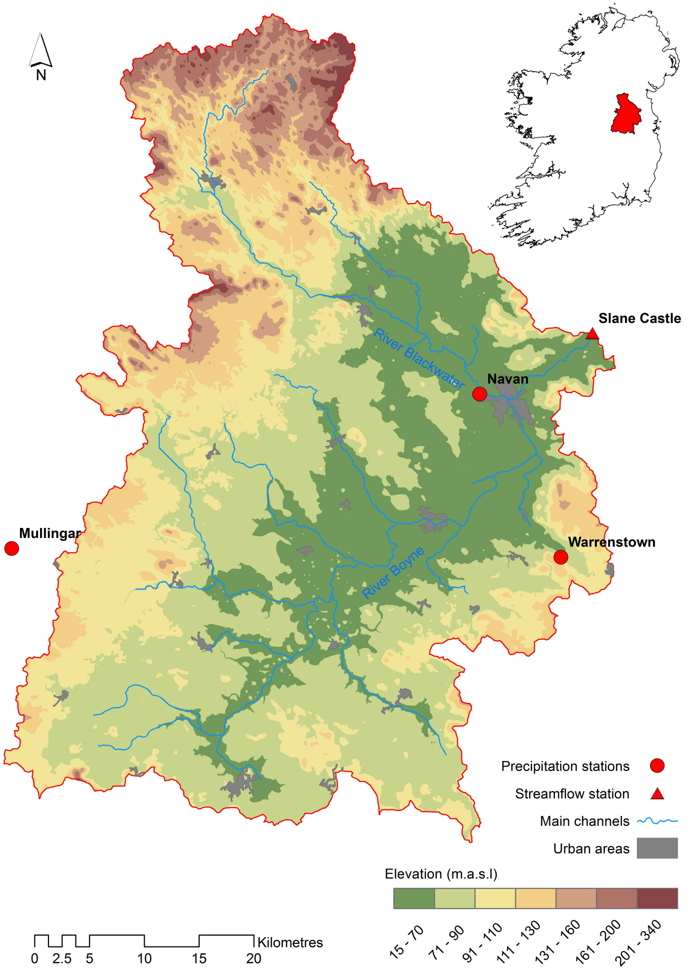

Fig. 2. The Boyne catchment, showing main urban areas, river flow and precipitation stations.

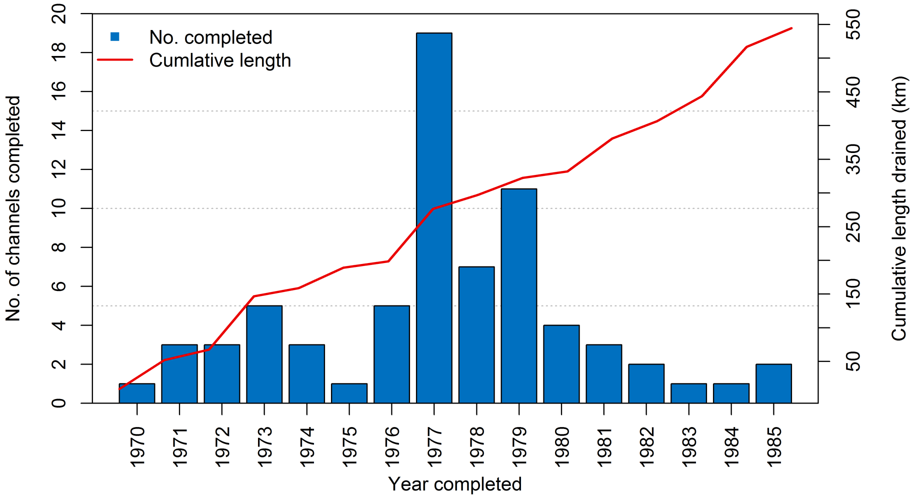

Fig. 3. The number of major watercourses per year in which arterial drainage was completed in the Boyne. The cumulative length (km) completed is shown by the red line.

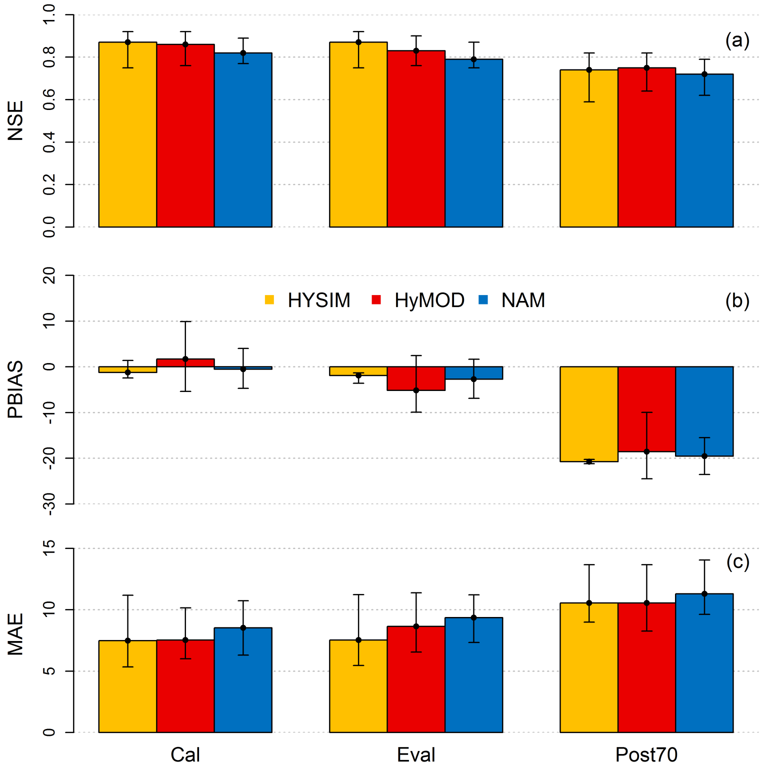

Fig. 4. Barplot of **(a)** NSE, **(b)** PBIAS and **(c)** MAE for HYSIM, HyMOD and NAM over the calibration (Cal: 1952–1959), evaluation (Eval: 1960–1969) and post 1970 (Post70: 1970–2009) periods. Each bar represents the median objective function for behavioural simulations with bars representing the maximum and minimum values.

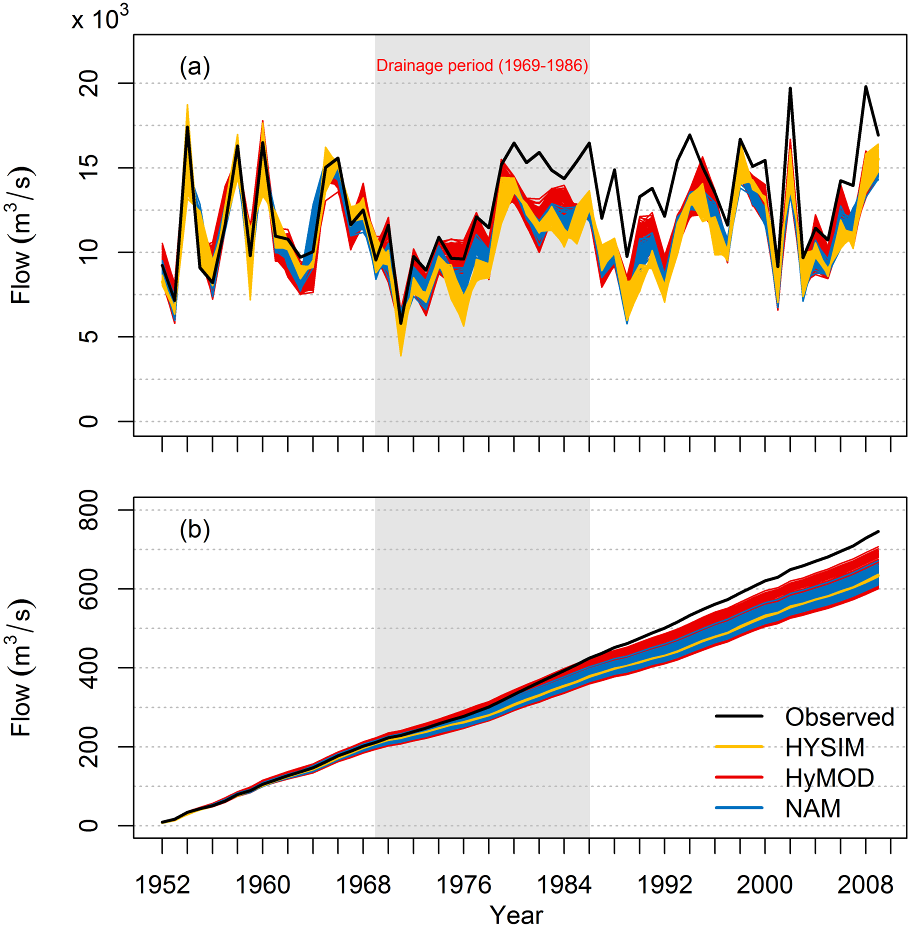

Fig. 5. Annual **(a)** sum and **(b)** cumulative sum of reconstructed and observed flow ($m^3 s^{-1}$ by 10^3) for 1952–2009. The period of drainage expansion is shown by the shaded grey area. Behavioural simulations for each model structure are colour coded.

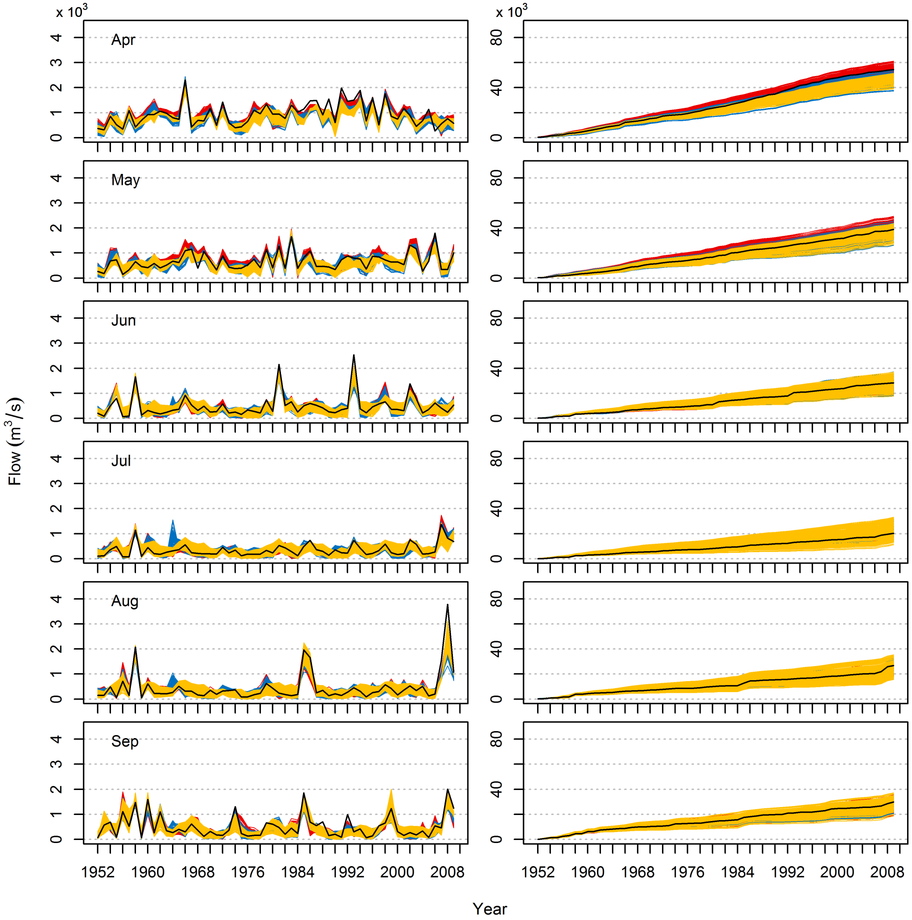

Fig. 6. Monthly (left) sum and (right) cumulative sum for reconstructed and observed flow for 1952–2009 for the summer half year (April to September). Colour code as in Fig. 5.

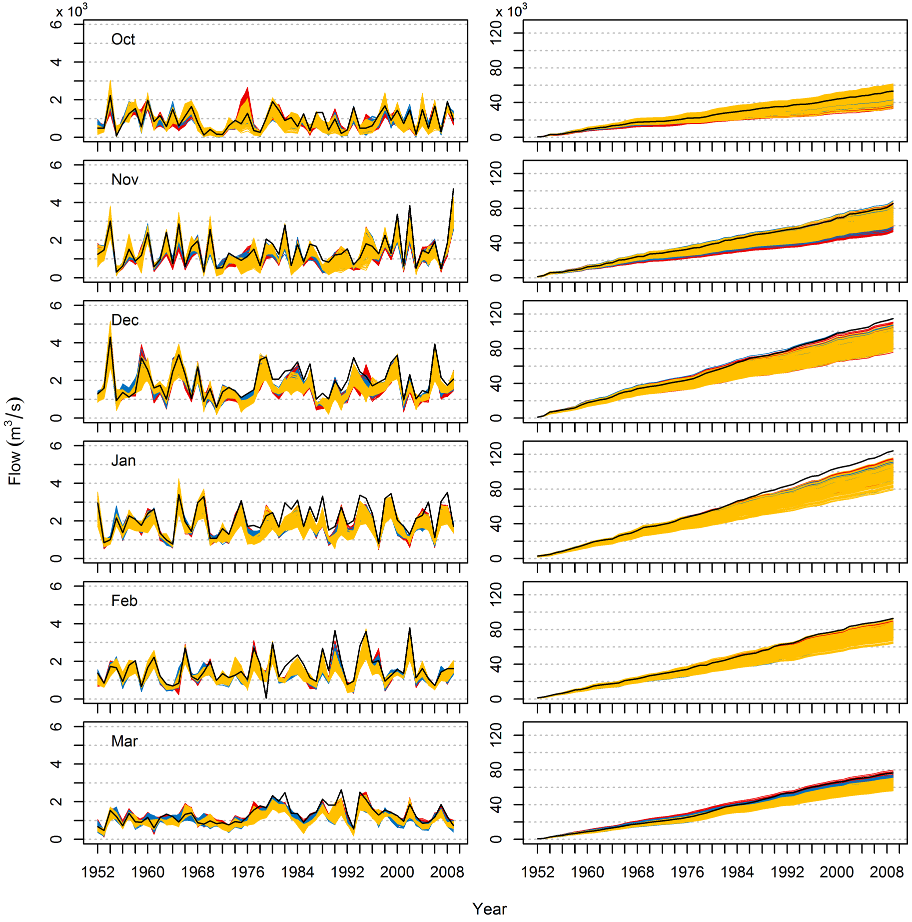

Fig. 7. As in Fig. 6 but for the winter half year (October to March).

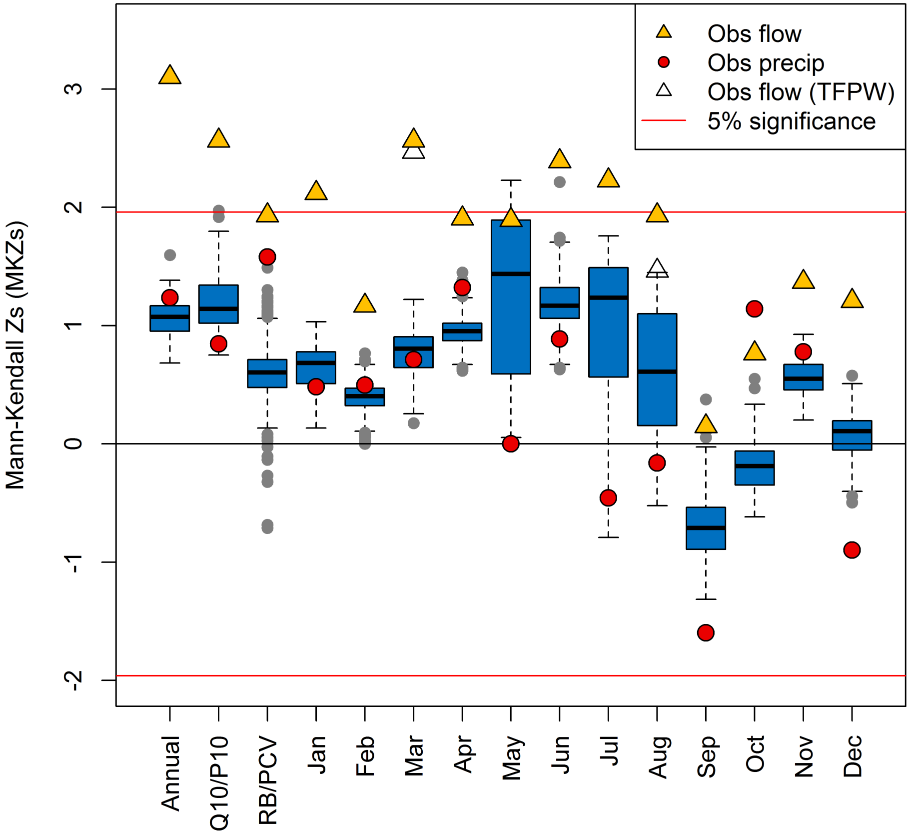

Fig. 8. Synthesis of Mann–Kendall tests for monotonic trend in precipitation and flow indicators. MKZs values above (below) 5 % significance line (|MKZs| > 1.96) indicate significant increasing (decreasing) trends. Boxplots summarise MKZs values for the 328 individual reconstructed time-series with the black line representing the median, box the 25th and 75th percentiles, whiskers the minimum and maximum value and the grey circles extreme outliers.

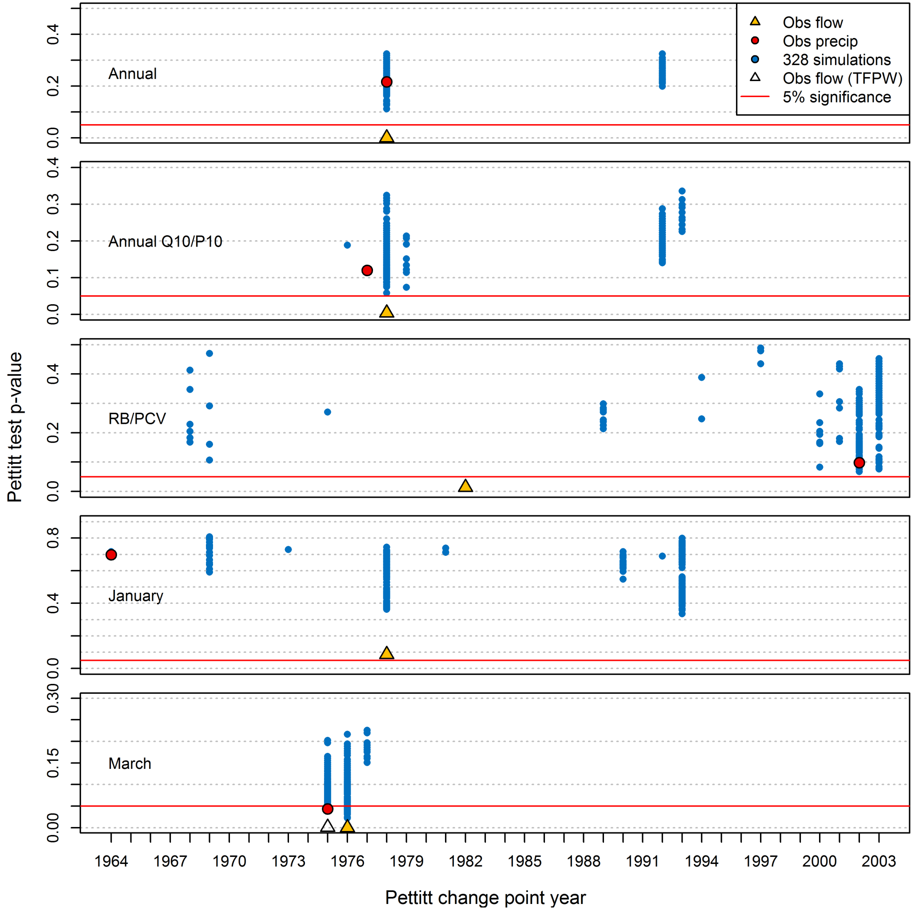

Fig. 9. Pettitt test for change points in selected indicators. Solid red lines represent the threshold for significant change points at the 5 % level with p values below (above) indicating a significant (non-significant) change point for corresponding year of change on the x axis.

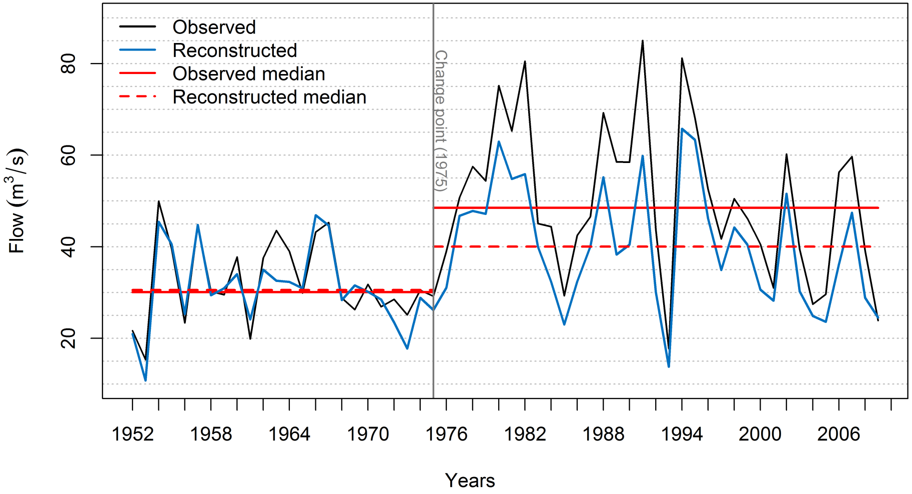

Fig. 10. Observed and median of 328 reconstructed series for March mean flow. Solid red line is the median of the period before and after the detected change point (pre is 1952–1975, post is 1976–2009) with the dashed reconstructed.