# 01 - CAN WE STILL PREDICT THE FUTURE FROM THE PAST? NON-STATIONARY FLOOD FREQUENCY ANALYSIS IN IRELAND

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## Abstract
Recent years have seen extreme floods affecting parts of Ireland. Several rivers in the west of Ireland, including the Shannon, Erne and Ballysadare, show evidence of an increasing trend in peak flows over a period of record covering at least 60 years. Decisions regarding flood risk management are usually made on the basis of stationary methods of flood frequency analysis that assume the probability of flood flows is unchanging over time. The FSU methods make this assumption. If the assumption is not correct, it may mean that flood defences or structures over rivers are being under-designed, or property developments are being permitted in areas where the flood risk is greater than thought.This paper examines how estimates of design flows change if non-stationary methods are used to fit flood frequency curves. Trend tests are used to detect both gradual and sudden changes in flood peak series from Irish rivers. Flood frequency curves are fitted with parameters that can vary through time, and also in conjunction with physical covariates such as the North Atlantic Oscillation, which can help to remove some of the year-to-year variability in peak flows. Results for Ireland are compared with those from a recent comprehensive study of trend and non-stationarity in flood peak data from Great Britain.

## 1. INTRODUCTION
Flood frequency estimation is critical to the optimal prioritisation, justification and development of flood relief schemes. Assessment of baseline flood risk requires consideration of the uncertainty in flood estimates, which are a significant source of uncertainty in flood damage estimates. This in turn influences the scale, type and extent of flood risk management measures, selection of the target standard of protection, and the benefit-cost ratio of the scheme. Multi-Criteria Analysis also requires an understanding of the uncertainty in flood frequency estimates, especially where major social, economic infrastructure is at risk or where environmental and cultural designations are constraints to proposed flood relief schemes.

The Office of Public Works (OPW) together with Local Authorities are in the early stages of the ten-year investment plan to implement the measures from the Flood Risk Management Plans produced in the Catchment Flood Risk Assessment and Management programme (OPW, 2018) . This investment plan has been allocated €1 billion for the 10 year period from 2018 to 2028, and contains 118 proposed flood relief schemes to protect 11,500 properties. These encompass 31 minor schemes (less than €1 million cost), 82 small and medium schemes (€1m to €5m costs) and 5 large schemes (>€5m costs) (OPW, 2018). In addition to this the FRMPs identified around 30 potential flood relief schemes subject to further assessment. In these potential cases, the indicative benefit cost ratio was between 0.5 and 1 or there was significant uncertainty in the cost or damage estimates.

Understanding how flood magnitudes and frequencies are changing over time could be critical to the further assessment of these possible flood relief schemes. Current methods of flood frequency estimation, such as those outlined in the Flood Studies Update (FSU), assume stationarity in flood frequency statistics, as discussed below. If this assumption is not valid, or signatures indicate possible future trends, some of the communities with no viable flood scheme may need to be revisited in the future. Even if such potential schemes are not deemed feasible, revised flood estimates can be used to guide the development of other flood risk management measures and give clarity to local communities. The impact of the stationarity assumption on individual flood schemes will depend on several factors, including the extent to which current designs allow for uncertainty in design flows and the way in which they incorporate projected climate change impacts.

The variability of trends by flood probability could have a large influence on the development of flood schemes. For example, trends in high frequency events will have a greater influence on Annual Average Damage (AAD) estimates, so affecting the benefits side of the cost : benefit calculation. Trends in the traditional 1% AEP design standard could influence the costs of potential flood relief schemes if raised defences need to be higher, greater attenuation is required or alternative measures need to be explored. Flooding is one of the biggest climate risks to Ireland. Understanding the potential future change in risk profile will assist national scale plans and programmes, such as evolution and implementation of the national and sectoral climate adaptation plans (DCCAE, 2018a). At the local scale, Local Authorities have recently published local adaptation strategies. These strategies do not require quantitative analysis of risks (DCCAE, 2018b), however successful implementation of adaptation measures through Development Plans, Local Area Plans, Strategic Flood Risk Assessment and other plans and programmes will be reliant on an understanding of the current and likely future trends in flood flow estimates.

In this paper, we present an analysis of trends in peak flow data across Ireland, along with results from an exploratory application of non-stationary flood frequency analysis to Irish and Northern Irish data. Section 2 introduces the concept of non-stationary analysis and provides some international context. Subsequent sections then describe the dataset, the statistical methods, the results and provide a discussion.

## 2. FLOOD FREQUENCY ANALYSIS IN A CHANGING WORLD

To our knowledge, all flood risk assessment and planning of flood relief schemes to date in Ireland has been based on an assumption of stationarity. The assumption is that the probability of a given river flow or storm rainfall depth occurring is the same now as it was throughout the whole period of hydrological and meteorological records. Statistically this is expressed by saying that the observations, such as annual maximum river flows, are identically distributed. In other words, we can fit a single frequency distribution to the whole dataset. This assumption is inherent in the FSU method of flood frequency analysis, and in the FSU analysis of rainfall frequency.

If in fact the probability of observing a given flow or rainfall has been changing, the assumption is invalid, and this calls into question one of the foundations of flood risk management. There are several potential causes of change, the most universally obvious being climate change driven by increasing greenhouse gas concentrations. More locally there may be other drivers such as urbanisation or other types of land-use change, or arterial drainage. The latter can result in striking and sudden alterations to flood frequency, and these have generally been accounted for already, for example, by excluding from analysis the pre-drainage portion of peak flow series.

Methods of extreme value frequency analysis that account for non-stationarity are widespread in academia, with new papers on the topic being published worldwide every few days. Some highlights abstracted from this torrent of research include Milly et al. (2008) (whose assertion that "stationary is dead" continues to reverberate around the research landscape); Rootzen and Katz (2013) (who propose a non-stationary replacement for return period); Prosdocimi et al. (2014) (a Great Britain-wide analysis); Debele et al. (2017a,b) (who compare three approaches) and François et al. (2019), a recent and comprehensive review.

These apparent shafts of illumination have yet to penetrate much of the twilight world where we engineering hydrologists ply our craft (to paraphrase Sellars, 2011). Practice is beginning to change, though. Prompted by a run of devastating floods in Cumbria between 2005 and 2015, the Environment Agency (England) commissioned an analysis of trend and non-stationarity in north-west England (Faulkner et al., 2019). This was followed up by a systematic review of literature on the topic of non-stationarity in UK flooding (fluvial, pluvial and coastal), taking the structured format of a rapid evidence assessment (Environment Agency, 2019). A current Environment Agency-funded project is developing guidance and software tools to help practitioners carry out non-stationary analysis of fluvial flooding. It has included research into several aspects of non-stationary frequency analysis; some emerging findings are described by Warren et al. (2019).

## 3. DATA

Data has been sourced from three of the authorities who record and manage hydrometric data in the Republic of Ireland, the OPW Environmental Protection Agency (EPA) and Electricity Supply Board (ESB), and also from the Department for Infrastructure (DfI Rivers) in Northern Ireland. Only one ESB station, at Parteen Weir on the Shannon, has been used in this study. Waterways Ireland hydrometric gauges are principally concerned with water level and none have been selected for use in this study. The Flood Studies Update (FSU) programme for the Republic of Ireland classified gauges into categories in terms of the gauge data quality (Murphy et al., 2014). In this study the focus has been on the highest quality A1 and A2 class gauges, as well as selected other gauges where the authors are aware of useful and long-term records. Table 1 summarises the number of gauges per authority and FSU classification used in this study.

The FSU studies used gauge data up to and including water year 2004. Up to another 14 years of AMAX data is now available from active gauges, and has been added for this study. Many gauges with insufficient length of record at the time of the FSU studies may now be suitable for use in deriving index flood and growth curve parameters for flood frequency estimation. Further, in the 14 years many more spot flow gaugings have been carried out to update gauge stage-discharge rating equations. The hydrological assessment stages of the CFRAM studies included many rating reviews, both based on spot flow gaugings, new river cross section survey and hydraulic models. Many of the gauge classifications should now be reconsidered, however this is outside the scope of this paper. Table 1 includes a summary of the gauges used and their FSU quality classification.

***Table 1****: Number of gauges used in this study, per gauging authority, and gauge classification as defined in the FSU 2004 studies*

| Gauging authority | Number of gauges per FSU class | | | | Non-FSU | Total |
|---|---|---|---|---|---|---|
| | A1 | A2 | B | Other | | |
| OPW | 20 | 25 | 13 | 0 | 10 | 68 |
| EPA | 4 | 10 | 0 | 0 | 1 | 15 |
| ESB | 0 | 0 | 0 | 0 | 1 | 1 |
| DfI Rivers | n/a as FSU does not cover N. Ireland | | | | 21 | 21 |
| Total | 24 | 35 | 13 | 0 | 33 | 105 |

This study assumes the AMAX data published or supplied to the authors is based on the most up to date validated stage-discharge rating relationship. The authors and gauging authorities acknowledge that not all rating reviews carried out during the CFRAM studies have been adopted in the hydrometric data archives, as full or partial adjustments to AMAX series. AMAX series for gauges where arterial drainage or other flood relief works are known to affect catchment hydrology or hydraulics at the gauge have been split into two records; the post-drainage (or works) AMAX series and the full AMAX series. Following change point tests, one of these two alternative series was selected for the remaining parts of the analysis.

It is also worth noting that the primary objective of the EPA gauges is for water quality monitoring as required by the Water Framework Directive. The location of the gauges and the ratings are therefore focused on low and normal river flows. Some EPA gauges do accurately record flood flows. The purpose of the OPW gauges is for flood risk management and so apart from level-only warning sites are designed to record data for use in flood frequency estimates.

In Northern Ireland, AMAX data was obtained via the National River Flow Archive Peak Flow dataset, version 8, released in September 2019. This provides peak flow data up to water year 2017-18. Gauges classed as suitable for pooling (equivalent to A1 and A2) were selected.
A selection of long term hydrometric gauges form the Irish Reference Network (IRN) HydroDetect Gauges (EPA, 2013). The purpose of this network is to monitor and detect climate-driven hydrological change. The network stations are selected to have a natural flow regime, principally on rural catchments with little land use change and high quality data, particularly for extreme flows.

The HydroDetect network includes 35 gauges in the Republic of Ireland and 8 gauges from the UK Reference Network in Northern Ireland. Six of the gauges from the Republic of Ireland are not included in this study. It is worth noting that not all HydroDetect gauges were classified as A1 or A2 in the FSU studies. Avoiding the selection of gauges subject to Arterial Drainage works during their record was not possible as many of these gauges have the longest record series. Trends in AMAX data are only one of many indicators of change which the HydroDetect gauges monitor. It should also be noted that the present study is not restricted to investigation of climate-driven trends.

## 4. METHODS

Two sets of analyses were carried out on the dataset with the aim of detecting and/or modelling non-stationarity. The first involved applying non-parametric tests for trend, i.e. tests that do not make any assumptions about the type of statistical distribution that the data follow. The second stage involved attempting to model the trend (if any) by fitting non-stationary distributions, a process that can also be viewed as a parametric test for trend.

### 4.1 Non-parametric trend tests

An initial step was to screen the AMAX series for step changes using the Pettitt test. This detects a sudden change in the average of a time series. It can be useful for detecting spurious changes in flow such as those due to a shift in channel hydraulics that has not been accounted for in the rating equation. At some stations it picked up change points associated with arterial drainage. However, in some cases there was no obvious physical explanation for a change point apart from a general shift from a flood-poor to a flood-rich period, or vice versa. Stations were only excluded from further analysis when it was clear that apparent changes in peak flow could be explained by local hydraulic influences.

The Mann-Kendall test was applied to detect monotonic upward or downward trends in a AMAX flows. The test is not dependent on the magnitude of the data but is based on the proportion of increases and decreases between pairs of values. It assesses the statistical significance of a trend rather than its strength. It was applied to 99 gauging stations with at least 30 years of record.

### 4.2 Non-stationary flood frequency analysis

In conventional flood frequency analysis, a frequency distribution is fitted to the flood peak data, either peaks over a threshold or (as here) annual maximum flows. Distributions are generally those intended for fitting to extreme values, such as the Generalised Extreme Value (GEV) or the Generalised Logistic (GLO). The parameters of the distribution, usually either two or three, are estimated from the data, either at one gauging station or averaged over a group of stations (a pooling group). The results in this paper are all from fitting of the GEV distribution.

In the non-stationary version, one or more of the parameters is allowed to change according to some other variable (a *covariate*), rather than being a fixed value for a particular station. Often, the parameters will change over time (water year), so that the non-stationarity is modelled as a smooth increase or decrease over the period of record. The change could be in the mean of the distribution (the location parameter), in its variance (the scale parameter) or in both. For example, an increase in variance would mean that the larger floods are becoming more large, and the smaller ones more small. In accordance with most published examples, we have kept the skewness (shape parameter) of the 3-parameter GEV distribution constant, so that a maximum of two parameters can be modelled as non-stationary.

A further step is to add one or more physical covariates to help model the non-stationarity. For example, the distribution parameters might vary over time and also according to annual rainfall, which may help explain some of the year-to-year variability in annual maximum floods. Another commonly-chosen class of covariates are atmospheric circulation patterns such as the North Atlantic Oscillation (NAO) or Eastern Atlantic pattern (EA), often expressed as seasonal averages. For instance, the winter NAO has been found to be significantly correlated with annual maximum 10-day flows along the Atlantic seaboard of Ireland (EPA, 2013). Similarly, Steirou et al. (2019) found that winter maximum flows for some stations in the west of Ireland could be better modelled using the winter NAO than other circulation indices. Their results were more mixed for stations further east.

Taking another step, the time variable can be removed altogether from the analysis. The logic here is that there is no physical relationship between time and flood frequency: if floods are changing over time it is because of some physical factor that is also evolving. For example, on some catchments, non-stationarity may be better related to changes in urban extent. A risk associated with this approach is the confusion of correlation for causation. In principle it would be possible to include any covariate with a trend, whether or not it had any physical connection with the processes that cause floods. This could lead to a false sense of confidence about our ability to estimate the future evolution of the flood frequency curve. It is vital to demonstrate a strong causal relationship for physical covariates if they are to be used for predictions.

Most results presented in this paper are from statistical models that use only the time as a covariate, although other covariates have also been explored. The form of the function linking the parameter(s) with the covariate(s) can in principle be specified in any way, but at its simplest it is a linear, or log-linear relationship. More complex functions require more parameters to be estimated, which increases the uncertainty of the estimate.

Distributions were fitted by maximum likelihood estimation. Several candidate statistical models were fitted for each station: a stationary distribution and three non-stationary distributions in which the location, the scale or both location and scale parameters varied with water year. For selected stations, the number of candidate models was increased to 75, including up to one physical covariate as well as or instead of water year, for either or both of the location or scale parameters, chosen from the following list: winter NAO, summer NAO, autumn NAO, winter EA, summer EA, autumn EA and annual global mean temperature anomaly. So, for instance, one candidate model would vary the location parameter with both water year and autumn NAO and vary the scale parameter with winter EA.
One important consideration is the effect of collinearity on results when including multiple covariates. It is desirable that covariates included in a nonstationary statistical model are independent, otherwise computational issues may arise during inference and the fitted model may suffer from problems with interpretability. For models that included water year as a covariate, the physical covariates were detrended to help remove any collinearity.

There are many factors to consider when choosing a preferred statistical model, including physical realism as well as statistical fit. However, for the purpose of this national-scale analysis we used two measures:

- For models with only time as a covariate: A likelihood ratio test, which assesses which of a pair of nested statistical models is the better fit.
- For models with multiple covariates: Likelihood ratios are not practical when there are very many pairs of candidate models to compare against each other. In their place we used the Bayesian Information Criterion (BIC). The BIC establishes a trade-off between the goodness of fit and the simplicity of the model, measured by the number of parameters. It can be readily compared across a large number of candidate models, the lowest BIC indicating the preferred model. In comparison with the more widely-applied Akaike Information Criterion (AIC), the BIC gives a larger penalty to the complexity of a model, thus preferring simpler models.

Non-stationary frequency analysis was applied to 72 stations with at least 40 years of peak flow data.

## 5. RESULTS

### 5.1 Trend tests

Most rivers in Ireland show little evidence of trend in peak flows (Figure 1). At 68% of stations, the Mann-Kendall test found that the null hypothesis (of no trend) could not be rejected at a 5% significance level. 26% of stations showed an upward trend and 6% showed a downward trend.

Figure 1 shows no unequivocal geographical pattern to the results, although in general stations in the south-east show little trend. Upward trends are seen more in the midlands and the north-west.

Within the scope of the study it was not possible to investigate individual stations in detail. It can be expected that some apparent trends may vanish if they are found, for instance, to be due to inadequate updating of rating equations over the period of record. It may be that some different trends at nearby stations can be explained by differences in the period spanned by the record.

Similar results were reported in the FSU, using an older dataset that preceded the extreme floods of 2009 and 2015, with 28% of gauges showing evidence of trend at a 5% significance level.

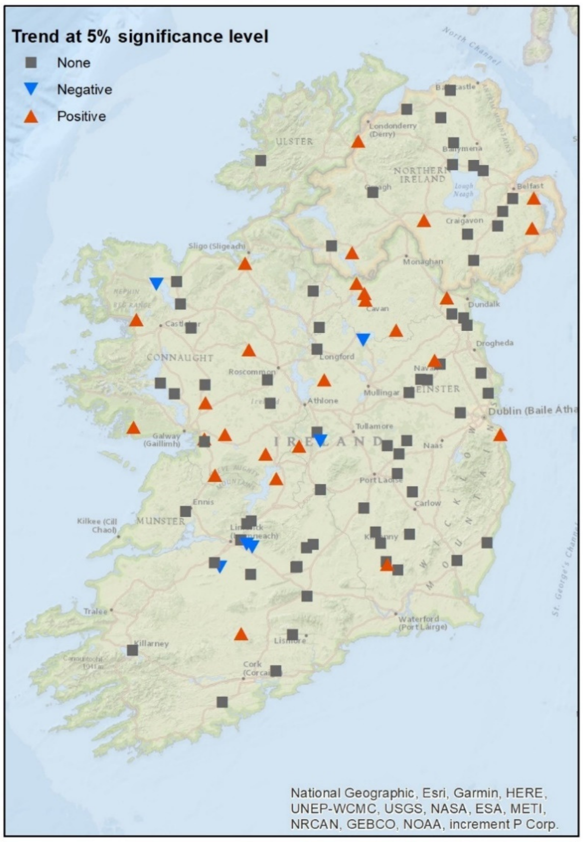


***Figure 1**: Mann-Kendall trend test results*

A much more in-depth analysis of trends in river flows, focusing specifically on climate-driven trends, is given by EPA (2013). At all but a handful of stations, results are provided for a fixed period of 1976-2009, which is rather shorter than many of the records analysed in the present study. EPA (2013) show generally increasing trends in annual maximum flows, both instantaneous maxima and 10-day and 30-day maxima. Some stations in Northern Ireland showed a decrease.

### 5.2 Non-stationary flood frequency analysis – an example

Example results are presented for the Ballysadare River at Ballysadare, County Sligo. This station has a long flow record, from 1945 to date. It has a marked upward trend in annual maximum flows, possibly exaggerated by the 2015 flood which appears unrealistically high and may be overestimated, perhaps because an improved rating equation derived in the Western CFRAM study has not been implemented. But even before 2015 there was a distinct upward trend, noted in the Western CFRAM study which included data up to 2009. The hydraulic control at the gauge is said to be stable. The catchment does not contain any designated arterial drainage schemes, although the Owenmore sub-catchment is a drainage district as permitted by The River Owenmore Drainage Act, 1926, and so it is possible that there is an element of the trend affected by channel works.

Figure 2 shows a time series of the annual maximum flows, with estimates of the 100-year return period (1% annual exceedance probability[1]) flow from four candidate statistical models, all fitting the GEV distribution. The stationary model plots as a horizontal line, with the design flow unchanging over time. In the varying location model, the estimated design flow increases linearly over the period of record. If the scale parameter is allowed to vary instead of or as well as the location, the increase is non-linear, leading to a dramatic difference between the start and the end of the record.

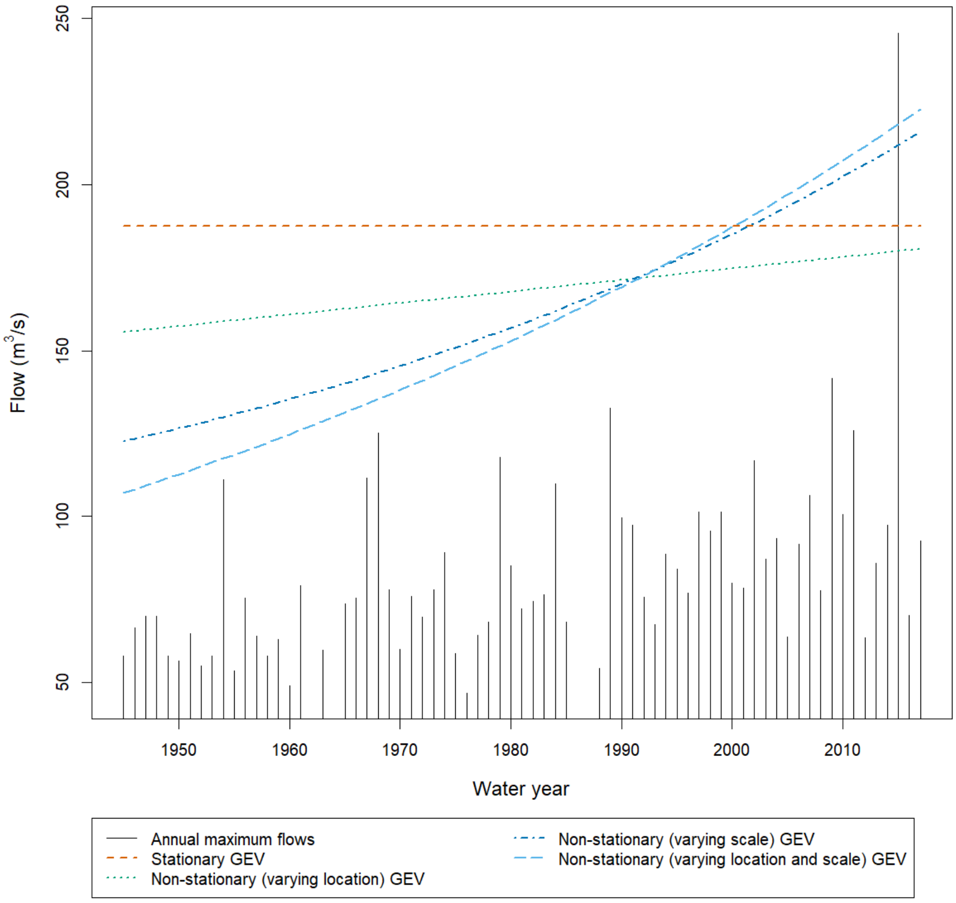


***Figure 2**: Time series of annual maximum flows at Ballysadare, with estimates of the 100-year return period flow from four candidate statistical models (one stationary, three non-stationary)*

The preferred model of the four, according to all three statistical measures mentioned in 4.2, is that with both location and scale varying. Figure 3a shows more results from this model, for a range of return periods, comparing them with the stationary estimates. The stationary estimate for the 2-year return period looks particularly unrealistic, with only one flood exceeding this during the first 16 years of record and nearly all floods lying above the line in recent decades. The non-stationary estimate appears more credible, although perhaps less so for longer return periods where it is probably heavily influenced by the (perhaps overestimated) outlier in 2015.

Figure 3b indicates a broadly similar confidence interval width for the stationary and non-stationary estimates, despite an increase in the degrees of freedom for the non-stationary model, for which it is necessary to estimate two more parameters (which describe how the location and scale change with time).

[1] Return period, a contentious concept even in stationary analysis, is even trickier in non-stationary conditions. There are alternative expressions for flood rarity such as the "design life level" or "reliability". To save space, we have not attempted to introduce them here.

An important question is to ask how the results of a non-stationary analysis can be used, for example in the assessment and design of flood relief schemes. It is certainly not appropriate to extrapolate the trends beyond the observed record. One approach is to adopt the present-day estimate. A challenge is then how to adjust this to account for the possible future impacts of climate change. To do so confidently it would be necessary to know how much of the change seen in the observed record can be attributed to climate change (as opposed to, say, periodic climatic variation, or changes in the catchment).

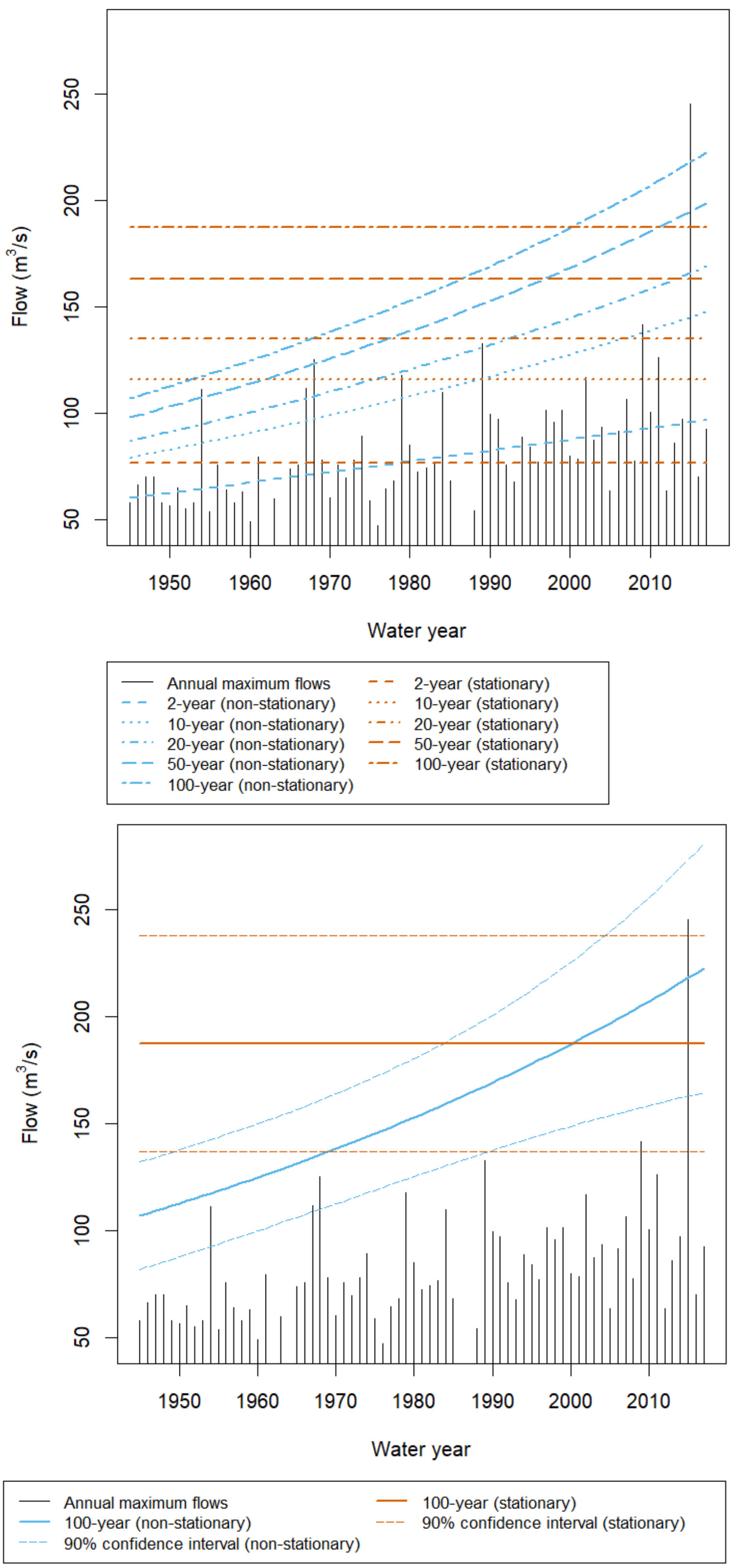


***Figure 3**: (a) Design flows at Ballysadare for a range of return periods, comparing the stationary GEV with the best-fitting GEV (varying location and scale); (b) Results for 100-year flood with confidence intervals.*

## 5.3 Non-stationary flood frequency analysis – physical covariates

Many authors strongly advocate including physical covariates rather than attempting to model non-stationarity solely as a function of time.

Staying with the Ballysadare example, we added the seven physical variables listed in 4.2 as candidate covariates. Out of the 75 candidate models with different combinations of covariates, the best-fitting (as judged by the lowest BIC) was the model already discussed, with only the water year as a covariate. The second best fitting included the autumn NAO as a covariate for the location parameter, as well as the water year as a covariate for both location and scale.

The fact that all of the better-fitting models included water year as a covariate indicates that the apparent non-stationarity at Ballysadare cannot be explained by changes in the considered atmospheric circulation indices.

Our ongoing research using data from Great Britain has found that a commonly-useful physical covariate is the catchment average rainfall, either annual or seasonal (Warren et al, 2019). Within the scope of the present study, we have not been able to investigate rainfall as a covariate.

A significant challenge is how to extract useful results, i.e. design flows, from non-stationary models using physical covariates. To illustrate this, Figure 4 shows the second-best fitting model fitted to the Ballysadare data as mentioned above. The points show the

conditional estimates of flow, i.e. conditional on each year's value for the autumn NAO. Superimposed on the general increase over time is a year-to-year variability due to the influence of the NAO.
For example, the conditional estimates for the last year of record, 2017-18, can be thought of as the expected T-year flows under the (clearly hypothetical) conditions that the autumn NAO always takes the value observed in 2017.

Figure 4 also shows, on the solid lines, a set of integrated non-stationary estimates. These correspond to the averaged exceedance probability, where averaging is over the covariates for a period of interest; here, the whole record length. By integrating out the covariates we remove the need to specify a particular value of NAO, or of water year. The mathematical details of this process, along with a more in-depth discussion, can be found in Warren et al. (2019), in which the integrated estimates of flow are referred to as *marginal return levels*. In the case of Figure 4, the integrated estimates over the whole period of record are very similar to the stationary estimates (dashed lines). However, it would also be possible to calculate integrated estimates for the present day, or, in theory for some future period, although this relies on knowledge of causal effects which typically is not available.

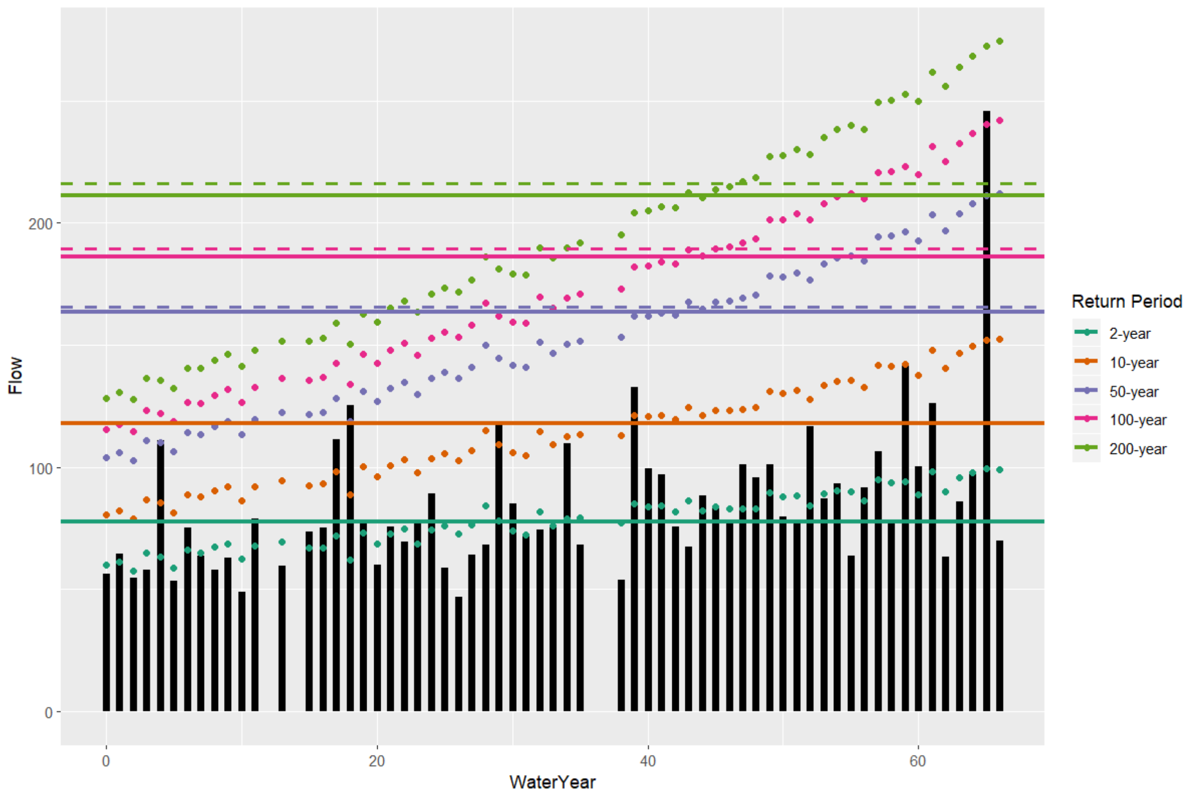


***Figure 4**: As for Figure 3a but showing non-stationary results from a model that incorporates autumn-average NAO as well as water year as a covariate. Points: conditional estimates. Solid lines: integrated estimates. Dashed lines: stationary estimates.*

It is very likely that at other gauges, physical covariates give an improved fit in comparison with models fitted only using water year as a covariate. However, for simplicity, the remaining results in this paper are derived using only the water year as a covariate.

## 5.4 Non-stationary flood frequency analysis – national results

To illustrate the national variation in results, Figure 5 shows which candidate model gave the best fit at each of the 72 stations analysed. The map is comparable with Figure 1. There is a clear tendency towards stationarity in the east and non-stationary in the west. Non-stationary models are preferred at 35% of stations. When a non-stationary model is preferred, it is most commonly one in which only the location parameter varies.

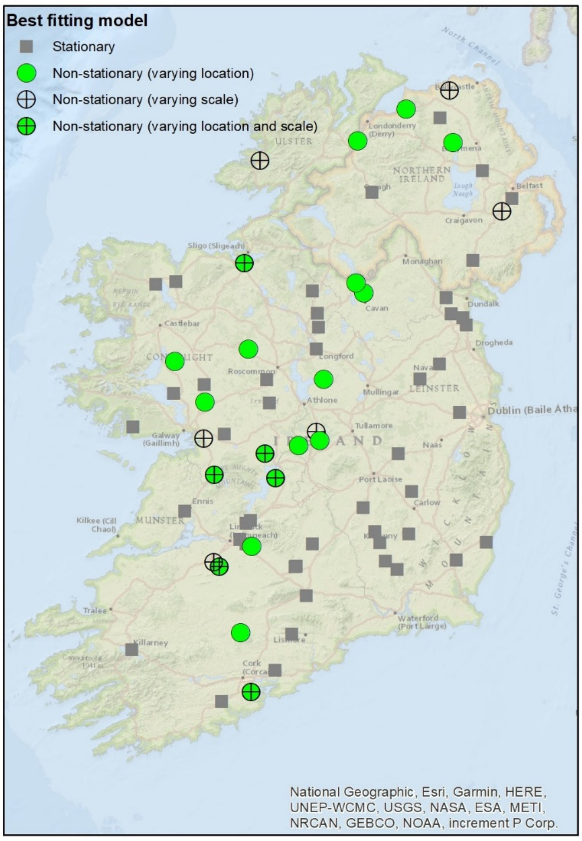


***Figure 5**: Best fitting version of the GEV model, according to likelihood ratios, at each gauge analysed*

Figure 6 compares the flood estimates from the best-fitting model at each station with those from the stationary model. For non-stationary analysis, results are taken for the last year of record.

At most stations the ratio is 1 because the stationary model fits best. Elsewhere, generally non-stationary analysis leads to an increase in the estimated present-day flow. This is not universal: 7 stations show a decrease. Where non-stationary analysis is preferred, the median change in estimated flow is modest, at less than 10%. There is a large range, with increases of up to 45% for the 2-year return period and up to 97% for the 100-year flood.

It is likely that in-depth investigation of individual stations would yield different results. Some of the distribution fits do not look entirely realistic when viewed individually. Others may be unduly influenced by individual flows that are not accurately measured. However, this broad-scale study gives an initial indication of how design flows may change if the universal assumption of stationarity is dropped.

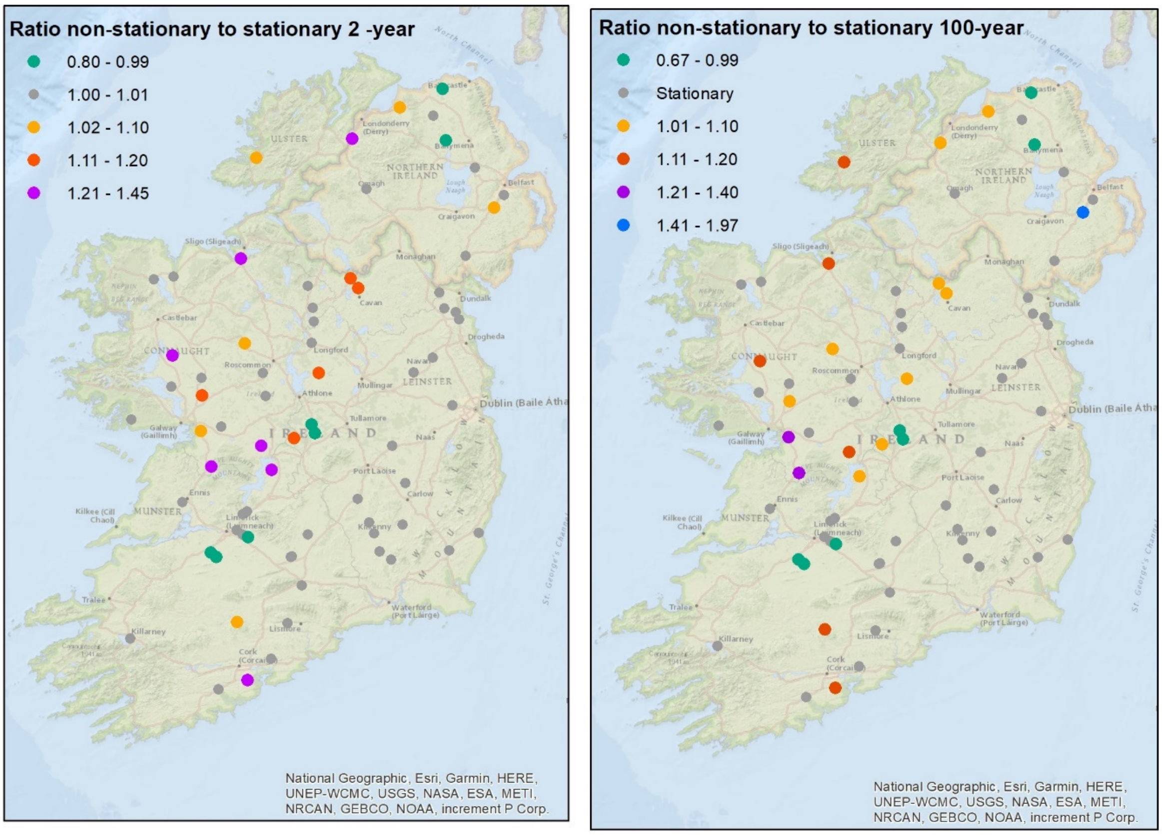


***Figure 6****: Ratio of present-day flood estimates from the preferred model to those from the stationary model. A ratio of 1 indicates that the stationary model is preferred.*

## 6. DISCUSSION

There is a lively debate in the research literature about the merits and drawbacks of non-stationary analysis, with several papers asserting that stationarity, far from being dead, is "alive and well" or even "immortal".

Serinaldi and Kilsby (2015) argue that when the model structure and physical dynamics are uncertain (and when is this not the case?), stationary models should be retained as they are simpler, more theoretically coherent and more reliable for practical applications. Similarly, Serinaldi et al. (2018) make the point that a non-stationary model can only be justified where one has deterministic information on the process of change, for example about an urban area increasing.

Along the same lines, Rehan and Hall (2016) explore the implications of non-stationary analysis for decision-making in flood risk management and conclude that there are reasons for at least considering stationary models alongside non-stationary analysis as the latter can lead to a higher variance in estimates of optimal flood protection.

Some of these objections reflect the difficulty of applying non-stationary analysis to estimate future floods, an important consideration for flood relief schemes. The various counter-arguments need to be set alongside the fact of climate change, which provides a clear physical explanation for why floods might be changing, even if we do not fully understand the physical processes at play and how they might evolve in the future. Members of the public often know or suspect that change is afoot, and they have a reasonable expectation that professionals involved in flood risk management ought to account for such changes in their analysis and modelling. This is particularly the case in locations that have been subjected to more than one exceptional flood in recent years, such as some communities in the west of Ireland that were flooded in both 2009 and 2015.

One way to improve confidence in the results of non-stationary methods would be to apply them in a pooled analysis, along the lines of the Flood Studies Update. A pooled non-stationary analysis in Canada is described by O'Brien and Burn (2014). The Environment Agency in England is currently funding development of non-stationary methods, including an attempt to reconcile them with pooled analysis. We recommend that the prospects for applying non-stationary analysis in Ireland are explored in more depth.

## References

DCCAE (2018a). National Adaptation Framework. https://www.dccae.gov.ie/en-ie/climate-action/topics/adapting-to-climate-change/national-adaptation-framework/pages/default.aspx

DCCAE (2018b). Local Authority Adaptation Strategy Development Guidelines. https://www.dccae.gov.ie/documents/LA%20Adaptation%20Guidelines.pdf

Debele, S., Strupczewski, W. & Bogdanowicz, E. (2017) A comparison of three approaches to non-stationary flood frequency analysis. Acta Geophysica, 1-21. 10.1007/s11600-017-0071-4.

Environment Agency (2019) Rapid Evidence Assessment of Non-Stationarity in Sources of UK Flooding. Report FRS18087. In press.

EPA (2013) HydroDetect: The Identification and Assessment of Climate Change Indicators for an Irish Reference Network of River Flow Stations. Report by the Irish Climate Analysis and Research UnitS (ICARUS),Department of Geography, National University of Ireland Maynooth.

Faulkner, D., Warren, S., Spencer, P. & Sharkey, P. (2019) Can we still predict the future from the past? Implementing non-stationary flood frequency analysis in the UK. Journal of Flood Risk Management, accepted.

Francois, B., Schlef, K., Wi, S. and Brown, C. (2019). Design Considerations for Riverine Floods in a Changing Climate – A Review. Journal of Hydrology. 574. 557-573. 10.1016/j.jhydrol.2019.04.068.

Milly, P. C. D., et al. (2008) Stationarity is dead: Whither water management?, Science, 319, 573–574.

Murphy, C., Cunnane, C, Das, S and Mandal, U. (2014). Flood Studies Update. Technical Research Report, Volume 2: Flood Frequency Estimation. Office of Public Works.

O'Brien, N.L. and Burn, D.H. (2014) A nonstationary index-flood technique for estimating extreme quantiles for annual maximum streamflow. J. Hydrol., 519, 2040-2048.

OPW (2018). Implementing the National Flood Risk Policy. https://www.opw.ie/en/media/Implementing_the_Gov_Nat_Flood_Risk_Policy_WEB.pdf

Prosdocimi, I., Kjeldsen, T.R. and Svensson, C. (2014) Non-stationarity in annual and seasonal series of peak flow and precipitation in the UK. Nat. Hazards Earth Syst. Sci.,14, 1125–1144.

Rehan, B.M. and Hall, J. (2016) Uncertainty and sensitivity analysis of flood risk management decisions based on stationary and nonstationary model choices. FLOODrisk 2016. DOI: 1 0.1051/e3sconf/20160720003.

Rootzén, H. and Katz, R.W. (2013) Design life level: quantifying risk in a changing climate. Water Resour. Res., 49, 5964–5972.

Sellars, D. (2011) Introduction to Common Sense and Other Heresies: Selected Papers on Hydrology and Water Resources Engineering by Vit Klemes. Canadian Water Resources Association.

Serinaldi, F. and Kilsby, C.G. (2015) Stationarity is undead: uncertainty dominates the distribution of extremes. Advances in Water Resour., 77, 17-36.

Serinaldi, F., Kilsby, C.G. and Lombardo, F. (2018) Untenable nonstationarity: An assessment of the fitness for purpose of trend tests in hydrology. Advances in Water Resour., 111, 132-155.

Steirou, E., Gerlitz, L., Apel, H., Sun, X., and Merz, B.: Climate influences on flood probabilities across Europe, Hydrol. Earth Syst. Sci., 23, 1305-1322, https://doi.org/10.5194/hess-23-1305-2019, 2019.

Warren, S., Faulkner, D., Sharkey, P., Spencer, P., Longfield, S. and Tawn, J. (2019) Towards incorporating physical covariates in nonstationary flood frequency analysis in the UK. IMA Flood Risk conference, Swansea, September 2019.