An Analysis of Changes in the Long Term Characteristics of River Flows in the Munster Blackwater Catchment

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I dedicate this thesis to my little family

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Abstract

This project is an analysis of the changing characteristics of river flows in the Munster Blackwater catchment. The portion of the Blackwater catchment above the river flow gauge at Kilavullen was the focus of this study. This is amongst the oldest continuous flow stations in the country with continuous flow data available from 1955 to the present day. Indeed, it can be said that prior to the 1950's Ireland did not possess a formal continuous flow gauging network, which inhibits the examination of long term trends in Irish river flows.

To examine the long-term characteristics of flow at the Kilavullen gauge, the 54 years of flow data that are available are insufficient and a method of extending the flow record at the site was required. Fortunately, organised precipitation and temperature measurements in Ireland date back further than their river flow counterparts. Within this study digital and historical paper based precipitation and temperature records from Met Éireann were compiled for the area in and around the Kilavullen catchment extending back to 1926. This data was quality controlled and where necessary was used to synthesise historical values of potential evapotranspiration before making it fit for purpose for hydrological modelling.

This historical data was then used as inputs to the HYSIM and IHACRES lumped conceptual rainfall-runoff models and used to reconstruct flows (hindcast) at the Kilavullen gauge from 1926 to 2009. This hindcast effectively extended the record at Kilavullen from 54 to 84 years (representing a 55% increase in the period of record). Rather than relying blindly on the rainfall-runoff modelling to reconstruct historic flows, a database of historic floods in the catchment was used to validate the hindcasted flows.

Tests for gradual trend in the data show statistically significant persistent positive trends in Annual temperatures, rainfall and flows within the catchment. Evidence of trend in spring flows was found to be the overall driving factor of trends in annual flows. Overall results of the trend analysis on the reconstructed flows general shows that in over the last 84 years, floods in winter months are becoming more common, and that floods in summer months are less evident.

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List of Abbreviations

Amax	Annual Maximum (Flood or Water Level)
AR4	IPCC Fourth Assessment Report
ASCII	American Standard Code for Information Interchange
BFI	Base Flow Index
BFI_{Soil}	Base Flow Index based on Soils
BHS	British Hydrological Society
CEH	Centre for Ecology and Hydrology
CGER	Centre for Global Environmental Research
CORINE	Co-Ordination of Information on the Environment
COST	European Cooperation in Science and Technology
CSET	Comhlacht Siucra Éireann Teoranta (Irish Sugar Company Ltd.)
CSV	Comma Separated Variable
CV	Coefficient of Variation
CWPU	Central Water Planning Unit
DMF	Daily Mean Flow
DRAIND	Drain Density
DTM	Digital Terrain Model
ECHAM	European Centre Hamburg Model
EDA	Exploratory Data Analysis
EPA	Environmental Protection Agency
FARL	Flood Attenuation from Reservoirs and Lakes
FLATWET	An Index of typical wetness
FLOODFreq	European procedures for FLOOD FREQuency estimation

FSSR	Flood Studies Supplementary Report
FSU	Flood Studies Update
GCM	Global Circulation Model
GHG	Greenhouse Gas
GLUE	Generalised Likelihood Uncertainty Estimation
HGF	Highest Gauged Flow
HYSIM	Hydrologic Simulation Model
IDW	Inverse Distance Weighting
IHACRES	Identification of unit Hydrographs And Component flows from Rainfalls, Evaporation and Streamflow data.
IPCC	Intergovernmental Panel on Climate Change
IRA	Irish Rainfall Association
MAF	Mean Annual Flow
MCRS	Monte Carlo Random Simulation
MFC	Mallow Field Club Journal
NAO	North Atlantic Oscillation
NCR	Non Confirmed Report
NERC	National Environmental Research Council
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe Efficiency
NUI	National University of Ireland
OD	Ordnance Datum
OPW	Office of Public Works
OSI	Ordnance Survey of Ireland
PE	Potential Evapotranspiration
POT	Peaks over Threshold

PSDI	Pore Size Distribution Index
QMED	Median Annual Maximum Flood
r^2	Coefficient of determination
RCA3	Rossby Centre Atmosphere Model
S1085	Mainstream River Slope
SAAPE	Standard Period Annual Average Potential Evapotranspiration
SAAR	Standard Period Annual Average Rainfall
SLR	Simple Linear Regression
STMFREQ	Stream Frequency
UCC	University College Cork
URBEXT	Urban Extent
WMO	World Meteorological Organisation

1 INTRODUCTION

1.1 Background

Evidence of the effects of climate change on global temperatures and weather patterns has been clearly proven and on a regional scale these effects have been detected in temperature and rainfall patterns in the UK and Ireland (Kiely, 1999 and 2010). The evidence on whether climate change is affecting river flows is, however still not clear. Studies on trends in river flows in the USA, Canada, mainland Europe, the UK and Ireland have yielded differing results without consensus being reached. This may be due to a number of factors, such as insufficient record length, changes to catchments, or natural climatic variation. Many recent studies have suggested that flow record lengths of at least 50 years are required before performing analysis of trends in river flows (Kundzewicz and Robson, 2004). The average record length at gauging stations in Ireland is approximately 32 years and the current length of record for many of the older stations in Ireland is of the order of 50-60 years. This would suggest that based on observed data, a definite trend in river flows in Ireland may not be detectable for some years to come. Flood policy in Ireland over the next few years will depend on the ability to quantify the expected increase in flood magnitudes due to climate change. It is therefore of great interest that a means of detecting trend in river flows in a timely manner is developed so that its effects in the future may be quantified as early as possible.

1.2 Aims of the Study

The primary aim of this project is to examine the changes in the long term streamflow characteristics of the Munster Blackwater catchment. The Munster Blackwater was chosen because it is possesses a long record of flow measurements and has a well documented flood history. The catchment characteristics suggest that it is representative of other catchments in Ireland, and they also show that it is also relatively free from catchment changes and artificial influences such as arterial drainage and impoundment.

This study will focus on the portion of the catchment down to the village of Kilavullen for the period from 1926 to 2009. In order to achieve the primary aim of the project, a number of secondary objectives must first be satisfied. These objectives are:

- To review in detail the existing measured hydrological and meteorological time series data for the catchment and with the aim of correcting any deficiencies.
- To perform a detailed literature review of all documented historical flood events in the Munster Blackwater catchment and compile a comprehensive flood event database.
- From a knowledge of the data availability in the Irish context, propose a suitable method for hindcasting of river flows in the Blackwater catchment using hydrological modelling techniques that can also be repeated on other Irish catchments. The hindcasting of flood events are to be validated against the floods documented in the flood event database.
- To test for the existence of changes in the flow regime of the catchment by applying monotonic and step change tests for trend, seasonality and flood frequency analysis to the extended flow series.

This study aims to devise a method for extending the length of flow record so that the early signs of trends in Irish rivers may be identified. In contrast to recent studies (Steele-Dunne *et al.*, 2008; Murphy and Charlton, 2008) that have examined the predicted trend in future scenarios, this study will examine the possibility of early detection of trends in flows by reconstructing historical flows (hindcasting) using hydrological models and other available measured historical data that extends further back in time, as illustrated in Figure 1.1. These include rainfall, temperature, potential evapotranspiration and other meteorological data. Relatively good quality historical rainfall data is available back as far as the 1920's.

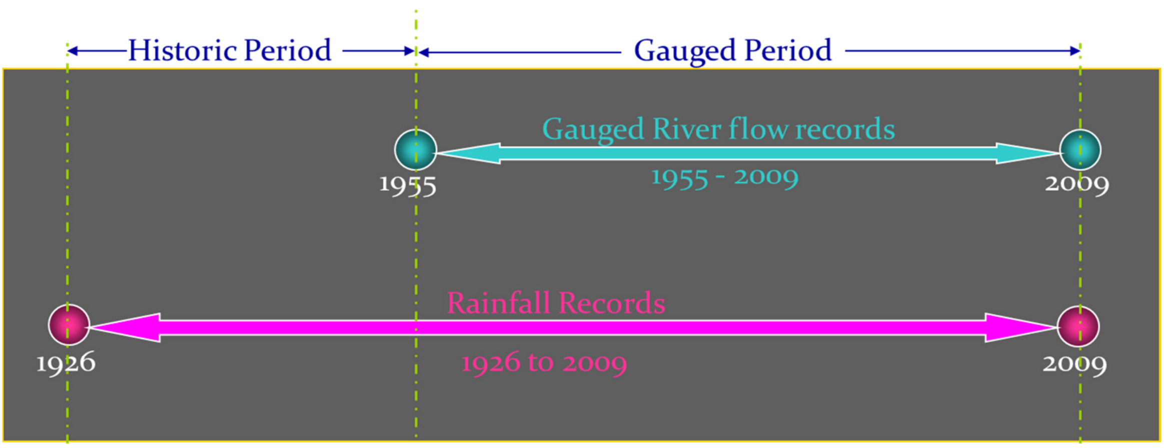


Figure 1.1 Schematic of the hindcast periods for rainfall-runoff modelling

This approach will not rely on modelling alone. There is a wealth of information on floods recorded in historical documents and newspapers that pre-date the era of gauged flow records. Another aim of this project was to compile a database of all the documented flood reports on the Munster Blackwater Catchment. This would entail an extensive trawl of historical records to provide anecdotal information on past floods that can be used to validate the reconstructed historic flows. This will give added confidence to the results of the hindcast model.

The primary objective of the study is to examine the long term changes in the river flow behaviour of the Munster Blackwater catchment. This is to be achieved by performing a number of exploratory and statistical analyses on the reconstructed flows. It is also intended that the methodology proposed here for repeating this research in other catchments will be of benefit to other researchers, and will prompt the renewed interest in the digitisation of historical rainfall and temperature records.

1.3 Thesis Structure

The following sections outline the thesis structure used in this research. They give a brief description of the aims and contents of each chapter.

1.3.1 Chapter 2

Chapter 2 involves a review of the literature relevant to this study. Consideration is given to the effects of climate change on meteorological and hydrological time series and current literature on testing such data for the presence of trend is examined. The chapter also focuses on the selection and performance of rainfall runoff models for the purposes of reconstructing river flows.

1.3.2 Chapter 3

Chapter 3 involves the description of the Kilavullen catchment, with a view to gaining an understanding of the flow regime in the catchment and to enable the parametrisation of rainfall runoff models based on catchment characteristics identified. The latter half of this chapter also details the collection of the data for use in the rainfall runoff models. It provides information of the sources of data that can be utilised for a study such as this.

1.3.3 Chapter 4

Chapter 4 deals with the analysis of the raw data that was collected from various sources in order to make it fit for purpose in the hydrological modelling stage of this research. In most cases this simply involves the quality control of the data and correction of errors. In other cases it involves the adaptation or augmentation of the data to enable it to be used in rainfall runoff models. It puts forward some suggestions on future best practice for rainfall runoff modelling in Irish catchments.

1.3.4 Chapter 5

Chapter 5 of this thesis describes the steps in the model selection process. It describes the models that were considered for this study, and rationalises the reasoning behind the choice of the models used here. It follows on by providing a description of the calibration and validation steps carried out in modelling process, carrying through to the reconstruction of the historical flows from 1926-2009.

1.3.5 Chapter 6

Chapter 6 gives a brief description of the exploratory and statistical tests carried out on the reconstructed flows, temperature, and rainfall in order to test for the presence of trend. The results of these tests are analysed and conclusions on the changing flow characteristics in the catchment are drawn.

1.3.6 Chapter 7

Chapter 7 details the conclusions drawn from the overall body of the research, and puts forward a methodology for reconstruction of streamflows in Ireland using observed meteorological data. It further presents some suggestions for further research in related fields.

2 LITERATURE REVIEW

2.1 Introduction

This literature review examines a selected body of literature on the past and future effects of climate change at both a global and a national scale. It also describes the growing body of work being undertaken to study the effects of climate change on temperature, precipitation and more importantly, river flows. The review presented here was used to guide the formation of the methodology that would be employed for the remainder of the study, with the aim of distilling out best practice procedures for studying the effects of climate change on river flows at a local catchment scale within the Irish context. The review of existing literature was used to gain an understanding of the current state of knowledge and the possible obstacles that could be encountered during the research in order to inform how best to go about performing such a study. The knowledge gained was used to define a methodology for reconstructing historical river flows on which to base tests for trend analyses. This involved review of best practice in selecting a suitable study site, analysing hydrological and meteorological data, selecting rainfall runoff models, and statistical tests for trend. The following sections describe the review of literature that guided the eventual choice of the project methodology.

2.2 Evidence of Global Climate Change

There is now an indisputable correlation between climate change and an increase in atmospheric greenhouse gas (GHG) concentrations. In the Fourth Assessment Report (AR4) the IPCC state "*warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level*" (IPCC 2007). During the twentieth century the mean global annual temperature increased on average by 0.07˚C per decade, however during the last 50 years of the twentieth century, the decadal temperature increase has accelerated to approximately 0.13˚C per decade (IPCC, 2007). Climate model projections in the Fourth Assessment Report indicate that during the 21st Century the global surface temperature is likely to rise a further 1.1°C to 2.9°C for low emissions scenario, or 2.4°C to 6.4°C for the high emissions scenario. The effect of climate change on global temperature is already evident in that eleven of the thirteen hottest years since temperature records began in 1850 have occurred since 2001 (NOAA, 2012), and the warmest year on record occurred in 2010. Model predictions reported by the IPCC (2007) suggest that:

- Global temperatures are likely to increase by between 1.8°C to 4.0°C by 2080-2099, relative to 1980-1999.
- An increase in the frequency of hot extremes, heat waves and heavy precipitation events is very likely (>90%).
- Precipitation is likely to increase in mid- to high-latitudes, with reductions in the lower latitudes. Large inter-annual variations in precipitation are also projected.

Based on a range of models, it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures. The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than that simulated by current models (IPCC, 2007). There is already evidence that anthropogenic changes in climate due to increases in greenhouse gases have had a direct impact on the observed global water cycle over the last 50 years (Gedney *et al.*, 2006; Huntington, 2006; IPCC, 2007; Barnett *et al.*, 2008). This includes increases in the extremes of runoff patterns in regions at higher latitudes with increased frequency of extreme floods (Milly, 2002) and drought (Dai *et al*, 2004).

2.3 Evidence of Climate Change in Ireland from Observed Data

Studies of trends in Irish meteorological data have shown general agreement with the wider literature on climate change. In a study of 12 Irish rain gauging sites, Sheridan (2001) showed that most of these rainfall stations exhibited increasing annual trends over the period from 1941 to 1999, and that monthly totals generally increased for the months of February, March, and April. This was accompanied by decreases in totals for July, August and September. The research provides support for the assertion by Kiely (1999) that an increase in annual precipitation was found to occur after 1975. Both studies note that this change point in Irish precipitation corresponds to the change in the North Atlantic Oscillation (NAO) index that occurred around 1975. Annual rainfall since 1960 has increased in the north and west while decreases and some slight increases are shown for the south and east (McElwain and Sweeney, 2007). Kiely *et al.* (2010) note that change points in the total annual rainfall occurred for synoptic stations near the west coast, marked by a transition to increased rainfall levels since 1975-1978. This is subsequently reflected in streamflows for the Suir, Nore, and the Fergus.

2.4 Future Projections of Climate Change for Ireland

Future projections based on downscaled Global Circulation Models (GCMs) indicate that autumn and winter months could become wetter by 5-10% by the middle of the 21st Century, and summers could generally be drier (Steele-Dunne *et al*, 2008). This evidence of the projected change in rainfall has direct implications for river flows and would seem to suggest that droughts in summer and floods in winter months could become more common. The most important reports in the area of climate change research in Ireland include 'Climate Change: Refining the Impacts for Ireland' (Sweeney *et al.*, 2008), 'Ireland in a Warmer World: Scientific Predictions of the Irish Climate in the Twenty First Century' (McGrath *et al.*, 2008), 'Implications of the EU climate protection target for Ireland' (McElwain and Sweeney, 2007) and 'Climate Change: Regional Climate Model Predictions for Ireland (McGrath *et al.*, 2005). The main findings of these reports were as follows:

- The climate of Ireland will continue to warm, particularly in the summer and autumn seasons with possible increases of 3 to 4ºC towards the end of the century. The greatest warming will occur in the south and east of the country.
- While there are differences between modelling approaches it is generally agreed that the autumn and winter seasons may become wetter with increases in rainfall in the range 15-25% towards the end of the century. Summers are likely to become drier with a 10-18% decrease towards the end of the century (McGrath *et al.*, 2008), however regional details remain elusive, due to the large uncertainty in more local projections.
- The frequency of very intense cyclones affecting Ireland is likely to increase.
- The seas around Ireland have been warming at the rate of 0.3-0.4ºC per decade since the 1980s;
- Sea levels are rising on average about 3.5 cm per decade around Ireland.

- Ocean modelling results indicate an increase in the frequency of storm surge events around Irish coastal areas; in the northwest the increase in surge heights between 0.5 and 1.0 metres is around 30% by mid-century. Extreme wave heights are also likely to increase in most regions.
- Changes in precipitation and temperature are likely to lead to a rise in winter and spring stream flows (increasing the risk of flooding), and a reduction in summer flows.
- The increases in winter flows are expected to be in the order of 20% by mid to late century. Reductions of flows in summer and autumn months of over 40% are likely in many catchments.

It is very clear from the review of literature that climate change impacts on meteorological variables may be substantial over the next century, and that an analysis of emerging trends in river flows is warranted.

2.5 Studies of Trends in Observed River Flow Data

It is widely accepted that studies of trends in European meteorological data have shown clear changes in precipitation and temperature. The next logical step is to examine if this behaviour has been translated into a corresponding change in river flows. A number of studies have been carried out on observed flow records in the Europe, the UK and Ireland to attempt to examine the existence of trend in river flows. These studies of observed flows appear to give contradictory results showing increases at some sites but also decreases at others, season-specific differences may be identified, while some studies find no evidence for any change at all.

Detection of changes in river flows at a regional scale is much more problematic because of the natural inter-annual and decadal variability of river flows (Burn and Hag Elnur, 2002; Wilby, 2006; Fowler and Wilby 2010), human induced land use change, and natural catchment changes. A number of streamflow series in different countries such as the USA (Lins and Slack, 1999; Ziegler *et al.*, 2005), the United Kingdom (Robson *et al.*, 1998; Robson, 2002; Wilby, 2006), Canada (Burn and Hag Elnur, 2002), Sweden (Lindstrom, 1999), and China (Guowei and Jingpen, 1999) have been examined, but do not as yet provide conclusive evidence of a climate change signal. A more recent study by Villarini (2011) looked at daily flow records from 55 monitoring stations in Europe – 32 in Germany, 13 in Switzerland, 6 in the Czech Republic and 4 in Slovakia, with between 75 and 192 years of continuous flow data. No sites were found to have significant long-term trends. No trends were found in the seasonal timing of flood peaks at any site, and no trends in the spring, summer, autumn or winter data were detected. It is believed that the lack of a definite climate change signal may be due to its relative weakness in comparison to natural climatic 'noise' and anthropogenic effects (Wilby, 2006).

Similar studies in the UK have more or less led to the same conclusions (Robson, 2002) and (Wilby *et al*., 2008). They found that there was little clear and robust evidence of climate change in observed flow data. They generally found that:

(i) Climate variability is seen to have a very strong effect on trend detection. For monthly rainfall series, historical 40-year sub-series repeatedly show apparent significant trends, both upward and downward. This suggests that 40-year records (a typical flood-record length) are insufficiently long for distinguishing between climate change and climate variability.

(ii) Long-term monthly rainfall series show a tendency to increased winter rainfall and decreased summer rainfall, but with a non-significant trend in the annual rainfall total.

(iii) Over the past 60–120 years there is little evidence of any long-term trends in UK flood frequency. However, it should be noted that there are data limitations, both for the early years and for the very recent past.

(iv) The North Atlantic Oscillation (NAO) has a marked effect on runoff and disguises the climate change signal.

Hannaford *et al*. (2005) studied trend in annual and seasonal runoff time series from a network of largely undisturbed catchments across the Celtic Region of Northwest Europe (the British Isles and Brittany), with a view to discerning natural variability from artificial influences on flow regimes. Strong evidence of runoff increases over the last 40-years was found for Scotland and Ireland, and there were some significant increases in Wales, western England and Brittany. The findings showed some parallels with climate change scenarios, although there were also strong associations with the North Atlantic Oscillation Index over this timescale. The influence of the NAO was found to be the likely cause for the spatial variability in the significance of trends that were observed over the region.

Studies specific to Ireland have shown increasing trends at selected flow gauging stations since the mid 1970's. Increasing trends were noted on the Erne at Belturbet, the Boyne at Slane, The Munster Blackwater at Ballyduff, and the Brosna at Ferbane (Kiely, 1999). This study was performed on four gauged sites, two of which were subject to arterial drainage in the early 1970's and so the increase in flow rates at these gauges may have been contributable to the increased land drainage and corresponding increase in runoff rates in those catchments. In a recent study by NUI Galway (Das, 2010), six statistical tests were applied to the Annual Maximum (Amax) series of 117 river flow gauging stations across Ireland, where the study also concluded that the impact of climate change on the trend and other changes in Amax series in Ireland was found to be insignificant. The impact of drainage works on Amax flows at 16 of these stations was initially identified through exploratory data analysis. Where catchments were subject to arterial drainage, an abrupt change in the flow regime at these sites occurred at the beginning of the post drainage period (Das, 2010) and reinforces the evidence that arterially drained catchments are least suitable for studies in trend analysis related to climate change.

The research to date would appear to suggest that even though the presence of climate change is clearly detectable in observed temperatures and precipitation, it is difficult to distill out the presence of trend in observed river flows. This should not be taken as proof against climate change but instead may indicate that due to the effects of other factors such as human driven changes in catchments, short length of records, and natural climate variation we cannot yet distinguish the climate change signature in existing observed data.

2.6 Projected Future Effects of Climate Change on River Flows in Ireland

Studies of the expected future effects of climate change on river flows in Ireland, while few in number are now gradually increasing. These are almost solely based on future climate scenarios based on a range of global climate models, different regionalisation approaches and numerous rainfall runoff models that predict notable increases in winter flows and decreases in summer flows (Murphy and Charlton, 2008; Steele-Dunne *et al*., 2008; Bastola *et al*., 2011).

One of the earliest studies into the future projected impact of climate change in Ireland dates back to the McWilliams Report (1991), which put forward simple climate scenarios for use in climate change modelling. Subsequently, Sweeney *et al*. (2003) used the HYSIM conceptual lumped model, in conjunction with a single downscaled global climate model to produce meteorological data as input to predict the effect of climate change on annual runoff. While future decreases in annual runoff were predicted for the Bonet, Feale, Slaney, and the Suir, it was suggested that "*the magnitude and frequency of individual flood events will increase in the western half of the country*" and that "*seasonal flooding may occur over a larger area and persist for longer periods of time*".

The study of the effects of climate change in nine Irish catchments carried out by Steele-Dunne *et al*. (2008) used data from the European Centre Hamburg Model version 5 (ECHAM 5) GCM to force the Rossby Centre Atmosphere Model (RCA3) regional climate model to produce dynamically downscaled precipitation and temperature inputs to the HBV light conceptual rainfall runoff model. Comparison of the simulated flows for the period 2021-2060 with flows for the WMO standard period 1961-1990 suggested that winter flows will increase and summer flows will decrease while river flows from October to April are expected to increase by up to 20% by 2060. Due to the combination of reduced summer precipitation, increased temperature and as a consequence increased evaporation, stream flow is expected to decrease by up to 60% from May to September. The study also points to an increase the annual maximum daily mean flow indicating that the severity of large flood events will increase. In a similar study by Murphy and Charlton (2008) also based on nine Irish catchments it was also predicted that reductions in streamflows are likely for autumn months, accompanied by higher flows in winter and spring. Again, extended dry periods were forecast for the summer and autumn months in the majority of catchments studied showing a general agreement between the two studies in the prediction of future conditions.

2.7 Obstacles to the Detection of Climate Change in Observed Flow Records

Current evidence would seem to suggest that there are no identifiable trends in observed river flows or at least there is a lack of robust trends in peak flows (Kundzewic *et al*., 2005). This strongly contradicts the evidence of increasing observed precipitation taken in conjunction with modelled future scenarios where increases in flood magnitude and frequency are expected. Brázdil *et al*. (2006) have described this apparent mismatch as a 'conceptual controversy'. Wilby (2006) and Wilby *et al*. (2008) have examined the factors that most likely mask the effects of trend due to climate change. The length of record used in the analysis of trends combined with inadequate statistical testing is seen to be one of the more obvious reasons for the variation of results from trend studies, but also the effects of natural climate variation, and human driven land use change may be also be masking the climate change signal. Some of these effects are examined in the following sections.

2.7.1 Short or Inadequate Record Length

It has been argued that natural climate variability and man-made changes to catchments exert a very strong effect on trend detection and that typical gauged record lengths of 40 years or so are insufficiently long for distinguishing between climate change and climate variability (Robson, 2002) while CEH and the UK Meteorological Office (2001) as well as Kundzewicz *et al*. (2005) recommend a minimum record length of 50 years when testing for trend in observed flow data. Studies of trend rely heavily on the period of record being analysed (Wilby, 2006). When studying the presence of trend in a catchment, using such criteria as the Mann Kendall Z-statistic (which is a measure of trend significance) different periods of record may give differing results. Trend tests based on examination of a single period of record should not be taken alone as an indicator of trend but rather persistence in the trend for varying lengths of record should be used when testing for the existence of trend (Wilby, 2006).

Furthermore, studies on large catchments in the eastern U.S. have concluded that the length of record required to detect trend in those areas due to climate change is anywhere between 60-120 years (Ziegler *et al*., 2005). In this study, a method for calculating the number of years of data required to detect a climate change signal (detection time) was proposed. This study was based on catchments that are very much larger than those in Ireland, and further evidence from catchments in Ireland and the UK would be required to assess the effects at a local scale. Within Ireland, Harrigan (2010) examined 5 catchments, and based on the methods put forward by Ziegler *et al* found that the length of record required in order to be able to detect trend in annual average flow data ranged between 49 and 69 years. Interestingly, outputs from this research also agreed with the findings of Wilby (2006) where it was found that as a rule of thumb, the coefficient of variation (CV) of observed flows at a site provides an indication of how easily a trend may be detected at a site. The CV measure can be thus used as a first indicator when selecting potential study sites for the detection of climate change.

2.7.2 Natural Climatic Variation

It is widely accepted that not only does weather vary from year to year, but that climate varies from decade to decade. The behaviour of a river catchment in one decade may be quite different to its performance in another. Decadal mean runoff can easily be 50% different from the long-term average – and in some months much more (Arnell, 2003). The effects of climate change will be superimposed onto this inter-decadal variability, which may either completely mask or exaggerate the climate change signal (Arnell, 2003). A corollary of this is that it may be difficult to detect a clear climate change signal for several years. However, studies have shown that climate change effects may be visible (and implicitly statistically detectable) as early as the 2020s (Dettinger *et al*., 2004), particularly where changes in temperature are producing changes in the timing of streamflows. Where hydrological regimes are more sensitive to changes in precipitation than to changes in temperature, it is possible that the effects of climate change will take longer to detect.

2.7.3 The North Atlantic Oscillation

One of the main factors driving natural climate variation in Ireland is the North Atlantic Oscillation (NAO). Regional patterns are affected by the NAO which is the difference in atmospheric pressure between the northern Atlantic (near Iceland) and the southern Atlantic (near the Azores). A higher index indicates a larger pressure difference and seems to move the tracks of Atlantic storms to the north, with more making landfall in Scandinavia. A low NAO index value indicates a smaller pressure difference and is associated with more southerly tracks of Atlantic storms, with more than usual arriving in the Iberian Peninsula (Trigo *et al*., 2002). Variations in the NAO have been used to explain increases/decreases in precipitation over Western Europe. The Index was strongly positive between 1975 and 1996, but in recent years has alternated to a negative behaviour. An increase in the index indicates a corresponding increase in westerlies resulting in more rain over Ireland. No periodical pattern in the NAO has been detected (Figure 2.1) nor is there a reliable method for its prediction.

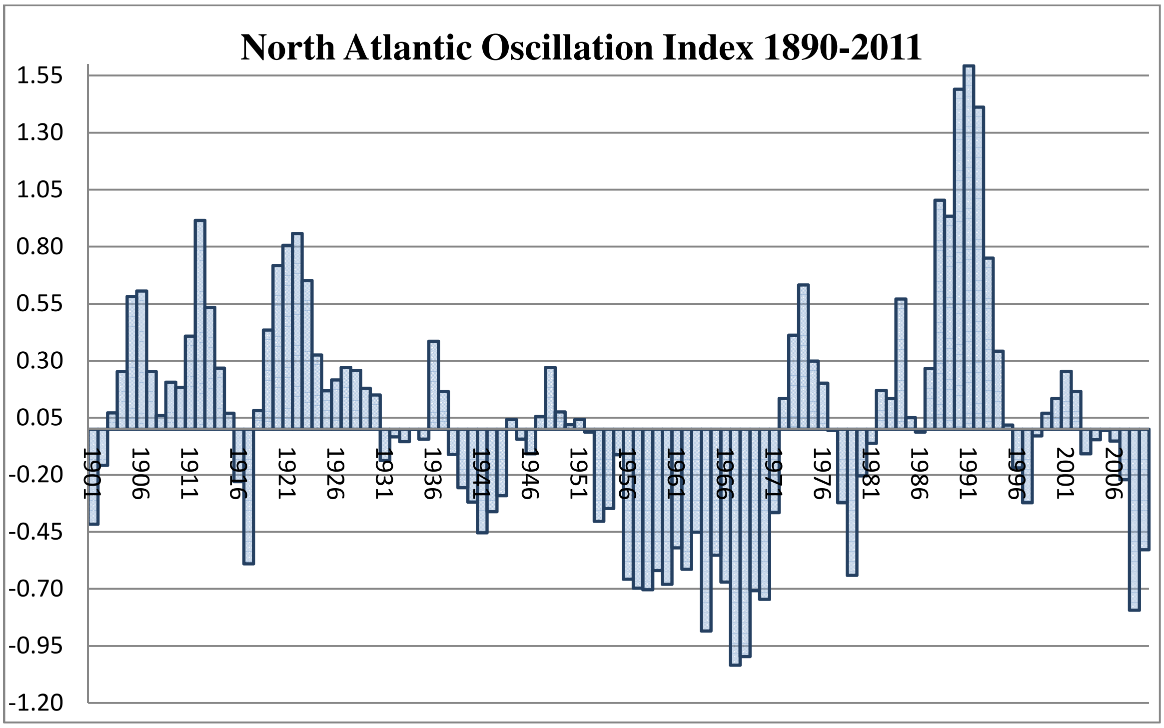


Figure 2.1 Variation of the North Atlantic Oscillation Index since 1890 - 3 year moving average. (Source: National Centre for Atmospheric Research (NCAR) *http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-pc-based*)

2.7.4 Arterial Drainage

The purposes of arterial drainage are to improve land drainage and reduce the frequency and extent of overland flooding. Embankment construction, river diversions and lake storage are widely used in relevant circumstances as means of achieving these purposes but, for the greatest part, arterial drainage relies on deepening and widening channels and so improving their discharge capacity. In the undrained state overland flooding acts in a manner similar to a large lake, causing downstream floods to be attenuated resulting in hydrographs with low peaks and long sluggish recessions. Following drainage there is an acceleration of the response to rainfall, with flood peaks of increased intensity and more rapid recessions back to low flows (Bailey and Bree, 1981). Earlier research on the effects of arterial drainage (Cunnane and Bree, 1979) revealed marked reductions in response times and increases in the 2 or 3-year flood magnitudes at points downstream of major arterial drainage schemes.

Arterial channel improvements lead to increased flood peaks downstream due to the higher channel flow velocities and a reduction in overbank flooding and attenuation. This increase is greater for larger channels and for bigger flows (Robinson, 1986), and may in some cases be confused with the effects of climate change, indicating that a prior knowledge of the history of a catchment is extremely important when identifying case study areas.

2.7.5 Afforestation

Intuitively, one would expect that afforestation would attenuate peak flows in a river catchment due to increased interception and evaporation from the canopy. However studies in the USA and the UK (Robinson *et al.*, 2003) have shown that in the long term, afforestation does not greatly affect river flows. The land drainage that is associated with preparations for planting has a greater effect in the short term. Robinson *et al.,* (2003) studied six North West 'Atlantic' climate catchments to determine how forest (mainly coniferous) affects low flows and floods. With regard to low flows they identified that in deep peat catchments that receive aggressive drainage and ditching, the low flows can increase immediately after the land preparation but that this effect reduces over time as the tree cover establishes and the drains deteriorate.

This same aggressive drainage of peaty soils by drainage ditches in preparation for the planting of conifer plantations have been shown to also increase peak flows, and increase the rate of rise to peak discharge (Acreman, 1985; and Robinson 1986). Following afforestation and extensive forest drainage in Coalburn, England, peak flows increased by over 15% (Robinson *et al.*, 2003). However, in a similar fashion to the affect on low flows, once a forest begins to develop and has become established, longer-term tree growth leads to a decrease in peak flows, typically in the range of 10-20% (Robinson *et al.*, 2003) which points to a balancing out of effects. Price *et al.* (2000) collated the results from several research catchment studies (many from USA due to absence of relevant studies in the UK). These suggested that a change to 100% forest cover (without aggressive drainage) can attenuate flood peaks by 0-20%, and that the larger floods are likely to be attenuated to a lesser extent than smaller floods. This evidence suggests that afforestation/deforestation effects on catchment flows have a short term effect on flows before returning to their original behaviour.

2.7.6 Changes to flows caused by urbanisation

It is generally accepted that the effect of urbanisation is to increase the lower part of the flood frequency curve much more strongly than the upper part. Increases in paved areas associated with increased urbanisation can result in "peakier" hydrographs due reduced surface permeability leading to a faster rate of runoff reaching rivers. The Flood Studies Supplementary Report No 16 (FSSR 16, 1985) suggests an amended version of the six variable equation for calculation of the average annual maximum flood (Qbar) to include for the effects of urbanisation. Similarly in Work Package 2.3 the Flood Studies Update for Ireland – "Estimation of the Index Flood for Ungauged Locations" (Murphy, 2009) a 7-variable equation was developed for the calculation of the median annual maximum flood (QMED). This enabled the calculation of the index flood at ungauged locations when treated as being 100% rural. The study also carried out a wide scale regression analysis on the effects of urbanisation on QMED. The adjustment to QMED to account for urbanisation was defined as $(1+URBEXT)^{1.482}$.

Similarly, In studying the effects of urbanisation elsewhere it has been proposed (Naden *et al*., 1990) to increase the estimates of the median annual flood (QMED) made from rural catchment parameters by the factor $(1+URBEXT)^2$. While the two methods show a slight contradiction in the exponent applied to the (1+URBEXT) value, it still indicates that the typical adjustment factor for a 100% urbanised catchment would be somewhere between 2.8 and 4. The effects for urbanisation are much less pronounced in Ireland compared to the UK due to the far lesser degree of urbanisation in most Irish catchments.

From an understanding of the confounding factors that can affect/mask the effects of climate change on catchment hydrology we can use this knowledge to identify the most suitable study sites for the detection of climate change. While we cannot avoid climatic factors such as the NAO, we can focus on catchments that are as free as possible from the effects of afforestation (or deforestation), urbanisation, and arterial drainage. These catchments should also exhibit low coefficients of variation in the flow metrics being examined, and ideally should have the longest possible period of record. In many cases however the period of record just may not be long enough and means of somehow extending this record by reconstruction of historic flows must be investigated. This literature study also explores the most suitable method for doing so in the Irish context.

2.8 Use of Conceptual Rainfall-Runoff Models in Hindcasting River Flows

There are currently numerous rainfall runoff models in use around the world. Most of these rainfall runoff models have been employed to predict future flow conditions. These are usually linked to future scenarios from downscaled Global Circulation Models (GCMs). In Ireland, HYMOD, HBV-light, TANKMODEL, SIMHYD, MIKE NAM, IHACRES and HYSIM have all been used successfully for studying the future effects of climate change on river flows. A literature review to assess the advantages and disadvantages of available rainfall runoff models and their applicability to reconstruction of historic flows (see chapter 4) led to the selection of two models for use in this project, namely HYSIM (Manley, 1978) and IHACRES (Jakeman *et al.*, 1990).

One of the first criteria for selection of a model for reconstruction of historic flows is that it should require as few input variables as possible. The reconstruction of historical flows can be difficult due to poor data availability and so the choice of models to be used will be affected by this constraint. Models that use unit hydrograph methods to construct flow series were seen as particularly advantageous in that they require the least amount of data and require a greatly reduced number of parameters. To construct a unit hydrograph, only two parameters are required, namely percentage runoff and time-to-peak. The IHACRES model of Jakeman *et al.* (1990) is one such model, and was chosen for use in this study. IHACRES (Jakeman *et al.*, 1990; Littlewood *et al.*, 1997) is an example of a hybrid conceptual-metric model as it uses a conceptual module to estimate the effective rainfall and a transfer function module to convert effective rainfall into streamflow. IHACRES requires only precipitation and temperature as inputs and has been used in other studies for the reconstruction of river flows. IHACRES has been used to reconstruct historical flows for 10 river systems in Adelaide (Wilkinson, 2005) and for parameter regionalisation studies in the UK (Sefton and Howarth, 1998; Littlewood, 2003).

Few catchment models have been specifically developed for reconstruction of historic river flows. Exceptions are the conceptual models HYDROLOG (Porter and McMahon, 1971), HYSIM (Manley, 1978), and the empirical model developed by Wright (1978), at the Central Water Planning Unit (CWPU). HYSIM has also been used extensively in Ireland for studying future flow scenarios (Murphy and Charlton, 2008). It requires only precipitation and potential evapotranspiration (PE) as inputs to the model, and has been used in conjunction with a stochastic weather generator on the Wye catchment in Wales to reconstruct historic daily river flows back to 1889 (Mountain & Jones, 2006). The stochastic weather generator used daily airflow indices calculated from actual daily observed pressure fields by the Climatic Research Unit at the University of East Anglia. Observed rainfall and PE values were regressed against the indices to calculate the inputs for the reconstruction period.

While historical rainfall records are available in Ireland, PE records are not so easily obtainable. The issue of how to calculate potential PE for use in reconstruction of historical flows is dealt with in differing ways depending on the approach to modelling. In the example of the Wye catchment, air flow indices were used, however some use a sine curves to approximate values of Potential evapotranspiration that are calibrated on measured PE values as in the PDM model of Moore, while others simply use the long term monthly average values of PE (Jones *et al*, 2006). Research by Oudin *et al* (2010) compared the performance of 27 methods for estimating potential evapotranspiration for rainfall runoff models and found that PE values based on temperature and radiation alone gave superior results to the commonly used Penman-Monteith method (1948). This approach was adopted for the current study and enables the use of observed historical temperatures to calculate PE directly for the purposes of rainfall runoff modelling. These PE values are then used as inputs to the chosen rainfall runoff models in addition to historic rainfall data.

2.8.1 Model Uncertainty

No rainfall runoff model is perfect, they are simplified representations of real life processes and simplifications must be made in order to implement them. Calibration of any rainfall runoff model involves finding the parameter set that best suits the study catchment and modelling purpose. The task of selecting the most suitable parameter set is made difficult due to a range of uncertainties that are related to the modelling process. The sources of these uncertainties are summarised by Wagener *et al*. (2004) as being:

- Data Uncertainty – errors introduced by errors in measuring physical data;

- Model Specification Uncertainty – The inability of the model to converge on a single best parameter set;
- Model Structural Uncertainty – Uncertainty from simplifications of real world processes in the model structure.
- Randomness Uncertainty – This is referred to as the unmeasurable randomness in the natural processes themselves.

Many experts agree that there is no single set of parameters that fully describes the processes being modelled, and instead the concept of equifinality has emerged. This is the idea that a number of different combinations of parameters can produce equally suitable results. Sets of parameters that produce these suitable results are often termed "behavioural" models, and these can be used to assess model uncertainty. One of the most popular methods for estimating uncertainty in rainfall runoff modeling is the GLUE approach (Beven and Binley, 1992). In this approach a large number of combinations of parameters are generated using a Monte Carlo Random Sampling (MCRS) or Latin hypercube simulation procedure. A model run for each combination of the parameters is then performed and a corresponding likelihood (goodness-of-fit) measure is calculated. A threshold value of the likelihood measure is then chosen to differentiate between behavioural and non-behavioural models. Models below this threshold are then assigned a likelihood measure of zero whereas those above the threshold are assigned a weighting based on their likelihood measures with the condition that the sum of all the weightings sum to 1. Uncertainty limits are then calculated using the behavioural models at a specified percentile (usually the 5 and 95 percentiles). Uncertainty limits are calculated against the period of observed record, but may also be assumed to apply to the reconstructed period of the flow series. Further qualitative checks (sanity checks) on the performance of reconstructed flows may be carried out by comparing historical reports of flooding with the modelled flows.

2.9 Use of Historical Meteorological Data to Hindcast River Flows

Most river flow records in the UK and Ireland are relatively short, with some of the longest continuous series beginning in the mid to late 1950s. In contrast, rainfall and temperature records are relatively plentiful with many extending back into the early decades of the nineteenth century (Dixon, 1986).

Many methods used in the UK for extending river flow records use the relatively abundant precipitation records which extend back at least 100 years for a number of sites in England and Wales. These can be used as the inputs to hydrological simulation models to reconstruct past river flows as demonstrated by Jones and Lister (1998) and Jones *et al*. (2006). These studies used an empirical, black box method to reconstruct monthly flows back as far as 1865 based on monthly rainfall data. Comparisons of reconstructed against observed flows for 1980–2002 implied that land-use changes showed little effect on flows, at least at the monthly time step. A further suggested use for the reconstructions for flow naturalisation was put forward in the case of some catchments where artificial effects such as arterial drainage may have occurred.

Other methods generate precipitation series based on sampling from a probability density function fitted to observed records, however the use of actual measured historical data is preferred because it more accurately represents the actual weather conditions for that time in the past. It is also important to develop a means of validating these reconstructions so that the modeller is not blindly reliant on model alone. This leads to the requirement of documentary evidence of floods to back up the results of the modelling process. The study of documentary evidence of past rainfall and flood events has given rise to a new field of hydrology termed *Historical Hydrology*.

2.10 The Field of Historical Hydrology

Historical hydrology can be defined as a research field occupying the interface between hydrology and history, with the objectives: to reconstruct temporal and spatial patterns of river flow and, in particular, extreme events (floods, ice phenomena, hydrological droughts) mainly for the period prior to the creation of national hydrological networks; and to investigate the vulnerability of past societies and economies to extreme hydrological events. It is a significant tool for the study of flood risk (Brázdil *et al*., 2006). The use of historical hydrology for this project looked at two different aspects. The first was the use of historical flood data to validate the reconstructed historical flows, and the second was to look at how these reconstructed flows could be used to improve flood frequency analysis.

2.10.1 Use of historical data in flood frequency analysis

Research by Potter (1978), Bayliss & Reed (2001) and Williams and Archer (2002) have put forward methodologies for the use of historical anecdotal information in flood frequency analysis. These methods generally use evidence from historical records to rank flood events relative to others. These rankings are used to define plotting positions on flood frequency graphs. However some shortfalls have been identified with these methods (Bayliss and Reed, 2001) in that where only one or two large events higher than any in observed records events are identified, they may skew the upper end of the flood frequency curve for that site. A useful source of information in the UK for such studies is the British Hydrological Society's *Chronology of British Hydrological Events* (Law *et al*., 1998), while in Ireland, The OPW's floodmaps.ie website is the equivalent repository for such information. It details confirmed reports of flooding across Ireland and uses a geospatial search tool to locate the area of interest. It contains details of flood events in Ireland dating back to the great flood of 1763 that devastated Kilkenny City. The Irish Newspapers Archive website is also a useful tool for searching for evidence of past flood events in regional and national newspapers in order to describe and assign severity measures to same. Other local studies by Historical Societies may be also used to extract information about past flood events, and in the example of the Munster Blackwater catchment, the Mallow Field Club Journal (Sullivan, 1988) is one such source.

2.10.2 Use of historical flood reports for validating the results of rainfall runoff models

This project will use documentary reports of historic flood events found from historical documents to validate the results of the rainfall runoff models for the period from 1926-1955 when no continuous gauged flow data existed. Historical reports generally contain useful information on the severity of each event from the point of view of extent, depth, damage caused and loss of life. The most comprehensive treatise on the use of documented flood events to analyse historical series is given in Sturm *et al*. (2001) and Glaser & Hangl (2010). They present a means of classifying flood events based on their description in historical reports. This information can then be used to assign an intensity (severity) to each event. There are few references in the literature to the use of historical reports of flooding in the validation of rainfall runoff models, however it is proposed that the approach proposed by Sturm *et al.* be used to assign severity ratings to documented flood events for the Munster Blackwater. The approach used by Sturm *et al.* was developed with the intention of applying the method to larger rivers such as the Rhine through Germany however it will need to be slightly modified to reflect the scale of a typical Irish catchment.

2.11 Flood Frequency Analysis

2.11.1 The issue of non- stationarity in flood frequency analysis

An underlying assumption of traditional flood frequency analysis is that climate, and hence the frequency of flood events, is stationary, or unchanging over time. Stationarity simply assumes that statistical properties will be the same in the future as they have been in the past. Anthropogenic climate change and better understanding of decadal and multi-decadal climate variability (e.g. The North Atlantic Oscillation) present a challenge to the validity of this assumption (Kiang, 2010). The stationarity assumption in flood frequency analysis has survived mainly due to the existence of short historical records that limit a formal analysis of non-stationarities, the lack of a formal framework for analysing non-stationary flood processes, and institutional adherence to engineering practice guidelines (CGER, 1999). Flood frequency analysis for non-stationary processes has become highly relevant in the light of recent findings on climate change, as it is expected that most parts of Europe will experience more frequent and more severe floods in the future. The issue of no available guidance on flood frequency analysis for non-stationary flood data has prompted the initiation of an EU COST Action entitled “FloodFreq – European procedures for flood frequency estimation”.

A key-component of FloodFreq is to develop a scientific framework for assessing the impact of environmental change on flood frequency characteristics. The framework will be based on analysis of trends in historic data, combined with projections of future climate conditions from Global and Regional Climate Models (GCM/RCM) and analysis of historical developments of human induced changes in hydrological and hydraulic conditions. Process based modelling is being used to analyse human induced changes and isolate climatological changes in flood frequency characteristics. Powerful statistical tools are also being used to detect changes or trends in extreme flood characteristics and to model time dependent statistical properties (COST, 2009).

It is expected that flood frequency analysis based on different record lengths of the reconstructed flows will expose the trends in catchment flood behaviour by identifying marked changes to the catchment flood growth curve. Although this method of identifying trends in the flood behaviour of the catchment is not as powerful as statistical tests for trend, it does, nevertheless show graphically the effects of using flood rich and flood poor periods for such an analysis.

2.12 Summary of Best Practice for Reconstructing River Flows and Detection of Trends in Flood Data Identified in the Literature Review

In the past decade, different methods of performing trend analysis on river flows have been put forward. Best practice guidelines are put forward as part of the overall World Climate Programme document *Detecting trends and other changes in hydrological data* (Kundzewicz and Robson ed., 2000).

For this study, guidance on how to select the most suitable study catchment was drawn from the recommendations of Pilon (2000). The selection of suitable catchments should focus on undisturbed sites that are as free as possible from man-made effects and have long periods of record. In the absence of long periods of record, it may be possible to conceptually reconstruct natural flows.

Kundzewicz and Robson (2000) stress the importance of quality controlling any data that is to be used in the testing from the point of view of checking for instrumentation errors and alterations to rating equations at gauged sites. The form and frequency of the data to be examined is also crucial in the testing. For floods, annual maximum series or peaks over threshold series may be examined, whereas in the case of droughts it may be the duration of low flows. The frequency of the quantities to be examined will also have a bearing on the computational demands that must be satisfied.

Before performing formal tests for trend on the extended flood series, Exploratory Data Analysis (EDA) will be carried out in order to understand the processes at work and visually assess the data (Grubb and Robson, 2000) to look for obvious trends or sudden changes in the distribution of the data. When drawing the final conclusions, the results of the EDA will be used to enhance the results obtained from the formal testing for trend.

The formal tests for trend will include a selection of the methods put forward by Robson *et al*. (2000), and will include tests for gradual trend and step changes. The occurrence of serial persistence in gradual trend will be in keeping with the method used by Wilby (2006).

2.13 Conclusions

From the review of the relevant literature on climate change and its perceived effects on river flows, a clear understanding of the factors that may change flood behaviour can be gained. Once the underlying reasons for these changes in river flows are appreciated, it is used as a knowledge base for choosing a test catchment, the models and the types of input data that can be applied in modelling process. Other recent studies on the reconstruction of historic floods were used to guide the formation of the modelling strategy, and the chosen approach is to reconstruct time series of flow using lumped conceptual rainfall runoff models that use quality controlled observed rainfall and temperature data as their raw inputs. The HYSIM model was chosen as the most suitable model for detailed analysis and will be used for uncertainty analysis in conjunction with the GLUE method. The results from the IHACRES model will be used to corroborate the results of the HYSIM model and to refer to documented historical flood events that will be used to verify the flow series reconstructed by the models. In turn the reconstructed data is to be used to test for changes and trends in river flows in the Kilavullen catchment since 1926.

3 DESCRIPTION OF CATCHMENT AND DATA COLLECTION

3.1 Introduction

This chapter describes the features of the catchment that was chosen for examination in this project, the Munster Blackwater catchment to Kilavullen. It involves a full description of the catchment characteristics that affect river flows in order to gain an understanding of the processes at work in the catchment. The latter part of the chapter is concerned with the collection of the raw data for the project that will be quality controlled in later stages of the project.

3.2 Choice of Study Catchment

In order to examine the possible effects of climate change on catchment response, it was necessary to choose a catchment that had experienced the minimal amount of physical change over the study period. The Munster Blackwater is considered to be one such catchment. For this project, the western portion of the Munster Blackwater catchment down to the Kilavullen gauge was chosen as the case study catchment. This catchment was chosen for the following reasons:

(a) There is a relatively long record of continuous flow gaugings available at Kilavullen since 1955;

(b) The gauge at Kilavullen has a high quality rating curve classification (HydroLogic, 2005);

(c) There is a well-documented history of flooding within the catchment, especially at Mallow and Fermoy;

(d) It is quite a large catchment (approx. 1,256 km^2), and is therefore a representative part of the whole Blackwater catchment;

(e) The slope of the catchment is gradual in nature (i.e. not flashy)

(f) The catchment has not been the subject of any arterial drainage schemes;

(g) There are no widespread unique geological features such as karst or raised bogs;

(h) There are no major floodplains that would affect flows (i.e. attenuation).

(i) There has been very little increase in the urban area within the Kilavullen catchment over the last 150 years;

The following sections provide a description of the Kilavullen catchment, as well as providing the rationale behind the choice of input parameters for hydrological models.

3.3 Catchment Location

The portion of the Munster Blackwater Catchment down to Kilavullen is situated in the south west of the country and is contained almost wholly within County Cork (see Figure 3.1). The Munster Blackwater rises in County Kerry in the Mullaghareirk Mountains and flows in a southerly direction through Ballydesmond, and then turns eastwards at Rathmore before passing through the urban centres of Mallow, Fermoy and Lismore and eventually enters the sea at Youghal.

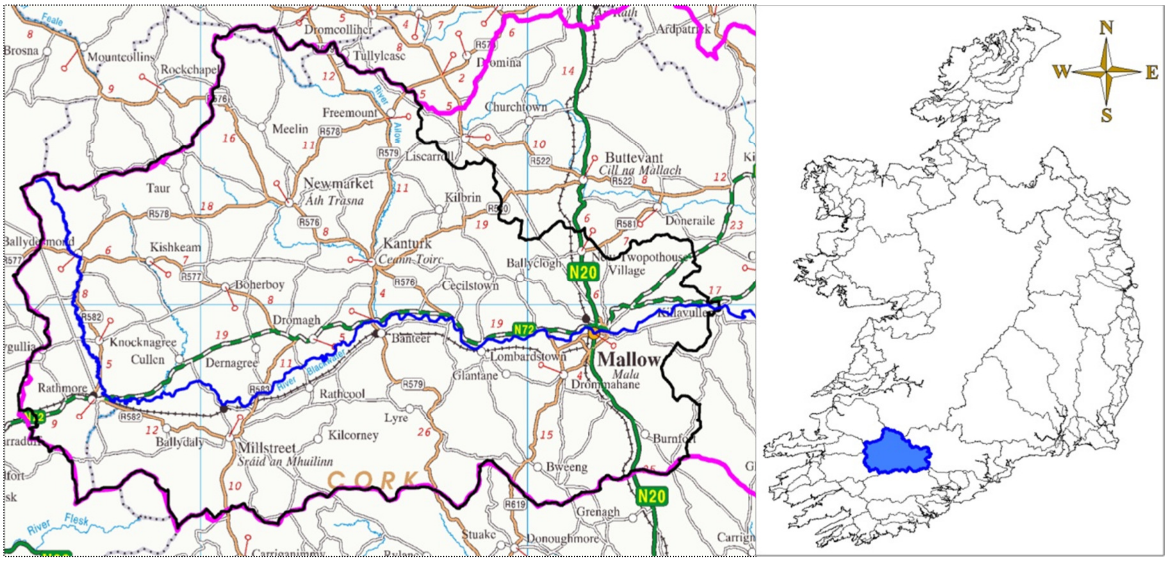


Figure 3.1 Location of the Kilavullen Catchment (showing the Mainstream of the Munster Blackwater)

3.4 Topography and river network in the Kilavullen catchment.

Effectively, the Blackwater can be considered as a river flowing from west to east with a series of sub catchments flowing into it from both the north and south. The tributaries within the Kilavullen catchment are shown in Figure 3.2. The main tributaries of the portion of the Blackwater Catchment to Kilavullen are the Owentaraglin which is close to Millstreet, the Finnow, The Allow, the Awbeg (lesser), the Glen, and the Clyda.

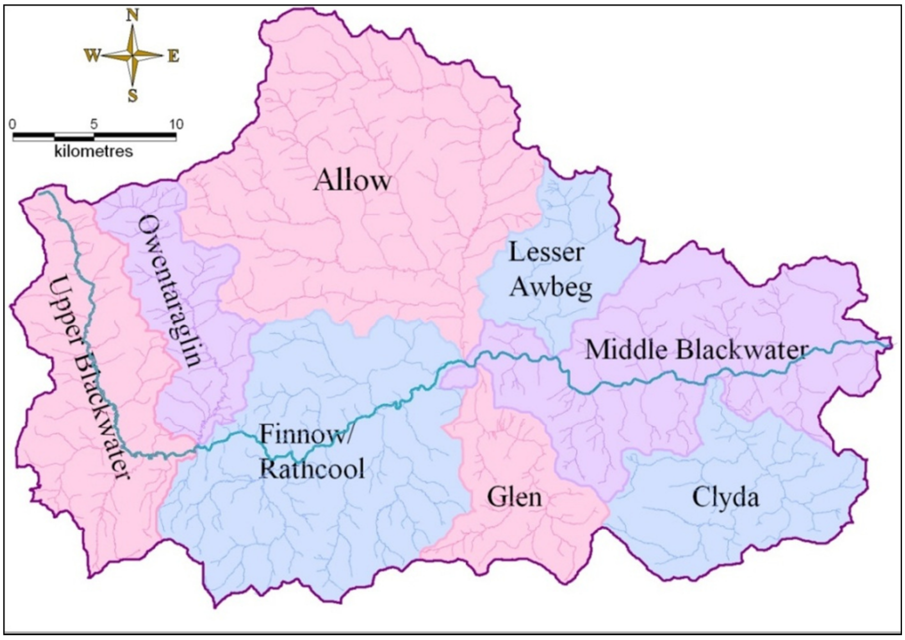


Figure 3.2 Tributaries of the Munster Blackwater to Kilavullen (main channel in blue)

At its source near Ballydesmond, the elevation of the Blackwater is 674m above sea level, and its main stream length down to Kilavullen is 90 kilometres, providing a catchment area to this point of 1,256 km^2. The Blackwater valley is broad and relatively flat and is surrounded by mountains. To the north there are the ranges of Knockmealdown, Kilworth, Galtee, Ballyhoura and Mullaghareirk and to the south is the Boggeragh range, as can be seen in Figure 3.3

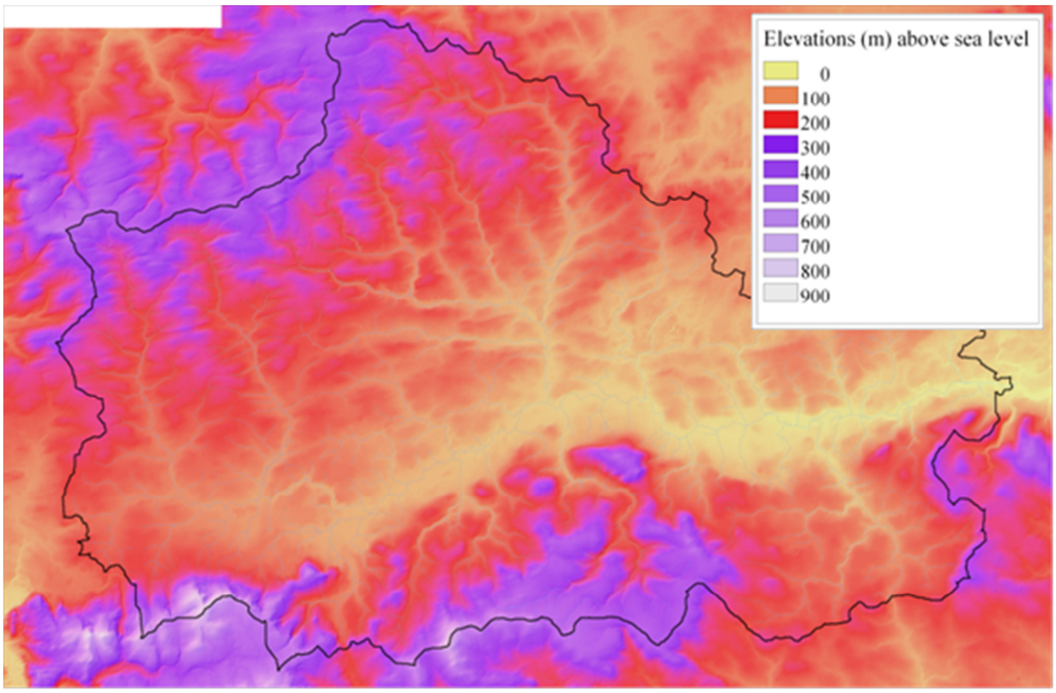


Figure 3.3 The Digital Terrain Model (DTM) of the Kilavullen Catchment (source Ordnance Survey of Ireland)

The catchment is almost entirely rural, dominated by pasture and grazing with lesser extents of cultivated land and some forest cover principally in the west. No significant urban areas exist that are likely to affect the flood flow characteristics of the river. For such a large catchment it is also important to note a complete lack of large and medium sized water bodies (lakes or reservoirs) that can have an influence on flood flows.

The climate is dominated by the prevailing south westerly air flow. This generally leads to moist mild conditions with most of the precipitation falling as rain during the winter period. Significant snowfalls are rare and are not in general linked to the floods on the Blackwater. The last major flood in Ireland with a significant snowmelt component occurred in March 1947.

3.5 Soil and Subsoil Description

The Northern and Southern parts of the catchment are characterised by different soil types. This difference in soil types is defined by the course of the Blackwater river. North of the Blackwater river the catchment the soils are dominated by the low permeability soils, the southern half of the catchment, by contrast has large areas of soils of high permeability

As can be seen from Figure 3.4, the amount of different soil types in the in the Kilavullen catchment are quite few. There is a north/south divide between the two main soil types. Immediately north of the Blackwater main stream the soil types are predominantly poorly drained mineral soils (shown in blue), with small pockets of peat fractions at the far west of the catchment (shown in yellow/orange). To the south of the Blackwater the soil type is predominantly shallow well drained mineral soils (shown in green). The areas covered by mineral alluvium (shown in red) give a good indication of the location of historical floodplains.

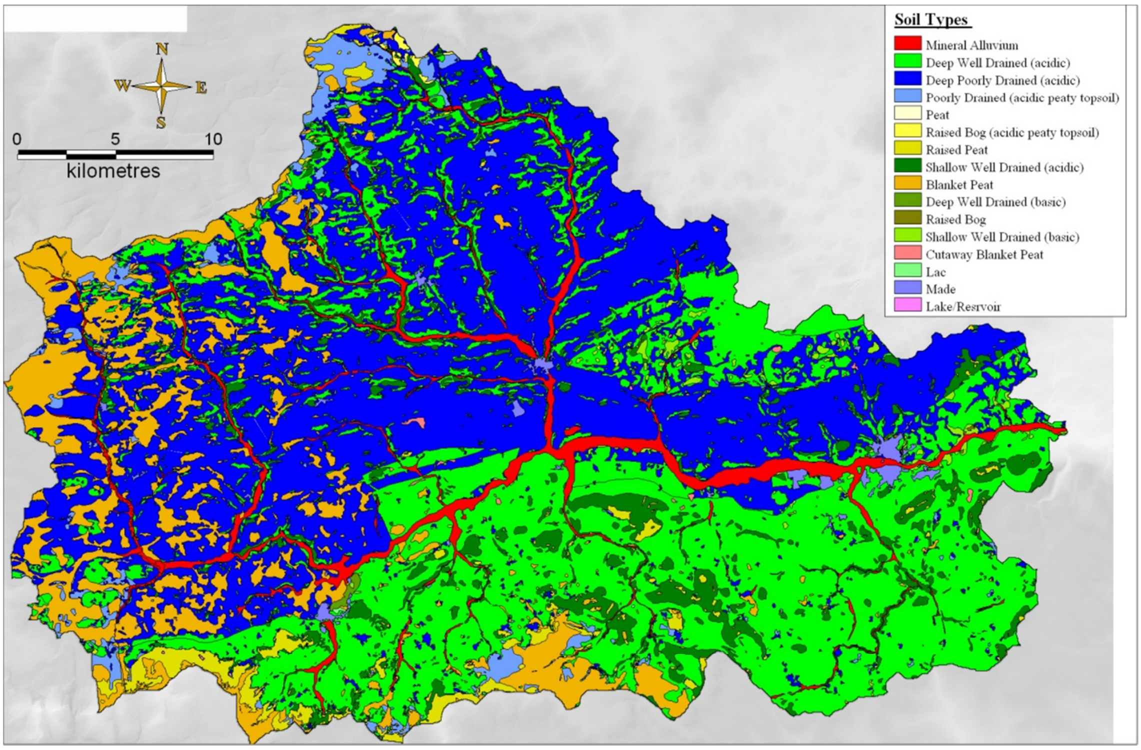


Figure 3.4 Soil types within the Kilavullen Catchment (Source: EPA, 2005)

The sub-soils towards the west of the catchment are predominantly a mixture of shales and sandstone till. There is a clear division between the subsoils north and south of the Blackwater valley. To the North the dominant subsoil type is Namurian Till, while on the southern side, the dominant soil type is Till derived from Devonian Sandstone (see figure 3.5).

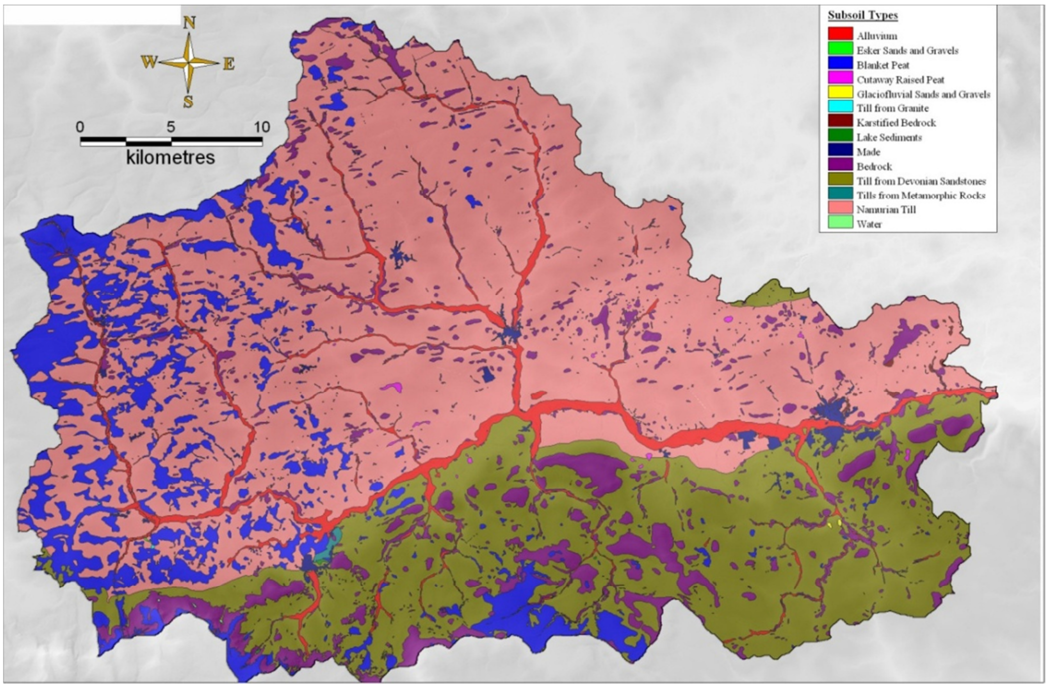


Figure 3.5 Subsoil types within the Kilavullen Catchment (Source, EPA, 2005)

Some blanket peat covers the high areas to the west and south of the catchment.
Rocks close to the surface are often associated with shallow well drained areas, and so the general runoff of the catchment is quite uniform. There are two main rock types in the Munster Blackwater catchment again divided by the Blackwater valley. Devonian Sandstone is the principal rock type to the South and Dinantian Limestone is the dominant rock type north of the river (Geological Survey of Ireland, 2004)

3.6 Land Use within the Catchment

Land use information and spatial distribution is available through the CORINE (Co-Ordination of Information on the Environment) Land Cover database elaborated by the EPA. The survey covers the whole catchment and classifies the different land uses that are present using three different levels. Figure 3.6 shows the different land uses, according to level 3 of the CORINE nomenclature.

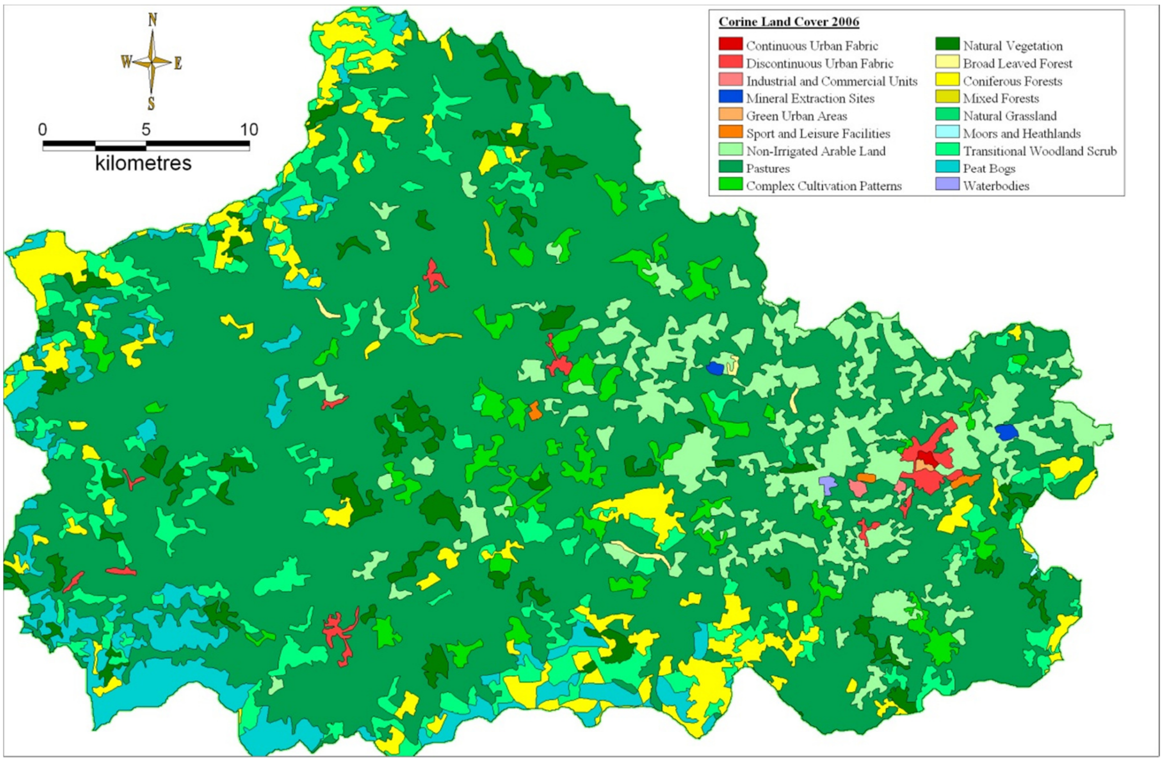


Figure 3.6 Corine Landcover Classifications (level 3), 2000

In short the vast majority of landcover is from pastures and arable land shown in varying shades of green). The forest cover within the catchment is shown in varying shades of yellows, while the urban areas are shown in different shades of red.

Agriculture is dominant with more than 80% of the land surface being used as pastures or arable lands (shown in varying shades of green). Forest and semi-natural areas come second with a much lower proportion, in the order of about 12% (shown in varying shades of yellow). Peat bog covers approximately 6% of the catchment (shown in light blue) while the urban area stands at only 0.74% (in varying shades of red). The artificial surface over the catchment represents a very small amount of the total area, which mainly reflects the low urbanisation level of the catchment. The main urban centres within the Kilavullen catchment that have been affected by flooding from the Blackwater in the past are Kanturk, Millstreet, and Mallow, with Mallow being the most regularly affected. Fermoy is also regularly affected by flooding, and although it is outside the study area information on flooding from there can be used to reinforce the findings of this study.

3.7 Climate

Precipitation over the catchment is the most important climatic factor for hydrological response. Precipitation can be considered as being the rainfall only considering the really low occurrence of snow and hail. The catchment has a standard period annual average rainfall (SAAR) of 1298mm and a standard period annual average potential evapotranspiration (SAAPE) of 508mm. The rainfall occurs during the whole year with larger amounts from October to March. Evapotranspiration losses are considered significant only during the summer months (May to September). Precipitation amounts are higher on the western edge of the catchment and around the highest hills and peaks. The rainfall regime is characterised by long duration events of low hourly intensity. Short duration events of high intensity are more seldom and mostly occur in summer. A more precise study of the catchment rainfall is reported Chapter 4.

Considering the catchment latitude, the daily air temperatures over the course of the year have a small range of variation, mainly because of the influence of the North Atlantic Drift. Temperatures go from a maximum of ~20ºC to a minimum of ~0ºC, with an average of 15ºC in summer and 5ºC in winter (Jaksic, 2004). The prevailing wind direction is from the southwest

3.8 Description of the Kilavullen Gauge

The gauge at Kilavullen was opened in 1940 by the installation of a staff gauge upstream of the bridge (see Figures 3.7 and 3.8). Records at the site were taken on a daily basis at 09:00am up to 1955. In October 1955 an automatic recorder was installed, and from this date onwards, continuous flow measurements are available.

It is an open channel gauging station with a channel control at low levels and a channel and bridge control at higher levels. At high flows, the arches of the bridge exert an increasing effect upon in-channel flows as the water level approaches their soffits. The station is known to be bypassed on the left bank during the largest events, with water extending as far as 200m from the river, and bypassing flows in some locations with sufficient energy to cause severe damage to the approach road to the bridge.

Figure 3.7 Bridge at Kilavullen Looking downstream (showing staff gauge location on left). Photo is taken from the upstream side of the bridge

Figure 3.8 View of the Blackwater taken from Kilavullen bridge looking downstream. Note the wide floodplain on the left bank.

The highest flow recorded by current meter gaugings is about 250 m^3/s (approximately bankfull). However much of the annual maximum series have peak levels higher than this, and the maximum on record (2^{nd} November 1980) reached a level approximately 2m higher than this bankfull level. The OPW have estimated the peak of the November 1980 event as being 502.74 m^3/s.

3.9 Summary of Catchment Descriptors

Table 3.1 gives a summary of the catchment descriptors for the Kilavullen catchment. The table is taken from the Flood Studies Update (OPW, 2004) list of catchment descriptors for gauged sites. These catchment descriptors are used to assist in the formulation of parameters for the rainfall runoff modelling stage of this research. They are also used to give a first impression of the hydrological behaviour of the catchment. For instance the ARTDRAIN descriptors indicate if the catchment has been the subject of arterial drainage, and the FARL index indicates the presence of large lakes or reservoirs in the catchment.

Descriptor	Value	Descriptor	Value
Station Number	18003	Annual Average Rainfall - SAAR (mm)	1298.98
Location	Kilavullen	Urban Areas (%)	0.74
Waterbody	Munster Blackwater	Forest cover (%)	12.17
Catchment	Blackwater (Munster)	Peat Land Cover (%)	6.24
Gauging Authority	OPW	Pasture Land Cover (%)	80.34
Arterial Drainage	No	Alluvial Soils (%)	4.13
Hydrometric Area	18	FLATWET (index)	0.63
Gauge Easting (m)	164770	Annual Average Potential Evapotranspiration SAAPE - (mm)	508.73
Gauge Northing (m)	99775	BFIsoil (index)	0.461
Catchment Area (km^2)	1256	QMED gauged (m^3/s)	285.11
Mainstream Length (km)	89.989	Maximum Annual Flow - MAF (m^3/s)	525
Network Length (km)	1274.759	Highest Gauged Flow - HGF (m^3/s)	249
STMFRQ (no. of junctions)	1168	HGF/Qmed	0.873347129
DRAIN Density (km/km^2)	1.014	Bankfull Level (m)	~4.8m (staff gauge)
S1085 (m/km)	1.65818	Start of record	1955
FARL (index)	0.999	End of record	(ongoing)
Catchment Centroid Easting (m)	137680	Gap (years)	0
Catchment Centroid Northing (m)	102000		

Table 3.1 Kilavullen Catchment Descriptors

3.10 Data Collection for use in Hydrological Models

This project utilises the IHACRES and HYSIM lumped hydrological models to hindcast river flows in the Kilavullen catchment, and as such requires hydrological and meteorological data to construct that model. The sections that follow describe the process of hydrometeorological data collection from varied sources.

3.11 Collection of Rainfall Data

This research examined as many possible sources of rainfall data as possible in order to build up the most complete dataset of daily areal rainfall possible. At the outset of this study it was decided that the search for rainfall data should focus both on all locations inside the Kilavullen catchment, and those within a 15km zone external to the catchment. Obviously rain gauges within the catchment are the first choice for use in modelling, but those outside of the catchment serve many useful purposes such as gap filling of data and in cases where data availability is limited they may sometimes become the pivotal sites for use in the calculation of areal rainfall. Poor data will inevitably lead to poor model results, and a full understanding of the data and its associated errors is essential to ensure the best possible model. The rainfall data pertaining to the Kilavullen catchment for this study was obtained from different sources and varies in terms of quality and coverage over time. There are three periods of rainfall records in Ireland, and they broadly defined by who performed the observations.

(a) Pre 1920 – Private gauge network records;

(b) 1920-1940 – Irish Rainfall Association (I.R.A.) and Met Éireann paper records;

(c) 1941-2009 – Met Éireann digital records

In the 19th Century apart from the existing climatological stations, rainfall records in Ireland were mainly collected by voluntary private individuals who had a scientific interest meteorology (Dixon, 1987). The earliest relevant rainfall records for the study area date from as early as 1889 at St. Finans Hospital Killarney and 1893 at Summerhill, Mallow as well as Springmount, Abbeyfeale (opened 1917). Apart from a few intermittent periods, the early part of the record at all these stations has been lost over the years. The earliest consecutive run of data found was for the gauge at Summerhill, Mallow. From 1899 to 1920 there is a continuous record of monthly rainfalls available at this location. These records were submitted by Mr. J.F. Williamson to the Irish Times newspaper and were published on the first week of each month. At this time there was no coordinating body for the coordination of these private gauging networks, and publication of rainfall records in national newspapers was the recognised method of reporting rainfall measurements.

To address the absence of a coordinating body, the Munster and Connaught Rainfall Association was founded in 1918 by E.W. Montagu Murphy in Cashel Co. Tipperary. It was founded to encourage meteorological observation in Ireland, and to assist the British Rainfall Organisation, without competing with it. At first its activities were confined to Munster, but they were extended in 1920 to include all Ireland, North and South and hence it change to “The Irish Rainfall Association (IRA)” to reflect its new brief as an all-Ireland organisation (Murphy, 1926). The main areas of activity were to be the collection of new and old rainfall records and publication of Annual Reports as well as education of the general public on meteorology through lectures and research work in all areas of meteorology, but especially in the field of rainfall. From 1920 to 1937, rainfall records in Ireland were coordinated and collected by the IRA in parallel with the British Meteorological Office network. Shortly after the establishment of the Irish Meteorological Service (now Met Éireann) in 1936 the records of the Irish Rainfall Association passed over to Met Éireann as did the task of collecting records from those gauging stations. The rainfall records of the IRA are currently in held in chart and book form at the Met Éireann library in Glasnevin, Dublin.

For the period from 1937 until the current day, the vast majority of rainfall records in Ireland have been processed by Met Éireann. These records are available in digital form from 1941 onwards.

3.11.1 Monthly Rainfall Data from 1899-1920 at Mallow – From Newspaper Records

The earliest records in the vicinity of the Kilavullen Catchment were collected at Summerhill, Mallow. This data was sourced from early editions of the Irish Times. Correspondence from all the observers around the country was published on a monthly basis in the paper, and so a database of monthly rainfall amounts could be compiled on the basis of these reports. This has a particular relevance where records have been lost over the years. These newspaper records can be used to fill gaps in other records and where reports are readily available could replace formally recorded measurements.

Figure 3.9 shows an example of the yearly summary of monthly rainfalls for 1912 at Summerhill, Mallow, published in the Irish Times of 2nd January 1913. Publication of the yearly summaries in the Irish Times in early January of each year was common practice at in the early part of the 20th Century. This rainfall data can be used as a rough indicator of the rainfall in the catchment. Extreme daily rainfall totals that are linked to large flood events have also been noted in some of these reports in a remarks section beneath the table of rainfalls.

SUMMER HILL, MALLOW, CO. CORK.

Diameter of funnel, 5 in.. Height of Top—Above ground, 1 ft. 10 in.; above sea level, 261 ft.

Month.	Total Depth. Inches.	Number of days with .01 or more recorded
January	4.29	20
February	5.53	23
March	4.21	30
April	1.29	8
May	1.45	15
June	5.33	26
July	4.84	13
August	3.42	27
September	.98	11
October	3.00	20
November	2.33	17
December	5.47	31
Total	42.14	241

REMARKS.

1912 has been a year of very constant rainfall (though no very heavy individual falls occurred, an inch being only once exceeded), several long periods of consecutive daily rain being experienced, viz.:—25 days in March, 21 days in August, and the whole of the 31 days of December, and including the latter part of November there was only one day without rain during the last 40 days of the year. The total rainfall amounted to 42.14 inches, being 2.93 inches over the average (39.21 inches) for the past 23 years. The number of days on which measurable rain fell in 1912 constituted an easy record here, being 241, the average being 206. With the year 1909 there ended a cycle of six consecutive "dry" years of less than average rainfall, while the last three have all been over average, from which it would appear that we have now entered upon an alternative cycle of "wet" years.

J. F. WILLIAMSON.

Summer Hill, Mallow, 1st January, 1913.

Figure 3.9 Monthly Rainfall Totals at Summerhill, Mallow. (Irish Times January 2nd 1913)

Based on other historical reports the flood event of 17th November 1916 has been identified as one of the largest flood events of the last one hundred years. From historic newspaper reports we can ascertain information about the antecedent conditions in the catchment and the daily rainfall total for the day before the flood event. Newspaper reports in the days after the flood event contain valuable information that could be used as input to rainfall runoff models to allow estimates of the flood flows for this event.

Period	Rainfall (mm)
October 1916	180.09
November 1916	249.43
01/11/1916 – 18/11/1916	202.44
16/11/1916	80.01
20/11/1916	93.22

This information can be used to infer a short daily rainfall series for use in a hydrological model, the flows from which can be used in an extreme value analysis.

Figure 3.10 shows the Annual Rainfall totals for the Summerhill Gauge in the two decades up to 1920.

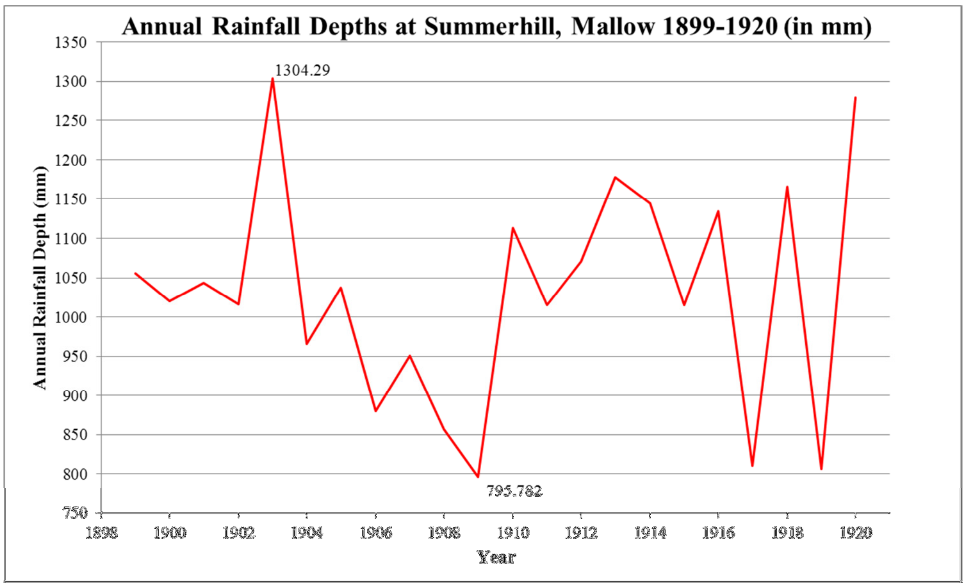


Figure 3.10 Annual Rainfall Depths at Summerhill, Mallow (1899-1920).

3.11.2 Rainfall Data from 1926-1940 – From Irish Rainfall Association and Met Éireann Paper Charts

For the pre-1920 period, before the formation of the IRA, there were a number of gauges in operation in or near the catchment. However, many of these gauges only had a short lifespan of 3-4 years, and were not maintained.

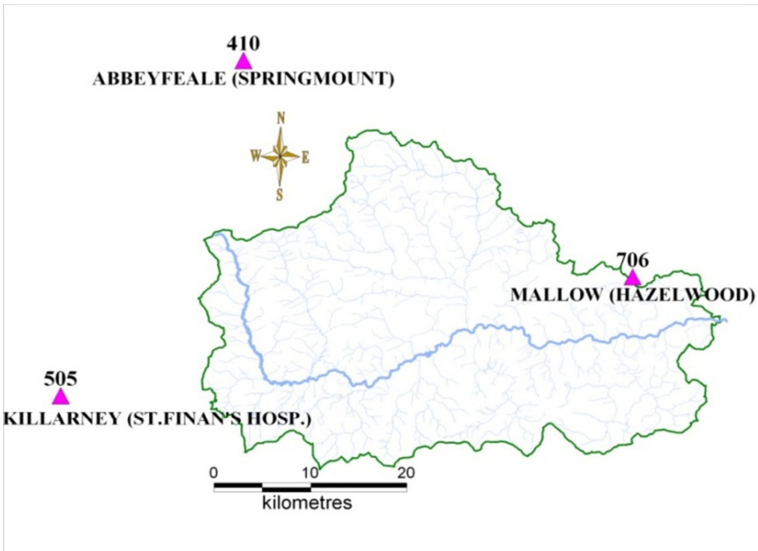
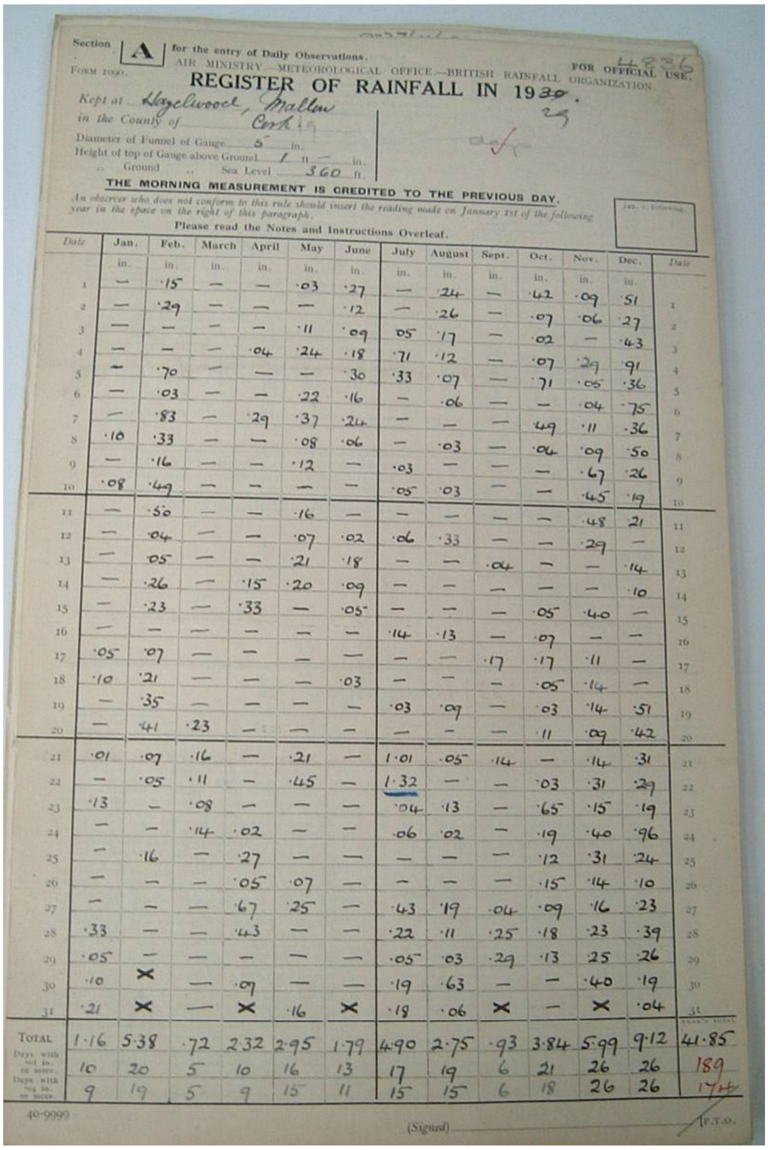


Figure 3.11 Locations of rain gauges in operation from 1926-1940 and used for modelling

The only three gauges in operation in the study area that have an appreciable record length are at St. Finans Hospital Killarney (opened 1889), Springmount, Abbeyfeale (opened 1917) and Hazelwood, Mallow (opened 1925), and their locations can be seen in Figure 3.11. The common period to all three begins on 1st January 1926, and ends on 31st December 1974. These are the three gauging stations that are used in the hydrological model of the catchment to cover the years from 1926 – 1940. At present, even though extensive rainfall records prior to 1940 are in the possession of Met Éireann, they have not yet been digitised. It was therefore necessary to visit the Met Éireann library at Glasnevin to manually digitise the rainfall records for these stations from paper charts. It involved digitising of over 15,000 days of rainfalls in total. An example of one of these paper charts is shown in Figure 3.12.


Section A for the entry of Daily Observations.
FORM 1090.
AIR MINISTRY.—METEOROLOGICAL OFFICE.—BRITISH RAINFALL ORGANIZATION.
FOR OFFICIAL USE. 4836
REGISTER OF RAINFALL IN 1930. 29
Kept at Hazelwood, Mallow
in the County of Cork
Diameter of Funnel of Gauge 5 in.
Height of top of Gauge above Ground 1 ft — in.
" Ground " Sea Level 360 ft.
THE MORNING MEASUREMENT IS CREDITED TO THE PREVIOUS DAY.
An observer who does not conform to this rule should insert the reading made on January 1st of the following year in the space on the right of this paragraph.
Please read the Notes and Instructions Overleaf.

Date	Jan. in.	Feb. in.	March in.	April in.	May in.	June in.	July in.	August in.	Sept. in.	Oct. in.	Nov. in.	Dec. in.	Year's Total
1	—	·15	—	—	·03	·27	—	·24	—	·42	·09	·51	
2	—	·29	—	—	—	·12	—	·26	—	·07	·06	·27	
3	—	—	—	—	·11	·09	·05	·17	—	·02	—	·43	
4	—	—	—	·04	·24	·18	·71	·12	—	·07	·29	·91	
5	—	·70	—	—	—	·30	·33	·07	—	·71	·05	·36	
6	—	·03	—	—	·22	·16	—	·06	—	—	·04	·75	
7	—	·83	—	·29	·37	·24	—	—	—	·49	·11	·36	
8	·10	·33	—	—	·08	·06	—	·03	—	·04	·09	·50	
9	—	·16	—	—	·12	—	·03	—	—	—	·67	·26	
10	·08	·49	—	—	—	—	·05	·03	—	—	·45	·19	
11	—	·50	—	—	·16	—	—	—	—	—	·48	·21	
12	—	·04	—	—	·07	·02	·06	·33	—	—	·29	—	
13	—	·05	—	—	·21	·18	—	—	·04	—	—	·14	
14	—	·26	—	·15	·20	·09	—	—	—	—	—	·10	
15	—	·23	—	·33	—	·05	—	—	—	·05	·40	—	
16	—	—	—	—	—	—	·14	·13	—	·07	—	—	
17	·05	·07	—	—	—	—	—	—	·17	·17	·11	—	
18	·10	·21	—	—	—	·03	—	—	—	·05	·14	—	
19	—	·35	—	—	—	—	·03	·09	—	·03	·14	·51	
20	—	·41	·23	—	—	—	—	—	—	·11	·09	·42	
21	·01	·07	·16	—	·21	—	1·01	·05	·14	—	·14	·31	
22	—	·05	·11	—	·45	—	1·32	—	—	·03	·31	·29	
23	·13	—	·08	—	—	—	·04	·13	—	·65	·15	·19	
24	—	—	·14	·02	—	—	·06	·02	—	·19	·40	·96	
25	—	·16	—	·27	—	—	—	—	—	·12	·31	·24	
26	—	—	—	·05	·07	—	—	—	—	·15	·14	·10	
27	—	—	—	·67	·25	—	·43	·19	·04	·09	·16	·23	
28	·33	—	—	·43	—	—	·22	·11	·25	·18	·23	·39	
29	·05	—	—	—	—	—	·05	·03	·29	·13	·25	·26	
30	·10	×	—	·09	—	—	·19	·63	—	—	·40	·19	
31	·21	×	—	×	·16	×	·18	·06	×	—	×	·04	
TOTAL	1·16	5·38	·72	2·32	2·95	1·79	4·90	2·75	·93	3·84	5·99	9·12	41·85
Days with ·01 in. or more	10	20	5	10	16	13	17	19	6	21	26	26	189
Days with ·04 in. or more	9	19	5	9	15	11	15	15	6	18	26	26	174

40-9999 (Signed) P.T.O.

Figure 3.12 Daily rainfall chart for 1929 at Hazelwood, Mallow

Quality control of the data was performed in tandem with the digitisation process, and followed much the same approach as was used to quality control the digital records (see Section 4.2)

There are extremely few gaps in the rainfall records at these three stations, and so only a handful of values needed to be filled. Where data was missing for certain days in the record, the average of the rainfall totals for the other two stations for that day was used as a replacement value. This was done more so to ensure a continuous rainfall record for the modelling software. The digitised rainfall data from this exercise has been submitted Met Éireann so that it may be incorporated into their database of digital records.

3.11.3 Digital Met Éireann Rainfall Data

Records of rainfall at Met Éireann gauges for the period from 1941 to the present day are readily available in digital form for the study area. For the purposes of this study, the rainfall from a total of 68 stations was examined (See Figure 3.13). The temporal coverage of the data at these gauges varies, and so not all of these stations were in operation at the same time.

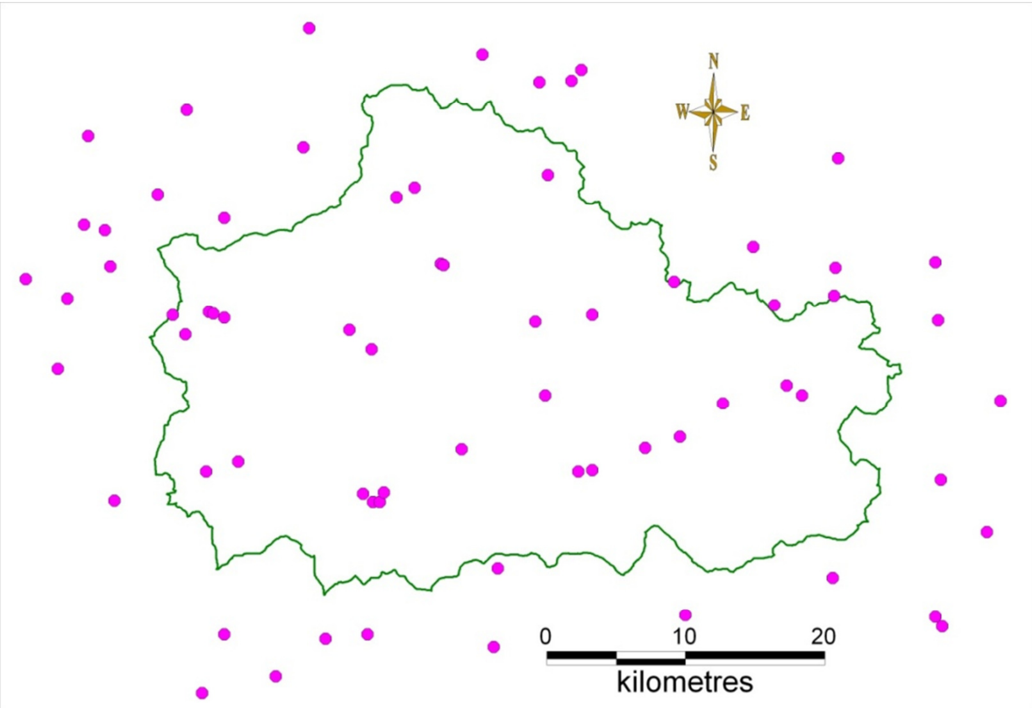


Figure 3.13 Locations of the 68 Daily Rain gauges used in the precipitation analysis from 1941-2009

In order to calculate an areal average daily rainfall within the catchment, an understanding of the variation in rain gauge availability within the catchment is required. This will be of most importance when delineating the Thiessen polygons for the catchment. The data availability of rain gauge records may also affect the performance of the hydrological model, and thus it is possible to directly compare model performance with the data availability in the study area. Figure 3.14 below shows the variation of rain gauge coverage over time.

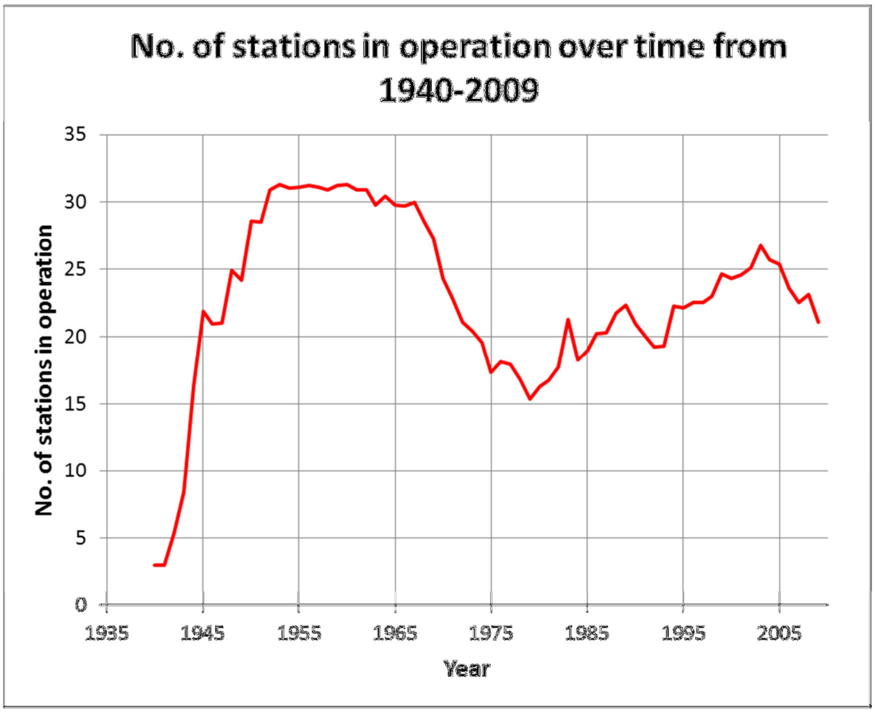


Figure 3.14 No. of digital daily rainfall records available from 1940 – 2009

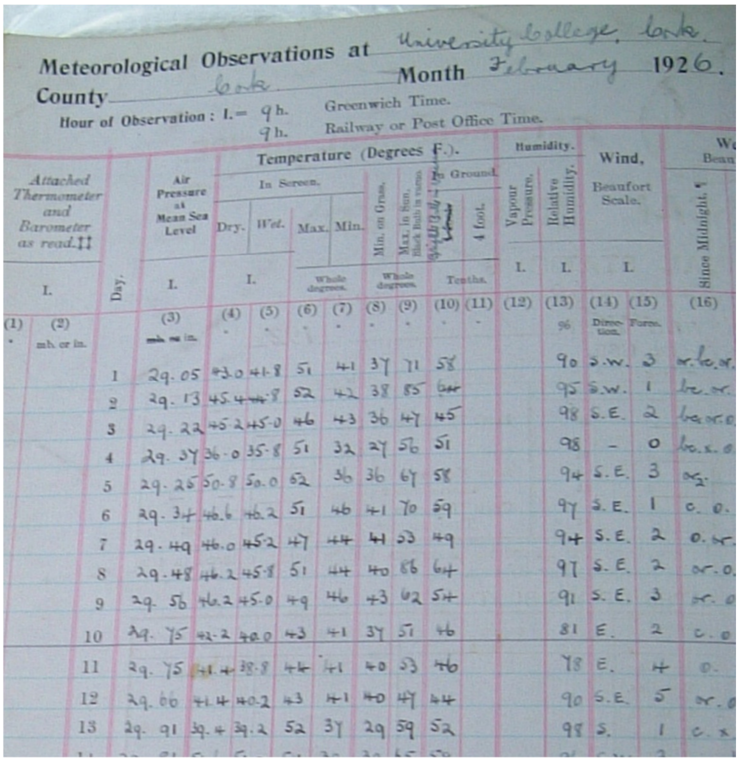
From the 1940's there was a steep increase in the number of stations in operation in the study area. This figure was at an all-time high in 1953, when there were a total of 32 stations in operation. From 1967 to 1979 there was a steady decrease in the number of stations in operation. From the low of 11 stations in 1979 until the current day there has been a steady rise in those available. The digital records at each station were not fully quality controlled and therefore this exercise had to be carried out as part of the current study.

3.12 Collection of Temperature Data

Temperature data was required as an input to the hydrological models. The IHACRES model directly uses temperature data, while for the HYSIM model, temperature was used for the calculation of potential evapotranspiration.

3.12.1 Paper Records of Temperature Data

While rainfall readings were kept at various locations around the country, the coverage of temperature monitoring in the early part of the 20th Century is quite sparse. Operational meteorology is said to have begun in October 1860 with the opening of the Valentia Observatory (Met Éireann, 2007). This was soon followed by the opening of other climatological stations around the country. The climatological station at University College Cork (then Queens College) was opened in 1862. There are no temperature records within the catchment, and seeing as this is the closest temperature monitoring station to the Kilavullen catchment, it is deemed the most relevant station for temperature measurements.



Meteorological Observations at University College, Cork. Month February 1926.
County Cork
Hour of Observation: I.= 9h. Greenwich Time. 9h. Railway or Post Office Time.

Day	(3) Air Pressure at Mean Sea Level	(4) Dry	(5) Wet	(6) Max.	(7) Min.	(8) Min. on Grass	(9) Max. in Sun	(10) In Ground	(13) Relative Humidity %	(14) Wind Direction	(15) Wind Force	(16)
1	29.05	43.0	41.8	51	41	37	71	58	90	S.W.	3	[illegible]
2	29.13	45.4	44.8	52	42	38	85	64	95	S.W.	1	[illegible]
3	29.22	45.2	45.0	46	43	36	47	45	98	S.E.	2	[illegible]
4	29.37	36.0	35.8	51	32	27	56	51	98	-	0	[illegible]
5	29.25	50.8	50.0	52	36	36	67	58	94	S.E.	3	[illegible]
6	29.34	46.6	46.2	51	46	41	70	59	97	S.E.	1	c. o.
7	29.49	46.0	45.2	47	44	41	53	49	94	S.E.	2	[illegible]
8	29.48	46.2	45.8	51	44	40	86	64	97	S.E.	2	[illegible]
9	29.56	46.2	45.0	49	46	43	62	54	91	S.E.	3	[illegible]
10	29.75	42.2	40.0	43	41	37	51	46	81	E.	2	c. o
11	29.75	41.4	38.8	44	41	40	53	46	78	E.	4	o.
12	29.66	41.4	40.2	43	41	40	47	44	90	S.E.	5	[illegible]
13	29.91	39.4	39.2	52	37	29	59	52	98	S.	1	[illegible]

Figure 3.15 Excerpt from UCC Temperature records for February 1926

Digital records in the study area are not available earlier than 1939, and so it was necessary to obtain temperature information from paper charts. These were obtained from the Met Éireann Library in Glasnevin. The daily minimum and daily maximum temperatures from 1926-1940 were manually extracted from the paper charts of the U.C.C. climatological station, and made up 11,000 individual temperature measurements (See Figure 3.15)

.

The record at UCC both in terms of Temperature and Rainfall is impeccable, with only two days of temperature data missing in the period 1926-1940. This can also be said for the rainfall record at the site. After a viewing of the data from the other climatological stations in the country, it would appear that this attention to detail is replicated in them also. Future studies of this nature could benefit greatly from the data at these sites.

3.12.2 Digital Met Éireann Temperature Data

Daily maximum and minimum temperature data is readily available from Met Éireann at each of the current synoptic weather stations in Ireland. The synoptic stations that are in the south west of the country are Valentia, Shannon Airport, and Cork Airport. The temperature data is available at these sites in .csv format as follows:

Synoptic Station	Length of digital record available
Valentia	October 1939 – present
Shannon Airport	September 1945 - present
Cork Airport	January 1962 – present day

3.13 Collection of Potential Evapotranspiration (P.E.) Data

3.13.1 Met Éireann Potential Evapotranspiration records

Daily potential evapotranspiration data is readily available from Met Éireann at each of the current synoptic weather stations in Ireland in .csv format. The potential evapotranspiration is calculated at these sites uses the Penman Monteith equation. This requires four meteorological parameters in order to derive the P.E. They are Relative Humidity, Wind Speed, Temperature, and Radiation. The IHACRES model requires P.E. as one of its input variables. The P.E. data availability at these sites are as follows:

Synoptic Station	Length of digital record available
Valentia	October 1939 – present
Shannon Airport	September 1945 - present
Cork Airport	January 1962 – present

There are no available measurements of P.E. prior to 1939 for the study area.

3.14 Collection of Daily Mean Flow Data

3.14.1 Daily Mean Flow Data from the Office of Public Works and the EPA.

Daily Mean Flow values were obtained at a number of sites along the Munster Blackwater. Daily mean flow values may be downloaded directly from the website of the OPW's hydrometric section in .csv format. It was found that some gaps existed in the flow record at Kilavullen, and so it was decided to obtain flow data from other stations both upstream and downstream of the Kilavullen gauge. The nearest upstream gauge was at Mallow, and the nearest downstream gauge was at Ballyduff. The most suitable station for filling gaps in the flow was the gauge at Mallow. The period of record available at each station was as follows:

Station no.	Station Name	Period of record
18002	Ballyduff	October 1955-present
18003	Kilavullen	October 1955 – present
18006	CSET Mallow	July 1977 - present

The gauges initially examined in the early part of this study are shown in Figure 3.16. Some of these stations were retained for quality checking the flows at the Kilavullen gauge.

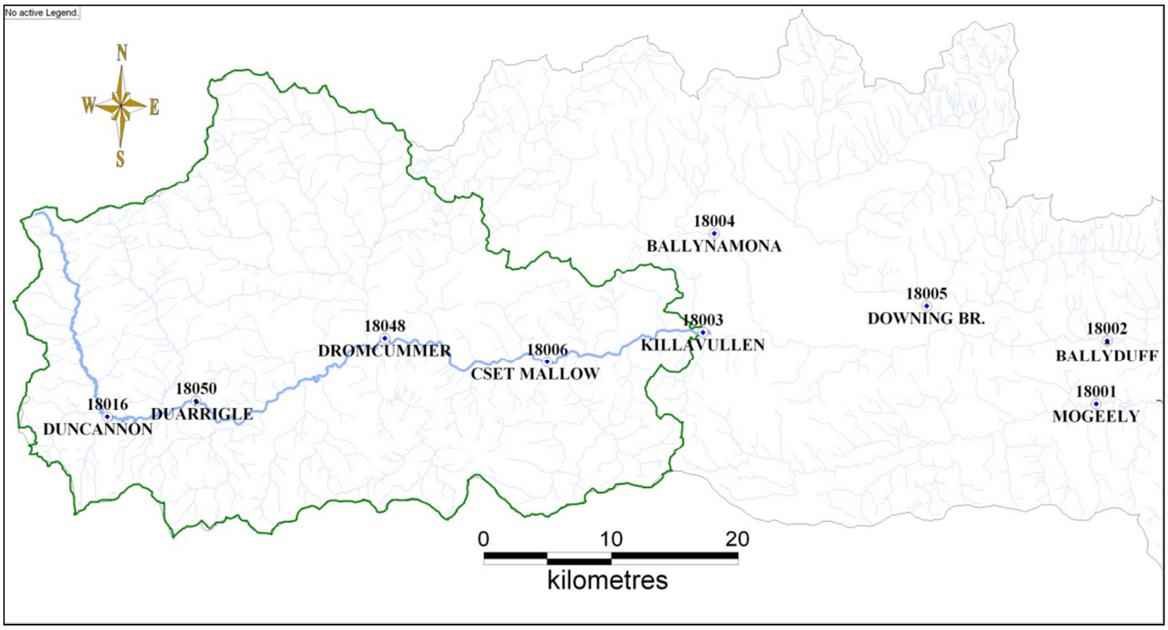


Figure 3.16 Flow gauging stations within the Munster Blackwater catchment possessing high quality ratings (Flood Studies Update, 2005).

3.15 Collection of Historical Flood Data

3.15.1 Newspaper Records

A large part of this study involves hindcasting daily mean flows by using meteorological data. Rather than blindly rely on the results of the model, historical reports of flooding in the catchment were compiled with the aim of identifying dates of major events in the catchment. These reports were also used to assess the magnitude of these floods, the time of the peak, time of rise of the flood, flood duration, economic damages and fatalities.

The *Irish Newspapers Archive website* (www.irishnewsarchive.com/) was the first explored source of information. The archives are searchable by keyword, newspaper title, and date. Reports on this website of historical flood events in the Munster Blackwater catchment were found from the following Newspapers:

- The Freemans Journal (1763-1924);
- The Anglo Celt (1846-present);
- The Irish Independent (1905-present);
- The Sunday Independent (1906-present);
- The Munster Express (1908-present);
- The Kerryman (1950-present);
- The Southern Star (1892-present);
- The Irish Press (1931-1995)

The *Historical Irish Times* archive is also available online at www.search.proquest.com. This Historical Irish Times archive was a valuable source of not only flood information, but rainfall information as well.

The archives of the *Cork Examiner* (later *"The Examiner"*) have not yet been made available online. Historical editions of the Cork Examiner were viewed at the Cork County Library. These were mostly on microfiche and references to flood events from other sources were used as a means of focusing the search on specific flood reports. A further local newspaper, *The Evening Echo* was also viewed at the Cork County Library.

Perhaps the most notable record since 1926 is that of the Flood of 10^{th} November 1941. The progression of the flood over a number of days can be traced through the following newspaper reports from that time.

Source:- Evening Echo, November 10th, 1941

Extensive Damage by Floods

Mallow town under several feet, rivers sweep away livestock, many roads impassable, Skibbereen area inundated with flood water & high tide (highest in 20 years), especially Townsend St. Caravan residents, Carrigrohane road, rescued.

The Flood Damage

Sheep rescued, UCC grounds, 6' at Mardyke, roads impassable, Mallow at Bridge St. & Spa Walk, Blackwater Inches cattle lost, In Mallow, the flood was as high as goalpost in Town Park, Fermoy: several feet, Skibbereen worst in 20 years, Livestock swept away in raging torrents, around Cork city many roads impassable,

Source:- Cork Examiner, November 11th, 1941

The Floods

In Mallow isolated, Bridge St & Spa road are completely under water & impassable, William's Mills is damaged . Many Macroom roads flooded, Livestock drowned, lost or isolated.

Amazing Scenes

Mallow evacuations, Fermoy flooded to several feet, worst since 1916, Bantry area flooded. Evacuations from Kilocrim & Ennismore, 4 houses destroyed, Brick & Lixnaw valleys a lake, Listowel Island bridge swept away, 6' nearby

Source:- The Irish Times,, November 11th, 1941

Extensive flooding in the south

Worst flooding in 25 years in Cork, 50 years Kerry, evacuations in Bridge St area of Mallow, & 50 people from Kilorcrin/Ennismore. Many cattle sheep drowned on Blackwater. Part bridge washed away in Listowel, county resembles a lake.

Source:- Cork Examiner, November 11th, 1941

Enormous damage done by floods in Munster area

Mallow houses flooded, as bad as 1916, Bandon water came through sewers and flood many streets to 1', highest since Nov 1917. Feale valley a lake, Abbeyfeale area impassable. Macroom worst in 50 years, Fermoy extensive damage.

Source:- Irish Independent, November 12th, 1941

Roofs as a refuge from floods in south

Listowel 50 people evacuated to hospital, 4 houses destroyed, some spent night on top of hay barns, Cork 26 people rescued from caravans, Inagh overflows into Ennistymon & low lying lands

Source:- Cork Examiner, November 14th, 1941

Flood aftermath

Flood has subsided, description of relief work, £2,000 grain damaged. Worst since 12 Nov 1916 which was 2' higher, greatest flood on record was 1853

Source:- Kerryman, November 15th, 1941

Old Mallow floods recalled

Mallow evacuations, livestock swept away, Red Cross relief, £2,000 grain damage, not as bad as Nov 12 1916 & 1853. Fermoy worst since 1916 when 2 soldiers lost their lives. Now flooding of premises, sheep lost Kilmurry, Fermoy floods 3 hours after Mallow.

Flooding in Cork and Limerick

Extensive coverage for Limerick, lands & houses flooded, animals rescued, Deel worst for 30 years. River Blackwater overflowed at mallow causing some flood damage to houses in the town.

From the historical reports we can extract a lot of information about the flood. It was not as bad as 1916, which was 2’ higher, and the Flood of 1853 was the largest on record. There was an estimated £2,000 worth of damage to grain crops.

3.15.2 Floodmaps.ie Database

The OPW flood hazard mapping website, www.floodmaps.ie was also a useful source of flood reports. Reports on this website are subjected to rigorous verification before being placed on this website, and so can be taken as being a reliable source of information.

3.15.3 Daily Read Paper Records from 1940-1955

Flow data at 15 minute intervals are available from the Office of Public Works for the Kilavullen gauge from October 1955 when the gauge was automated. However, this was not the start of records at Kilavullen. A staff gauge was installed upstream of the Bridge at Kilavullen in October 1940. River levels were recorded at 9:00am each morning at the gauge. While these levels are only read at point in time, each day they are a good indication of times when the river would have been in flood, but also indicate the duration of the flood in some instances.

3.15.4 Other Sources of Historical Information

There are numerous sources of information on historic floods in the catchment. The Mallow Field Club Journal (Parts I and II) has been used to identify levels of the largest floods (Sullivan, 1986 and 1988). The flood reports contained in the Mallow Field Club Journal is perhaps the most comprehensive summary of flood reports for the town of Mallow

Level measurements have been taken at Golden's Bar (Sullivan, 1988). These level measurements suggest that the largest event experienced on the Blackwater on record occurred in 1853 with a level of 3.85m and that the 1948 event (1.62m) was greater than that experienced in 1916 (1.54m). The exact level of the 1853 event should be treated with caution due to the age of the source material and changes in the channel and structures over time. There is also very little difference in recorded levels between the 1948 and 1916 events, probably within measurement accuracy achievable at that time. The Mallow Field Club Journal Reports have been used to form a preliminary ranking of flood events for the town of Mallow as can be seen in Table 3.2

Event	Level (mOD Malin)
1853	52.50
1948	50.25
1916	50.15
1980	50.00
1941	49.70
1988	49.50
1986	49.00
1995	49.00
1969	48.90
1996	48.60

Table 3.2: Estimated historic flood levels at Mallow (Mallow Field Club Journal)

3.16 Conclusions

The description of the catchment given in this chapter provides an understanding of the behaviour of the catchment and the factors that may affects flows within the catchment. It is also extremely useful for studying catchment characteristics that will eventually be used in the hydrological modelling of the catchment. A visit to the site of the gauge at Kilavullen proved useful in understanding on-site issues that would affect the measurements of high flows at the site.

The collection of data described in this chapter highlights the varying sources of information available for use in a hydrological study of the catchment. It also was useful in identifying where there were shortfalls in the data. Perhaps the most important outcome of the second part of the chapter is that there is a wealth of information available in historical documents and especially in historical newspaper reports, that up until now have not been used for the purposes of improving flood estimation methods.

4 ANALYSIS OF DATA AND METHODOLOGIES EMPLOYED

4.1 Introduction to Analysis of Data

One of the central requirements for reconstruction of river flows using rainfall runoff modelling, is a quality controlled set of data for use as inputs. The data used here came from varied sources and in some instances data quality was poor, in others augmentation of the data was deemed necessary to render it of use in the modelling stages of this project. The following sections describe the collection of data from various sources and the quality control procedures and adjustments that were applied to that data.

4.2 Analysis of Rainfall Data

In a similar way to the division of the hydrometric network, the meteorological network is divided into catchments. In meteorological terms, the Munster Blackwater comprises Catchment 06 of the meteorological network. Prior to the collection of rainfall data for this project, it was first necessary to define the extent of the study area to be examined. Rain gauges in Ireland are relatively densely distributed for the modern era, however as we progress further back in time, the availability of data at gauging stations inevitably decreases. Single rain gauges are chosen to be representative of the rainfall in an area in their vicinity, however due to the possible area of influence of rain gauges extending outside of their meteorological catchment and contributing to rainfall patterns in others, gauges from within a buffer zone of 15km around the catchment were also selected for use in the analysis. It should be noted that there are no synoptic stations within the Munster Blackwater catchment, nor are there any sub-daily recording stations.

The collection of rainfall data can be loosely divided into two periods, the modern and the historical period. For the purposes of this project, the modern rainfall period is taken as being from 1st January 1941, when the earliest digital Met Éireann records are available, up to the present day. As of the 1st January 1941, digitised records for five gauges in neighbourhood of the Kilavullen catchment were available.

The historic period is defined as the period prior to the 1st January 1941 when no digitised rainfall data is available. Rainfall data from the period 1926-1941 are nevertheless available for the study area from Met Éireann in paper form. In total, data from 68 no. rain gauges were examined, with a temporal coverage from January 1926 to December 2009. Table 9.1 in Appendix A of this report gives full details of the daily rainfall stations that were obtained from Met Éireann for the modern period. The average length of record over the 68 sites was 31.3 years, with the longest available record being 84 years at Summerhill, Mallow. Five stations had to be removed because there was very little or no data available for them, leaving the final number of stations available for analysis at 63. The exercise of collecting and manipulating rainfall data at these 63 stations was conducted with the ultimate aim of producing a continuous time series of daily areal rainfall for the Kilavullen catchment from 01/01/1926 – 31/12/2009, a total of 84 years. This dataset was then to be used as an input to rainfall runoff modelling software.

Not all of the 63 stations in the neighbourhood of the catchment were in operation over the full period of analysis from 1926 to 2009. Over the total period of record the network (arrangement) of stations in the study area changed gradually. Between 1952 and 1960 there were up to 32 gauging stations operating at any one time, however by 1979 this number had declined to 11. Thereafter the number of operational stations in the catchment began to increase. By 2003 there were up to 27 stations in operation in the catchment at any one time. In order to represent the areal rainfall over the study area, as accurately as possible, the analysis takes into account the changing network of gauging stations over time. This was done by examining the period of records at each gauging station, and then identifying the periods where the optimum overlap of records occur. This process resulted in 27 different sub-periods being defined for the period between 1926 and 2009. For each of these sub periods, a different arrangement of the gauging stations was used to calculate the catchment areal rainfall.

The rainfall analysis presented here begins by carrying out extensive quality control of the digital data provided by Met Éireann. The quality control of the rainfall data was concerned with identifying and correcting errors in the data, and then filling gaps in the record where it was reasonable to do so. This is followed by grouping the stations that are available for each sub-period. Once the arrangement of gauging stations for each sub period is finalised the daily catchment areal rainfall is then calculated using the Thiessen method (Thiessen Polygons).

4.2.1 Filling of gaps in rainfall data

It must be strongly noted that the data received from Met Éireann was not immediately fit for purpose, and various quality control checks were carried out before progressing further with the data. Errors had to be removed and in some cases filling of gaps in the data was necessary. Gap filling was then applied to the rainfall data. In general, where more than 7 days of data were missing at a station in any one month, the record for that month was not deemed suitable for further analysis, and was not gapfilled. Where the total number of missing days at a station in any sub-period exceeded 20% of the length of the sub-period, the record for that station in the sub-period was not used for further analysis. Where partial records were not used for further analysis, the data from those stations was still retained for use in gap filling at other sites. The following errors/problems were encountered with the data.

(a) Missing rainfall data

For many records there are periods where a rainfall value was not recorded for a given day (or number of days). The amount of missing days can range from one day to one year, or even more.

Date	Depth (mm)
01/11/1944	0.2
02/11/1944	0.3
03/11/1944	2.7
04/11/1944	
05/11/1944	
06/11/1944	17.1
07/11/1944	20.1
08/11/1944	3.5
09/11/1944	0.4

Table 4.1 Example of missing data in rainfall records

(b) Missing record followed by cumulative total for the missing dates

On numerous occasions, there were records where a rainfall value did not appear to be recorded for a given day (or number of days). However the next rainfall depth recorded immediately after the gap was suspiciously or unreasonably high. The reason for this occurring is because in practice, the gauge had not been read on a daily basis for a number of days and was eventually read after a period of time. Rainfall measurement practice dictates that when the individual daily rainfall amounts are not measured, the cumulative depth at the end of the period should nevertheless be recorded. The accumulation of rainfall for this missing period was often incorrectly attributed to a single day (as in table 4.2). It was necessary to look at nearby gauges to check if these large values were reasonable. In order to somehow systematically identify this type of error, the median of all the rainfalls across all available stations on each day was calculated. If any recorded rainfall at a particular station exceeded twice the median value, then it was examined further. This type of error was difficult to identify, especially where the gap in data may have been only three or four days. Each gap in the data still had to be manually checked for this type of error, seeing as it required a certain amount of judgement to identify.

Date	Depth (mm)
01/04/1942	---
02/04/1942	---
03/04/1942	---
04/04/1942	---
05/04/1942	---
06/04/1942	---
07/04/1942	---
08/04/1942	---
09/04/1942	---
10/04/1942	---
11/04/1942	---
12/04/1942	---
13/04/1942	---
14/04/1942	---
15/04/1942	143.8

Table 4.2 Example of cumulative missing data in rainfall records incorrectly attributed to a single day.

When gapfilling the missing entries was complete, care was taken to ensure that after gapfilling, the cumulative total of the infilled values matched that of the recorded total for the missing days. This was done by scaling the gapfilled values up (or down) by the ratio of the measured cumulative rainfall total to the gapfilled cumulative rainfall total.

(c) Missing record entered as zeroes followed by cumulative total for the missing dates

Some stations showed long periods that had been entered as zeroes (e.g. one week or more) followed by a suspiciously or unreasonably high rainfall depth. This has been known to occur where the gauge had not been read on each day of the missed record was incorrectly assigned a value of zero, and the accumulation of rainfall for this missing period was often incorrectly attributed to a single day at the end of the series of zeroes (as in the example of Table 4.3 below).

Date	Depth (mm)
17/09/2006	0.8
18/09/2006	17.5
19/09/2006	0
20/09/2006	0
21/09/2006	0
22/09/2006	0
23/09/2006	0
24/09/2006	0
25/09/2006	0
26/09/2006	182.6
27/09/2006	14.2

Table 4.3 Example of cumulative missing data in rainfall records incorrectly shown as zeroes and attributed to a single day.

Again, when gapfilling the missing entries, care was taken to ensure that after gapfilling had been carried out, the cumulative total of the gapfilled values matched that of recorded total.

(d) Step changes in the dates

For many records there are periods where a rainfall value was not recorded for a given day (or number of days). The actual date of the missing data was not recorded either, and this showed up as a step change/ jump in the dates of the record (See Table 4.4). The amount of missing days can range from one day to 1 year, or even more. In order to fix these problems, all of the data was first sorted into chronological order. This cleaned out the step jumps in dates.

Date	Depth (mm)
25/06/1944	0
26/06/1944	3.3
27/06/1944	0
28/06/1944	1.7
29/06/1944	3.7
30/06/1944	9.8
01/01/1945	0.5
02/01/1945	0
03/01/1945	7.4
04/01/1945	0.2
05/01/1945	3.4
06/01/1945	0.5
07/01/1945	0

Table 4.4 Example of step jump in dates where data was missing

The approach to gapfilling missing values followed that used by Sheridan (2001). Where gaps occurred in the data at a particular subject station, up to five geographically close stations were selected as possible "candidate" sites for gapfilling. Where there was a period of overlap between the subject site and any of the candidate sites, that record was retained for analysis. Once the common period of data with each of the candidates is established, dates with gaps and dry days are removed from the data for all stations.

The coefficient of determination (r^2 value) between the non-zero values at the subject site and each of the candidate sites is then calculated. The candidate site that yields the largest value of r^2 is then chosen as the "donor" site for gapfilling. Simple Linear Regression (SLR) is then used to calculate the missing values using the data at the donor site. If there is no data at the donor site for the gap period at the subject site, then the next candidate is chosen and so on. In almost all situations the gaps in the record were filled by the use of the first and second donor sites. Only four gap periods required the use of the third, and none relied on the fourth or fifth. Where there were missing entries followed by a cumulative total, care was taken to ensure that after gapfilling, the cumulative total of the gapfilled values calculated by linear regression matched that of the recorded cumulative total for the missing days. This was done by scaling the gapfilled values up (or down) by the ratio of the measured cumulative rainfall total to the gapfilled cumulative rainfall total. Table 4.5 shows how this disaggregation of cumulative rainfalls was achieved.

Date	Rainfall Depth (mm)	Gapfilled values using a donor site (Gf)	Adjustment of the gapfilled values = Gf * (143.8/123.6)
01/04/1942	---	5.1	5.9
02/04/1942	---	0.5	0.6
03/04/1942	---	3.1	3.6
04/04/1942	---	2.2	2.6
05/04/1942	---	12.1	14.1
06/04/1942	---	28.9	33.6
07/04/1942	---	32.2	37.5
08/04/1942	---	0.1	0.1
09/04/1942	---	2.1	2.4
10/04/1942	---	4.5	5.2
11/04/1942	---	15.9	18.5
12/04/1942	---	3.1	3.6
13/04/1942	---	0.9	1.0
14/04/1942	---	0	0.0
15/04/1942	**143.8**	12.9	15.0
Gapfilled Total		**123.6**	**143.8**

Table 4.5 Disaggregation of cumulative rainfalls

4.2.2 Division of the study period into sub periods depending on data availability

Once gapfilling had been carried out, the overall data set had to be divided into sub periods that contained the optimum number of stations that possessed overlapping records. As a general rule, the overlap between stations had to be at least three years, however this criterion was relaxed to accommodate periods where only a small number of gauging stations were in operation. Smaller sub-periods are required when the data is scarce so that the maximum number of stations are utilised. If for instance a single further station becomes available or drops out of the network, a new sub period begins.

The data availability at each station for each year was examined, and the full length of record was divided into sub-periods that provided the maximum overlap of data at stations within the catchment as outlined in Table 4.6. Once errors had been fixed in the rainfall, the number of stations available for modelling and the periods to which they applied were as follows:

Start Date	End Date	No. of Stations
01/01/26	31/12/40	3
01/01/41	31/10/41	5
01/11/41	31/12/41	7
01/01/42	20/10/42	8
21/10/42	30/09/43	9
01/10/43	31/05/44	10
01/06/44	09/07/44	17
10/07/44	31/01/48	21
01/02/48	14/04/50	23
15/04/50	22/04/52	27
23/04/52	31/12/63	31
01/01/64	31/12/67	29
01/01/68	31/01/70	18
01/02/70	31/05/73	16
01/06/73	30/09/74	12
01/10/74	31/07/77	11
01/08/77	31/01/79	11
01/02/79	31/03/82	9
01/04/82	31/10/84	12
01/11/84	30/04/87	15
01/05/87	30/04/88	16
01/05/88	30/04/91	18
01/05/91	31/10/93	15
01/11/93	30/04/97	20
01/05/97	28/02/02	17
01/03/02	04/05/06	22
05/05/06	31/12/09	21

Table 4.6 Sub periods selected for analysis and associated data availability

4.2.3 Calculation of catchment areal rainfall using Thiessen Polygons

From a review of the literature it was noted from previous studies (Singh and Birsoy, 1975) that the more complex modern methods of calculating catchment wide areal rainfall such as Kriging offered little more advantage over the Thiessen Method for the extra effort required in a study of this scale. The Thiessen method was therefore adopted for use in this project. For each period identified in Table 4.6 the Kilavullen catchment was divided using the Thiessen method. The Thiessen method is widely used and was proposed by A.M. Thiessen in 1911. This method accounts for the variability in spatial distribution of gauges and the representative area for each. The areas representing each gauge are defined by drawing lines between adjacent stations on a map. The perpendicular bisectors of these lines form a pattern of polygons (Thiessen polygons) with one station in each polygon. Stations outside the basin boundary were included in the analysis as they could have polygons which extend into the catchment area. A buffer zone of 15km outside the catchment boundary was chosen as the extents from which stations could be chosen. The area of a polygon for an individual station as a proportion of the total basin area represents the Thiessen weight for that station. Areal rainfall is thus estimated by first multiplying individual station rainfall values by their Thiessen weights, and then summing the weighted totals as follows:

$$\text{Catchment Areal Precipitation} = r_1\left(\frac{A_1}{A}\right)+r_2\left(\frac{A_2}{A}\right)+.......+r_i\left(\frac{A_i}{A}\right) \text{....} \textbf{Equation 4.1}$$

where:

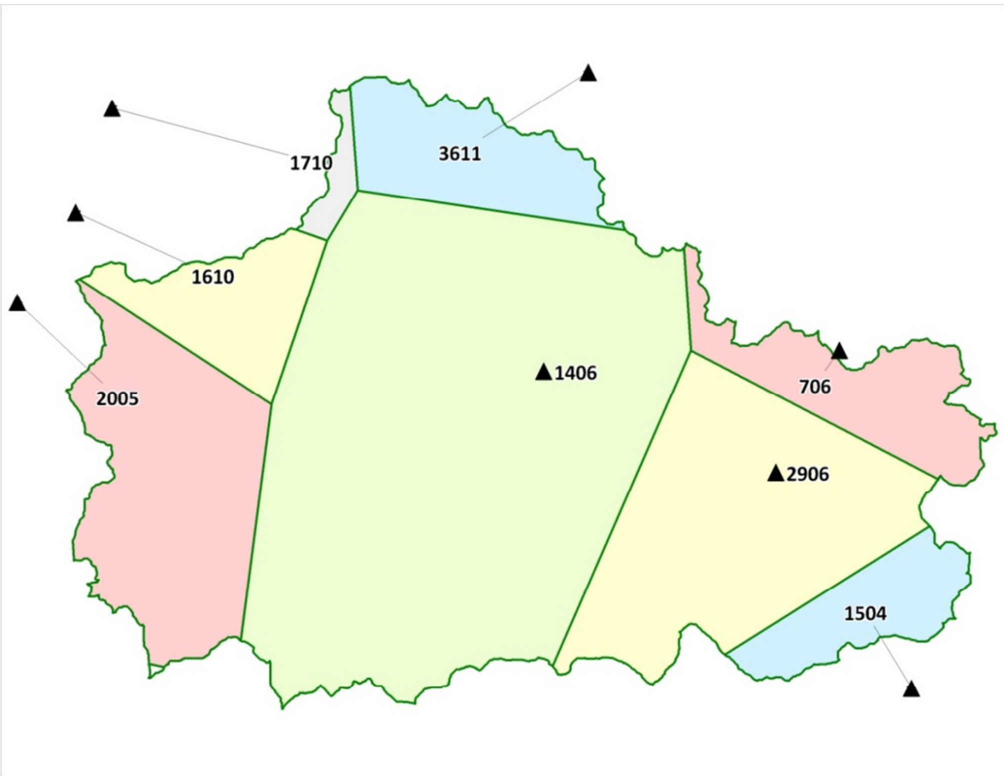
r_i = rainfall at station no. i

A_i = the area of Thiessen polygon for station i

A = total area under consideration (Kilavullen catchment area = 1,256 km^2)

$\left(\frac{A_i}{A}\right)$ is known as the Thiessen weight

The mapping of the Thiessen Polygons and their respective areas for each period is given in Appendix B. An example of the Thiessen polygons for the period 01/02/1979 to 31/03/1982 is shown in Figure 4.1



Station No.	1504	1205	2005	706	1406	2906	1610	1710	3611
Polygon Area	56.91	0	168.6	81.06	569	221.6	66.27	12.49	79.59
Thiessen weight	0.045	0	0.134	0.065	0.453	0.176	0.053	0.010	0.063

Figure 4.1 Example of Thiessen Polygons for the sub-period 01/02/'79 - 31/03/1982

The Thiessen method was used to calculate the areal rainfall for all the sub-periods identified for use in this study. However where data availability was restricted, a means of correcting the data poor periods had to be identified.

4.2.4 *Adjustment of historical rainfall using quantile mapping and linear regression*

Rainfall inputs to the rainfall runoff models used in this study span from 1926 up to the end of 2009, a total of 84 years. In the model that is used, the period from 1941 to 2009 (modern period) is represented very well by gauging stations within or near the Kilavullen catchment boundary. The period between 1926 and 1940 (historic period) is not so well represented with only three daily recording stations in operation in the neighbourhood of the Kilavullen catchment.

As we move further back in time, before 1941, the number of stations within the catchment boundary reduces to zero, and so we must resolve to use gauging stations outside of the catchment. They are the stations at Mallow, Abbeyfeale, and Killarney, the locations of which are shown in Figure 4.2.

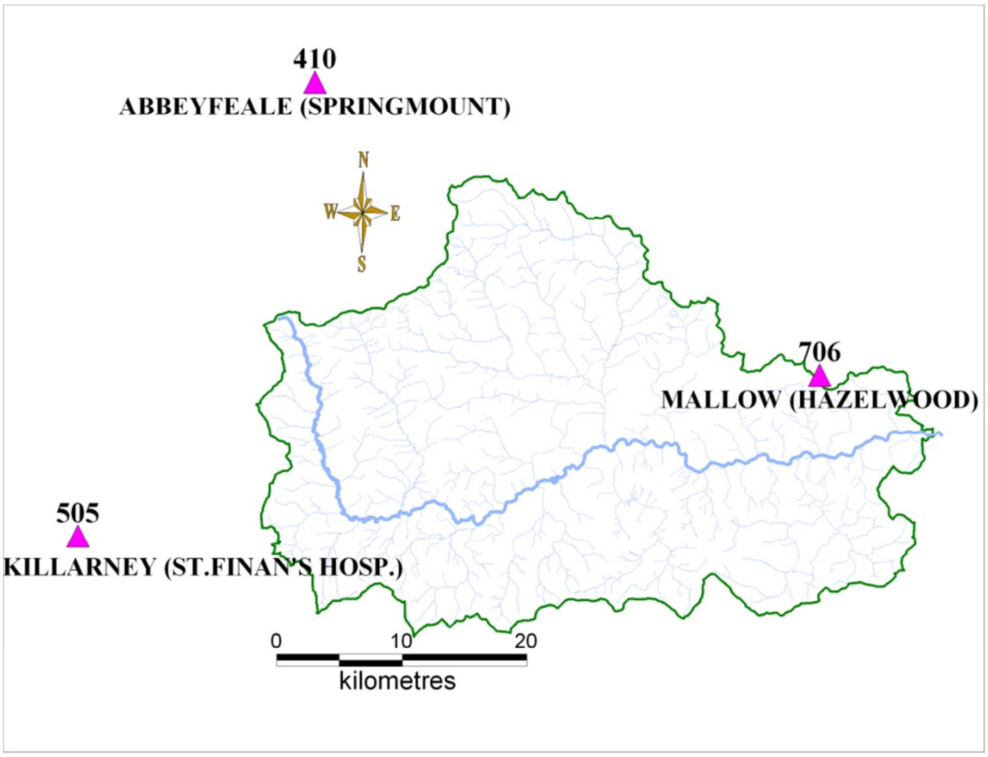


Figure 4.2 Location of the three "historic" stations used in the modelling from 1926 onwards

The hydrological modelling from 1926 to 1941 relies on only these three gauging stations. These stations are widely spread out and are at lower altitudes to the groups of stations used in the analysis of rainfall for the modern period (1941-2009) and would contain a bias towards slightly lower rainfall totals. In order to be able to use these three stations, we must first ensure that the catchment rainfall characteristics exhibited by these three "historic" stations are consistent with that which is exhibited by the better represented "modern" period from 1941 to 2009.

As a start point we can compare the overlap between the historic rainfall patterns and the modern rainfall patterns. Luckily there is an overlap between the coverage of the three historic stations and the modern rainfall record. This period stretches from 1941 to 1974 (incl). It was expected that the areal rainfall obtained by using just these three stations would lead to underestimation of the catchment rainfall, and therefore some preliminary analysis of the three station arrangement was carried out. Figure 4.3 illustrates the comparison when using just the three historic stations to calculate the catchment areal rainfall as opposed to using a number of stations.

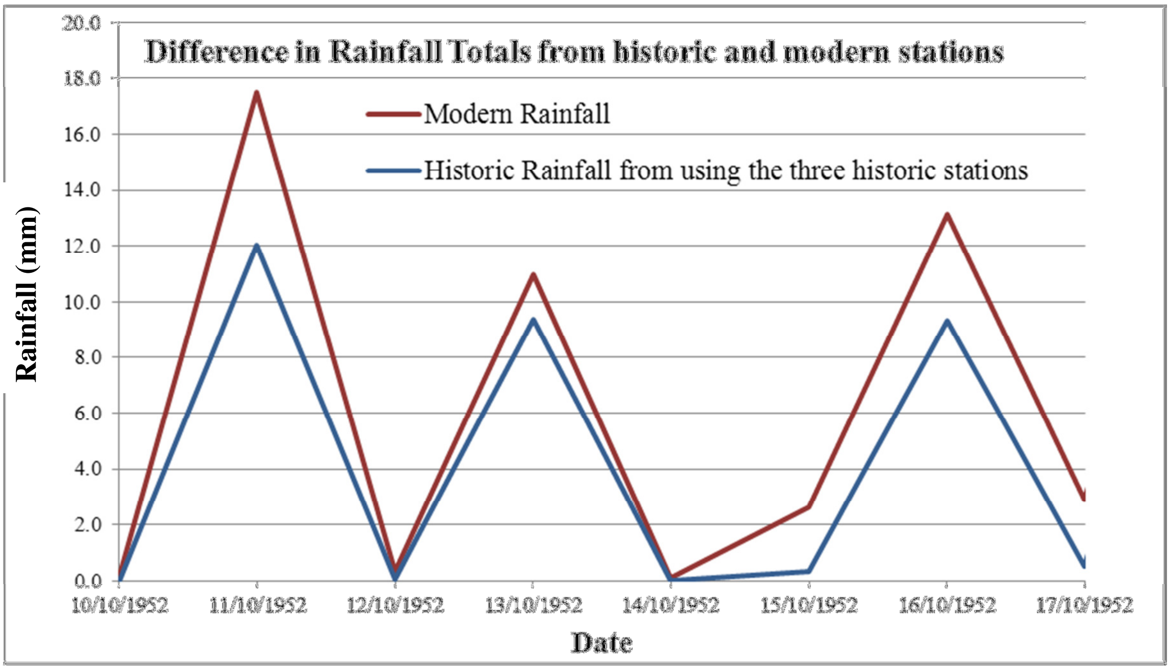


Figure 4.3 Difference in catchment areal rainfall totals when the three station (historic) arrangement is used.

The lack of spatial representation of gauges leads to underestimation of the areal catchment rainfall. Use of simple linear regression on rainfalls in the overlap period (1941-1974) would suggest that by using the three historic stations would, on average lead to an underestimation of catchment areal rainfall by approximately 12%. This underestimation is caused by the poor spatial representation of gauging stations in the historic period, i.e. only three stations that were all outside the catchment boundary down to Kilavullen. In all there are three main reasons for this underestimation

- The sample points may be unrepresentative of the catchment in that no gauge may lie in the section of catchment having extreme rainfall.
- The record may be constantly higher or lower than the true rainfall at one of the stations.
- Factors may combine to cause the rainfall amounts recorded at gauges to differ from their true values in an unsystematic manner.

It was therefore deemed necessary to adjust the historic rainfall to ensure that its behaviour matched that of the better represented modern rainfall period. Two methods were explored in this analysis, Linear Regression and Quantile Mapping of rainfall totals.

(a) Linear regression

Simple Linear Regression was carried out to find a relationship between the historic rainfall data and that from the better represented modern period over the years from 1941-1974. The estimated rainfalls were then then scaled up by the ratio of the total cumulative rainfalls in this 34 year overlap period. Initially it was thought that the use of simple linear regression was deemed to be primitive and unsuitable as it is biased towards the average of the daily rainfalls over the whole period and did not take into account the full range of statistical characteristics of the rainfall. It was therefore decided to explore the concept of quantile mapping to adjust the rainfalls from the historic period as well.

(b) Quantile Mapping of rainfall

This approach has been used in the downscaling of regional climate models, first suggested by Panofsky and Brier (1968) and has been used successfully by Dettinger et al (2004). Rather than use linear regression over the whole period of the record overlap, the cumulative distribution of daily values in each of the 12 months of the year in the overlap period are examined. The daily rainfall totals in each month in the historic and modern record are sorted in increasing order (by rank). A threshold for “dry” days is then chosen. Above this threshold, linear, quadratic or cubic regression is then carried out on the daily values in each month. The regression equations for each month of the year are then applied to the historic daily rainfalls.

The assertion that this approach does not address climate long range variability can dismissed in this case by noting that that the regression is only applied to the historic rainfall over a short period of 15 years (1926-1940). The results of the analysis are as shown in table 4.6. Surprisingly, simple linear regression was found to outperform the quantile mapping approach.

Statistic	Modern Period catchment areal Rainfall	Unadjusted Historic Rainfall from stations 505-410-706	Historic Rainfall - adjusted using quantile mapping	Historic Rainfall – Adjusted using Linear Regression
Average	3.36	2.92	3.32	3.36
Median	1.16	0.89	1.23	1.02
Standard Deviation	5.34	4.71	5.11	5.41
Maximum	96.4	81.1	100.5	93.3
NSE	-----	0.896	0.884	0.904

Table 4.7 Comparison of results of adjustment by linear regression and quantile mapping

Adjustment by linear regression was therefore chosen as the preferred method of adjustment of the historic rainfall data. Figure 4.4 shows a graphical representation of the performance of the two methods when attempting to replicate rainfall based on a wealth of stations.

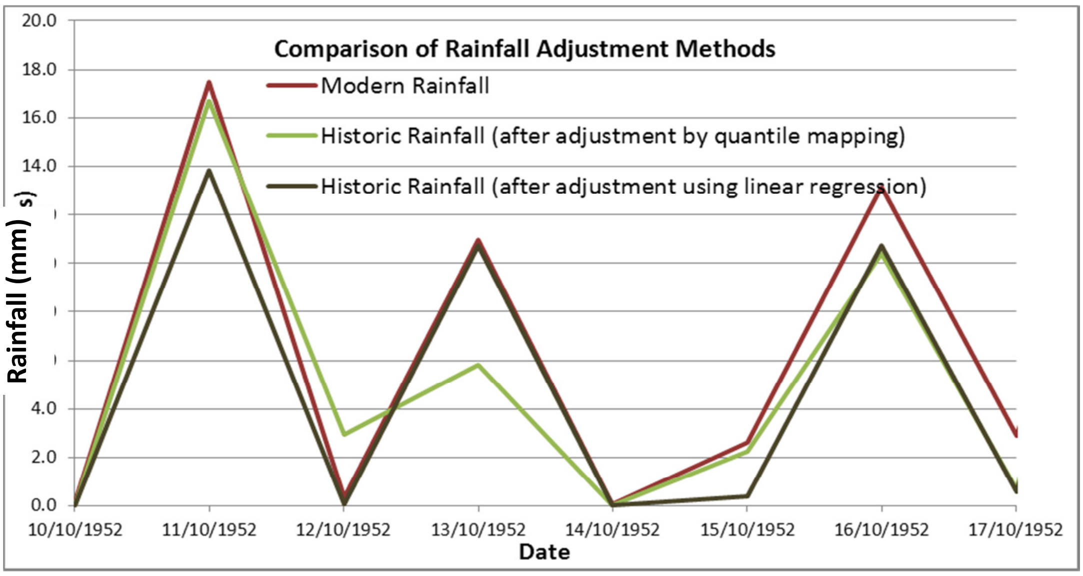


Figure 4.4 Comparison of rainfall adjustment methods applied to historic rainfall.

4.3 Analysis of Temperature Data

4.3.1 Introduction to Analysis of Temperature Data

Temperature data was required for creating the inputs to both the IHACRES and the HYSIM models in this project. For the IHACRES model, Temperature data was directly inputted to the model, whereas for the HYSIM model, it was used indirectly to produce estimates of potential evapotranspiration. In a similar fashion to the rainfall data, the temperature data was available in both digital and paper form for modern and historic periods respectively. Digital Temperature data was available from 1939 onwards at the Valentia Synoptic Station, and was soon followed by data at Shannon Airport (1945) and Cork Airport (1962). Temperature data was available at University College Cork (UCC) for the period 1926-1940, however this was in paper form and had to be manually digitised from the records available at the Met Éireann Library.

In Summary, the availability of Temperature data in the neighbourhood of the catchment is as follows:

Record Period	No. of Stations Available	Stations Names
01/01/1926 – 31/09/1939	1	UCC
01/10/1939 – 31/12/1940	2	UCC/Valentia
01/01/1941 – 31/08/1945	1	Valentia
01/09/1945 – 31/12/1961	2	Valentia/Shannon Airport
01/01/1962 – 31/12/2009	3	Valentia/Shannon Airport/Cork Airport

Table 4.8 Temporal Variation in Temperature Gauging Network

4.3.2 Spatial Interpolation of Temperature Data (Digital Record)

The most data rich period of temperature data was from 1962-2009. This was taken as the control period for the temperature analysis. Throughout this period, daily minimum and daily maximum temperatures were available at three synoptic stations, Valentia, Shannon Airport, and Cork Airport. None of these stations were within the catchment, and so it was necessary to interpolate between the stations in order to calculate the representative catchment average daily air temperature. Linear Inverse distance weighting (IDW) to the catchment centroid was used to generate the daily average catchment temperatures for the Kilavullen catchment. The locations of the synoptic stations at Valentia, Shannon Airport and Cork Airport are shown in Figure 4.5.

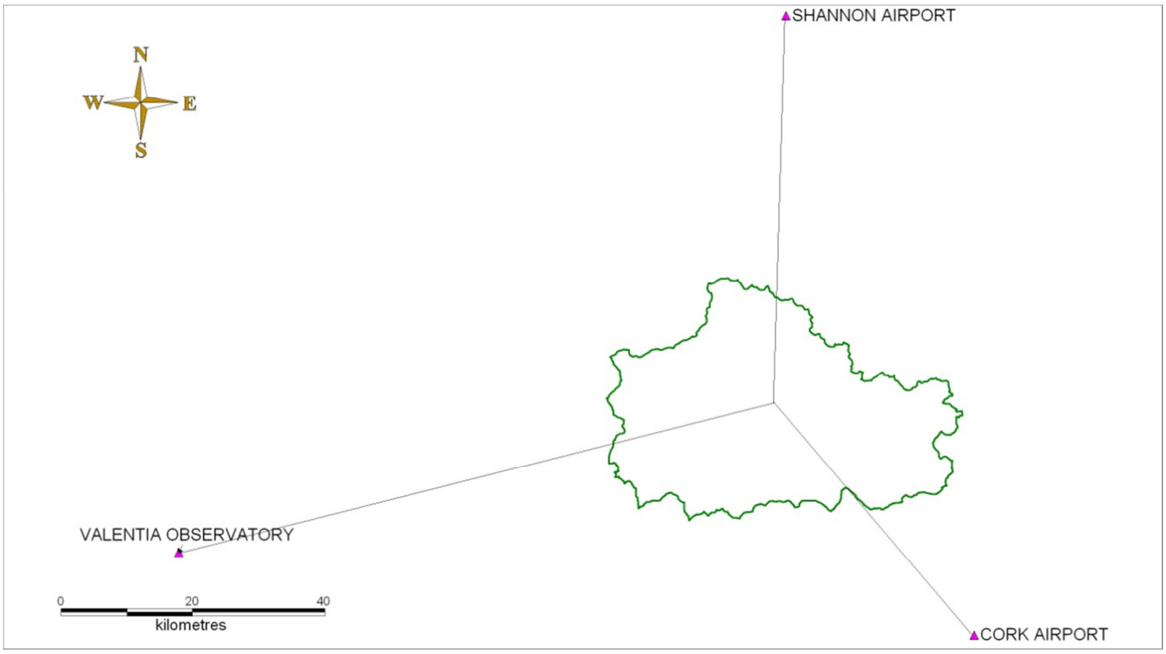


Figure 4.5 Three station arrangement for interpolation of average daily temperatures for the Kilavullen Catchment

The distances from the catchment centroid to each of the three synoptic stations were as outlined in Table 4.9:

Synoptic Station	Distance to catchment Centroid (km)	Inverse Distance Weighting
Valentia Observatory	94.86	0.0105
Shannon Airport	58.30	0.0171
Cork Airport	45.96	0.0217

Table 4.9 Distances from Synoptic Stations to Kilavullen Catchment centroid.

The daily average temperature values for this three station arrangement were used in the temperature analysis to enhance the data where fewer stations were available.

(a) Catchment Daily Average Temperatures 01/01/1962-31/12/2009

Catchment daily average temperatures were made available by Met Éireann in digital form from 1962 to the present day. This data was available for the three synoptic stations at Valentia, Shannon Airport and Cork Airport, and was considered to be fit for purpose in its raw form and did not require any corrections. This period was identified as the most accurate period over which the temperatures were measured and was retained as being the control period for the rest of the temperature analysis.

(b) Catchment Daily Average Temperatures 01/09/1945 - 31/12/1961

The next most data rich period was from 1945-1961, when there was a two station arrangement defined by the stations at Valentia and Shannon Airport. In order to augment this data to act is if it would under the three station arrangement, IDW interpolated temperatures obtained for this two station arrangement were compared with the full three station arrangement for the control period from 1962-2009. Linear regression of the daily average temperatures yielded the best relationship for this exercise resulting in a correlation coefficient value of 0.991 (see figure 4.6).

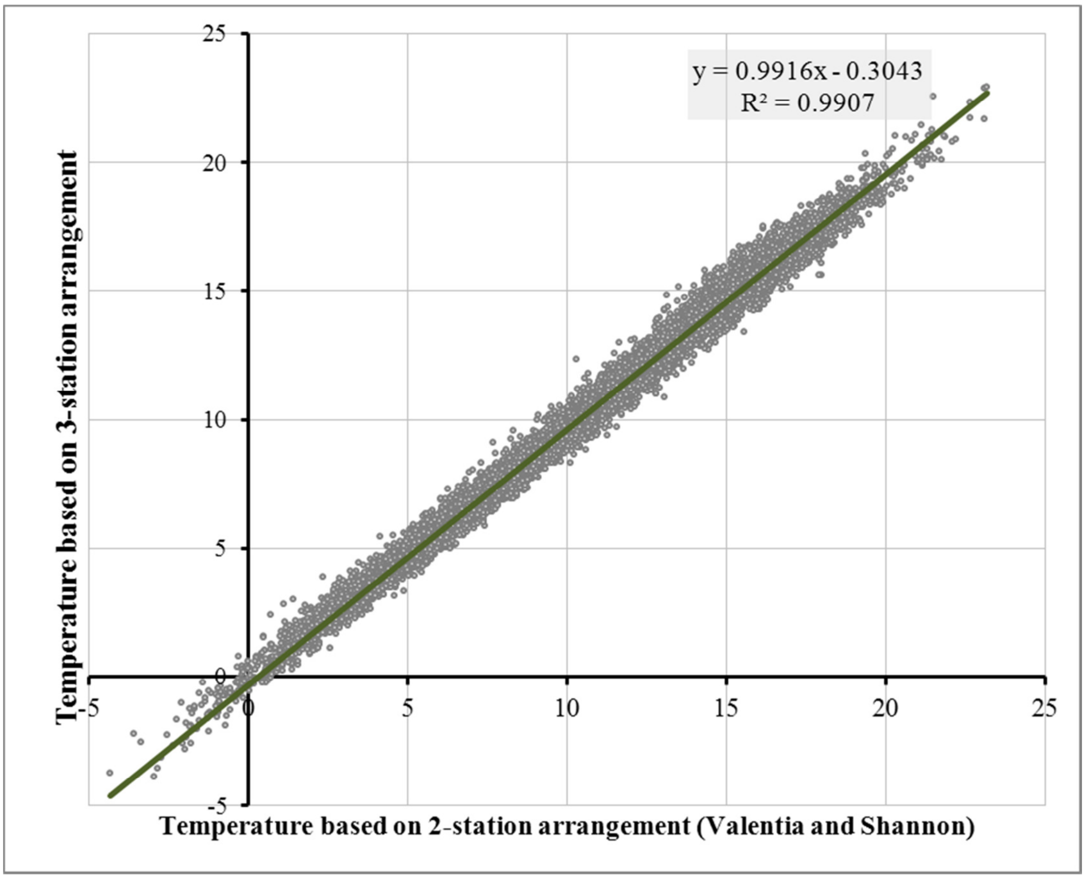


Figure 4.6 Comparison of Temperatures for two and three station arrangements for IDW interpolation over the period 1962-2009.

Based on the relationship obtained, the temperature values for the two-station arrangement between 1945 and 1961 were adjusted to reflect the behaviour of the three station arrangement.

(c) Catchment Daily Average Temperatures 1939-1945

Between 1939 and 1945 there was only one synoptic station in existence in the neighbourhood of the catchment, namely Valentia Observatory. In order to be able to infer temperature values for the Kilavullen catchment temperatures at Valentia were compared with the full three station arrangement for the control period from 1962-2009. Linear regression of the daily average temperatures showed an acceptable correlation between the two resulting in a correlation coefficient value of 0.956 (see Figure 4.7). The temperatures at Valentia were then adjusted to reflect the three station arrangement based on the results of the linear regression.

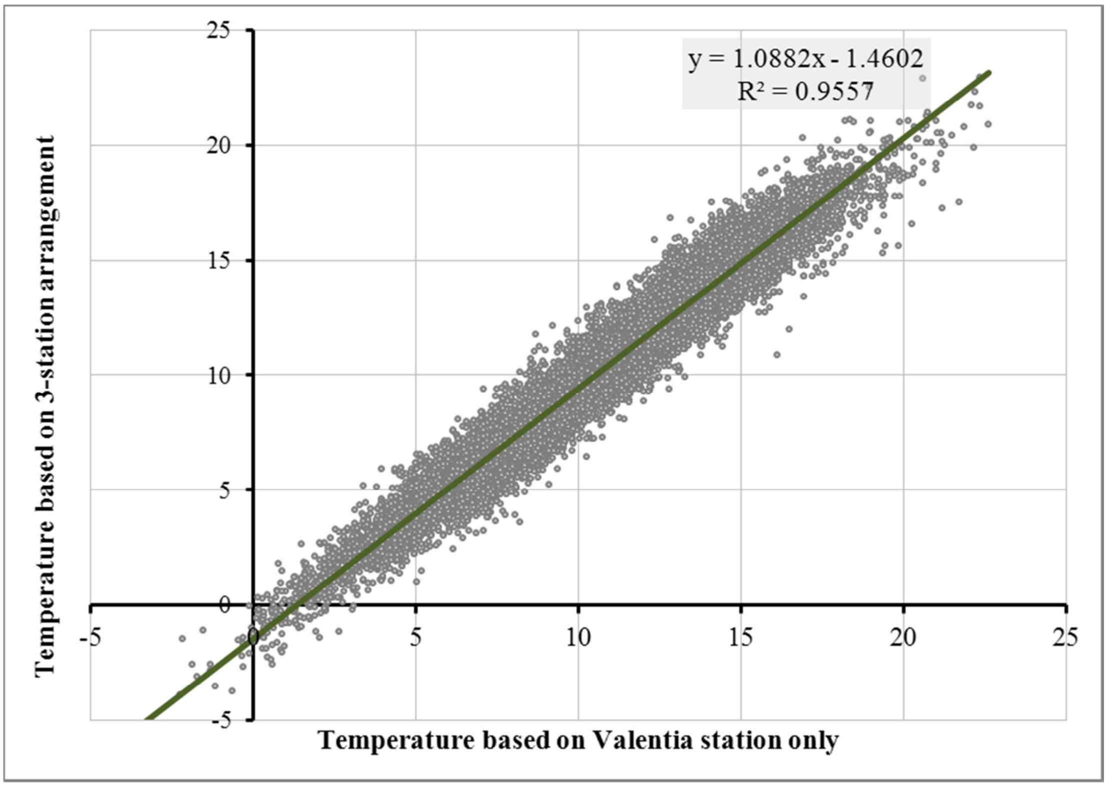


Figure 4.7 Comparison of Temperatures between Valentia and three station arrangement over the period 1962-2009.

Based on the relationship obtained, the temperature values for Valentia between 1939 and 1945 were adjusted to reflect the behaviour of the three station arrangement.

(d) Catchment Daily Average Temperatures 1926-1939

For the period from 1926-1939 data was only available at the University College Cork (UCC) climatological station. The record at this station did not overlap with the record for the 3-station arrangement, and so the catchment daily average temperatures could not be inferred from a direct comparison with the three station arrangement. However, there was an overlap in the temperature records with Valentia. This overlap was from 01/10/1939 – 31/12/1940. The adjusted temperatures at Valentia were compared with those at UCC for this period, again using simple linear regression.

Linear regression of the daily average temperatures showed an acceptable correlation between the two resulting in a correlation coefficient value of 0.817 (see Figure 4.8).

The relationship between the two stations was used to adjust the temperature values at UCC to reflect the three station arrangement for the catchment temperature for the period from 1926-1939.

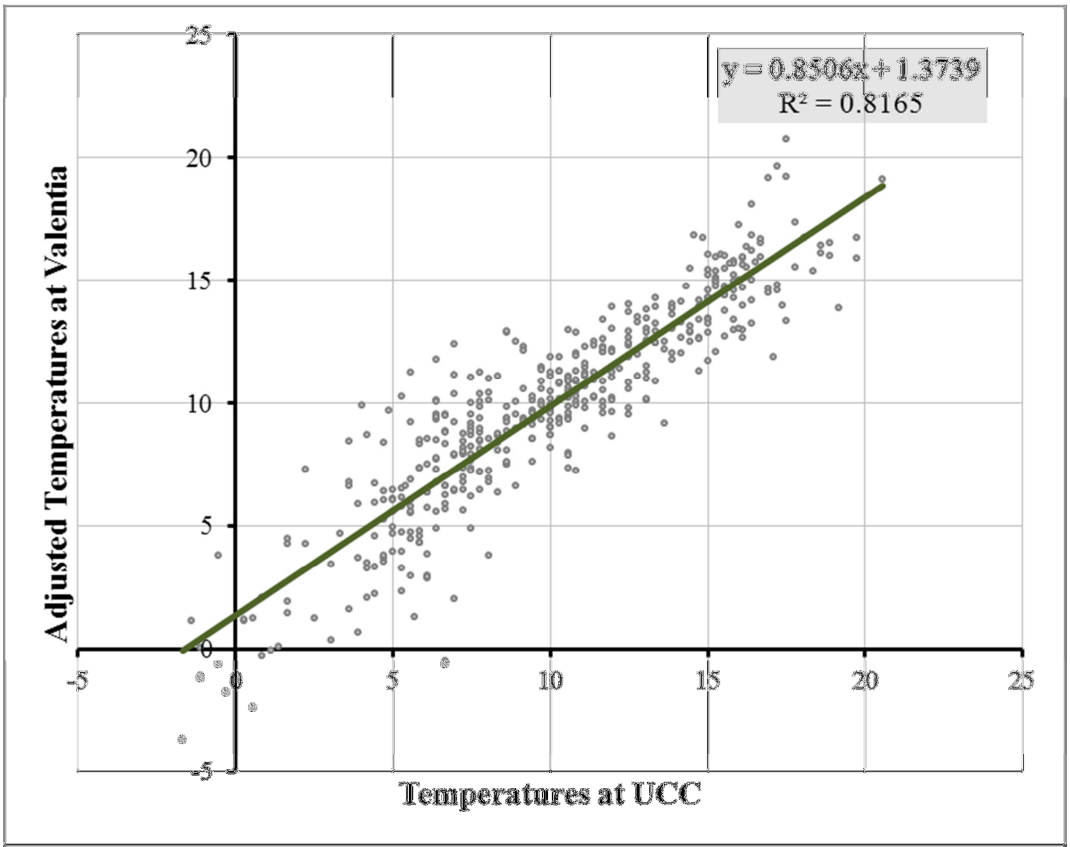


Figure 4.8 Comparison of Temperatures between UCC and Valentia (Adjusted) over the period 01/10/1939-31/12/1940.

4.4 Analysis of Potential Evapotranspiration Data

4.4.1 Introduction to Analysis of Potential Evapotranspiration Data

Potential Evapotranspiration (PE) is defined as the amount of evapotranspiration that would take place if a sufficient water source was available. A continuous time series of PE data is required as one of the inputs to the HYSIM hydrological model. There are numerous methods for calculating Potential Evapotranspiration that range in terms of complexity and purpose.

PE values at Irish synoptic stations are estimated by Met Éireann using the Penman-Monteith formula and were available in digital form for the three stations in the vicinity of the Kilavullen catchment with varying temporal coverage (See Table 4.10).

Period	No. of Stations Available	Stations Names
01/10/1939 – 31/08/1945	1	Valentia
01/09/1945 – 31/12/1961	2	Valentia/Shannon Airport
01/01/1962 – 31/12/2009	3	Valentia/Shannon Airport/Cork Airport

Table 4.10 Temporal Variation in PE gauging network

No PE data prior to 1939 were available in digital form for this project at any location. As previously stated, the method used to calculate PE at Irish synoptic stations is the Penman-Monteith formula (1965).

$$PE = \left(\frac{\Delta R_n + \gamma (e_a - e_d) W}{\lambda \rho \left[\Delta + \gamma \left(1 + \frac{r_s}{r_a} \right) \right]} \right) \text{............ \textbf{Equation 4.2}}$$

Where:

$W = (1500/r_a)$ and $r_a = (208/U)$

R_n = net solar radiation (MJ m^{-2} day)

γ = psychrometric constant (kPa $^{o}C^{-1}$)

e_a = saturation vapour pressure (kPa)

e_d = actual vapour pressure (kPa)

λ = latent heat of vaporization (MJ kg^{-1})

ρ = Density of water (=1,000 kg L^{-1})

Δ = slope of vapour pressure curve (kPa $^{o}C^{-1}$)

r_s = surface resistance of reference crop (=69 s m^{-1})

r_a = aerodynamic resistance (s m^{-1})

U = wind speed 2m above the soil surface (m s^{-1})

The data needed to calculate PE when using the Penman Monteith formula are Relative Humidity, Air Temperature, Wind Speed, Sunshine (h day^{-1}). It can be clearly seen that the data requirements for calculating PE using this method are quite onerous, and this data is simply not available for the period prior to 1939. In order to produce a continuous time series of PE data for the Kilavullen catchment, a suitable method for its estimation using the minimal amount of data required.

4.4.2 Alternative method for calculating PE

In a study by Oudin *et al*. (2004), 27 PE formulae were examined to find which method of calculating potential evapotranspiration (PE) was the most suited to the specific task of hydrological modelling. Traditionally the Penman-Monteith equation has been used in Ireland to calculate PE, but the motivation behind its use is agrarian based. The work by Oudin *et al*. showed that PE formulae based on just temperature and radiation provide the best estimations of streamflow when used in rainfall runoff models. Oudin *et al*. proposed a simple and efficient method for the calculation of PE based on the following formula:

$$PE = \frac{R_e}{\lambda \rho} \frac{T_a + 5}{100} \text{.......} if\ T_a + 5 > 0 \text{ ....} \textbf{Equation 4.3}$$

and PE = 0 otherwise

Where:

PE is the rate of potential evapotranspiration (mm day^{-1})

R_e is the extra-terrestrial radiation (MJ m^{-2}day^{-1})

λ is the latent heat flux (MJ kg^{-1})

ρ is the density of water (1,000 kg m^{-3})

T_a is the mean daily air temperature (^{0}C)

The extra-terrestrial radiation (R_e) is dependent on the Julian day and the latitude of the location of interest, which in this case is the centroid of the Kilavullen catchment.

$$R_e = \left(\frac{(24)(60)(G_{SC})}{\pi} \right) D_r \left[\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s \right] \text{...........} \textbf{Equation 4.4}$$

Where:

R_e = extra-terrestrial radiation (MJ m^{-2} day^{-1})

G_{sc} = solar constant (=0.0820 MJ m^{-2} min^{-1})

D_r = inverse relative distance from the earth to the sun.

ω_s = sunset hour angle (radians)

φ = latitude (= 0.909701 radians, equivalent to 52.122 decimal degrees for the Kilavullen catchment centroid)

δ = solar declination (radians)

The inverse relative distance from the earth to the sun (D_r) is calculated from:

$$D_r = 1 + 0.033\cos\left(\frac{2\pi J}{365}\right) \text{............}\textbf{Equation 4.5}$$

Where: J is the Julian day = (1 to 365 or 366 for leap years)

$$\omega_s = \arccos(-\tan\varphi\tan\delta) \text{...........}\textbf{Equation 4.6}$$

$$\delta = 0.409\sin\left(\left(\frac{2\pi J}{365}\right) - 1.39\right) \text{...........}\textbf{Equation 4.7}$$

In effect, the extra-terrestrial radiation may be calculated for any day at any location once its latitude is known. The method proposed by Oudin *et al.* was chosen as the preferred method for calculating the PE for the Kilavullen catchment. It was deemed to be the most suitable method because essentially it only requires one type of measurement to calculate PE, namely Temperature. In the study carried out by Oudin *et al*. it was also found to outperform the use of PE calculated using the Penman-Monteith formula.

4.4.3 Synthesising Potential Evapotranspiration for the period 1926-2009

The temperature inputs used for the calculation of PE values for the Kilavullen catchment were chosen to be those that were calculated by spatial interpolation and regression earlier in this chapter.

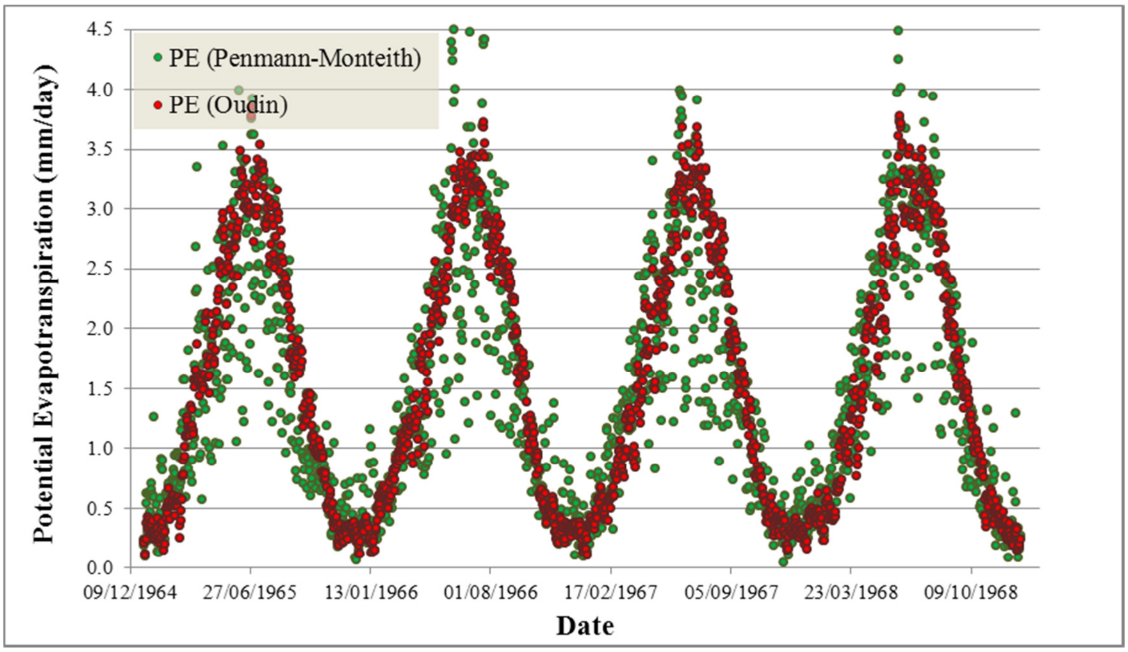


Figure 4.9 Comparison of Penman-Monteith and Oudin methods for calculating Potential Evapotranspiration in the Kilavullen catchment.

The resulting PE data exhibited a strongly sinusoidal behaviour, and showed substantially less scatter of the values compared to those obtained from the Penman-Monteith method (see Figure 4.9). The scatter of Penman-Monteith PE values is most notable in the Summer months and especially in July when the range of values varies from anywhere between 1mm and 5mm per day. When using the Oudin method, the scatter of PE values for the month of July is much less, and generally ranges from 2.7mm to 3.8mm. It should be understood that the use of the Oudin method for calculating PE gives a value dominated solely by latitudinal considerations. Water surplus is controlled both by PE and rainfall. Both these vary altitudinally and the catchment has some significant upland areas. The focus of this study is mainly on high flows. It was considered that at high flows, that the sensitivity to altitudinal differences in PE would be small in magnitude, and the Oudin method was considered just as applicable to the calculation of PE values as the Penman Monteith mmethod (which incidentally does not take altitudinal effects directly into account).

4.5 Analysis of Daily Mean Flow Data

4.5.1 Introduction to Analysis of Daily Mean Flow Data

Daily mean flow data was required as inputs to both the IHACRES and the HYSIM models in this project for use in the calibration stage. Flow data at a number of gauging stations was made available by the Hydrometric Sections of the OPW and the EPA. quality checks on the data for the Kilavullen gauge were performed by comparing with data at other sites along the Munster Blackwater. The names and locations of these sites, including Kilavullen are as shown in Figure 4.10 and Table 4.11.

Station No.	Station Name	Period of Record	Catchment Area (km^2)	BFI_{SOIL}	SAAR (mm)
18002	Ballyduff	01/10/1955 - present	2334	0.607	1200
18003	Kilavullen	01/10/1955 - present	1256	0.461	1298
18006	Mallow CSET	16/07/1977 - present	1055	0.462	1331

Table 4.11 Gauges used for quality check of daily mean flows at Kilavullen

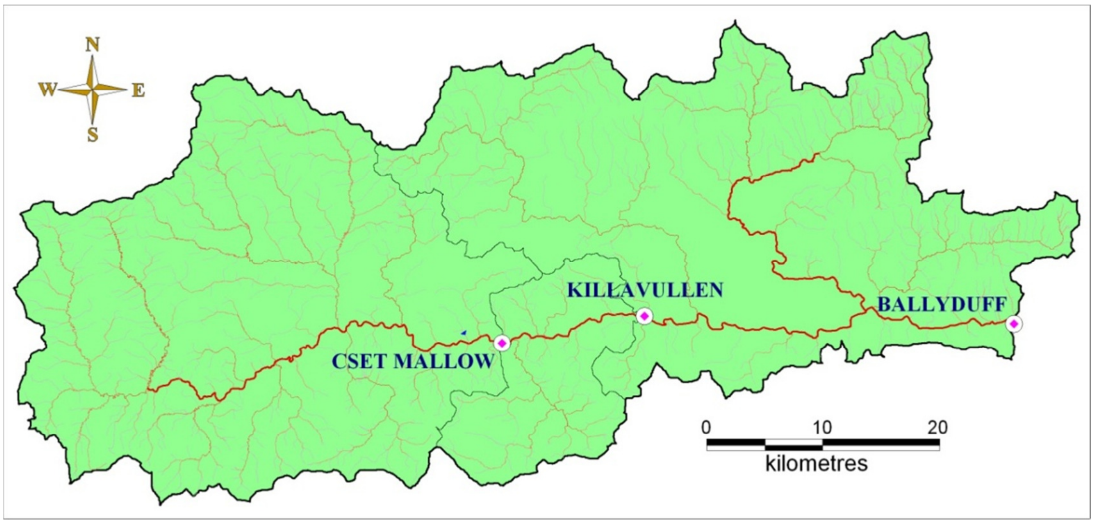


Figure 4.10 Locations of gauges used for quality checks at Kilavullen (showing their respective contributing catchments)

4.5.2 Identification of problems with flow measurements at Kilavullen.

Before using the data at Kilavullen in the model calibration stage, a number of checks were carried on the data to ensure that it was fit for purpose.

The checks that were carried out were as follows:

(a) Issues with rating curves (stage-discharge relationships)

(b) Identification of unusually high/low observed values

(c) Identification of gaps in the data

Where errors were identified appropriate steps were taken to adjust the flow data based on the best available information from the stations at Mallow and Ballyduff.

(a) Issues with rating equations and curves

At the beginning of this study in 2010, flow data at the Kilavullen and Ballyduff gauges were provided by the OPW, and data at the Mallow CSET gauge was provided by the EPA. As part of the Flood Studies Update a review of the high flow ratings of all of the gauging stations in the country was carried out. The study assigned high flow classifications for each gauging station. Each station was assigned a classification of A1, A2, B, C, or U with A1 being the best classification. These classifications are based on the ratio of the Highest Gauge Flow (HGF) to the median of the annual maximum flow series (QMED). The ranges for classification of stations based on HGF/QMED ratio are shown in Table 4.12

FSU Classification	Means of classification	Used in the FSU
A1	HGF/QMED≥1.3	Yes
A2	QMED≥HGF/QMED≥1.0	Yes
B	HGF/QMED≈1.0	Yes
C	HGF/QMED<1.0	No
U	Unusable - Poor Data coverage /no rating developed	No

Table 4.12 FSU criteria for rating classification of gauging stations

The gauge at Kilavullen has been assigned a B rating for the period from 1955-1972, and an A2 rating from 1972-2009. From notes provided in the FSU ratings review (HydroLogic, 2005), it is noted that at Kilavullen the record from October 1955 to September 1961 there are very few medium and high flow spot gaugings. The period from 1961 to 1972 is better represented, and the period from 1972 to 2005 is the richest period from the point of view of high flow spot gaugings. This information gives some initial information on what periods within the flow record are more reliable than others.

At the beginning of this study in 2010, daily mean flow data at Kilavullen was provided by the OPW for the period 1955-2009. In November 2011 it was discovered that a revised rating for the period from October 2001 onwards had been produced by the OPW. The flow values obtained by using each of the two ratings varied by approximately 20%, the newer rating producing flows that were much lower than the previous. It was unclear which rating should be used, and there was no definite information as to which was the correct rating to use. The two stage discharge relationships are shown in Tables 4.13 and 4.14 for the 2010 and 2011 ratings.

Equation Number	Rating Equation	Upper Limit (metres)	Quality Code
1	62*(x+-0.54)^2.401	0.977	16
2	38*(x+-0.54)^1.809	1.381	6
3	36.2*(x+-0.54)^1.528	2.490	6
4	36.2*(x+-0.54)^1.528	4.800	16
5	6.954*(x+-0.02)^2.47	6.699	56

Table 4.13 OPW rating equations for the Kilavullen gauge in use in 2010

Equation Number	Equation	Upper Limit (metres)	Quality Code
1	62*(x-0.68)^2.401	1.118	16
2	38*(x-0.68)^1.809	1.521	6
3	36.2*(x-0.68)^1.528	2.630	6
4	36.2*(x-0.68)^1.528	4.940	16
5	6.954*(x-0.10)^2.47	6.699	56

Table 4.14 Revised OPW rating equations for the Kilavullen gauge in use in 2011

As a result of the discrepancies in flow values for each rating, a new rating for the period 01/10/2001 to 31/12/2009 was developed for the purposes of this project. This was done by plotting the stage discharge relationship from information contained in the spot gaugings for the Kilavullen gauge. The revised rating equations developed for the period 01/10/2001 to 31/12/2009 for this project are as shown in Table 4.15.

Equation Number	Equation	Upper Limit (metres)	Quality Code
1	62*(x-0.61)^2.401	1.090	16
2	38*(x-0.61)^1.809	1.521	6
3	36.2*(x-0.61)^1.528	2.630	6
4	36.2*(x-0.61)^1.528	4.940	16
5	6.954*(x-0.06)^2.47	6.699	56

Table 4.15 Rating relationships at the Kilavullen gauge developed for this study Current project rating equations

It is unfortunate that there were no spot gaugings recorded in November 2009 at the Kilavullen gauge. The overall monthly flow volume for November 2009 was the largest on record, and would have presented the perfect opportunity to obtain high flow spot gaugings in order to better define the upper end of the rating curve. The differences between the three rating curves are shown in Figure 4.11. It was found that the revised rating developed for this project generally produced flows that were somewhere between the 2010 and 2011 ratings produced by the OPW. It should be noted that the revised rating for the current project flattens out at higher levels, which based on knowledge of the site at Kilavullen would seem to be a realistic representation of the high flow conditions at the site which contains a long flat floodplain on the left bank of the river at the gauge location.

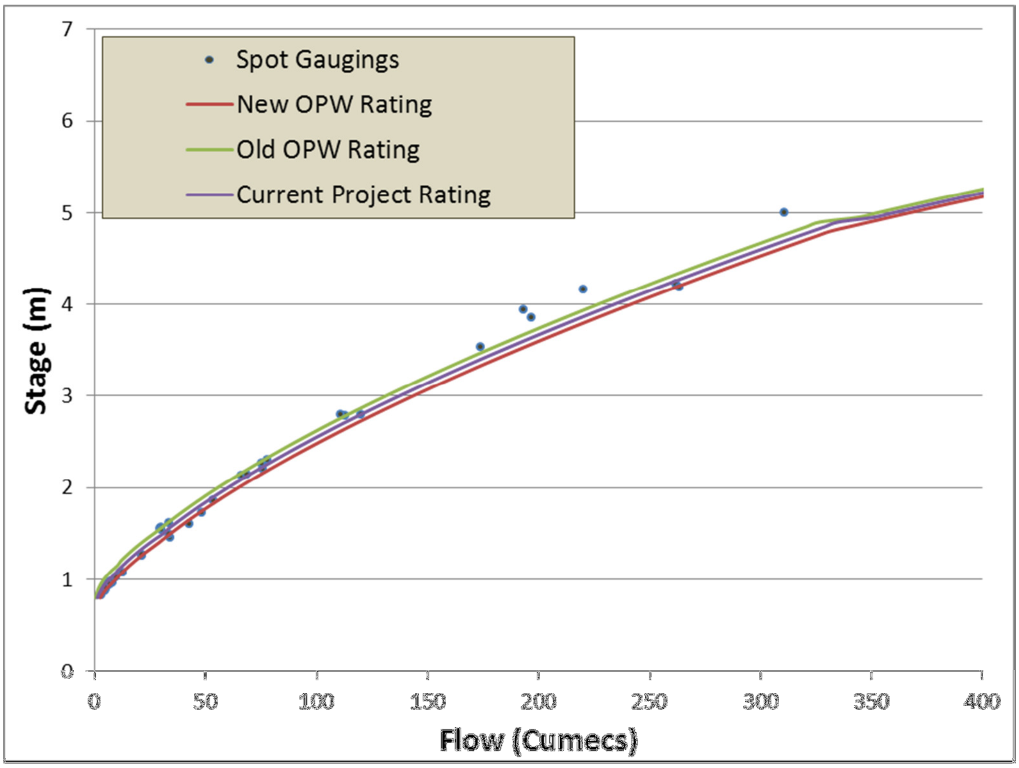


Figure 4.11 The three possible rating curves for the period 2001-2009

(b) Identification of unusually high/low observed flows

Before proceeding to fill any gaps in the record, the full record was examined for unusually high or low flows that could affect the calibration of the models. This was done by choosing the two nearest gauging stations in the upstream and downstream direction and scaling them by the ratio of their areas to that at Kilavullen.

The two stations that were used were the stations at Mallow and Ballyduff. The scaling ratios for the flows at those stations are shown in Table 4.16.

Station Number	Station Name	Period of Record	Catchment Area (km^2)	Scaling Ratio
18002	Ballyduff	01/10/1955 - present	2334	0.538
18003	Kilavullen	01/10/1955 - present	1256	1.000
18006	Mallow CSET	16/07/1977 - present	1055	1.19

Table 4.16 Scaling ratios for flows at Mallow CSET and Ballyduff.

While it was not expected that the scaled flows at each station would match exactly with the flows at Kilavullen due to the effects of lateral inflows along the intervening stretches of river, they could be used to identify any anomalies in the flows at Kilavullen. An example of one such anomaly is that period shown in Figure 4.12.

Between 30/06/1980 and 13/07/1980, the flows at Kilavullen are uncharacteristically high in comparison to the scaled flows at Mallow and Ballyduff. This period of record was therefore treated as a gap in the data, and the erroneous period was recorded. At a later stage in the quality control exercise, this period was included in the gapfilling exercise. Periods in the record were only treated as erroneous if the scaled flows at Mallow and Ballyduff matched up closely and were substantially different to that for Kilavullen.

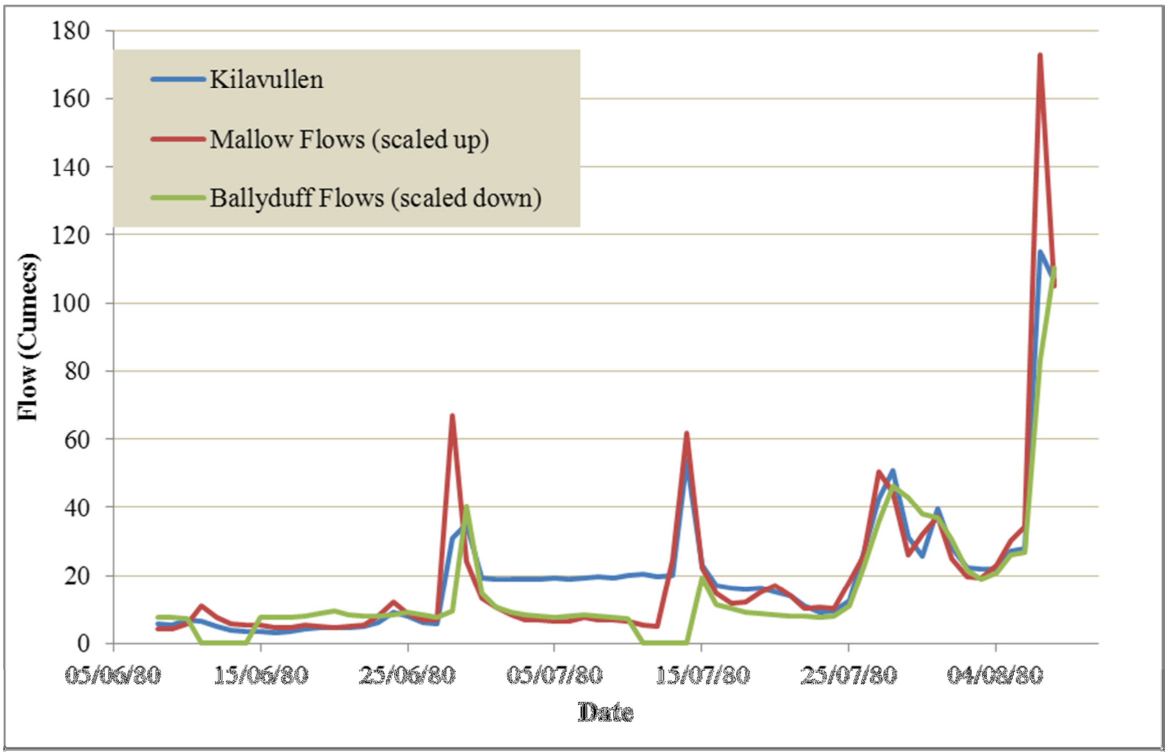


Figure 4.12 Anomalous flows at Kilavullen identified by the quality checking exercise.

For the period prior to 1977 the station at Mallow was not in operation, and so the checking exercise was based on the station at Ballyduff only. A large degree of confidence could be placed in the scaled flow values at Ballyduff for this period because they show a surprisingly good agreement with the flows at Kilavullen, with an r-squared value of 0.96 for the post 1977 period.

(c) Identification of gaps in the data

After examining the full record of flows at Kilavullen, it was found that the total number of missing days of data amounted to 775. A total of 478 of these were in the period from 1955-1977, while 297 of these were in the period from 1977-2009. The more notable gaps in the record were as follows:

From	To	No. of Days
25/08/1959	09/11/1959	77
26/04/1960	11/05/1960	16
24/05/1960	07/06/1960	15
14/06/1960	17/07/1960	34
09/08/1960	21/08/1960	13
28/08/1960	13/09/1960	17
16/05/1961	12/07/1961	58
18/07/1961	28/09/1961	73
01/02/1972	08/07/1972	159
21/11/1989	03/01/1990	44
30/04/1990	22/05/1990	23
25/09/1990	17/10/1990	23
07/05/1991	27/05/1991	21
24/09/1991	09/10/1991	16
13/01/2006	10/05/2006	118
24/12/2007	02/01/2008	10

Table 4.17 Gaps identified in the Kilavullen daily mean flow series

The gaps in the data were filled by using the flows from Mallow and Ballyduff scaled according to the ratio of the catchment area at Kilavullen to the catchment area at Mallow and Ballyduff respectively. Where records were available at both stations, preference was given to the data from the gauge at Mallow. As it accounts for 83.4% of the catchment to Kilavullen and does not have any major tributaries joining along the main channel of the Blackwater on the intervening stretch of river. It also is the more hydrologically similar catchment from the point of view of its SAAR value and the BFI value for the catchment.

4.6 Analysis of Historical Flood Data

4.6.1 Introduction to Analysis of Historical Flood Data

The historical reports of flood events that have been collected as part of this project are to be used to validate the modelled flows for the period prior to gauged records from 1926-1955. While it is not possible to estimate flows directly from this data, it is possible to assign measures of severity based on the information contained within these reports. Once a database of documentary historical flood events is compiled they can be used to reinforce the results of the rainfall runoff modelling phase of this project by correlating reports back to modelled events.

4.6.2 Ascribing Measures of Severity to Historical Floods

In ascribing measures of severity, various details about flood events can be extracted from documented historical reports. The most comprehensive treatise on the use of documented flood events to analyse historical series is given in Sturm et al. (2001) and Glaser & Hangl (2010). The approach outline by Sturm et al. was used adapted for use in this study.

In order to assign measures of severity to flood events, we must first define a scale of severity. For this project the following a scoring scale based on 3 groupings of severity was established:

1. Extreme Event (Score of 3): Events that are estimated to be among the top ten events in documented history. These events would have caused extensive damage to property, crops, livestock and possible human fatalities. They would usually involve the most vulnerable properties being flooded above first floor level, and would affect a whole town or large areas of agricultural land. An indication of their severity would be the number of reports of these floods, and whether they constituted national news. There would also be references to the floods being the "largest in living memory" or as being similar to other extreme floods in terms of magnitude. These events would generally be in excess of a 25-year flood event.

2. Major Event (Score of 2): Major events would be those that cause a large amount of damage to property, crops and livestock. These reports would usually be limited to the more flood prone areas of towns and would involve inundation of the ground floors of the most vulnerable properties. These events would have been widely covered in local newspapers and may have made their way into some of the national newspapers. These floods would generally have a rarity of between a 5-year and 25-year flood event.

3. Minor Event (Score of 1): The floods that are classed as minor events would have involved minor flooding of roads and properties. The flood duration would

be less than a day, and would be documented in local newspapers only. Some of these minor events may not have been recorded in local newspapers at all. However evidence of flooding in nearby towns in neighbouring catchments may indicate that the river may have been close to flooding. These would generally have a rarity of between a 2-year and 5-year event.

4.6.3 Details of Extreme Events

In performing the review of historical reports of flooding at Kilavullen only a handful of reports relating specifically to Kilavullen were found. This is more than likely because Kilavullen is a small village located at a much higher elevation than the river and would not directly suffer from flooding. However, Kilavullen is situated between the towns of Mallow and Fermoy, and reports of flooding at these locations are numerous and can be used to infer the occurrence of flood events at Kilavullen. Prior to 1900 there are 16 recorded flood events of differing severity recorded in the Munster Blackwater catchment, the earliest of these is from 1578 where the writer reported being delayed by "a considerable flood at Mallow".

Flood Date (approx.)	Mechanism	Other comments
September 1628	Rainfall	"higher than was ever seen by the oldest living man"
2nd November 1853	Snowmelt + rainfall	Reported to be the largest in documented history
31st December 1869	Rainfall	
26th September 1875	Rainfall	
17th November 1916	Rainfall	
8th December 1916	Rainfall	
10th November 1941	Rainfall	Not referred to in Blackwater flood studies by any consultants reports or MFC Journal.
12th August 1946	Rainfall	
17th March 1947	Snowmelt + rainfall	Commonly known as one of the largest snowmelt floods of the 20th century in this and nearby catchments
2nd December 1948	Rainfall	
5/6th December 1948	Rainfall	
25th October 1949	Rainfall	

Table 4.18 Documented Extreme floods in the Munster Blackwater catchment prior to 1955

Reports such as this contain no information on the severity of the flood and hence could not be categorised as major events and were given a score of 1 based on the scoring scheme. Only those that give details of the severity of the floods were brought forward for inclusion. An independence criterion was also applied to the identification of flood events in that they must be at least three days apart. In chronological order, the flood events prior to instrumental gauged records at Kilavullen that fall into the "extreme" category and were afforded a score of 3 are as detailed in Table 4.18. The historical reports were examined to find documentary information that could help to indicate the severity of each event. The following sections are a record of the extracts from historical reports that were used to assess the severity of each event to give an indication of how the severity scores were applied to each event, but also to show how the relative rankings of each flood were assigned. The most relevant sections of text that were used to assign severity scores are shown in italics, and those that compare the event to other floods are highlighted in blue. The full text of the historical reports can be found in Appendix C.

4.6.4 Documented reports of extreme flood events

Estimated Flood Event Date: 2nd November 1853

"*….. These measurements suggest that the largest recorded event occurred in 1853 and that the 1948 event was marginally greater than that experienced in 1916*" (OPW, 2003)

"The bridge was almost totally swept away by a flood event."……… The Blackwater began to flood the Town Park at around midnight, and began to flood Bridge Street at 1:00 am, having sufficient force to carry away large household objects. The river was observed to rise 10 feet in 40 minutes, with the peak occurring at about 06:30am. At the peak of the flood, the lower streets were beneath 12 feet of water, so that the only upper stories of houses were visible. Water receded from the floodplain at about 7pm that evening. The town was subjected to severe damage, including destruction of the bridge." (O' Sullivan, 1986)

"At *Mallow, we were informed of the death by drowning of a whole family occupying a cottage on the bank of the Blackwater, which also overflowed. Not yet has it been ascertained how many lives were lost."*(Anglo Celt, 10th November, 1853)

"The 1853 flood happened on 2nd November, the same day that Loreto Convent opened. In the history of Loreto Convent, this flood is described as causing enormous damage in Fermoy."(Avondhu, 8th March, 2007)

Estimated Flood Event Date: 31st December 1869

Great Flood At Mallow

Since the great flood which took place here on the 1st November 1853, and did great damage to life and property, such a flood as that of this day has not been witnessed in this town. A thaw set in yesterday and rain began to fall. From the time it commenced raining yesterday at four o' clock there was one continuous downpour until twelve o clock this day. Text was written on the Thursday before 3pm.

"The different tributaries of the Blackwater near the town have all overflowed their banks . The lower part of the town of Mallow is completely flooded up to the entrance to the steam mills, Bridge Street, and Gallows hill lane. The Spa Walk and Norcotts Lane are one sheet of water, and the flood has done considerable damage. The poor of the districts that were flooded have suffered very much. As I write, the water is still rising." (Irish Times, 31st December 1869)

Estimated Flood Event Date: 17th and 18th November 1916

"Disastrous flooding causing extensive damage".

"Flood waters rose rapidly, and by 4:00am Bridge Street, Bridewell Lane, St. Josephs Rd., Spa Walk, and Spa Terrace were flooded, along with the lower portions of Ballydaheen and Broom Lane on the South Bank. Water was 4.5 feet deep in Bridge St., with water reportedly running through the upper stories of the lower houses. Significant flow occurred across the bridge deck, such that pillars supporting the railings were torn up." (O' Sullivan, 1986)

Floods in Mallow

Large tracts of land around Mallow flooded to 6-9 ft. Town flooded: Clockhouse, Mallow Bridge, Lower Bridge St., flooded to 4-5 ft. Impossible to cross the river at Mallow. Most railway lines flooded and out of action. Crops damaged, Cattle drowned.(Cork Examiner, 18th November 1916)

Estimated Flood Event Date: 8th December 1916

.....*These records suggested that the worst event during the 20th century occurred on 8 December 1916 and the second worst on 2 November 1980*. (University College Cork, 2000).

The 1916 flood occurred on 8th December. Earlier that year on 18th November two soldiers, members of the 2nd and 5th Leicesters, were swept away from the bridge and lost their lives……The levels recorded in Fermoy for the 1916 flood put the flood level at Brian Boru Square at approximately the top of the window on what is now the Flower Shop, Deerpark Florist (about 2.2 metres). The predicted flood level for the 100-year flood is 2.5 metres at the same point. (Avondhu, 8th March, 2007)

Estimated Flood Event Date: 10th November 1941

Extensive Damage by Floods

Mallow town under several feet, rivers sweep away livestock, many roads impassable…..

The Flood Damage

Sheep rescued, UCC grounds, 6' at Mardyke, roads impassable, Mallow @ Bridge St. & Spa Walk, Blackwater Inches cattle lost, (Evening Echo, 10th November 1941)

The Floods

In Mallow isolated, Bridge St & Spa completely under water & impassable, William's Mills damaged . ……. Livestock drowned, lost or isolated

Amazing Scenes

Mallow evacuations, Fermoy flooded to several feet, worst since 1916.

Enormous damage done by floods in Munster area…….Mallow houses flooded, as bad as 1916, Macroom worst in 50 years, Fermoy extensive damage. (Cork Examiner, 11th November 1941)

Extensive flooding in the south

Worst flooding in 25 years Cork, evacuations in Bridge St area of Mallow,….many cattle sheep drowned on Blackwater. …….. county resembles a lake. NCR.(Irish Times, 11th November 1941).

Roofs as a refuge from floods in south

Listowel 50 people evacuated to hospital, 4 houses destroyed, some spent night on top of hay barns, Cork 26 people rescued from caravans, Inagh overflows into Ennistymon & low lying lands (Irish Independent, 12th November 1941).

Flood aftermath

Flood has subsided, description of relief work, £2,000 grain damaged. Worst since 12 Nov 1916 which was 2' higher, greatest flood on record was 1853 . (Cork Examiner, 14th November 1941)

Old Mallow floods recalled

Mallow evacuations, livestock swept away, Red Cross relief, £2,000 grain damage, not as bad as Nov 12 1916 & 1853. Fermoy worst since 1916 when 2 soldiers lost their lives. Now flooding of premises, sheep lost Kilmurry, Fermoy floods 3 hours after Mallow.(The Kerryman, 15th November 1941)

Estimated Flood Event Date: 12th August 1946

During the early morning, houses on Spa Walk were flooded as the Spa glen("the canal") overflowed. At 4pm the town was flooded, with Bridge Street being inundated by several feet of water. Water reached an average height of 12 feet on the racecourse. By 7am the following morning the water had receded. (O' Sullivan, 1986)

A local Fermoy flooding report (reference unknown) identified the 1946 event as 18 inches lower than the 1916 event in Fermoy. This report included photographs of the event in the town. From this direct evidence this flood has been ranked between the 1916 and 1980 events. In an attempt to better understand the relative magnitudes of the 1948 and 1946 events historic daily rainfall records were provided by OPW. High rainfall totals were evident for the 11 August 1946 with a notable maximum of 115.1mm *recorded in the Cork area. The 1946 event was in August and one may assume it was characterised by intense rainfall and runoff from a dry catchment.*

Estimated Flood Event Date: 17th March 1947

Cork: Midleton & mallow flooded by River Blackwater to 3 ft. in places.(Irish Times, 17th March 1947).

Estimated Flood Event Date: 2nd December 1948

The Town Park flooded to a depth such that the water reached the height of the crossbars of the hurling goalposts, suggesting a depth of flooding in the park of 2.5 metres. (O' Sullivan, 1986).

Estimated Flood Event Date: 5th and 6th December 1948

Bridge Street flooded at 7pm, to a greater depth than had occurred on the 2nd December. The Spa Glen Flooded during this event, increasing water levels in Bridge St. By midnight the flow across the bridge was so high that attempts to cross the bridge by boat had to be abandoned. Navigation Road was closed to traffic during the flood. Flooding occurred again the following day following a large thunderstorm, with houses in Ballydaheen being flooded up to 4 feet deep.(Babtie Group, 2003)

"In Mallow the low lying eastern portion of the town was completely isolated by flood waters resulting from the overflowing of the Blackwater. In Bridge Street the water rose to a depth of more than four feet. A house in the street partially collapsed. The back wall falling out into the town park, which was covered to a depth of between six and seven feet. (Irish Independent, 6th December 1948).

Estimated Flood Event Date: 25th October 1949

Ireland swept by rainstorm

Many streets in the centre of Cork temporarily flooded due to high tides and heavy rainfall, Town park in Mallow flooded, flooding outside Millstreet along the Blackwater river. (Cork Examiner, 26th October 1949).

Floods follow storm

"Parts of Mallow flooded to a depth of 3 feet, shops flooded in Fermoy, river Ilen flooded inundating large areas of farm land. (Cork Examiner, 27th October 1949).

4.6.5 Documented reports of extreme flood events for the reconstruction period 1926-1955

Based on historical reports and the information contained within them, the extreme flood events for the period between 1926 and 1955 were ranked in order of their estimated severity at Mallow as shown in Table 4.19. These floods were assigned a severity score of 3. Ranking of extreme events outside this period are included as they were used as the basis for ranking other events. The ranking of these flood events relate to the magnitude of the peak flow for each event. They do not refer to the daily mean flows.

Flood Date (approx.)	Rank	Estimated Level (OD Malin)
2nd November 1853*	1	52.50
5/6th December 1948	2	50.25
17th November 1916*	3	50.15
12th August 1946	4	50.05
10th November 1941	5	49.55
September 1628*	6	Not quantifiable
26th September 1875*	7	Not quantifiable
17th March 1947	8	Not quantifiable
31st December 1869*	9	Not quantifiable
2nd December 1948	10	Not quantifiable
17th November 1916*	11	Not quantifiable
25th October 1949	12	Not quantifiable

Table 4.19 Ranking of the extreme flood events prior to 1955. (* flood outside the period of flow reconstruction, but used to assign rankings)

4.6.6 Details of major events

The flood events that were classified as major events are as shown in Table 4.20. These floods were assigned a severity score of 2.

Flood Date (approx.)	Flood Date (approx.)
04/03/1846	30/01/1940
06/11/1845	16/02/1940
22/11/1892	23/02/1940
30/12/1869	20/11/1944
13/01/1925	13/08/1946
27/01/1927	08/01/1947
21/12/1927	05/01/1948
15/04/1928	03/12/1948
01/04/1931	26/10/1949
16/09/1935	05/11/1951
12/02/1936	28/12/1951
22/01/1937	01/03/1955
17/01/1937	13/12/1968

Table 4.20 Documented Major floods in the Munster Blackwater catchment prior to 1955

4.6.7 Details of minor events

The minor events that were recorded in the catchment were awarded a score of 1. Most of these events can be referenced in only local newspapers and give very little information about these events other than to state that there was flooding. While it is unlikely that these events will be clearly identifiable from the reconstructed series it is possible that they will be contained in the relevant peaks over threshold series.

4.7 Conclusion

The analysis of rainfall, temperature and flow data performed in this study highlighted a number of issues with the raw data that was collected. The extensive quality control and corrections that were applied to the data indicates that all data must be rigorously checked prior to use. This is especially true in the case of rainfall data which is the pivotal input variable for modelling. Many of the errors in the rainfall data could lead to the erroneous prediction of extreme floods that in fact did not actually occur. Flow data must also be closely scrutinised as it is the main variable that is used to calibrate the rainfall runoff models.

It is also important to emphasise the significance of the method used to calculate the potential evapotranspiration values for the HYSIM model. This allows a quick and simple means of using daily average temperatures to produce PE data that is specifically suited to rainfall runoff models and has wide reaching implications for future modelling of catchments in Ireland. The availability of this method also means that modellers do not have to rely on PE data that is only available from synoptic stations that have a limited spatial spread, but instead they can use other temperature records to generate this information. During the course of this study, the availability of rainfall and temperature records from the earliest monitoring sites such as Markree Castle, Armagh Observatory, and the Phoenix Park amongst climatological stations amongst others can be used to hindcast flows back to the mid-1800s based on actual gauged data as opposed to reliance on synthetic methods of producing meteorological data for inputs to rainfall runoff models. The application of documentary evidence of historical flows to validate hindcast flows is an approach that has rarely been used elsewhere and may also be the first step towards further development of such a method for Ireland.

5 RAINFALL RUNOFF MODELS: SELECTION AND APPLICATION IN RIVER FLOW RECONSTRUCTION

5.1 Review of Types of Hydrological Models

5.1.1 Overview of Selection Process

An important part of this research is the selection of a suitable model (or models) for the reconstruction of historical river flows. Before commencing any modelling it was deemed necessary to perform a detailed study of the models that are available, and more importantly, those that are relevant to this study. It soon became clear that there are numerous hydrological models available, and only those most widely used were selected for further scrutiny. The model selection process involved a literature review of the wide range of hydrological models that are in use around the world.

5.1.2 What is a Hydrological Model?

A hydrological model is a mathematical model used to simulate streamflow or any other type of hydrological process. Hydrological models are deemed necessary due primarily to the limitations of measured data, but are also used to test hypothetical scenarios. Where there is no measured data available we must find a way to estimate/ extrapolate catchment behaviour from readily available data. The earliest and simplest of the hydrological models was the rational formula (Mulvaney, 1851) which related catchment area and rainfall to the resulting flow rate.

$$Q = CiA \quad \text{...........}\textbf{Equation 5.1}$$

Where :

Q = Peak discharge, (m^3/s)

C= Rational method runoff coefficient

i = Rainfall intensity, (mm/hour)

A = Drainage area, (hectares)

Since then, more sophisticated methods of deriving flow estimates have evolved. The following sections describe these methods, and the applicability of the methods to this research. Refsgaard and Knudsen (1996) distinguished between three classes of hydrological models; Empirical, Conceptual and Physically based models

5.1.3 Empirical Models

Empirical models are also known as "black box" or "metric" models. These are the most basic and simplest type of model. They establish a relationship between input and output and do not attempt to model individual hydrological processes. The distinguishing feature of this approach is that the models are entirely data-based and have only a limited representation of physical processes (if at all). Empirical models are purely based on finding a relationship between rainfall and runoff based on measured data. This is usually done using regression analysis. A simplified example of an empirical model is as follows:

$$\text{Runoff} = a(\text{rainfall})^b$$

Where a, and b are derived from a regression analysis between measured rainfall and runoff. Empirical models work well within the range of measured physical data upon which they are based, however beyond the range of measured data, the physical significance is lost. The main disadvantage of these types of models is that they do not represent the whole hydrograph. For example, many empirical models will only provide the peak flow.

5.1.4 Conceptual-Empirical Models

The next degree of model complexity is the Conceptual-Empirical model. These models represent natural processes such as interception, infiltration, evaporation, surface and subsurface runoff separately. Based on classical soil moisture accounting principles, conceptual rainfall runoff models typically transform rainfall into catchment runoff by cascading the inputs through a series of conceptual reservoirs (stores) which are depleted and recharged. Effectively they are continuous volume accounting models based on the water balance in the catchment. Each conceptual store only bears an idealised physical resemblance to real reservoir processes and these techniques do not account for momentum/energy processes. Each element of the model is generally described by a non-linear store with an equation for outflow:

$$S = K * Qn \quad \textbf{………..Equation 5.3}$$

Where S is storage, Q is outflow, and K and n are model parameters that control the performance of the model. Parameters of conceptual models are estimated by optimisation against measured data. Conceptual models are defined by their parameters and can be further classified as Lumped, Semi-distributed or Distributed models depending on how the catchment is divided up (conceptualised). Lumped Conceptual models are represented by parameters that are averaged across a catchment treated as a single unit, whereas Distributed Conceptual models incorporate spatial variability within the catchment at many locations. At the most sophisticated level, rainfall runoff models may be fully distributed on a grid based pattern; that is, runoff is estimated for each grid and then accumulated to estimate total river flows. This approach is well suited for use with high resolution gridded input data; for example, Digital Terrain Models (DTMs), and weather radar data.

A lumped model is one in which the spatial variations of catchment characteristics are generally ignored. Precipitation is considered to be spatially uniform throughout the catchment and average values of catchment characteristics do not vary within the catchment, neither do they represent spatial variability in physical features (such as slope, vegetation, topography etc.) of hydrological processes and usually involve a certain degree of empiricism (i.e. they may require measured flow data for calibration). Hence, the results produced by these models display the average catchment conditions. The basis of lumped models is the equation of continuity that is the water balance equation. These models attempt to treat the catchment as a single unit with a single rainfall input value averaged across the catchment, usually using thiessen polygons. The streamflow is calculated at a single point, the catchment outfall. This type of model generally has the minimal data requirements of rainfall, potential evapotranspiration (or temperature), and streamflow (for calibration purposes), and where the desired output is streamflow only, they can perform almost as well as fully distributed models (Beven, 2000). Lumped conceptual models are considered to provide the best balance of model complexity with data availability.

The parameters of distributed models are allowed to fully vary in space, at high resolution. The catchment is divided (discretised) into a large number of elements, or grid squares, and the state equations are solved for each of the grid squares. Therefore distributed models can incorporate a variety of spatially varying land and rainfall characteristics. Distributed models can therefore predict streamflow at multiple points along a river. They generally require large amounts of data, (that are often unavailable), but where distributed models can be used they provide the highest degree of accuracy. Distributed models will not be used in this project due to their high degree of complexity and input data demands.

The parameters of semi-distributed models are partially allowed to vary in space by dividing the basin into a number of smaller sub-catchments. They approximately fall between lumped and distributed models in terms of complexity, and are often referred to as simplified distributed.

5.1.5 Physically Based / Process Based Models

Physically based models, also known as "process" or "complex conceptual" models attempt to mimic hydrological behaviour observed in the real world. These models are based on the fundamental physics and governing equations of water flow over, and through soil and vegetation. They are intended to minimise the need for calibration based on measured data. These models are based on complex physical theory, and require a large amount of data and computational time. The hydrological processes are represented by non-linear partial differential equations. These include partial differential methods, finite element methods, integral difference, and boundary integral methods.

5.1.6 Probablistic and Deterministic Representations

A further layer of distinction between models is whether they are deterministic or probabilistic (stochastic). The vast majority of models are deterministic, meaning that a single set of input parameters are used to produce a single result. Probabilistic models allow for a certain degree of randomness or uncertainty in the possible outcomes due to the uncertainty in input variables, boundary conditions or parameters. In general, if the model output variables are associated with some sort of variance or other measure of predictive dispersion, it is a probabilistic model.

5.1.7 Comparison of Lumped, Semi-distributed, and Distributed models

Table 5.1 is intended as a general summary of the features of the three types of model discussed above. It was decided that the focus of this study would be on lumped conceptual rainfall-runoff models. Unlike physically based models, conceptual models do not require large amounts of catchment topographical data nor do they have onerous meteorological input data requirements. They are simple models but are still more sophisticated and flexible than empirical models.

	Lumped	Semi-distributed	Distributed
Spatial variations	Not allowed	Partially allowed	Grid based
Data requirements	Minimal	Medium	Extensive
Representation of physical features	Limited	Partial	Detailed
Accuracy	good	Good/very good	Excellent
Model set-up	Easy	Medium	Difficult

Table 5.1 Summary of lumped, Semi-distributed, distributed models

5.2 Model Selection Process

The first step in the model selection process was a literature review of all the lumped conceptual models that were generally available. This review was used to assess the characteristics of each model, its data requirements, fields of application, and other performance features. For the initial selection process the models were assessed against the following criteria:

- Must be a lumped conceptual model;
- Must be low in cost (Is it free or readily available);
- Must be capable of continuous modelling (as opposed to event focused);
- Must be flexible from the point of view of temporal scale (hourly, daily, monthly etc.);
- Must be able to operate with limited data;
- Must have a parameter calibration functionality;
- Must be easy to learn and use;
- Must operate over a spatial scale that fits within the Irish context;
- Must have documentation provided (user's manual etc.);
- Must be implemented in software or spreadsheet form;
- Should be widely used in the hydrological community;
- Should have well documented reports of model testing and validation.

After the initial review of literature, the following conceptual rainfall runoff models (Table 5.2) were selected for closer examination.

Lumped Conceptual Rainfall Runoff Models		
HBV Light (Seibert, 2005)	IHACRES(Jakeman et al 1990)	WATBAL (DHI, 1986)
SWAT	SIMHYD	MIKE NAM (DHI)
AWBM (Boughton, 2005)	DrainMod (Skaggs, 1980)	SMAR
TANK (Sugawara, 1995)		

Table 5.2 Shortlist of the initial lumped conceptual rainfall-runoff models examined.

The initial list of models was further reduced after the elimination of models for different reasons. Some were eliminated because they are not yet widely used and therefore have not been tested or implemented in software. More models were eliminated because of the prohibitive cost of obtaining a license. Eventually the list was reduced to six models for detailed examination.

5.2.1 Second Phase of Model Selection

The set of models selected for more detailed examination to determine which would be the best model in the context of this project were:

- HYSIM
- IHACRES
- MIKE NAM
- WATBAL
- SWAT
- SIMHYD

A summary of the comparative features of each model is shown in Table 5.3. The preferred lumped model chosen was HYSIM. It is the UK Environment Agency's chosen hydrological model, and is also widely used within the Geography Department of NUI Maynooth. HYSIM has been used for modelling the future impacts of climate change on catchment hydrology in the Blackwater catchment under other studies (Murphy and Charlton 2008), and it is envisaged that any results from this study can be easily incorporated into those studies if required. HYSIM has been used for a variety of hydrological applications including assessing the impacts of climate change on the hydrological cycle (Pilling and Jones, 1999; Charlton and Moore, 2003; Murphy et al., 2006; Sweeney, 2003). There is also evidence of it successful use in the reconstruction of historical flows in the UK (Jones et al., 2006).

It also has a very detailed and easy-to-read user manual, and the user interface is easy to navigate. An added advantage of HYSIM is that it can be linked to the proprietary software AutoSim. AutoSim has the capacity to generate Monte Carlo simulations of HYSIM model parameters and automatically run these simulations within HYSIM for the purposes of analysing model uncertainty.

The second choice of lumped conceptual model is IHACRES. It is one of the most used hydrological modelling packages in Australia, and was developed in conjunction with the Centre for Ecology and Hydrology (CEH). Its uses are widely documented, and it is supplied with a comprehensive user manual with worked examples included. The package also boasts a parameter optimisation tool. There are also many other packages that have been developed by the Australian National University that can be interlinked with IHACRES. The IHACRES model can use unit hydrograph methods for the generation of continuous flow time series. The unit hydrograph approach would be seen to offer a major advantage in that it can be used with limited amounts of data. This will be particularly useful when modelling historical flows with limited rainfall and PET data. The following sections describe the model structures of the two chosen models and details the process of calibration and validation of each.

	LUMPED CONCEPTUAL RAINFALL-RUNOFF MODELS					
	HYSIM	**IHACRES**	**MIKE NAM**	**WATBAL**	**SWAT**	**SIMHYD**
Temporal Scale	hh/dd/mm/yy	hh/dd/mm/yy		dd/yy	Day +	
Spatial Scale	Small/Med/Large	Small/Med/Large		Small/Med/Large	Medium +	
Inputs	Rainfall, PET	(a)Rainfall (b) Temperature (used to get evapotranspiration), (c) Streamflow (for calibration)	(a) Rainfall (b) PET (c) some parameters from PCDs. (d) Area, topography, soil values, (e) Streamflow (calibration).	(a)Rainfall (b) PET (can be got from temperature, average monthly humidity and sunshine) and (c) Streamflow.		(a) Rainfall (b) PET.
Outputs	Streamflow	Streamflow	Streamflow	Streamflow, PET, ET, Albedo, effective precipitation, surface and subsurface runoff.	(a) Streamflow	Streamflow
Cost	Available under license	Free	Must be purchased with MIKE	Free	Free	
Set-up Time	Short	Short		Short	Long	
Expertise required	Low	Low	Low	Low	High	
Tech Support	In house NUIM experience	None	from DHI	None	Yes	
Documentation	Good	Good	little online information	Good	Good	little information
Ease of use	Easy	Easy		Easy	Difficult	
Extent of usage	Ireland, Scotland, England	Australia, UK Asia	Widespread		Medium	All over Australia
Subcatchments	Yes (up to three)	One at a time				
Linkages	Aquator	CatchmentSIM (not free)			AVSWAT	
Advantages	(a) Good in-house knowledge (b) Parameter Optimisation (c) Snowmelt option (d) Rainfall editing tool	(a) Easy to use (b) Minimal Inputs c) Widely used and tested (d) UH approach (e) Parameter optimisation (f) goodness of fit tool (g) Allows baseflow separation (h) temperature to calculated ET.	(a) moderate data requirements, (b)	(a) Developed for climate change (b) Optimisation of some parameters.	(a) comprehensive model structure, AVSWAT has a GUI	(a) easy to calibrate
Disadvantages	no uncertainty analysis	No snowmelt component		(a) Empirical Parameters	Extensive data demand/ limited available information on testing of the model.	
Uncertainty	No	no				
No. of modules	2 Subroutines					
No.of Stores	7 Stores		12 parameters (3 fixed by the user, 9 optimised)	Storage is lumped as a single bucket		7 parameters

Table 5.3 Summary of features of the Lumped Conceptual models examined.

5.3 HYSIM (Version 5.00) Hydrological Simulation Model

HYSIM was originally proposed by Manley in 1978 and was redeveloped under a SNIFFER project (2001) specifically for use in Scottish conditions. HYSIM has been recently adopted by The UK Environment Agency as their national standard rainfall/runoff model. It uses rainfall and potential evapotranspiration data to simulate river streamflow, and requires flow inputs for the purposes of model calibration. It comprises a linked set of stores as shown in Figure 5.1.

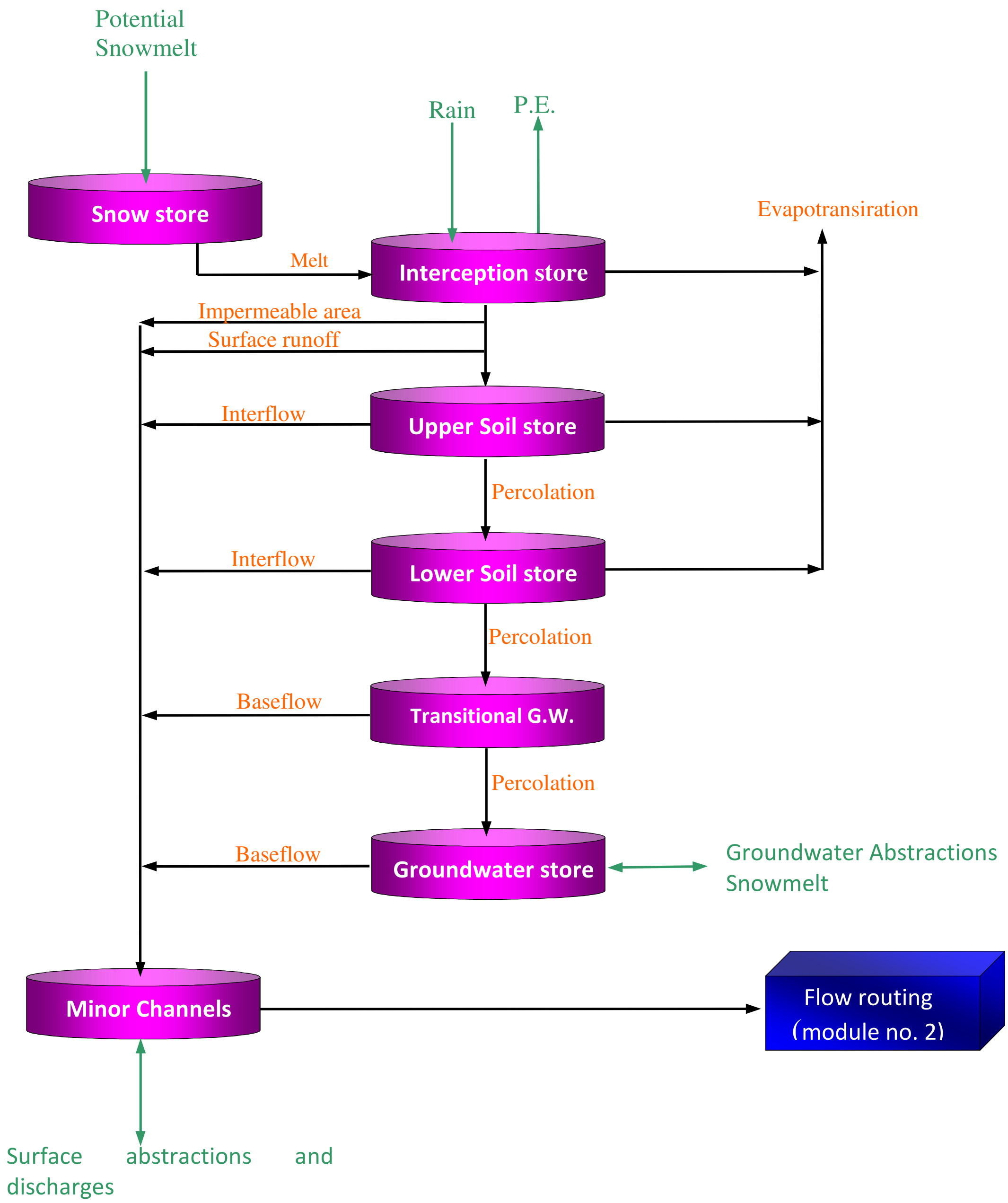


Figure 5.1 Schematic of the HYSIM model

Seven natural stores are employed to represent catchment hydrology. The main components of the model are the upper and lower soil stores, with the works of Brooks and Corey (1964) employed to represent the variation of effective permeability and capillary suction with changes in moisture content. A full description of the model and its structure is given in Murphy et al. (2006).

The capacity of each store, the maximum rate of transfer between them and the equations which govern the transfer processes are all defined by time invariant parameters. The volumes in each store and the rates of transfer vary with time. The model is built around two modules (sub-routines); the first of these simulates catchment hydrology while the second simulates channel hydraulics (performs the hydraulic routing calculations).

The module representing catchment hydrology comprises a linked set of stores. In relation to the hydrology module, seven natural stores are represented. These include (i) snow storage, (ii) interception storage, from which evaporation takes place at the potential rate, (iii) the upper soil horizon, (iv) the lower soil horizon, (v) transitional groundwater, (vi)groundwater and (vii) minor channel storage. The model can be divided into sub-catchments, but this number is limited to three, and these can then be combined by cascading the outputs from each.

HYSIM has been used in Europe, Africa, South America and Asia for the purposes of flow naturalisation, assessment of the conjunctive use of surface and groundwater, flood studies, both independently and with hydraulic models, groundwater studies, both independently and with hydrogeological models, and most importantly, studying effects of climate change (Murphy and Charlton, 2008).

The strengths of the HYSIM model and software are as follows:

- Includes a very useful rainfall editor for infilling of missing data,
- Graphics facilities include plotting of data, observed and simulated flows and double-mass plots. As well as on-screen plotting the graphs can be sent to a printer or to Windows Metafile format files.
- It has a built-in parameter optimisation algorithm.
- It has tools for measuring goodness of fit (accuracy summaries).
- It includes a snowmelt option (if required)

- The catchment may be split into up to three sub-catchments.
- Calibrating the model with daily data but studying major floods using hourly data. It is possible to output values of moisture storage on a daily basis and use these to restart the model on a particular day. One could then simulate a flood flow for a few days in hourly time steps.
- Outputting intermediate values of calculations. This enables HYSIM to be used with other more specialised models. For example runoff could be used with a hydraulic model for detailed studies of flood alleviation measures or the percolation to groundwater could be used as input to a hydrogeological model.
- The user manual is very easy to follow.
- Its outputs can be used in automation software such as AutoSim.

5.4 Parameterisation and Calibration of the HYSIM Model

Before reconstruction of historical flows using HYSIM could be performed, it was first necessary to calibrate the model by obtaining a suitably behavioural set of parameters. The parameters for the HYSIM model are divided into two main categories, physical parameters and process (free) parameters. The physical parameters are grouped under the heading of hydraulic parameters within HYSIM and represent the parameters that are physically measurable at the site of interest, their values being definite. Examples of the hydraulic parameters are channel top width, depth, and gradient. The process parameters are grouped under the heading of hydrological parameters within HYSIM and are not so easy to measure directly and initial estimates of the parameters must be based on best practice guidance provided by the model developers. Examples of the hydrological parameters are the lateral inflow rates from soils. Once the physical parameters were identified, initial estimates of the hydrological (process) parameters were made and then the HYSIM model was run in deterministic mode to refine the parameter set. A description of the parameters used in the HYSIM model is given in the following sections.

5.4.1 Hydraulic Parameters for the HYSIM Model (Physical Parameters)

The hydraulic parameters relate to the channel geometry in the proximity of the Kilavullen Gauge and can either be measured directly or estimated from existing sources. The Hydraulic Parameters of the HYSIM model are as follows:

Channel Top Width

Distance between top of bank on either side of the river. The average Channel Top width as measured by the local area OPW hydrometric technician was approximately 30 metres.

Channel Base Width

The average base width of the river in the proximity of the gauge was estimated by the technician to be approximately 10 metres.

Channel Depth

The Channel Depth at the centre of the river was estimated by the OPW area technician to be approximately 6 metres.

Channel Roughness

The channel roughness (also known as Manning's n) is a commonly used parameter in hydraulic modelling. There is no specific method for calculation of roughness however it can be estimated from tables once the on-site conditions are known. Tables contained in Chow (1959) are used to make estimates of the roughness based on the conditions that exist in the channel. For a clean straight full stage river with no riffles or deep pools, a roughness of 0.03 may be assumed. This roughness value is commonly used in hydraulic modelling in Ireland as a first iteration in calculating channel roughness.

Reach Gradient

The reach gradient was calculated as the slope of the river between Kilavullen and the confluence of the Blackwater with the first major upstream tributary, the Allow. The distance between the two points was 12.8 kilometres and the elevation difference (from the DTM) was 21.12 metres. This gives a reach gradient of 1.65 m/km.

Flood Plain Width

At Kilavullen the right bank of the river is enclosed by a vertical rock outcrop, and effectively there is no floodplain on that side of the river. On the left bank the floodplain extends approximately 200 metres across pasture grassland. From information contained in hydraulic modelling reports for the Kilavullen gauge it was noted that in high flows the bridge may be bypassed by out of bank flow, over this floodplain. The floodplain width was therefore taken to be the average of the floodplain widths on each bank. The floodplain width was taken to be 100 metres.

Floodplain Roughness

On the right bank of the river, trees and scrub grow above bank level. From Chow (1959) the roughness here is estimated to be 0.07. On the left bank, the floodplain consists of pasture. Again with reference to Chow, the floodplain roughness on this bank is estimated as 0.03. The average of the two floodplain roughness values was taken to be the representative floodplain roughness at the Kilavullen gauge and was set at 0.05.

Reach Length

The reach length was measured as the length of river between Kilavullen and the confluence of the Blackwater with the first major upstream tributary, the Allow. The distance between the two points was 12.8 kilometres.

5.4.2 Hydrological Parameters

The values for the hydrological parameters were estimated first from tables and information contained in the HYSIM User Manual (Manley, 2006). This information was used as a first estimate for each parameter. These parameters were subsequently refined as part of the calibration stage of the modelling process. The Initial Hydrological Parameters were estimated from knowledge gained in the description of the catchment (Chapter 3).They were initially set as follows:

Interception Storage

Typically the range of values for Interception Storage varies from 1.0mm for grassland and urban areas up to 5.0mm for woodland. Initially the interception storage was set at 2.0mm.

Impermeable Proportion

The Impermeable proportion of the catchment is made up of surfaces such as roads, car parks, and other paved areas. It also includes exposed rock and some very impermeable soil types. The value of Impermeable Proportion varies between 0.02 for rural areas up to 0.2 for urbanised areas. For the purposes of this project the initial estimate of Impermeable Proportion was set at 0.1.

Time to Peak – Minor Channels

Based on the equation given in the Flood Studies Report (NERC, 1975), the Time to peak for minor channels is given by:

$$T_P = 2.8\left(\frac{L}{\sqrt{S}}\right)^{0.47}$$ **............Equation 5.4**

Where: L = Stream length

S = Stream slope

The time to peak for the main tributaries above Kilavullen were calculated using this formula. Using the average time to peak for the Owentaraglin, Allow, Finnow, Awbeg, and the Clyda, the five were averaged to give an initial estimate of T_p of 11.8 hours.

Rooting Depth

The Soil Rooting Depth is the parameter that determines the capacity of the upper and lower soil storages. It generally varies between 500mm and 1,000mm for grassland, but can be as high as 5,000mm for woodland.

Pore Size Distribution Index (PSDI)

The PSDI is considered to be one of the more important parameters in the model. It is the parameter that controls the response of soils. The initial estimate for the PSDI was based on the hydrological grouping of soil types by Teagasc (2009) which shows that the soil types within the Kilavullen catchment vary between Peat and Loam. An initial value for the PSDI was chosen as 0.20. Details provided in the HYSIM user manual give guidance on the choice of value for the PSDI.

Soil Texture	Clay Content (%)	PSDI	Bubbling Pressure (mm)	Permeability mm/hr	Porosity	Residual Saturation
Peat	0	.50	100	500	.70	.10
Sand	3	.25	120	630	.40	.10
Loamy Sand	6	.23	90	560	.41	.10
Sandy Loam	9	.20	220	125	.44	.15
Silt Loam	14	.19	80	26	.49	.15
Loam	19	.18	500	25	.45	.15
Sandy Clay Loam	28	.14	300	23	.42	.15
Silty Clay Loam	34	.13	360	6	.48	.20
Clay Loam	34	.12	630	9	.48	.20
Sandy Clay	43	.10	150	8	.43	.20
Silty Clay	49	.10	490	4	.49	.20
Clay	63	.09	410	4	.48	.25

Notes:

1. These values are based on experimental data. Some of them are vary in a way which makes it difficult to estimate a suitable 'average' when several soil types are involved. For example, in the case of 'bubbling pressure', a default value of 250 should be used unless the catchment is clearly 100% of a particular type.

2. The 'Clay content' and 'Residual saturation' figures are not used by HYSIM but are included for completeness.

Table 5.4 Relationship between soil texture and pore size distribution index (Source: Manley, 2006)

Saturated Permeability at the Horizon Boundary

The saturated permeability at the horizon boundary controls the rate at which moisture moves between the upper and lower horizons. Its value can range from 5.0 mm/hr in clay soil up to 200.0 mm/hr in sandy soils. The HYSIM user manual recommends that the default starting value of 10 $mm.hr^{-1}$ is normally satisfactory. This parameter was then adjusted during the calibration process.

Saturated Permeability at the Base of the Lower Horizon

This parameter controls the rate at which moisture leaves the soil layers. The general range of values for this parameter is from 1.0 mm/hr for heavy soils up to 100.0 mm/hr or more for sandy or gravely soils. The HYSIM user manual recommends that the default 10 $mm.hr^{-1}$ is suitable as an initial estimate. This parameter is normally adjusted during the calibration process.

Interflow Run-off from the Upper Horizon at Saturation

This parameter controls the direct, or lateral, run-off from the upper soil horizon. It allows for movement of the moisture either directly to channels, in riparian areas, or to land drains in other areas. The HYSIM user manual recommends that the default value of 10 mm/hr should be used, and the parameter is then adjusted during the calibration process.

Interflow Run-off from the Lower Horizon at Saturation

This parameter controls the direct run-off from the lower horizon. Initially it can be set equal to the interflow rate from the upper horizon (10mm/hr) and adjusted during calibration.

Groundwater recession

The value of this parameter can be assessed by studying periods in a dry summer when little or no rain has fallen. Its value is given by:

$$\left(\frac{q_2}{q_1}\right)^{\frac{1}{m}} \quad \textbf{...........Equation 5.5}$$

where q_1 and q_2 are the discharge values at the start and end of the dry period and m is the length of the period in months. Where the natural recession rate is complicated by groundwater abstractions and/or discharges to the rivers the following is preferred:

$$\left(\frac{q_2 - a + b}{q_1 - a + b}\right)^{\frac{1}{m}} \quad \textbf{...........Equation 5.6}$$

where a is the net sewage discharge over the period being studied and b is the abstraction rate from groundwater, both these figures being given in the same units as the river flow. If there is no groundwater this parameter should have the value of zero.

Precipitation Correction Factor

This parameter is adjusted to allow for the fact that the rain gauges used may over- or underestimate the true catchment rainfall. As a standard rain gauge collects less than a ground level gauge this parameter is normally given the value of 1.04. This parameter used the value of 1.04 as an initial estimate with the expectation that its value would rise in the calibration process due to the wide variation in rain gauge heights used in this project.

Potential Evapotranspiration Correction Factor

Because the measurement of potential evapotranspiration is less accurate than that of rainfall, it may be preferable to adjust this factor to obtain a water balance. The choice of which to use is discussed further in the Model chapter under 'Single parameter determination'. For the calibration of the model the PE correction factor remained at the default value of 1.0.

Sub-catchment Area

This is the area of the sub-catchment in square kilometres, which for the Kilavullen catchment is 1,256km^2.

5.4.3 Calibration of the HYSIM model

The choice of calibration period is important in the calibration of a hydrological model. It must ensure that periods of both high and low flows are captured so that the model will be able to replicate these conditions at other times in the modelling process. A split sample procedure was adopted for calibration and validation. The calibration period for the HYSIM model was chosen as extending from 01/10/1955 to 31/12/1991, a total of 35 years. This left 18 years for validation of the model which effectively comprised a 2/3rd to 1/3rd split for calibration and validation. This period was selected so that the model could be trained on as much variability in streamflow as possible. Furthermore, the 20 years 1990–2009 present some of the largest flood peaks on record in Ireland, such as the November 2009 floods in the Blackwater catchment.

This calibration period was chosen for the following reasons:

(a) Because the model will be expected to hindcast flow conditions in the catchment, the earliest part of the gauged flow record had to be included. This ensures that the period over which the model is extended backwards in time was as short as possible.

(b) In order to capture the drought conditions experienced in 1975 and 1976, and the flood rich years of 1980 and 1988 the calibration period was required to take in these periods.

(c) Under the Flood Studies Update research programme, the gauge at Kilavullen has been assigned a rating curve type B classification for the period from 1955-1972, and an A2 classification from 1972-2009. It was important to include a sizeable portion of the period that was assigned an A2 classification to ensure that the large events used in the calibration stage were accurately measured so that the model will also recreate high flows accurately.

When calibrating the model, the initial estimated input parameters as described in section 5.4.1 and 5.4.2 were used as a starting point. The Hydraulic parameters remained unchanged seeing as these were measured directly. The Hydraulic Parameters used for the modelling were as shown in Table 5.5:

HYSIM Hydraulic Parameters	*Value*
Channel Top Width (metres)	30
Channel Base Width (metres)	10
Channel Depth (metres)	6
Channel Roughness	0.03
Reach Gradient (m/km)	1.65
Floodplain Width (metres)	200
Floodplain Roughness	0.05
Reach Length (metres)	12,800

Table 5.5 Hydraulic Parameters for the HYSIM model.

The advanced hydrological parameters were also left unaltered, and the default values were used. These are shown in Table 5.6

HYSIM Advanced Hydrological Parameters	*Value*
Permeability – top upper horizon (mm/hr.)	1000
Proportion upper horizon	0.3
Ratio of Groundwater to surface catchment	1
Proportion of catchment with no groundwater.	0
Riparian proportion	0
Porosity	0.48
Bubbling Pressure	100
Transitional Recession (per month)	0.5
Prop. transitional	0
Interception factor	1
Snow factor	1.5
Groundwater pumping constant A	0
Groundwater pumping constant B	0
Snow threshold	0
Melt Rate	0

Table 5.6 Advanced Hydrological Parameters for the HYSIM model.

The basic hydrological parameters were therefore the focus of the optimisation process. The calibration effectively involved refinements to the hydrological parameters which were varied manually until the optimum value of the Nash-Sutcliffe efficiency was achieved. The Nash-Sutcliffe efficiency is calculated using:

$$Nash\ Sutcliffe\ Effeciency = 1 - \frac{\sum (Q_m - Q_o)^2}{\sum (Q_o - \overline{Q_o})^2}$$ **…Equation 5.7**

Where: Q_m is the modelled flow quantity

Q_o is the observed flow quantity

$\overline{Q_o}$ is the mean observed flow quantity.

The basic hydrological parameters that were manually varied to optimise the value of the Nash Sutcliffe efficiency were as shown in Table 5.7

HYSIM Basic Hydrological Parameters	*Final Value*
Interception Storage (mm)	4.8
Impermeable Proportion	0.13
Time to Peak - Minor Channels (hours)	19
Rooting Depth (mm)	1050
Pore Size Distribution Index	0.22
Groundwater Recession	0.91

Table 5.7 Basic Hydrological Parameters for the HYSIM model that were manually optimised.

The basic hydrological parameters that were calibrated using the optimisation routine within HYSIM were as shown in Table 5.8:

HYSIM Basic Hydrological Parameters	*Final Value*
Permeability – Horizon Boundary	33.273
Permeability – Base Lower Horizon	10.504
Interflow Upper	18.51
Interflow Lower	10.882
Precipitation Factor	1.125

Table 5.8 Basic Hydrological Parameters for the HYSIM model optimised using HYSIM.

The highest value of the N.S.E. achieved for the Daily Flow values at calibration stage was 87.95%. This corresponded to a N.S.E. value of 96.43% for the Monthly Flows, which indicates that the model fits the observed data extremely well. The model was then validated over the period from 1991-2009. The results for the calibration and validation stages of the HYSIM model are detailed in Table 5.9:

Period	Daily N.S.E	Monthly N.S.E.
Calibration (1955-1991)	87.95%	96.43%
Validation (1992-2009)	91.36%	97.48%
Overall Period (1955-2009)	89.35%	96.84%

Table 5.9 Results of the calibration and validation of the HYSIM model.

The results of the calibration and validation stage were very encouraging and show that the model is performing extremely well over the full period of record. The next step in the modelling process is to assess the best way to express the uncertainty associated with the parameters used in the modelling process.

5.4.4 Uncertainty and Equifinality

All models contain uncertainties. These uncertainties can be attributed to a number of sources including data uncertainty from model inputs such as rainfall, simplifications used in the model structure, and uncertainties from unknown initial conditions (Wagener et al, 2004). While we cannot be certain of the true value, we can attempt to define a range within which we are confident that it lies. This is usually done by defining a "best estimate", and then defining the upper and lower confidence intervals associated with this estimate. It is usual to use the 5% and 95% confidence intervals.

There are various methods of quantifying uncertainty. The most popular approach for hydrological modelling is the Generalised Likelihood Uncertainty Estimation (GLUE) method (Beven and Binley, 1992). In this project we will use the GLUE methodology to first define a best estimate time series of modelled flows and also to estimate the uncertainty associated with the use of different parameter sets when attempting to find the best estimate solution.

In hydrological modelling there is no single definite solution. Depending on the goodness-of-fit measure used, there will be a different best fit solution. There is no single optimal solution as different combinations of parameters may yield equally acceptable solutions. This phenomenon is known as equifinality and is effectively the recognition that there is no single optimum parameter set. The closest we can get to an "optimal" solution, is one that we can say we have the most confidence in.

5.4.5 Estimating model flows using the GLUE method

In the GLUE methodology, a Monte Carlo Random Sampling (MCRS) scheme is used to generate a large number of parameter combinations for a given model. The model is then run for each of these combinations of parameters, and the performance of each run is given a likelihood measure that is based on some sort of measure of goodness-of-fit. In many cases this will be the Nash Sutcliffe Efficiency, and is termed the likelihood measure defined by:

$$L[M(\theta_i)|Y] = 1 - \frac{\sum (Q_m - Q_o)^2}{\sum \left(Q_o - \overline{Q_o}\right)^2} \quad \textbf{...........Equation 5.8}$$

Where $L[M(\theta_i)|Y]$ is the likelihood measure for the i-th model conditioned on the observations, Y.

A threshold value of the likelihood measure is then chosen. The parameter sets that are below this likelihood threshold are rejected as being non-behavioural and are given a likelihood of zero. The parameter sets that are above the threshold retain their likelihood measures and are allowed to contribute to the distribution of predictions.

The range of likelihood predictions are then weighted by their normalised likelihood measures such that $\Sigma L[M(\theta_i)] = 1$, where $M(\theta_i)$ now indicates the i-th Monte Carlo sample so that at any time step t, the mean weighted flow calculated from the Glue method is:

$$\overline{\overline{Q_t}} = \sum_{i=1}^{n} \mathrm{L}[\mathrm{M}(\theta_{\mathrm{i}})]\mathrm{Q}_{\mathrm{i.t}}$$

Where:

N is the number of behavioural models,

$Q_{i,t}$ is the value of the variable Q at time t for the i-th behavioural model

θ_i is the i^{th}set of model parameters,

$\overline{\overline{Q}}$ is the value of the variable Q at time *t* simulated by the model $M(\theta_i)$, and *L* is the likelihood measure.

In this work, a Monte Carlo Simulation was run which yielded 4,000 structurally different parameters sets. The parameters that were used to generate the parameter sets were those relating to soil water - groundwater interactions and the ranges that were defined for these parameters were those listed in Table 5.10

HYSIM Basic Hydrological Parameters generated from Monte Carlo Simulation	*Chosen Ranges for the Parameter Values*
Permeability – Horizon Boundary (PHB)	5-200
Permeability – Base Lower Horizon (PBL)	1-100
Interflow Upper (IUP)	5-200
Interflow Lower (ILO)	5-200
Groundwater Recession (GWR)	0.3-0.98

Table 5.10 Parameters used to generate 4,000 parameter sets by Monte Carlo Simulation

After the HYSIM model was run using all of these parameter sets, a threshold value for the likelihood measure (N.S.E.) was chosen as being 86.00%. This yielded a total of 684 behavioural parameter sets. The predictions for each run of the model were weighted by their normalised likelihood measures. For each time step the best estimate of the modelled flow was calculated by summing all of the weighted values of the predictions.

When compared against the observed flows for the calibration period (1955-1991) the Nash Sutcliffe efficiency for the daily flows estimated by the GLUE method was 87.64%, and 96.00% for the monthly flows (see Table 5.11).

Period	Daily N.S.E	Monthly N.S.E.
Calibration (1955-1991)	87.64%	96.00%
Validation (1992-2009)	91.74%	97.95%
Overall Period (1955-2009)	89.44%	96.81%

Table 5.11 Model Results using the GLUE method

The flows modelled using the GLUE method in HYSIM will be used for the remainder of this project, and are used to reconstruct the flow series between 1926 and 1956.

5.4.6 Estimating Prediction Uncertainty using the GLUE Method

Based on the methods outlined above, the weighted mean annual flow outputs and 5th and 95th percentile confidence bounds from HYSIM using the GLUE method are shown in Figure 5.2.

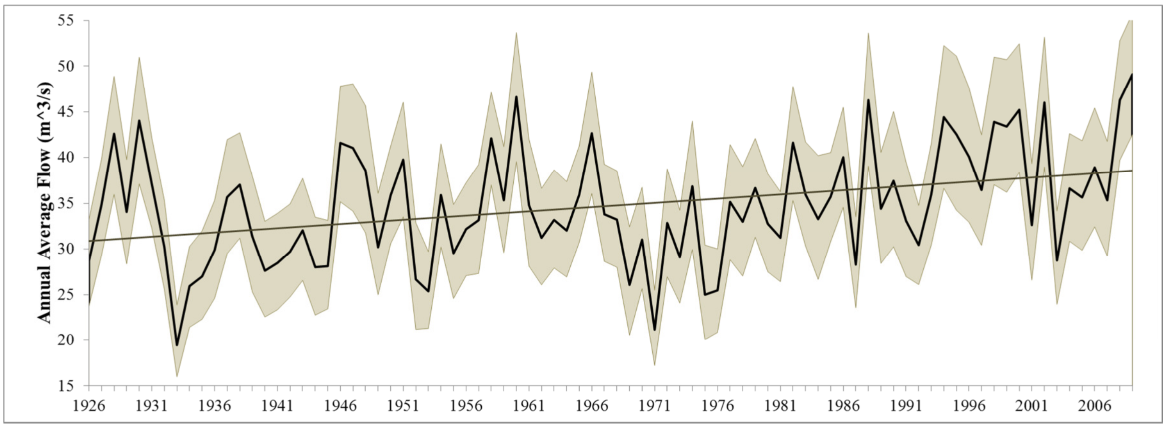


Figure 5.2 GLUE method applied to HYSIM annual average flows to predict 5% and 95% uncertainty bounds. The black line indicates the mean weighted average.

To examine the capability of the prediction intervals to capture the observed values, an index defined as the ratio of the number of observations falling within their respective prediction intervals to the total number of observations was used (Montanari, 2005). This index, henceforth referred to as the Monatanari index was found to be 100% for the annual average observed flows where all values fell within their respective confidence limits, showing that parameter uncertainty also captures the other sources of uncertainty in the model for annual flows. When the same analysis was applied to monthly flows it was found that 81% of the observed values fell within the parameter uncertainty interval, also indicating a satisfactory behaviour of the model.

Figure 5.3 shows an extract clipped from the daily flow series to illustrate the daily performance of the HYSIM model, and the uncertainty bounds that were calculated. It was found that 51% of all daily flows fell within these bounds showing that not all of the sources of uncertainty are covered by parameter uncertainty for daily flows.

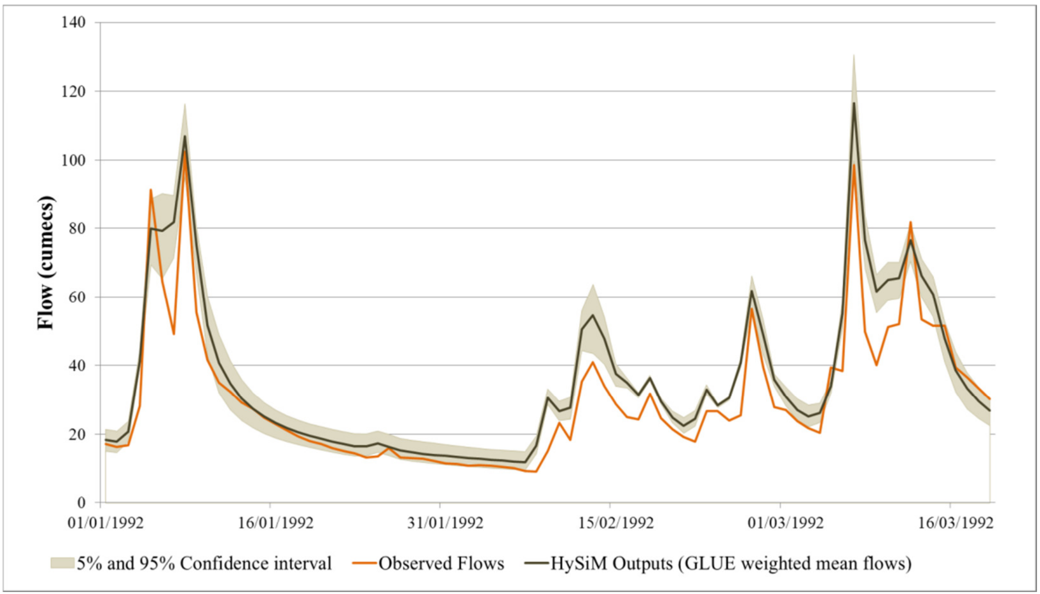


Figure 5.3 Uncertainty intervals for daily flows compared with observed flows.

The uncertainty bounds estimated by GLUE have been found to be sensitive to a number of factors such as the likelihood measure, and the threshold values employed (e.g., Viola et al., 2009). Furthermore, if the threshold value grows, the width of the uncertainty bounds and percentage of data captured by prediction limits will decrease. Thus the choice of the threshold value is important since it strongly influences the size of the uncertainty bounds (Bastola and Murphy, 2011).

5.5 IHACRES Model - Identification of unit Hydrographs And Component flows from Rainfalls, Evaporation and Streamflow data (PC Version, Version 1.02, September 2003)

The IHACRES model was also used to hindcast flows for the Kilavullen catchment for the purposes of comparison with the outputs of the HYSIM model. IHACRES was developed as a collaboration venture between CEH Wallingford and The Australian National University Canberra. It employs a transfer function/unit hydrograph approach to lumped hydrological modelling. The IHACRES model is a much simpler model than HYSIM, that requires only three inputs, observed flow (for calibration), precipitation and temperature which makes it well suited to modelling where data availability is limited and ideal for use in this research. It is suited to basins of all sizes and can accommodate time steps from a resolution of one minute upwards. Rainfall is converted to effective rainfall by a non-linear loss module, followed by a linear unit hydrograph (UH) module to convert effective rainfall to streamflow as shown in Figure 5.4. The rainfall filter introduces a soil storage variable and also, for longer simulation, uses temperature as an index of evapotranspiration.

IHACRES has been used in worldwide, but especially in Australia and the UK, and tested on catchments in the USA. A typical calibration period is about 3 years. These data must be in ASCII text format (comma, tab or space delimited). Its greatest strength is that it is very quick to set up and calibrate, but its other main strength is its simplicity, as it only requires rainfall and temperature for modelling. It also includes a parameter optimisation tool that quotes the measures of goodness of fit such as the Nash Sutcliffe Efficiency. It has been widely tested, but most reassuringly is its use in studies of the effects of climate change on catchment hydrology.

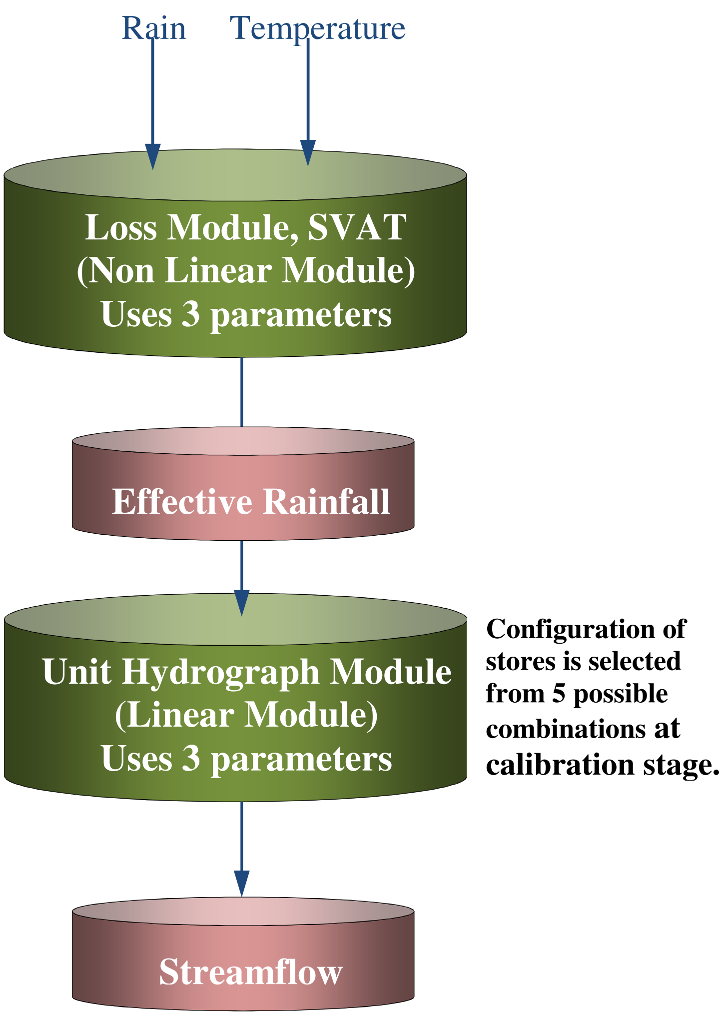


Figure 5.4 Schematic of the IHACRES modules

5.6 Parametrisation and Calibration of the IHACRES Model

The calibration period for the IHACRES model was chosen to be the same as that for the HYSIM model, namely 01/10/1955 to 31/12/1991. To date, generalised relationships between the IHACRES parameters and physical catchment descriptors have not been developed, and so the calibration stage relies solely on the optimisation routine within IHACRES. The parameters used in IHACRES are not physically measurable and are considered to be process parameters.

The calibration stage involves building the model structure for the linear and non-linear modules. The calibration period is the first detail to be entered. The linear module is then calibrated by a cross correlation tool that defines the delay between rainfall and streamflow. Here the delay was set at one time step (i.e. one day). The non-linear module is then calibrated by performing a grid search that searches through parameter space to find a best fit parameter set. Before performing the grid search the model structure must first be defined. In IHACRES six different structures can be accommodated. They are:

- A single exponential store;
- 2 exponential stores in series;
- 2 exponential stores and an instantaneous store in parallel;
- An exponential store and an instantaneous store in parallel;
- 2 exponential stores in parallel.

For this project, after sensitivity testing, the arrangement of 2 exponential stores and an instantaneous store in parallel was chosen as the preferred structure. The grid search can then be run to calibrate the parameters of the non-linear module. The non-linear module parameters and their recommended ranges are detailed in Table 5.12

Parameter	Value
Drying rate at reference temperature (tw)	2.0 - 30
Temperature Dependence of Drying Rate (f)	0 – 4.0
Reference Temperature	20 Celsius
Moisture threshold for producing flow (l)	0 - 30
Power on soil moisture (p)	0.0 – 1.0

Table 5.12 typical ranges for the parameters of the IHACRES non-linear module

The grid search is then run to optimise all of these parameters. Initial runs indicated that the Reference Temperature and the Moisture threshold for producing flow are very insensitive to change, and were set at their default values. Further runs of the grid search were used to converge on a best estimate for the model parameters. The final parameter set from the calibration stage is as shown in Tables 5.13 and 5.14.

Parameter	Value
Mass balance term (c)	0.007732
Drying rate at reference temperature (tw)	3.5
Temperature Dependence of Drying Rate (f)	2.0
Reference Temperature	20 Celsius
Moisture threshold for producing flow (l)	0
Power on soil moisture (p)	0.5

Table 5.13 Parameters of the non-linear module of the IHACRES model.

Parameter	Value
Recession Rate 1 (a^s)	-0.951
Recession Rate 2 (a^q)	-0.505
Peak Response 1 (β^s)	0.024
Peak Response 2 (β^q)	0.236
Peak Response 3 (β^3)	0.038
Time Constant 1 (τ^s)	19.991
Time Constant 2 (τ^q)	1.465
Volume Proportion 1 (υ^s)	0.485
Volume Proportion 2 (υ^q)	0.476
Volume Proportion 3 (υ^3)	0.038

Table 5.14 Parameters of the Linear Module of the IHACRES model.

Test Data	**Value**
P (mm/yr)	1236.98
Q (mm/yr)	845.28
Bias (mm/year)	4.48
Rel Bias	0.0053

Table 5.15 Summary Statistics for the calibration of the IHACRES model

These parameters were carried through for use in the simulation of historic flows. The other performance measures for the IHACRES model are detailed in Table 5.15

The IHACRES model was next run over the validation period from 1992-2009 and also for the overall period from 1955-2009. The results of the calibration and validation of the IHACRES model are shown in Table 5.16

Period	Daily N.S.E	Monthly N.S.E.
Calibration (1955-1991)	84.44%	90.60%
Validation (1992-2009)	88.07%	92.78%
Overall Period (1955-2009)	86.00%	91.54%

Table 5.16 IHACRES Model Results

5.7 Results of the Calibration-Validation Stages of Modelling and Conclusions

It is clear that the results from the HYSIM modelling are superior to those obtained from the IHACRES model. The HYSIM model outperforms the IHACRES model on both daily and monthly values. The plot of the annual average flows are shown in Figure 5.5.

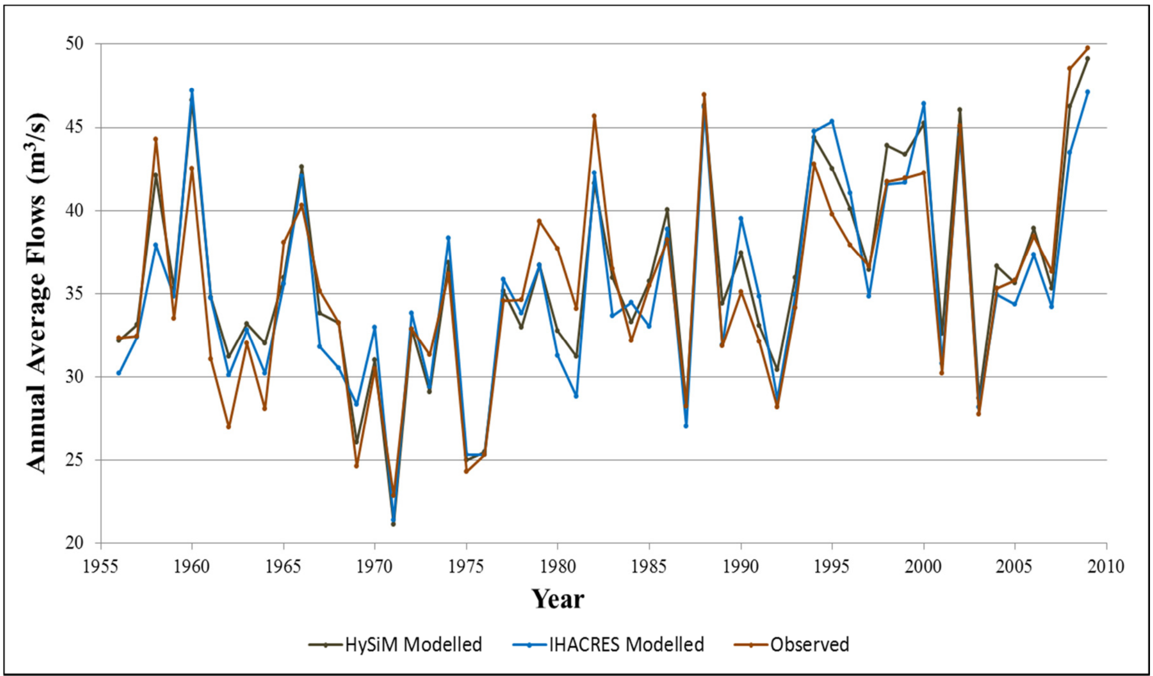


Figure 5.5 Annual Average Flows for the calibration and validation period – Observed and Modelled 1955-2009

In order to further assess the performance of the models the summary statistics for each model are compared with the observed flows for the period 1956-2009. The flows for 1955 are ignored in this analysis because only three months are available and so they would be not representative of the full range of flows for that year.

In addition to the Nash-Sutcliffe Efficiency, additional statistics were calculated for the models that were deemed to be good indicators of the performance, and these are shown in Table 5.17.

Nash-Sutcliffe Efficiency

The Nash-Sutcliffe efficiency was calculated for daily, monthly, seasonal (four seasons), and annual flows. The flow quantity that produced the highest N.S.E. was the monthly flow series at value of 96.81%.

Median of the Annual Maximum Series (QMED)

The QMED is a good indicator of the high flow characteristics of the catchment. It would appear from the results that high flows, in general may be underestimated by both models. The QMED for the HYSIM model underestimates by 10% whereas the IHACRES model underestimates QMED by 18.1%. The Annual Maximum (A-max) Series may not be fully representative of the high flow behaviour of the catchment because it does not take into account that there may be a number of large events in one year, but none in the another. A further measure of the high flow behaviour of the catchment that takes into account the full series of large events can be measured by reference to the peaks-over-threshold (POT) series.

Peaks-over-threshold Series using an average of 4 events per year (POT4)

The POT4 series is generated by taking on average the 4 largest events over the full period of record. The period from 1956-2009 contains 54 years of data, and thus we select the largest 216 daily mean flows for the period to generate the POT4 series. The threshold used is also a good measure of the high flow behaviour of the catchment. Again the results seem to show that the high flows are not fully represented by the models. The POT4 threshold is underestimated by 11.4% in the HYSIM model, and by 14.7% in the IHACRES model.

Daily Average Flow

The average of the full series of daily mean flows shows very good agreement with the observed flows. The largest variation out of the two models is 1.4% for the HYSIM model.

The 95 percentile Flow

The 95 percentile flow is a useful measure of the low flow behaviour of the catchment. It effectively represents the threshold above which 95% of all the flows in the catchment are seen to exceed. The HYSIM model underestimates the 95-percentile flow by 11.8% whereas the IHACRES model underestimates this statistic by just 4.5%.

Monthly Average Flows

From an examination of the average monthly flows over the full period, the months that show the greatest variation between the observed and modelled flow are July and August. The HYSIM model underestimates in these months by around 10% whereas the IHACRES model overestimates in these months by 25%.

The additional statistics assessed here show that while the models are not fully representing low and high flows, they are still within reasonable limits. The average flows are represented very well, and taken in conjunction with the high Nash-Sutcliffe Efficiencies for both models they are deemed to be performing as well as possible considering the sources of uncertainty already referred to. Table 5.17 details all of the flow statistics for the reconstructed flow series obtained from the HYSIM and IHACRES models. In summary, the HYSIM model is the better performer, however the results obtained by the IHACRES model show that for this simple model it yields extremely satisfactory results in replicating the long term flows within the catchment. It was decided to use the HYSIM model in all the analyses for trend in the following chapters. IHACRES is used as the secondary model to act as a backup where the HYSIM results were found to be suspicious. In this respect, the only flow statistic that was not deemed to give fully satisfactory results when compared to observed flows was the annual maximum series. It was therefore decided to analyse the POT4 series when studying high flow behaviour.

Measured Statistic	Observed 1956-2009	HYSIM 1956-2009	IHACRES 1956-2009
Daily N.S.E.	----	89.44%	86.00%
Monthly N.S.E.	----	96.81%	91.54%
Seasonal N.S.E. - Winter	----	92.77%	83.00%
Seasonal N.S.E. - Spring	----	83.42%	78.90%
Seasonal N.S.E. - Summer	----	81.40%	66.91%
Seasonal N.S.E. - Autumn	----	94.42%	82.82%
Annual N.S.E.	----	88.98%	80.62%
QMED (m^3/s)	233.20	210.75	190.95
Daily Average Flow (m^3/s)	35.44	35.94	35.33
Daily Standard Deviation	35.85	35.73	32.78
January Average (m^3/s)	64.98	68.08	61.33
February Average (m^3/s)	54.03	56.83	54.25
March Average (m^3/s)	41.13	44.80	41.80
April Average (m^3/s)	28.95	31.64	29.92
May Average (m^3/s)	21.47	22.36	23.84
June Average (m^3/s)	15.18	14.64	18.33
July Average (m^3/s)	12.70	10.93	16.66
August Average (m^3/s)	16.05	13.00	19.47
September Average (m^3/s)	20.91	19.19	23.42
October Average (m^3/s)	37.12	35.58	34.99
November Average (m^3/s)	51.51	51.32	45.41
December Average (m^3/s)	62.06	63.85	55.47
POT 4 Threshold (m^3/s)	152.61	135.16	130.16
No. of POT4 events recorded	233	229	238
95%ile flow (m^3/s)	5.52	4.87	5.27
Montanari Index – Annual Flows		100%	
Montanari Index Monthly Flows		81%	
Montanari Index – Daily Flows		51%	

Table 5.17 Summary Statistics for Observed and Modelled flows

6 TREND AND FREQUENCY ANALYSIS

6.1 Introduction to trend and flood frequency analysis

Detection of abrupt or gradual changes in hydrological records, and river discharge in particular, is of considerable scientific and practical importance, being fundamental for planning of future water resources and flood protection. Traditionally, design rules are based on the assumption of stationary hydrology, resulting in the principle that the past is the key to the future, which has a limited relevance in the field of climate change (Milly *et al*., 2008). If the stationarity assumption is not correct then the existing procedures for designing water-related structures: dams, dikes, etc. will have to be revised. Otherwise, systems, would be over or under-designed and might not serve their purpose adequately, or be over costly.

Changes in river flow can be caused directly by human activities such as urbanisation, storage (reservoirs), drainage systems, water abstraction, land-use changes or by natural catchment changes (e.g. natural changes in channel morphology), climate variability and problems linked to data such as, instrumental error, change in measurement techniques, etc. However, climate is the most important driver of the hydrological cycle. Since the climate system and water cycle are intimately linked, any change in one of the systems induces a change in another. Change in a series can occur in numerous ways: e.g. gradually (a trend), abruptly (a step-change). It may affect the mean, median, variance, autocorrelation, or almost any other aspect of data.

The purpose of trend testing is to determine if the values of a random variable generally increase (or decrease) over some period of time in statistical terms (Helsel and Hirsch, 1992). In this study, the period of record is extended by using reconstructed flows from two separate rainfall runoff models. These flows are used as the basis for the trend analysis described in this chapter.

6.2 Overview of Current Research in Trend Detection

As noted by Kundzewicz and Robson (2004) data are the backbone of any attempt to detect trend or other change in hydrological records with the identification of appropriate sites and quality assurance procedures essential for meaningful statistical analysis. By careful selection of index catchments a resilient measure of response to climate variability can be identified. Trend studies in the US (Lins and Slack, 1999; Douglas *et al*, 2000) and Canada (Adamowski and Bocci, 2001; Zhang *et al.,* 2001; Burn and Hag Elnur, 2002; Yue and Wang, 2002) have capitalised on networks of undisturbed, natural catchments. This task is more challenging for Ireland because of the high degree of heterogeneity in catchment geology, land use, climate, arterial drainage and peat extraction.

Detection of climate change at regional and local scales is inherently difficult because of the relatively weak climate change signal compared with large interannual variability of rainfall and river flows, the choice of index, spatial and temporal scale of aggregation, strengths and assumptions of statistical tests and significance testing and confounding factors all require careful consideration (Kundzewicz and Robson, 2004; Radziejewski and Kundzewicz, 2004; Legates *et al*., 2005; Svensson *et al,* 2005; Wilby *et al*., 2010; Fowler and Wilby, 2010).

- The choice of indices can be monthly, seasonal, annual, based on river flow or water levels, maxima, minima, N day totals, counts of peaks over thresholds, point or area average, based on individual records or pooled.
- Period of record has a huge bearing on derived trends where analysis of long records can refute the significance of trends from series of shorter duration that may be overly influenced by outliers or natural variability. The record length required to detect trends can vary depending on the strength of the trend, the variance about the trend, and the probability of type one and type two errors.
- The power of statistical tests to detect trends (monotonic or step change) can vary hugely and in the case of hydrological data assumptions of tests may be violated and increase the likelihood of false identification of trend.
- Factors such as changes in site instrumentation, observing or recording practices, land cover change, water abstraction, arterial drainage, channel engineering can all confound the detection and interpretation of trend.

The number of years of record needed to detect a statistically significant trend depends on: the strength of the trend; the amount of variance about the trend; the probability of erroneous detection (type 1 error); and the probability of missing a real trend (type 2 error). Preliminary estimates using data for river basins in the United States and United Kingdom suggest that statistically robust, climate driven trends in seasonal runoff are unlikely to be found until the second half of the 21st century (Ziegler *et al.*, 2005; Wilby, 2006). In Australian river basins an even greater change may be required for detection as the interannual variability of flows is twice that of Northern Hemisphere river basins (Chiew and McMahon, 1993). Detection time relationships can also be inverted to estimate the strength of trend required for detection by specified time horizons. For example, analysis of UK winter and annual precipitation totals suggests that changes of ~25% would be needed for detection by the 2020s in the most sensitive basins (such as the River Tyne). Although attribution of changes is not yet possible at regional scales, techniques are being developed for detection of trends in indices at river basin scales, and for estimating the time taken for specified anthropogenic climate change signals to emerge from climate variability (Fowler and Wilby, 2010).

6.3 The Trend Analysis Procedure

Before proceeding to perform formal statistical tests for trend, an Exploratory Data Analysis (EDA) is first carried out. It is used as a means of understanding and presenting the data in a visual way and usually comprises the use of plots and graphs to initially assess if there are any obvious trends or patterns in the data. EDA is furthermore used to identify other features of the data that could benefit from further investigation in the formal statistical testing phase.

The main stages of a statistical analysis of change in hydrological data include: (Kundzewicz, 2004)

- Decide what type of series/variable to test depending on the issue of interest (e.g. monthly averages, annual maxima, peaks-over-threshold (POT) series, etc.);
- Decide what type of changes are of interest (gradual or step change);
- Check out data assumptions (usually through exploratory data analysis);

- Select a statistical test. This means selecting a test statistic and selecting a method for evaluating significance levels;
- Evaluate significance levels;
- Investigate and interpret results.

Any statistical test includes (i) naming a null hypothesis, (ii) naming a test statistic and its distribution under the null hypothesis, (iii) naming a critical region for the test statistic in which, under the null hypothesis, the value of the test statistic falls with probability α, (iv) computing the test statistic from a sample, and (v) rejecting the null hypothesis or not according to whether the observed test statistic value falls in the critical region.

The choice of a significance level (α) is completely arbitrary (Barnett, 1983, 1991; Casella and Berger, 1990; Fisher 1958). An alternative way to conclude a test of hypotheses is to compare the p-value of the sample test statistic with a significance level (α). The p-value of the sample test statistic is the smallest level of significance for which we can reject H_0. In other words, the p-value of a statistical hypothesis test is the probability of getting a value of the test statistic as extreme as or more extreme than that observed by chance alone, if the null hypothesis H_0, is true. The p-value is compared with the actual significance level of our test and, if it is smaller, the result is significant. That is, if the null hypothesis were to be rejected at the 5% significance level, this would be reported as "$p<0.05$". The smaller it is, the more convincing is the rejection of the null hypothesis. It indicates the strength of evidence for say, rejecting the null hypothesis H_0, rather than simply concluding "Reject H_0" or "Do not reject H_0".

The p-value serves a valuable purpose in the evaluation and interpretation of research findings. It enables the researchers to set their own level of significance and to reject or accept the null hypothesis in accordance with their own criterion rather than that of fixed level of significance.

6.4 Types of Time Series/Variables to be Tested

It is important to consider carefully the form and frequency of the data that should be analysed. This usually depends on the focus of the study. For floods, the largest annual flow is often of interest; for droughts, it may be the duration of low flows. Selection of which stations to use in a study is also important (Kundzewicz & Robson, 2004). For example in order to study the climate change signature in river flow, data should ideally be taken from baseline rivers and should be of high quality and extend over a long period. Data should also be quality-controlled before commencing an analysis of change.

The main focus of this study is the analysis of flow time series, however for completeness trend analysis is also performed on annual rainfall and temperature data. The motivation behind the analysis of rainfall and temperature was to assess if the behaviour of these variables in the Kilavullen catchment were in keeping with that reported in the wider literature on the effects of climate change in Ireland, and also to understand the processes causing flood flows in the catchment. After the reconstruction of flows using rainfall runoff modelling, daily mean flow (DMF) series were available for the period from 1926-2009. This time series was used to produce monthly, seasonal, annual, annual maximum (Amax) and, peaks-over-threshold (POT) series.

6.4.1 Annual Temperatures

In this study, a cursory examination of Annual Temperatures is performed. Daily average temperatures were made available from Met Éireann. These daily averages were used to generate three separate time series;

(i) Annual Minima
(ii) Annual Averages
(iii) Annual Maxima

The main focus in the analysis of temperatures is the annual average series, as it gives a more complete description of the behaviour of temperatures over the full period of record, whereas the annual minima and maxima are only related to a single event per year.

6.4.2 Annual Rainfall Totals

Rainfall is the main driver of flood flows and so it is important to test for trends in rainfall totals from year to year. In this study, daily rainfall totals were collected for analysis. These were used to generate annual rainfall totals for each calendar year for the Kilavullen catchment. The annual rainfall total is generally used to define the climatic measure of rainfall, namely the standard period (1961-1990) annual average annual rainfall (SAAR).

6.4.3 Daily Mean Flow Series

The basic unit of flow used in the analysis of the data is the Daily Mean Flow (DMF) series. This is the average of the instantaneous flows measured at 15 minute intervals over each 24 hour period beginning at 12:00 midnight. DMF time series were used to calibrate and validate the HYSIM and IHACRES models to enable the hindcasting of historical flows back to 1926. For the purposes of this study the analysis is based on the modelled DMFs and the calendar year was used, as opposed to the hydrometric (water) year which runs from 1st October – 30th September. The hydrometric year is usually used because it is generally agreed that for most Irish catchments, this period contains the complete flood season of each year. For the purposes of this study we will be examining the long term behaviour of the catchment which should not be affected by the difference in choice of start and end dates for each year. Also, monthly and seasonal analysis will be carried out which is independent of the choice of calendar or hydrometric year.

6.4.4 Annual Flow Series

The Annual Flow Series uses the DMF series to generate the Average Annual Flow for each calendar year. As the name suggests it provides an insight to the average general behaviour of flows in each year without placing an emphasis on high or low flows.

6.4.5 Annual Maximum Flow Series (Amax)

The term Amax series usually refers to the maximum instantaneous flow in any hydrometric year. For the purposes of this study, the Annual Maximum (Amax) flow series will refer to the largest selected Daily Mean Flow (DMF) in each calendar year.

6.4.6 Seasonal Flows

For the purposes of this study analysis of winter, spring, summer, and autumn flows was performed. The calculation of Seasonal Flows used the average of the Daily Mean Flows over each season. The winter months are December (of the year before), January, and February. The spring months are March, April, and May, and so on for summer and autumn.

6.4.7 Monthly Flows

The monthly flows used in this study are calculated as the average of the daily mean flows for each given month. In the calibration stage of the rainfall runoff models, the monthly flows showed the best agreement with observed data and therefore any analysis based on the monthly flows can be deemed as the most robust.

6.4.8 Peaks over Threshold Flows

A peaks-over-threshold (POT) series consists of Daily Mean Flows above a selected threshold (Bayliss & Jones 1993). In any one year there may be a number of large flood events, whereas other years may not possess any notable event at all. Peaks-over-threshold series provide a more complete picture of the high flow behaviour in a catchment than the Amax series (Robson and Reed, 1999). They can be used to look at changes in flood frequency as well as flood magnitude and seasonality. For the analyses presented here, POT data have been standardised by selecting the threshold so that each data series averages four POT events per year and for brevity this series is known as the POT4 series. Preliminary analysis on observed data has shown that the threshold chosen for POT analysis based on an exceedance of four events per year approaches the type of flows that would be expected to produce flows to bankfull level and higher. The POT4 series effectively represents the flows that are associated with out of bank flows i.e. flood flows.

6.5 Exploratory Data Analysis Employed

Exploratory data analysis (EDA) is an advanced visual examination of the data and forms an integral part of any study of change. It involves using graphs to explore, understand and present data, and is an essential component of any statistical analysis. The first use of EDA is usually to examine the raw data in order to identify such features as data problems (outliers, gaps in the record, etc.); temporal patterns (e.g. trend or step-change, seasonality); and regional and spatial patterns. Exploratory data analysis also plays an important role in checking out test assumptions such as independence, or statistical distribution of data values. Common types of graph that can be useful for hydrological data series include histograms and normal probability plots, autocorrelation plots, scatter plots and smoothing curves. A well-conducted EDA is such a powerful tool that it can sometimes eliminate the need for a formal statistical analysis (Grubb and Robson, 2004). The following EDA techniques were used in this project:

- Time Series Plots
- Time Series Plots of Standardised Flows
- Histograms
- Locally Weighted Regression Smoothing (Loess)

6.6 Statistical Tests Used in the Trend Analysis

Statisticians have developed many test procedures for detecting any trend in hydrological time series. They are mainly classified as parametric and non-parametric. If any test depends on the form of parent distribution from which the sample is drawn, then the test is distribution free or non-parametric otherwise it is a parametric test. Non-parametric tests require few if any assumptions about the shapes of the underlying population distributions. Parametric tests make use of information consistent with interval scale measurement, whereas non-parametric tests typically make use of ordinal information only.

Non parametric tests are less powerful, because parametric tests use more of the information available in a set of data. Therefore, when the assumptions for a parametric test are met, it is preferable to use the parametric test rather than a non-parametric test. If the assumptions made in a statistical test are not fulfilled by the data, then test results can be meaningless, in the sense that the estimates of significance level would be grossly incorrect (Kundzewicz, 2004).

Hydrological data are often strongly non-normal and this means that tests which assume and underlying normal distribution are not adequate. In general, parametric tests are more powerful for a given n (record length) when the variable is normally distributed, but much less powerful when it is not, compared with the non-parametric tests (Hirsch et al., 1991). Distribution-free methods are recommended because they allow minimal assumptions to be made about the data and are therefore particularly suited to hydrological series, which are often neither normally distributed nor independent (Kundzewicz, 2004).

Based on the above and since it was found during the 1975-UK Flood Studies that the two-parameter extreme value type 1 (Gumbel) distribution can adequately describe the Irish Annual Maximum Flood Series, the use of normality based parametric tests was not considered to be appropriate in this case. Non-parametric tests are used in order to test the underlying assumptions of independent and identically distributed time series. However, in order to compare the power of the tests, two parametric tests are also used.

The null hypothesis H_0 for the tests for trend is that there is no trend in the data. The null hypothesis H_0 for the tests for changes or difference in means/medians is that there are no changes or difference in the means/medians between two data periods. The null hypothesis H_0 for the tests for randomness (independence) is that the data come from a random process. It is considered that the alterative hypotheses for all tests are non-directional i.e. all tests are two tailed tests.

The following 7 tests were employed in detecting trends, shift and serial dependency in Annual Maximum Flood Series of Irish Rivers. A full description of each test is given Appendix D.

A) Tests for serial persistence or trend:

i) Mann-Kendall (non-parametric test for trend)
ii) Spearman's Rho (non-parametric test for trend)
iii) Mean-weighted Linear Regression test (parametric test for trend)

B) Tests for progressive change in the mean with time:

iv) Distribution-free CUSUM (non-parametric test for step jump in mean)
v) Cumulative Deviation (parametric test for step jump in mean)

C) Tests for serial dependency of time series

vi) Turning Points (non-parametric test for randomness)

vii) Rank Difference (non-parametric test for randomness)

Streamflow records were examined for potential trends using a mixture of these tests. A significance level of 95% (p=0.05) was chosen as the criteria for determining if a trend was present. This means that if a trend is identified as significant (either positive or negative) that there is only a 5% (1 in 20) chance that the trend is actually not present. Conversely, it could also be said with 95% certainty that the trend is statistically significant.

6.6.1 Resampling

Resampling analysis is a robust method for estimating the significance level of a test statistic. It is particularly useful when the test assumptions are violated. In resampling analysis, the original time series (input data) is resampled to provide many replicates of time series data of equal length as the original data. The time series data for each replicate is obtained by randomly selecting a data value from any year in the original time series continuously until a time series of equal length as the original data is constructed. Here the data are resampled with replacement (bootstrapping method), i.e., a replicate series may contain more than one of some values in the original series and none of other values.

The test statistic value of the original time series data can then be compared with the test statistic values of the generated data (replicates) to estimate the significance level. For example, if the test statistic value of the original data is greater than the 950th or less than the 50^{th} highest test statistic value from 1000 replicates, H_0 is rejected at $\alpha = 0.05$ (i.e., a trend/change is detected, with a 5% probability that this trend/change is incorrectly detected). The critical test statistic values for significance levels of $\alpha = 0.1$, $\alpha = 0.05$ and $\alpha = 0.01$, are the 90th, 95th and 99th percentile values respectively of test statistic values from the generated (resampled) time series.

6.7 Analysis of Temperatures in the Kilavullen Catchment

The following sections describe the full set of exploratory data analyses and statistical analysis that was carried out on the temperature series used in this study.

6.7.1 EDA on Catchment Temperatures

For the analysis of temperatures in the Kilavullen catchment from1926-2009, daily average temperatures were made available by Met Éireann. The annual minimum, maximum, and average of these daily temperatures were studied. The exploratory data analysis used line fitting by simple linear regression and a locally weighted regression smoothing (loess) curve based on seven years of locally weighted data. The annual minimum series were first examined to see if there were any visible patterns in the data. Table 6.1 shows the linear regression best fit line and the loess curve for the annual minima.

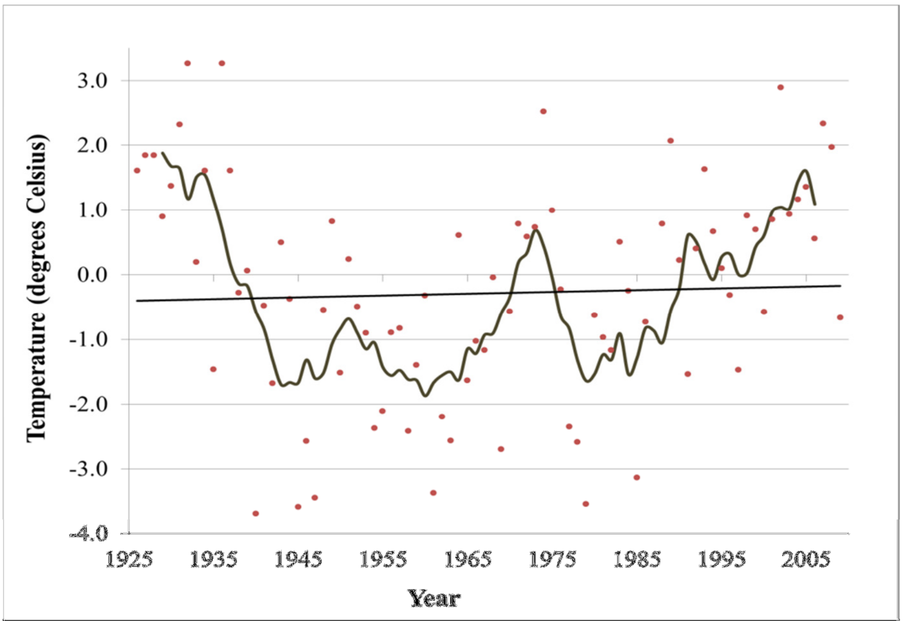


Figure 6.1 Annual minimum temperatures (based on daily average temperatures) in the Kilavullen Catchment 1926-2009 showing linear regression best fit line and 7-year loess curve

From a first viewing of the plot, there appears to be no discernable trend in the data, however the loess curve shows a steady increase in temperatures after ~1978. The annual average temperatures shown in Figure 6.2 show a steady increase from the mid-1980s onwards. The long range pattern identified by the best fit line also shows a clear tendency to increasing temperatures over the full period of record.

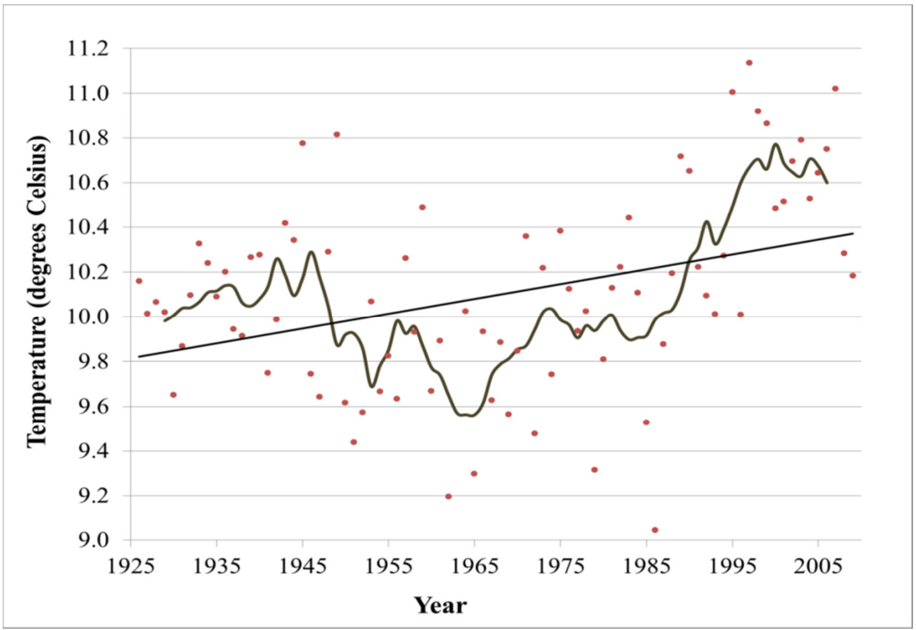


Figure 6.2 Annual average temperatures in the Kilavullen catchment 1926-2009 showing linear regression best fit line and 7-year loess curve

The annual maximum series does not exhibit such a tendency toward increased temperatures after the late 1980s, but instead seems to oscillate up and down from the mid-1970s onwards.

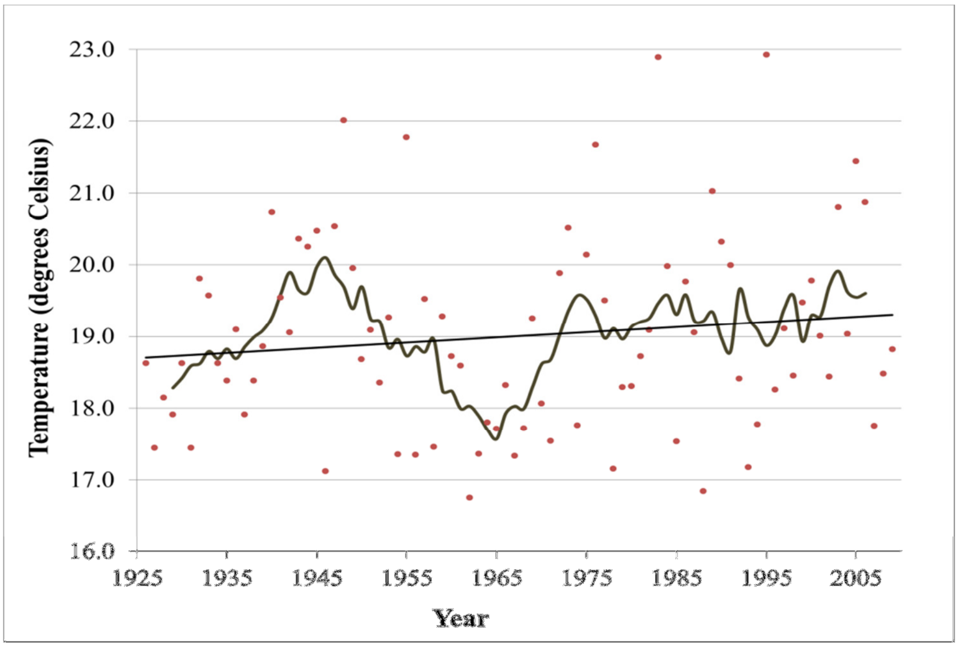


Figure 6.3 Annual maximum temperatures (using daily averages) in the Kilavullen catchment 1926-2009 showing linear regression best fit line and 7-year loess curve

In general the outcomes of the exploratory analysis seem to point to a clear change point in the late-1970s/early-1970s. The temperatures in the period up to the 1970s seems to exhibit a random behaviour, and over the full 84 year period of record the gradient of the best fit lines show a gradual increase in all the temperature quantities. This gradient is used to calculate the average change in temperature between 1926 and 2009.

Temperature Measurement	Gradient of best fit line	Average Temperature change 1926-2009 (C°)
Annual Minimum Temperatures (from daily averages)	0.0028	+0.235
Annual Average Temperatures	0.0066	+0.554
Annual Maximum Temperatures (from daily averages)	0.0072	+0.605

Table 6.1 Average increase in temperatures based on simple linear regression best fit line

6.7.2 Statistical Testing of Catchment Temperatures

For the statistical analysis of gradual trends in catchment temperatures, The Mann Kendall test was applied to the average annual temperatures. From statistical tables, the values of the Z-statistic can be related to significance levels as follows:

Value of the Mann Kendall Z-statistic	Associated Significance Level
2.58	1%
1.96	5%
1.645	10%

Table 6.2 Significance Levels for the Mann Kendall Z-statistic

For this project, the significance level of 0.05 (5%) is chosen as the level below which an observed trend can be said to be significant. Effectively, if the Mann-Kendall test statistic exceeds 1.96 we can say that a significant trend is present in the data. The detection of trend in a time series will depend on the start and end dates used for the analysis. Dependency of the trend on the period of record was investigated by varying the start year of the analysis while keeping the end year (2009) constant. The Mann-Kendall Z-statistic was first calculated for the full period of record from 1926-2009, it was then calculated for 1927-2009, then 1928-2009 and so on until 1980-2009. This gave sample sizes that ranged between 84 and 30 years. The test was not performed on samples less than 30 years in size as the Z statistic appears to become unstable as the number of years of record become smaller. This approach to the Mann Kendall test will be henceforth referred to as Mann Kendall Persistence Test for trend.

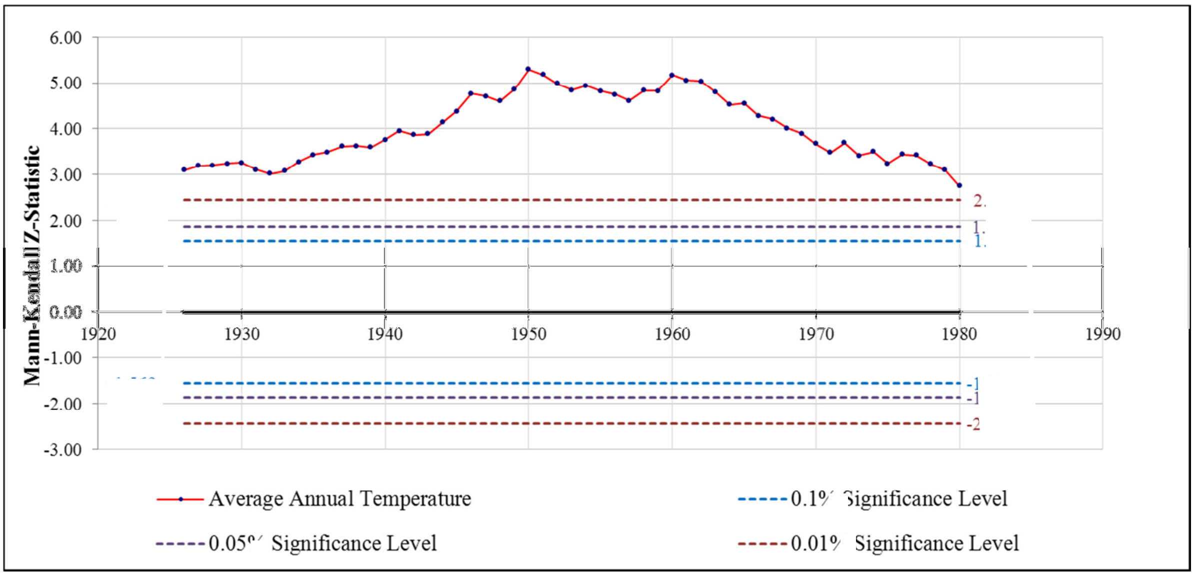


Figure 6.4 Test for persistence in trend in annual average temperatures using the Mann Kendall Z-Statistic. Dashed lines represent the 1%, 5%, and 10% significance levels.

A very strong positive persistent trend in catchment temperatures was detected over the full period of record. In fact, at no point in the record does the significance of detected trend fall below the 1% significance level as can be seen in Figure 6.4 for annual average temperatures. The trend in temperatures is strongest when using a start year of ~1950. The results of the Mann-Kendall test on catchment average annual temperatures shows that in general, year on year there is an increase in catchment temperatures.

Application of tests for the detection of step change also depend on the start and end year of record used. In this part of the study, the distribution free CUSUM test and the Cumulative deviation test for step change were used to identify the dates of statistically significant step changes in the annual average temperatures for the Kilavullen catchment.

If either test is performed on the full period it will tend to identify the most significant step change in the full series. Further step changes in the data are investigated by varying the start year of the analysis while keeping the end year (2009) constant. The date for step change was first calculated for the full period of record from 1926-2009, it was then calculated for 1927-2009, then 1928-2009 and so on until 1980-2009. This gave sample sizes that ranged between 84 and 30 years. The test was not performed on samples less than 30 years in size because by the time the sample had reduced to 30 years of record we could state with certainty that all of the major step changes had been identified.

In testing for step change in temperatures for the Kilavullen catchment the persistence testing approach was applied to the CUSUM and Cumulative deviation tests. This analysis identified more than one step change date in the data. When the persistence approach was applied to the CUSUM test, start dates for the test ranging from 1926 to 1954 identified a step change in 1980. When the test was performed on temperature series with start dates from 1955 to 1964, a change point was identified in 1987. By the same approach, a further change point was identified in 1993 (see Table 6.3). The same testing approach was applied to the cumulative deviation test, which identified change points in 1987 and 1988 (see Table 6.4).

CUSUM Test		
Year of step change identified	Start dates for persistence test	No. of years for which the date of step change persist
1980	1926-1954	29
1987	1955-1964	10
1993	1967-1976	10

Table 6.3 Years of step change in annual temperatures identified by the CUSUM test using the persistence approach.

Cumulative Deviation test		
Year of step change	Start Dates for persistence test	No. of years for which the date of step change persist
1987	1926-1963	38
1988	1964-1977	14

Table 6.4 Years of step change in temperatures identified by the cumulative deviation test using the persistence approach.

The results of both tests point to the most significant step change being in 1987/88 with a lesser change point in 1993. This is backed up by examination of the loess 7-year curve for annual average temperatures (Figure 6.2). There are also less significant step changes identified in 1980 and 1993.

6.8 Analysis of Precipitation in the Kilavullen Catchment

The following sections describe the full set of exploratory data analyses that were carried out on the precipitation series used in this study. As rainfall is widely accepted to be the driving factor in river flow and flood behaviour it is important to assess trends in rainfall to act as a quality control for any changes identified in river flows.

6.8.1 EDA on Annual Catchment Precipitation

In the examination of rainfall within the catchment, the total annual precipitation is the quantity studied. The best fit line to the data exhibits a positive increasing trend. The loess curve shows that from a low point around 1971, the observed catchment rainfall steadily increases up to 1997. It is also worth noting that out of the 84 years examined, 4 of the wettest years on record occurred in the last decade.

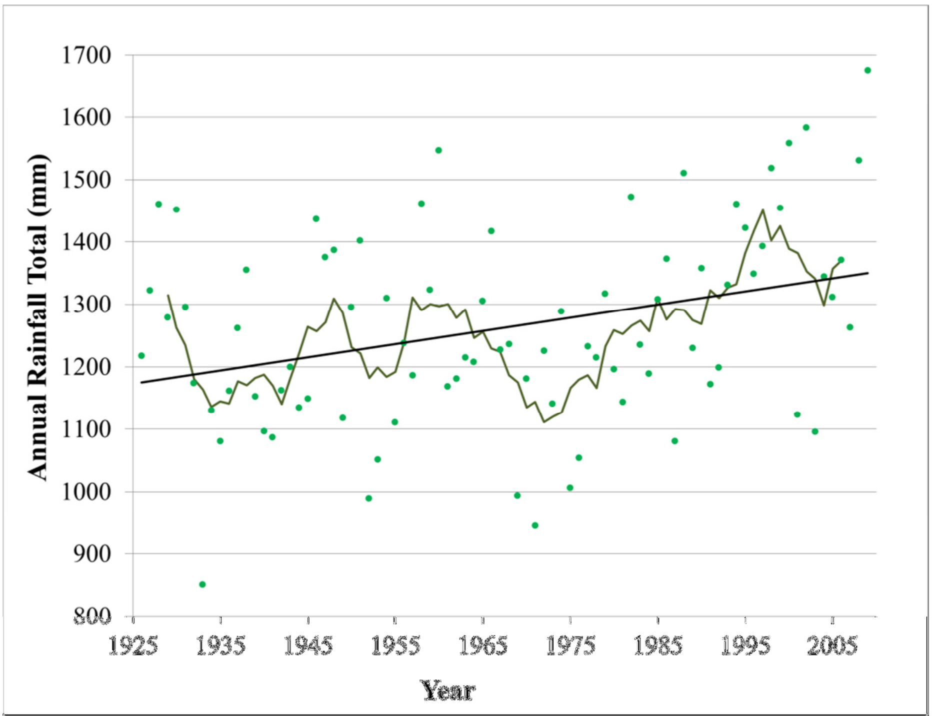


Figure 6.5 Annual total precipitation in the Kilavullen Catchment 1926-2009 showing linear regression best fit line and 7-year loess curve

The gradient of the best fit line is +2.106mm per year, which indicates an average increase in annual precipitation of 177mm over the period of record.

6.8.2 Statistical Testing of Annual Catchment Precipitation

For the statistical analysis of gradual trends in annual catchment precipitation, the Mann-Kendall persistence test using was used. This showed that the trend in the rainfall data persists throughout the record up to around 1969 onwards when the significance of the trend begins to decrease, although still remaining significant at the 5% level.

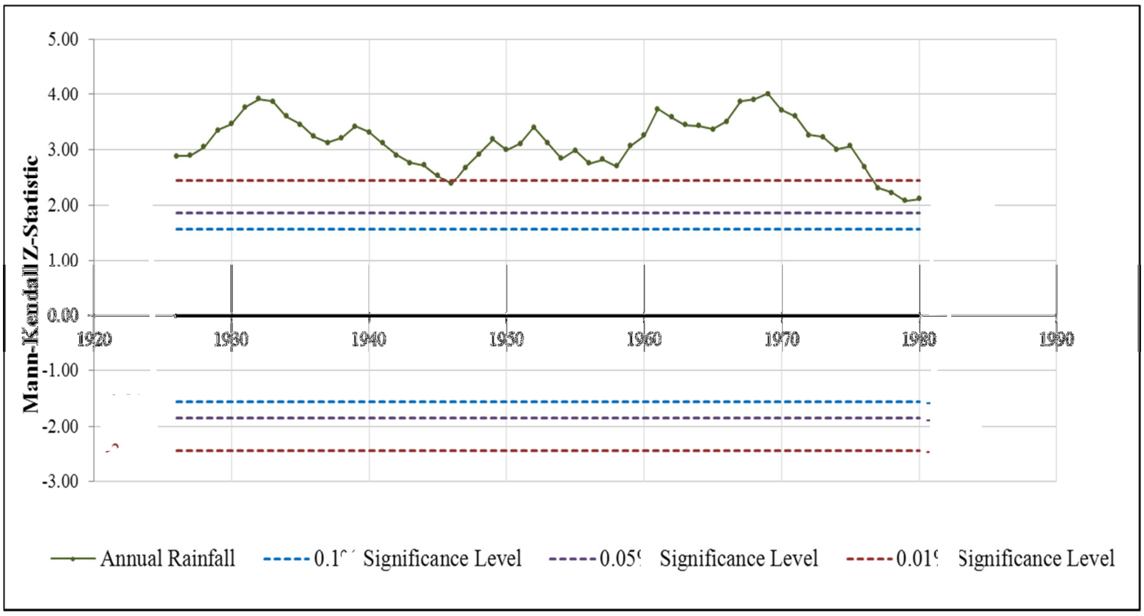


Figure 6.6 Test for persistent in trend in rainfall using the Mann Kendall Z-Statistic

In testing for step change in annual precipitation totals for the Kilavullen catchment the persistence approach to the CUSUM and Cumulative deviation tests was used. This analysis identified a number of step change dates that persisted to be identified over a number of years. The dates of the step changes that were identified are as shown in Table 6.5 and 6.6.

CUSUM Test		
Year of step change	Start Dates for moving window	No. of years for which the date of step change persist
1992	1926-1977	52

Table 6.5 Years of step change in precipitation identified by the CUSUM test using the persistence approach.

Cumulative Deviation test		
Year of step change	Start Dates for moving window	No. of years for which the date of step change persist
1981	1926-1943	18
1987	1944-1967	24
1992	1968-1977	10

Table 6.6 Years of step change in precipitation identified by the cumulative deviation test using the persistence approach.

The results of the CUSUM test strongly points to 1992 as the year of most significant step change. The cumulative deviation test points towards 1981 as the year that step change occurred while also identifying lesser step changes in 1987 and 1992, all in the upward direction. On balance, it would appear that the most significant step change occurred in 1992, with subsequent less significant step jumps in 1981 and 1987.

6.9 Analysis of Annual Average Flows in the Kilavullen Catchment

In the analysis of annual average flows in the Kilavullen catchment both the HYSIM and IHACRES models were used to hindcast flows back to 1926. The annual average flow time series was subjected to the most rigorous testing of any data set in this study. This was then followed up by testing the seasonal flows to see what is driving the yearly behaviour.

6.9.1 EDA on Annual Average Flows

Exploratory data analysis was firstly conducted on the standardised annual average flows produced by the HYSIM and IHACRES models. In order to standardise the flow data, a standard score was obtained for each observed annual mean flow value plotted against time (1926-2009). Each standardised score indicates how many standard deviations an observed annual flow value is above or below the mean. This process of standardisation has the effect of exaggerating the magnitude of the larger observations in the data, thus making it easier to visually assess the possible presence of trends (see Figure 6.7). The standardised score (Z) is given by:

$$Z = \frac{x - \mu}{\sigma}$$

where: x is the time series variable to be standardised e.g. flow/rainfall;

μ is the mean of the time series;

σ is the standard deviation of the time series.

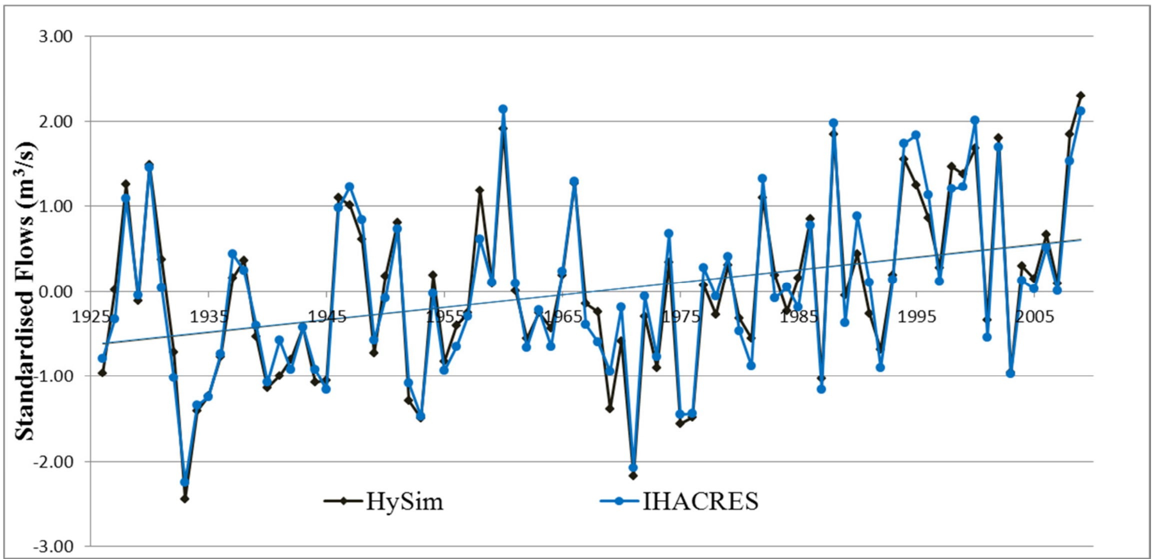


Figure 6.7 Graph of standardised annual flows from the HYSIM and IHACRES models.

The plot of standardised flows is shown in Figure 6.7. The gradient of the best fit line for both models is more or less identical, and shows a positive increasing trend. General increases in flows over the period of record are evident from the loess curve which is shown in Figure 6.8. In a similar fashion to the rainfall, the flows steadily increase after the early 1970s, which incidentally was one of the driest periods on record, containing the drought years of 1975 and 1976.

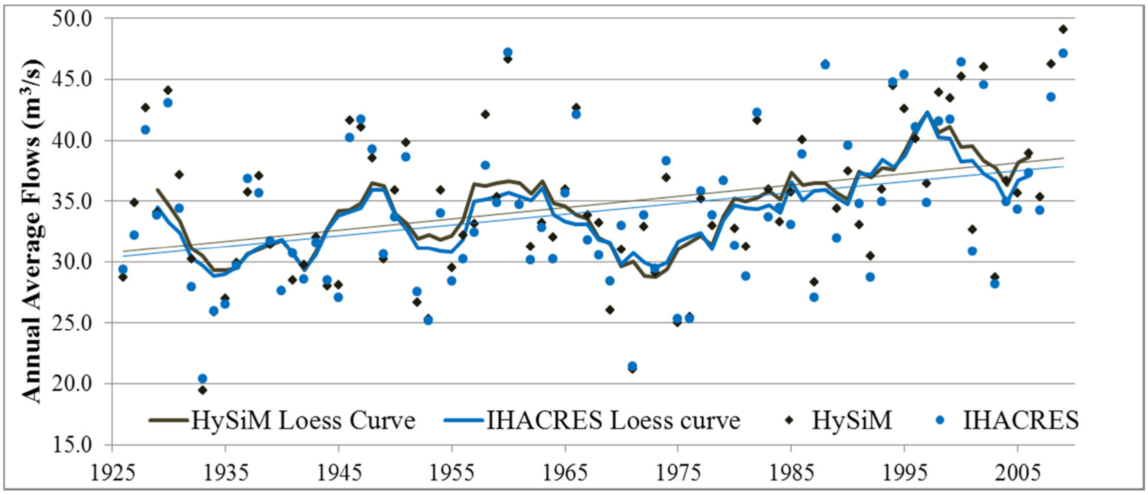


Figure 6.8 Loess 7-year curve applied to annual average flows

The gradient of the best fit line is +0.093 which equates to an average increase in the annual average flows of +7.81 cumecs. This represents quite a large increase in the flows considering that both models show an overall average of approximately 34 m^3/s. The use of best fit linear regression lines are a useful means of looking at possible trends, however they are sensitive to high/low outliers at either end of the time series and only give an idea of the behaviour of the full period of record (i.e. 1926-2009). The exploratory data analysis on the annual average flows indicates that there is indeed a positive increasing trend. There is clearly a steadily increasing upward trend after 1967/1968.

6.9.2 Statistical Testing of Annual Average Flows

For the statistical analysis of gradual trends in catchment precipitation, all three tests for gradual change were used with the persistence approach. Both the CUSUM and cumulative deviation tests were applied to the data to test for step change, while the turning points and rank difference tests for randomness were employed. In the testing of annual average data the significance levels were calculated using resampling by replacement (the bootstrap method).

The Mann-Kendall persistence test for trend shows that a very strong trend exists in the data (Figure 6.10). The Spearman's Rho test and the Mean Weighted Linear Regression test also show very similar results (Figures 6.11, and 6.12)

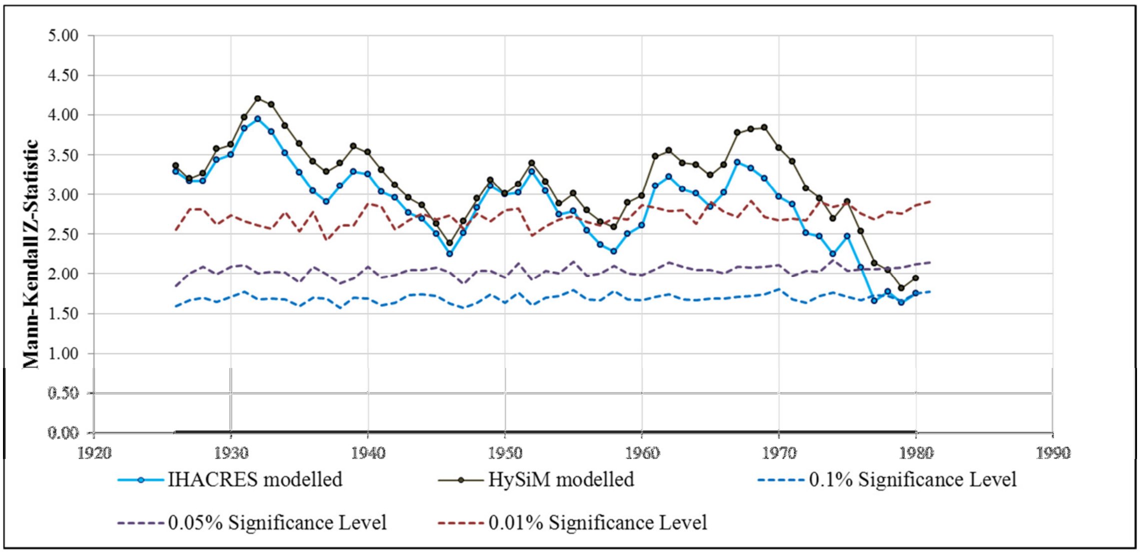


Figure 6.9 The Mann Kendall persistence test applied to annual average flows. Significance levels shown as dashed lines are estimated using the bootstrapping method.

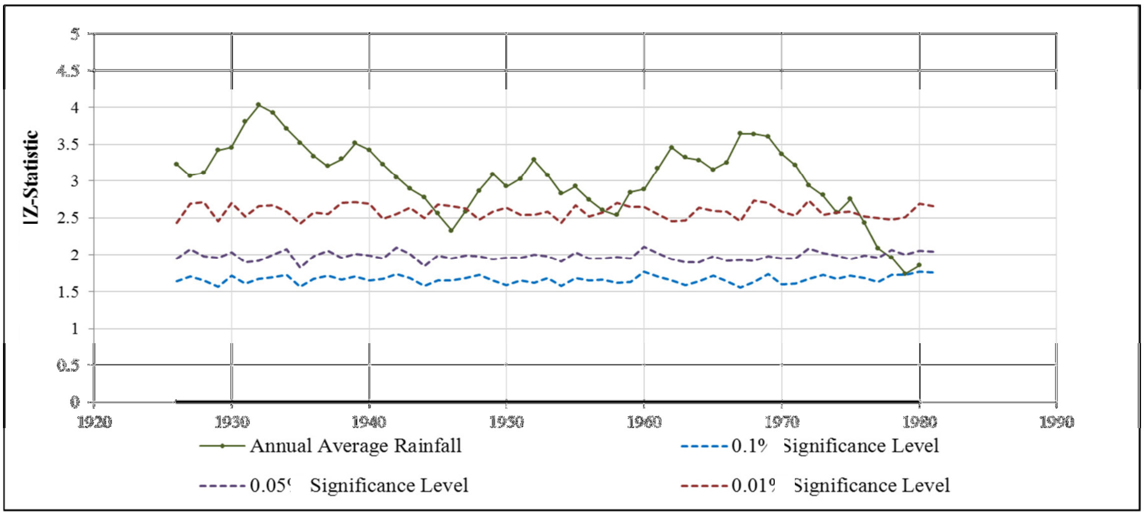


Figure 6.10 The Spearman's Rho persistence test applied to annual average flows. Significance levels shown as dashed lines are estimated using the bootstrapping method.

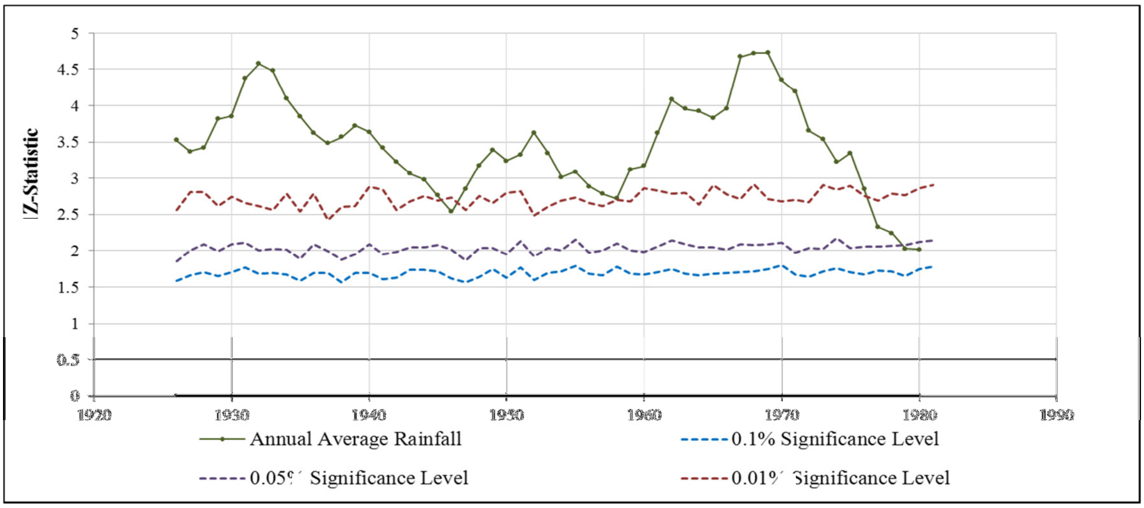


Figure 6.11 Mean-weighted Linear Regression persistence test applied to annual average flows. Significance levels shown as dashed lines are estimated using the bootstrapping method.

All three tests show that there is a very significant trend over the whole period of record. With the null hypothesis being rejected at the 1% significance level. After using the bootstrap method to determine the significance levels for the Z-statistic it was found that the significance levels for the Z-statistics did not differ significantly from those found in statistical tables, and so for further testing in this project, the significance levels for the Z-statistic were taken directly from statistical tables.

Additionally it was found that the Mann Kendall test and the Spearman's Rho test yield virtually identical results. This is in agreement with the findings of Yue *et al*. (2002). The mean weighted linear regression test showed the strongest trend of all three. It was therefore decided to no longer use the Spearman' Rho test in further analysis because of its strong similarities with the Mann-Kendall Test. The mean weighted linear regression test was rejected in favour of the Mann-Kendall test which gives more conservative estimates of trend. Both the HYSIM and IHACRES models reflect the persistence in trend, with the Z-statistic only falling below the 5% significance level for tests starting after 1976. The shape of the persistence plot for annual mean flows is similar to that derived for precipitation, however the fall off in significance towards the end of the record is more pronounced for flows than for rainfall.

After examining the persistence of trend for all three tests, there is a clear fall off in the significance of trend after 1967. The Loess curve for Annual flows also shows a gradual increase in flows after 1967. This appears to be strongly correlated with the North

Atlantic Oscillation Index (Figure 6.12) in that in during the next two decades after 1967 the Index went from being strongly negative to strongly positive. In addition to decadal variation, Hurrell (1995) identified the occurrence of predominantly positive and negative phases of the NAO in the twentieth century. The period from the mid-1970s to 1990 corresponded to a predominantly positive phase. A predominantly negative phase, from the early 1940s to the mid-1970s, and a strongly positive phase, from the turn of the century to the 1930s, preceded this.

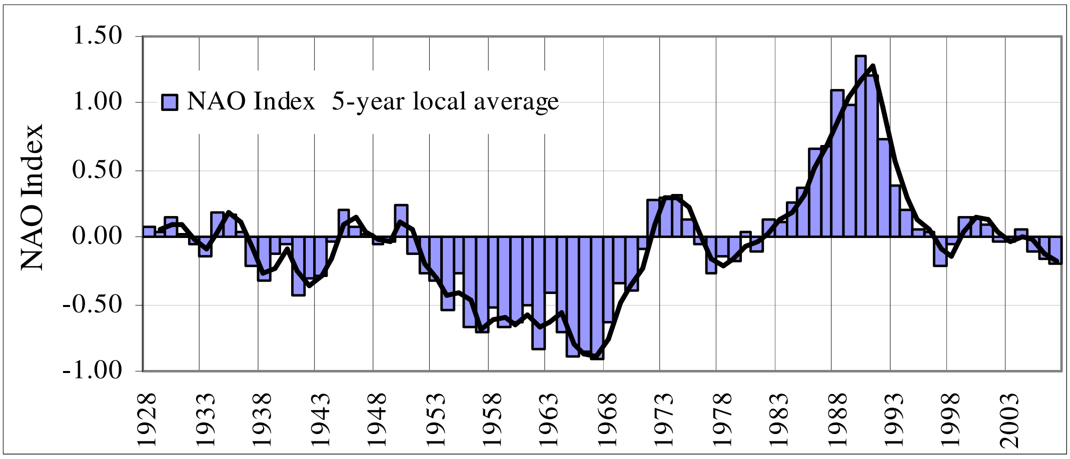


Figure 6.12 Annual North Atlantic Oscillation Index (5 year local average) – Source NCAR

When testing for step changes in the annual average flow time series both the CUSUM and cumulative deviation tests identify the strongest step change as occurring in 1981 (see Tables 6.7 and 6.8). It should also be noted that 1981 is a significant year in terms of the NAO Index. The NAO changes from negative to increasingly positive over the following decade. They also show less significant step jumps in 1987 and 1993. This is broadly in keeping with the results of the tests for step change in precipitation.

CUSUM test		
Year of step change	Start Dates for moving window	No. of years for which the date of step change persist
1981	1926-1964	28
1987	1954-1970	17
1993	1971-1981	11

Table 6.7 Years of step change in annual average flows identified by the CUSUM test using the persistence approach.

Cumulative Deviation test		
Year of step change	Start Dates for moving window	No. of years for which the date of step change persist
1981	1926-1968	43
1993	1969-1980	13

Table 6.8 Years of step change in annual average flows identified by the cumulative deviation test using the persistence approach.

6.10 Analysis of Seasonal Flows in the Kilavullen Catchment

From the analysis of annual average flows it is clear that trend in the yearly flows exists. It is now necessary to examine each season to identify if any one particular season is driving the annual trend.

6.10.1 EDA on Seasonal Flows

The plots of the reconstructed seasonal flows for the full period of record are shown in Figures 6.12(a), (b), (c), and (d).

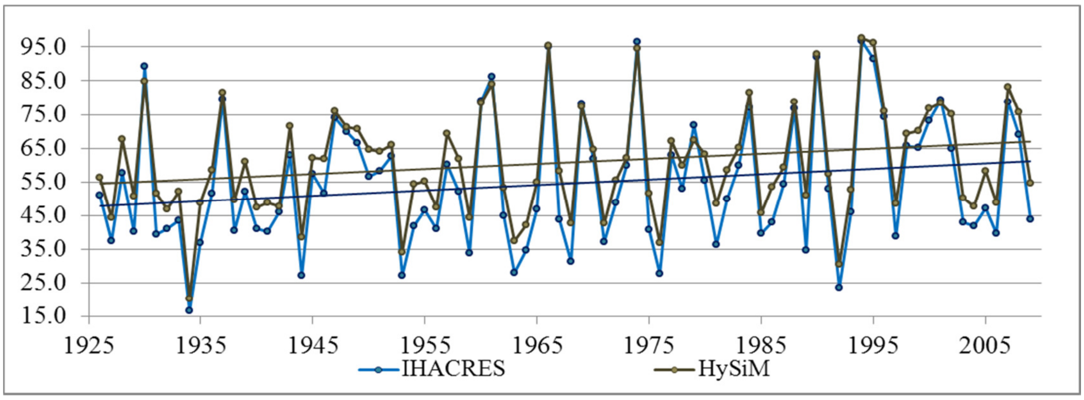


Figure 6.13(a) Winter Flows (m3/s) 1926-2009

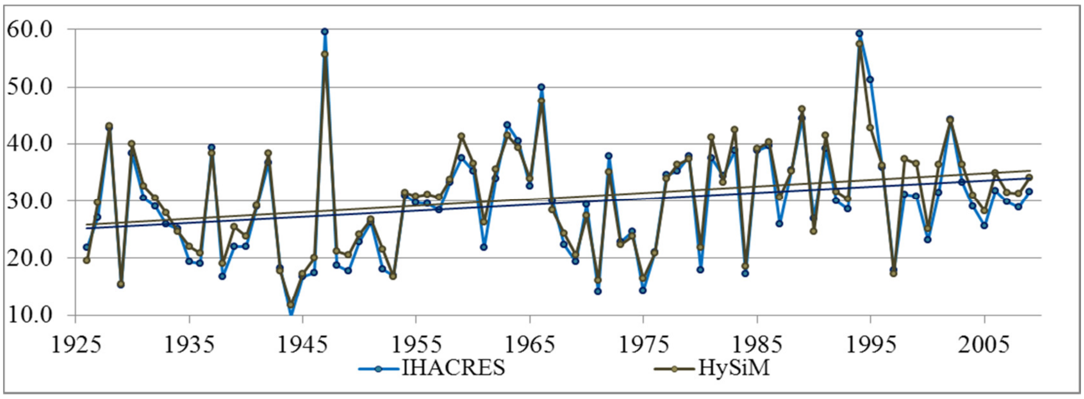


Figure 6.13(b) Spring Flows (m3/s) 1926-2009

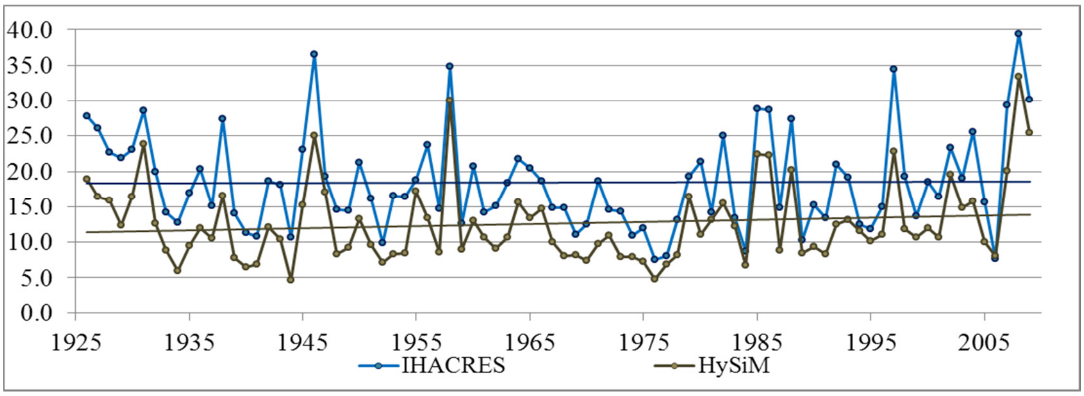


Figure 6.13(c) Summer Flows (m3/s) from 1926-2009

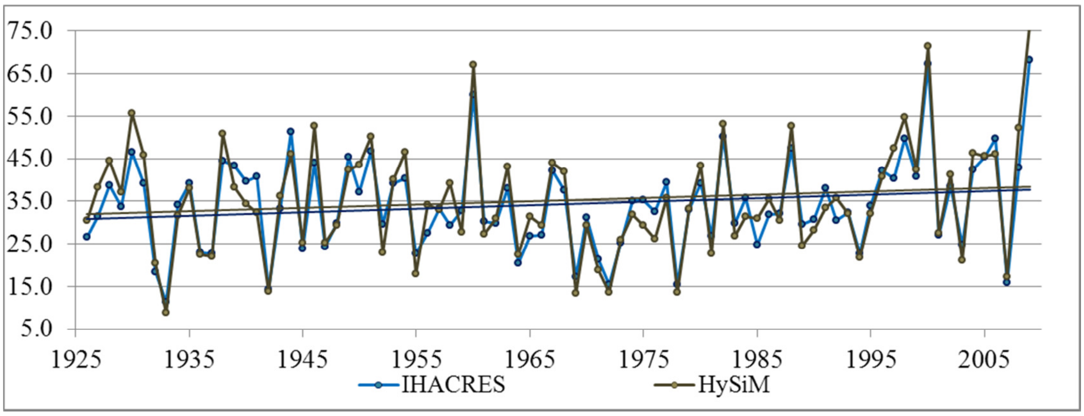


Figure 6.13(d) Autumn Flows (m3/s) from 1926-2009

While the magnitude of seasonal flows generated by the two models are shows some divergence for winter and summer the slope (discussed in section 5.7) of the best fit line to both of the data is the same. The best fit line for both datasets are very similar. It can therefore be said that while the two models give differing magnitudes of flow, their overall behaviour in terms of long term trends appear to be the same. The gradients of each best fit line are shown in Table 6.9.

	IHACRES		HYSIM	
Season	Gradient of best fit line	Average seasonal flow change 1926-2009 (m^3/s)	Gradient of best fit line	Average seasonal flow change 1926-2009 (m^3/s)
Winter	0.160	+13.44	0.149	+12.516
Spring	0.107	+8.97	0.115	+9.64
Summer	0.003	+0.25	0.031	+2.64
Autumn	0.083	+6.972	0.077	+6.43

Table 6.9 Average changes in flows based on simple linear regression.

The initial inspection of the data suggests that the strongest trend is in winter closely followed by spring. There is a very weak positive trend in autumn, and no detectable trend in summer flows. It should also be noted that no season shows a decreasing trend.

So effectively on first impressions it would appear that all the seasons contribute to an increasing trend in flows at the annual level, albeit some more than others.

6.10.2 *Statistical Testing of Seasonal Flows*

The Mann Kendall Persistence Test was also applied to the seasonal flows from this study to assess if any particular season was driving the overall trend in the annual flows. The persistence plots for each season are shown in Figures 6.14(a)-(d). The trend results from the HYSIM and IHACRES models both show almost identical results when compared to the persistence tests performed on observed flows for winter and spring. The two models show differing results for summer and autumn scenarios, and so the performance of each of the models were compared to persistence plots for the observed record. For summer, the IHACRES model most closely replicates the behaviour of the observed data (Figure 6.14c), and for autumn, the HYSIM model is the one that most closely resembles the behaviour of the observed data (Figure 6.14d).

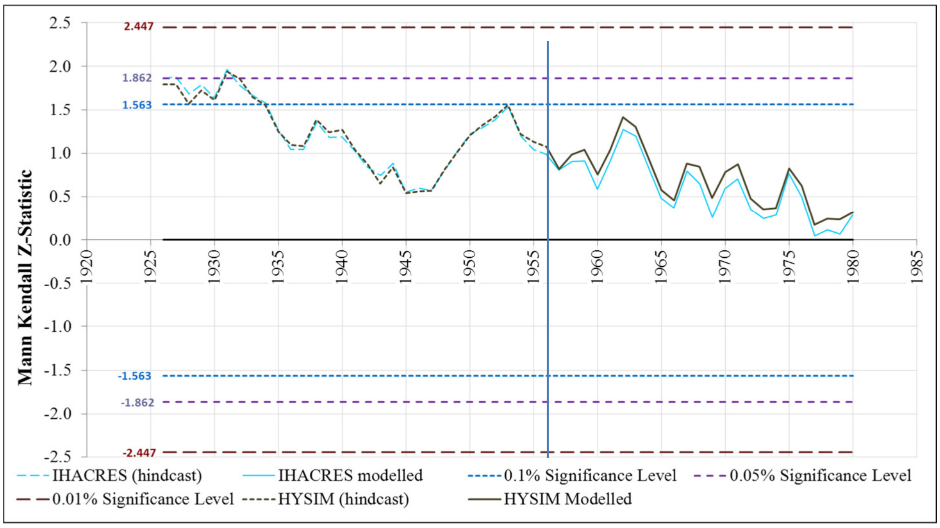


Figure 6.14(a) Mann Kendall persistence test applied to winter flows (Z statistics for hindcast flows shown as dashed lines).

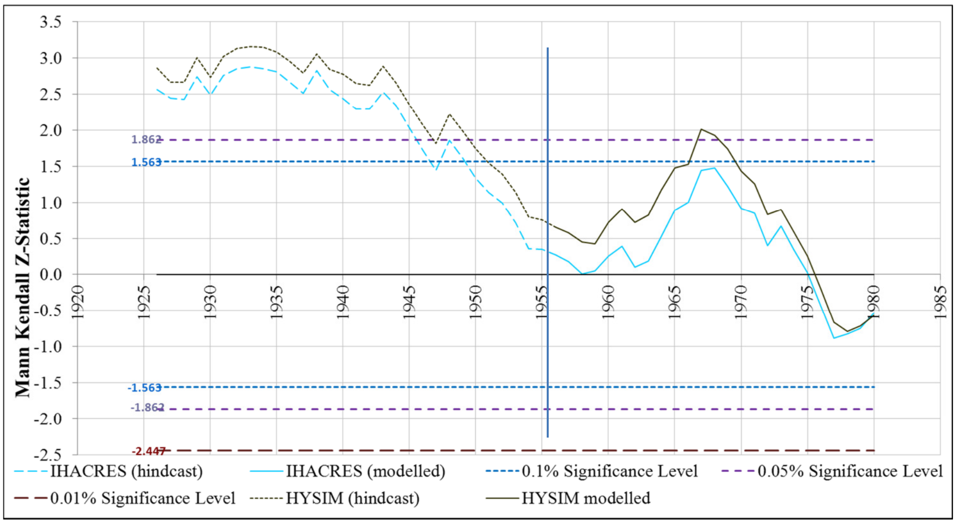


Figure 6.14(b) Mann Kendall persistence test applied to spring flows (Z statistics for hindcast flows shown as dashed lines).

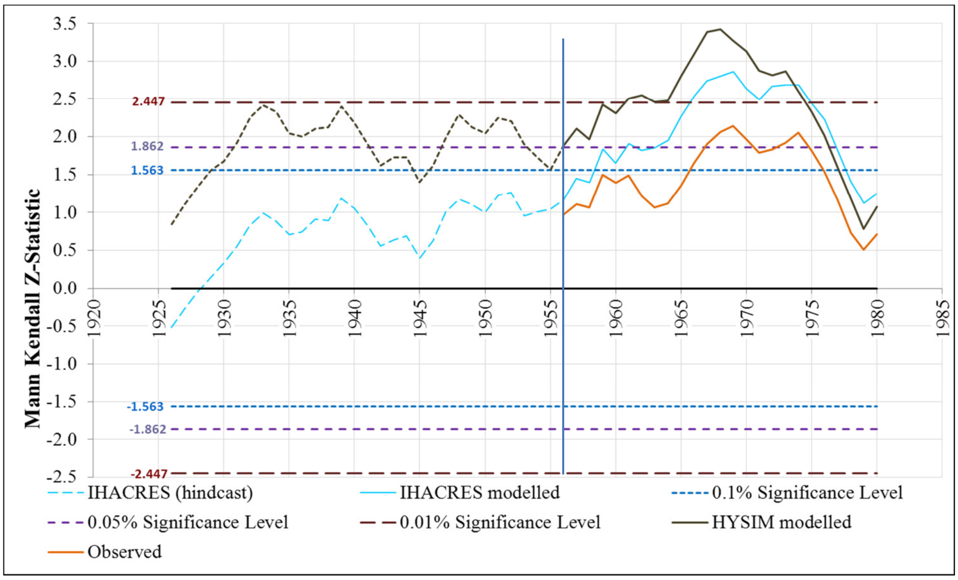


Figure 6.14(c) Mann Kendall persistence test applied to summer flows (Z statistics for hindcast flows shown as dashed lines).

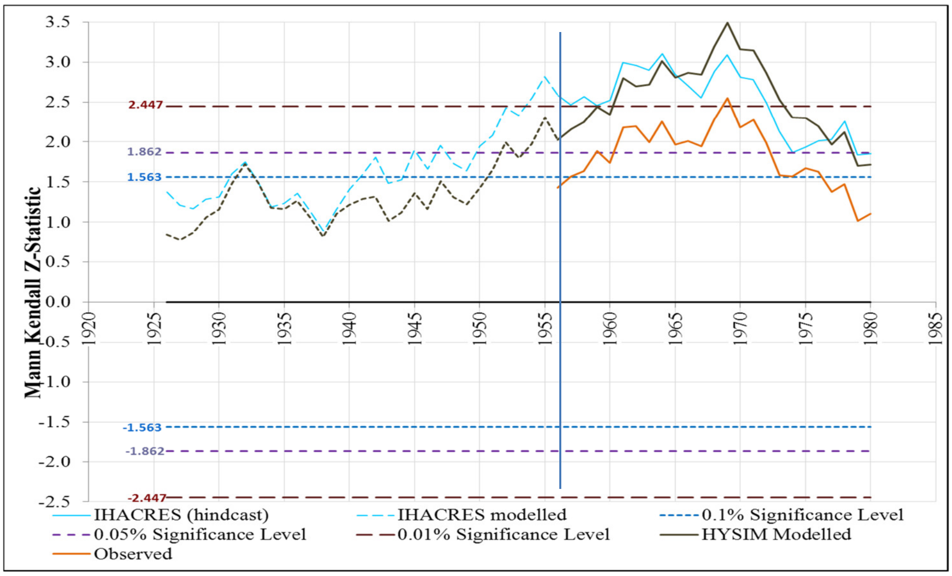


Figure 6.14(d) Mann Kendall persistence test applied to autumn flows (Z statistics for hindcast flows shown as dashed lines).

The general behaviour of the seasonal flows can be divided into two types. For winter and spring the persistence of trend decreases the later the start year of the analysis. The converse happens for summer and autumn with the magnitude of trend increasing with the magnitude of the trend increasing with later start years. The steep drop in persistent trend that is witnessed in annual rainfall and flows after 1967 can also be seen in spring, summer and autumn flows. The decrease in the strength of trend signal for winter flows occurs in a more gradual fashion after 1963. The importance of long records are also obvious from the analysis justifying the effort expended in reconstructing river flows. All seasons show a systematic fall off in trend persistence after around 1967. Again, this behaviour seems to be driven by the relationships with modes of natural climate variability.

Spring is the season that shows the most significant positive trend when persistence test start dates earlier than 1935 are used. The Mann-Kendall persistence test for trend effectively shows that all four seasons contribute the sum of their parts to the persistently positive trend signal identified in annual flows. Winter and spring drive the trend when the start dates for the persistence test are before 1946, and summer and autumn account for the persistence in trend for test start dates after around 1946.

The behaviour of the trend in seasonal flows bears a marked resemblance to the behaviour of 8 UK catchments that were studied by Hannaford and Harvey (2010) using observed flow records dating back to 1920. The general shapes of the persistence plots for this study and the UK show the following common features from 1926 onwards:

- Winter Z-statistic – gradual slow decrease in Z-statistics
- Spring Z-statistic – Z-statistics sharply decreasing from a high in the early 1940s to a low point in the 1960s, before increasing to a local high in the early 1970s and falling off again towards the end of the period;
- Summer Z-statistic – gradual increase in Z-statistics up to early 1970s
- Autumn Z-statistic – gradually increasing up to a high point around 1970.

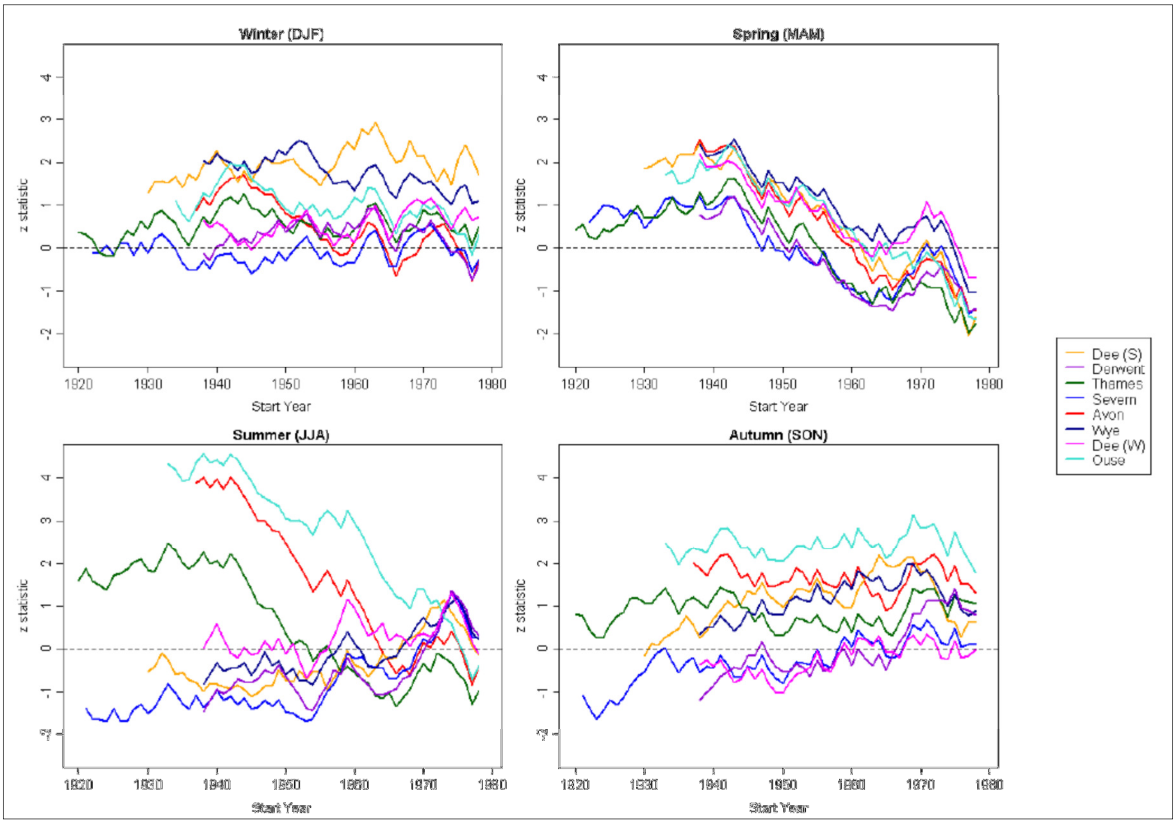


Figure 6.15 Seasonal Trend Persistence plots for 8 UK Catchments (source: Hannaford and Harvey, 2010)

The striking similarity in behaviour between persistence plots of the Kilavullen catchment and the further afield UK catchments would seem to indicate that the trend behaviour is not being driven by local effects. This again points to the influence of the NAO. In order to test the effect of the NAO Index, the NAO for each season was compared to the annual NAO Index. All four seasons were used for the comparison for completeness. A plot of the annual NAO Index against the winter NAO Index (Figure 6.16) shows that there is an extremely strong correlation between the winter NAO and the Annual NAO (r^2=0.78). This would seem to suggest that the winter NAO is driving the annual behaviour of the NAO. The summer NAO was the season that showed the least correlation to the annual NAO.

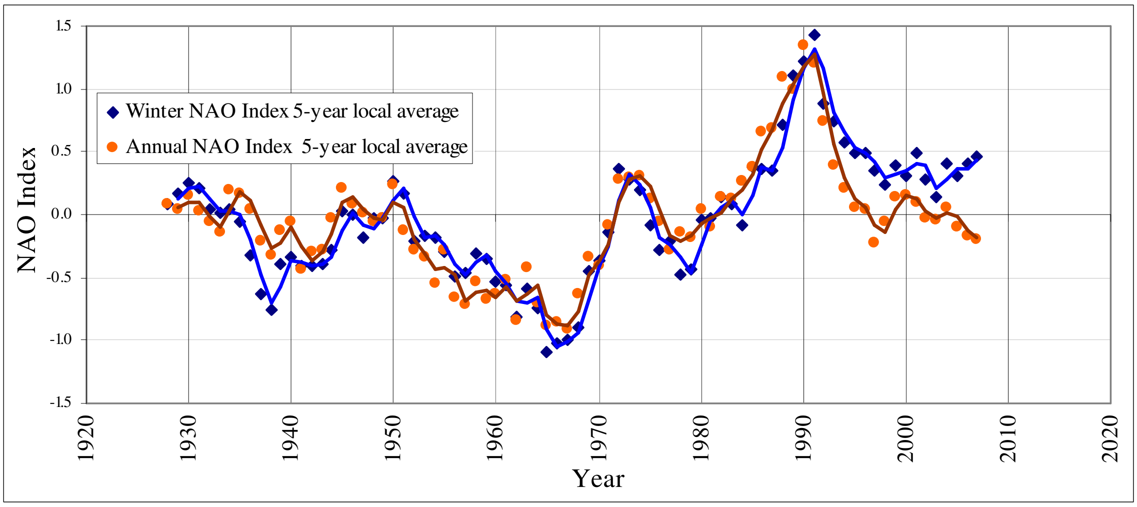


Figure 6.16 Correlation between annual and winter NAO Index.

In order to study the effects of the NAO on seasonal flows, both seasonal flows and the NAO index were compared using the Spearman's Rank Correlation co-efficient (Table 6.10). Interestingly, there is evidence that seasonal flows are also affected by seasonal variations in the NAO.

	Winter flows	Spring flows	Summer Flows	Autumn Flows
Winter NAOI	0.46	0.28	0.27	0.25
Spring NAOI	0.34	0.23	0.02	-0.11
Summer NAOI	0.12	-0.01	-0.48	-0.52
Autumn NAOI	-0.24	-0.25	0.01	-0.09

Table 6.10 Spearman's rank correlations between seasonal NAO and seasonal flows.

The dominant winter NAO and spring NAO are in general positively correlated with all seasonal flows, while there is a negative correlation between the summer and autumn NAOI and all seasonal flows. Furthermore, from the analysis of seasonal NAO Indices against seasonal flows, it seems that the winter NAO Index primarily drives the winter and spring flows.

The average effect of a positive NAO is to increase rainfall amounts substantially throughout the autumn and winter periods, with little effect in the summer. This agrees with the general understanding of the NAO as a phenomenon whose effects are mainly confined to winters in the northern hemisphere (Hurrell, 1995). It can be concluded that the winter NAO drives the behaviour of the annual NAO, winter and spring flows, and the annual flows in the catchment. By association it can be stated that the winter NAO seems to be driving the long term trend in the flows for the Kilavullen catchment.

A more detailed examination of the correlation between the seasonal NAO Indices may prove useful from the point of view of flood forecasting. Further still, if a close relationship between monthly NAO Indices could be developed then it could possibly be used to aid flood forecasting for the Kilavullen catchment and in particular, the towns of Mallow and Fermoy. The monthly NAO index could be used for advanced warning of possible high flood risk months. This would allow forecasters to be particularly vigilant during the high risk periods indicated by the NAO Index.

6.11 Dependence of trend on flow record length

If the Mann-Kendall test is carried out on the seasonal flows over the period of gauged record at Kilavullen from 1956-2009 it shows that autumn flows display a propensity for trend, and are the main driver for trend in the annual series. However, after performing the Mann-Kendall test on the full period of reconstructed flows from 1926-2009, spring is identified as having a more significant trend signal, and is replaces autumn as the main driver of trend in the annual flow series. This example illustrates the importance of quoting the period over which the trend analysis takes place, and also proves that the approach testing for trend on a set period of flows will uncertainly lead to misgivings as the presence (or not) of trend in a catchment. This has lead researches to ask what length of record is required in order to reliably test for trend in a catchment.

6.12 Detection time for trends

Other studies have advocated that between at least 40 and 50 years of data years' worth of flow records should be available at a site before testing for trend for climate change studies (Robson, 2002; Kundzewicz et al., 2005). However a more quantitative estimate of the number of years is often required. In this study we examine annual and seasonal flows to calculate the number of years of record required to detect trend in the series.

Trend detection in environmental series can be confounded in two ways. First, by Type I errors in which stochastic variations in the record are mistakenly accepted as a trend, and second by Type II errors where a real trend is not identified because it is swamped by short-term stochastic variations (Wilby, 2006). Errors of Type I are addressed by setting the probability of erroneous trend detection (α) at a predetermined level of confidence. This has already been decided as 0.05. The probability of making a Type II error (1-β) depends on the power of the statistical test to detect a specified trend at the required confidence level α, so varies with record length, trend magnitude and the distribution of the time series (Ziegler *et al.*, 2005) . For this study, β is taken conservatively as 0.1, and the number of years of data required detect a trend (τ) for a specified α and β:

$$\sum_{i=1}^{y_{\det ect}} \left(t - \bar{t}\right)^2 = \frac{\sigma^2}{\tau^2}\left(W_{1-\frac{\alpha}{2}} - W_{\beta}\right)^2$$

Where: t_i is a year in the record,

$\bar{t}$ is the mean year of the record

$W_{1-\alpha/2}$ and W_{β} are the normal deviates at cumulative probability 1-α/2 and β respectively, and σ^2 is the sample variance of the time series.

The above equation can be re-written thus:

$$y_{\det ect} = \left[\frac{12\sigma^2}{\tau^2}\left(W_{1-\frac{\alpha}{2}} W_{\beta}\right)^2\right]^{\frac{1}{3}}$$

For α=0.05 and β=0.1 the quantity _ becomes 10.507.

To calculate the number of years of data required in order to detect trend (y_{detect}), two items of information must be known, firstly the plausible trend (τ) that would be expected in the future taken from an independent sample, usually future projections of flow based on some climate change scenario, and secondly the estimated variance (σ_ε) of the observed record against which the plausible trend is compared.

Estimates of the plausible trend are calculated from two independent sample periods and produce two possible scenarios

- Scenario 1: calculated from the streamflow projections for the Munster Blackwater by Murphy and Charlton (2008) under the A2 SRES global warming scenario.(1990-2025)
- Scenario 2: calculated from the streamflow projections for the Munster Blackwater by Murphy and Charlton (2008) under the A2 SRES global warming scenario. (1990-2055)

The magnitude of plausible trend is calculated as the slope of the Kendall-Theil Robust Line (Theil, 1950) that is fitted to the n-years of data of the independent sample. The equation of the Theil Robust Line is as follows:

$$Y = m \times t + b$$

$$\text{Where: } m = median\left(\frac{y_j - y_j}{t_j - t_i}\right) = median\left(\frac{\Delta t}{\Delta y}\right)$$

for all years (t) and time series values (y), for $i = 1, 2, \ldots, (n-1)$ and $j = 2, 3, \ldots, n$.

and: $$b = y_{\text{median}} - m \times t_{\text{median}}$$

The Theil slope estimate m is computed by comparing each data pair to all others in a pairwise fashion. A data set of n (t,y) pairs will result in n(n−1)/2 pairwise comparisons. For each of these comparisons a slope Δy/Δt is computed. The median of all possible pairwise slopes is taken as the nonparametric slope estimate, *m* (Helsel and Hirsch,2002).

For each scenario, two different sub-periods are used to calculate the variance of the time series being studied.

- Scenario 1: A long series (LS1) 1927-1990 and a short series (SS1) 1956-1990
- Scenario 1: A long series (LS2) 1927-1990 and a short series (SS2) 1956-1990

The input variables for calculating Y_{detect} and the results were as follows:

Scenario	Independent sample for trend	Plausible Trend (τ)	Period for variance	Variance (σ_ε)	Y_{detect} (Years)
Scenario 1	1990-2025	21.3%	1927-1990 (LS1)	33.39	**45.33**
			1956-1990 (SS1)	31.26	**44.34**
Scenario 2	1990-2055	7.18%	1927-1990 (LS2)	33.39	**93.47**
			1956-1990 (SS2)	31.26	**91.44**

Table 6.11 Periods used for calculation of plausible trend and variance showing number of years required to detect the plausible trend.

For the two scenarios, the variances for each selected period are almost identical, and by using the long or short series, there is no large variation in the calculated detection time.

Each scenario can be used to plot a curve relating the detection trend to the number of years of data required to detect that percentage change in the data (Figure 6.17). If we examine the Thiel Robust Line for the full period of record used in this study (1926-2009), the overall trend for the full period of record is 9.25%. Depending on which scenario is examined, this corresponds to a detection time of between 88 and 111 years.

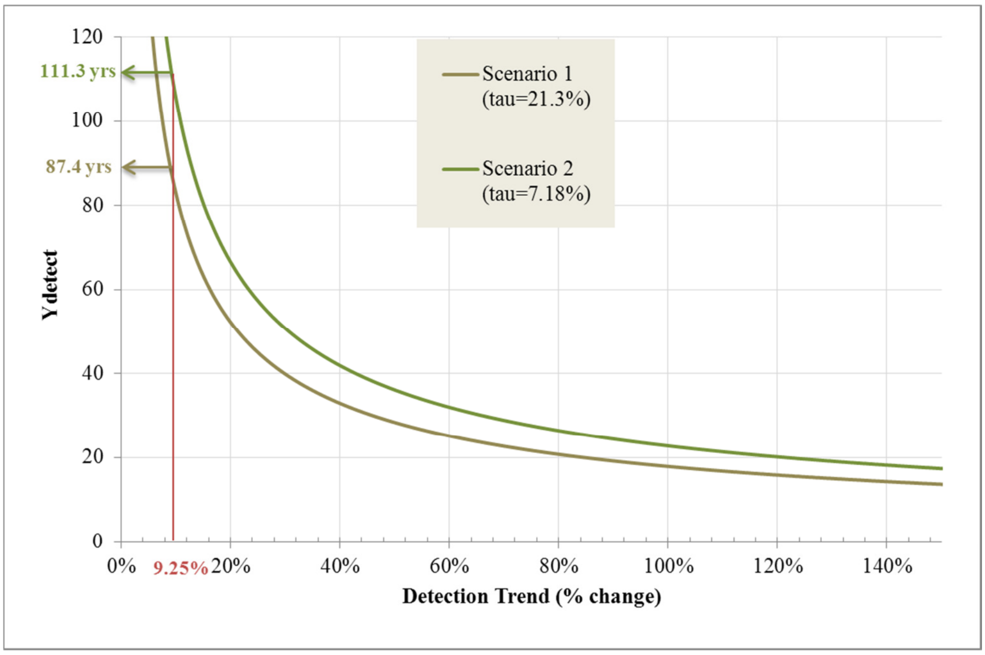


Figure 6.17 Detection time as a function of the trend (% change in mean) and variance of annual flows.

6.12.1 Detection of Trend in the Annual Flow Series

By an inspection of the persistence plots of the annual flow Mann Kendall Z-statistic we can see that for test start years earlier than 1930 (80 years of record) the Z-statistic gives a reliable estimate of the trend in the data. The Mann Kendall test applied to seasonal flows using start dates prior to 1930 show that spring contributes the most towards this trend followed closely by winter. Summer and autumn do not greatly contribute to the trend in annual flows. This is generally in keeping with the exploratory data analysis showing that the greatest increases have been in spring and winter flows, with summer an autumn not showing any discernable increasing trend.

6.12.2 Detection of Trend in the Seasonal Flow Series

The detection times required for each of the seasonal flows were calculated in a similar fashion to that for annual flows. The streamflow projections for the Munster Blackwater by Murphy and Charlton (2008) under the A2 SRES global warming scenario calculated plausible trends using winter and summer flows only (based on 6 months each). For the purposes of calculating y_{detect} for each season, the plausible trends for winter and autumn use the projected winter scenario, while spring and summer use the summer projected scenario. The range of detection times for each season are shown in Table 6.12.

Season	1927-2009 Trend (τ)	Scenario 1 Y_{detect}	Scenario 2 Y_{detect}
Winter	15.1%	65	104
Spring	10.9%	100	136
Summer	3.8%	180	245
Autumn	7.5%	98	155

Table 6.12 Y_{detect} for seasonal flows based on three possible trend scenarios.

The analysis of seasonal flows show that for winter, a record length of between 65 and 104 years of record are required to confidently detect trend, for spring the range is 100-136, for summer 180-245, and for autumn 98-155 years.

6.12.3 Detection of trend in the monthly flow series

From the analysis of the number of years required to detect a trend in the annual flow series, it was found that the reliable estimates of trend can be taken from persistence tests on sub periods of flow beginning earlier than 1930. We can further look at the months in the year that are driving this trend by examining the Mann Kendall persistence test for data sub periods starting prior to 1930. It was previously found that spring is the season that is driving the trend in the annual flow series. March was found to be the main driver of the trend within spring followed by May and then April. This seems to echo the results of Sheridan (2001) where it is noted that the largest increases in rainfall over the past 80 years has been in the month of March. June is the main driver of trend in summer, with October responsible for the trend in autumn, and January is the sole driver of trend in the winter months.

The months of December, February, August, September and November are trend neutral, in that the trend signals for these months are neither strongly positive nor negative.

6.13 Peaks Over Threshold Seasonality Analysis

The two main types of flood data series used to assess the behaviour of high flows are the annual maximum (Amax) series and the peaks-over-threshold (POT) series. In the calibration stage of this project it was found that the HYSIM model was superior to IHACRES when replicating high flows, and so was chosen for use in the peaks-over-threshold analysis. POT analysis is used to assess the overall behaviour of high flows as well as changes in seasonality. In the POT analysis used here, the threshold corresponding to 4 peaks per calendar year (POT4) is used to generate the series. When generating the POT4 series it was necessary to introduce an independence criterion to ensure that the floods identified were fully independent of previous events. It was decided that for an event to be fully independent there should be a separation of at least three days from the last event. The POT4 series were also used to identify the flood events for identification against documented historical reports during the validation of the HYSIM and IHACRES models between 1926 and 1955.

In order to assess the changes in seasonality of the flows the POT series was split into two separate equal periods, 1930-1969 and 1970-2009. The number of POT4 values for each of the twelve months were calculated for the two periods of the split sample and the results are outlined in Table 6.14. The first noticeable statistic of the data is that the total number of POT4 events increased by 12 (15.7%) for the latter period. In order to visually assess the changes in seasonality of the flows the results were plotted on a spider web-plot (Figure 6.18) to demonstrate where the greatest changes had taken place.

	Split Period for POT Seasonality Analysis		Change in no. of
Month	1930-1969	**1970-2009**	**Change in no. of POT4 events**
December	30	39	+30%
January	37	42	+11.9%
February	22	23	+0.05%
March	9	7	-0.22%
April	4	4	0%
May	0	0	0%
June	1	1	0%
July	0	0	0%
August	2	4	100%
September	6	1	-83.3%
October	9	19	+111%
November	20	22	+10%
TOTAL	**140**	**162**	**+15.7%**

Table 6.13 Monthly POT4 Analysis on split samples from 1930-1969 and from 1970-2009

From October through to January there were notable increases in the number of POT4 events witnessed.

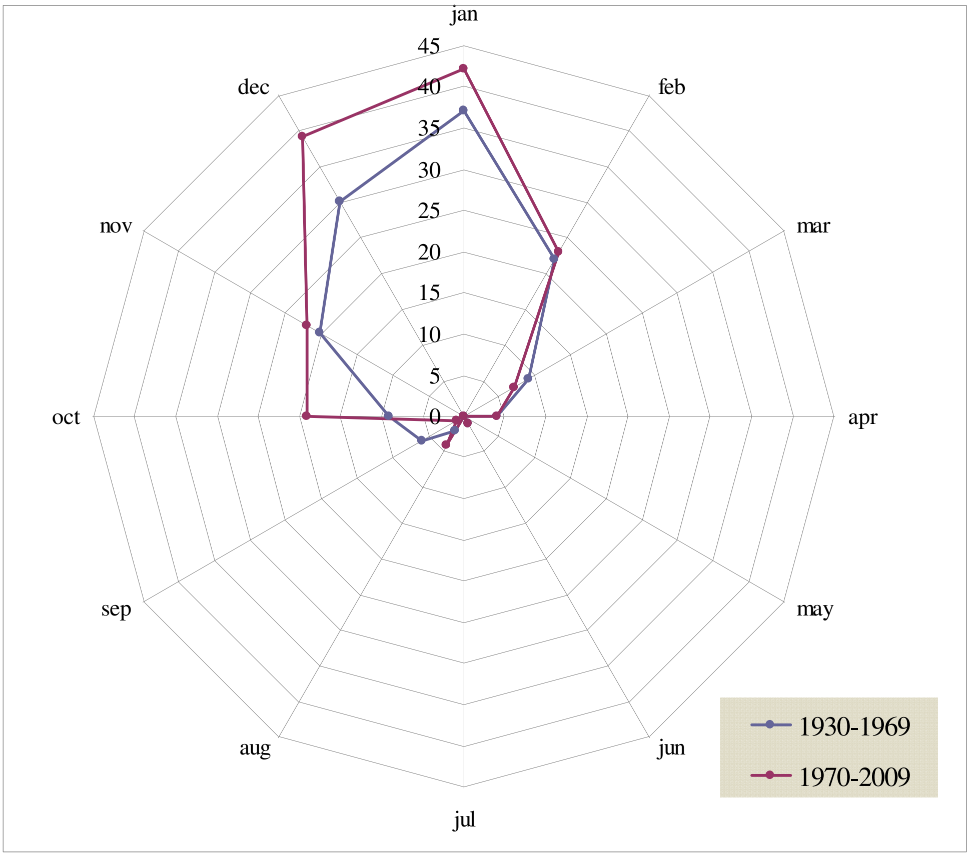


Figure 6.18 Monthly POT4 analysis on split sample

The number of events occurring in September fell between the two periods, while the number of floods in the following month of October have increased. This would suggest a shift of the POT4 flood events closer to winter. A similar behaviour can be seen to a lesser extent with the March POT events which also seem to have been shifted towards the winter months. When looking at the number of POT events per decade, there is a very clear upward trend in the occurrence of larger flows. In the 1930s there were only 28 POT4 events as compared to 63 in the 1990s. The 1990s and 2000s are easily the most flood prone decades, with the average for this 20-year period amounting to 55 POT events per year it is substantially greater than the average for the first 60 years of the analysis which is 35 POT events per year.

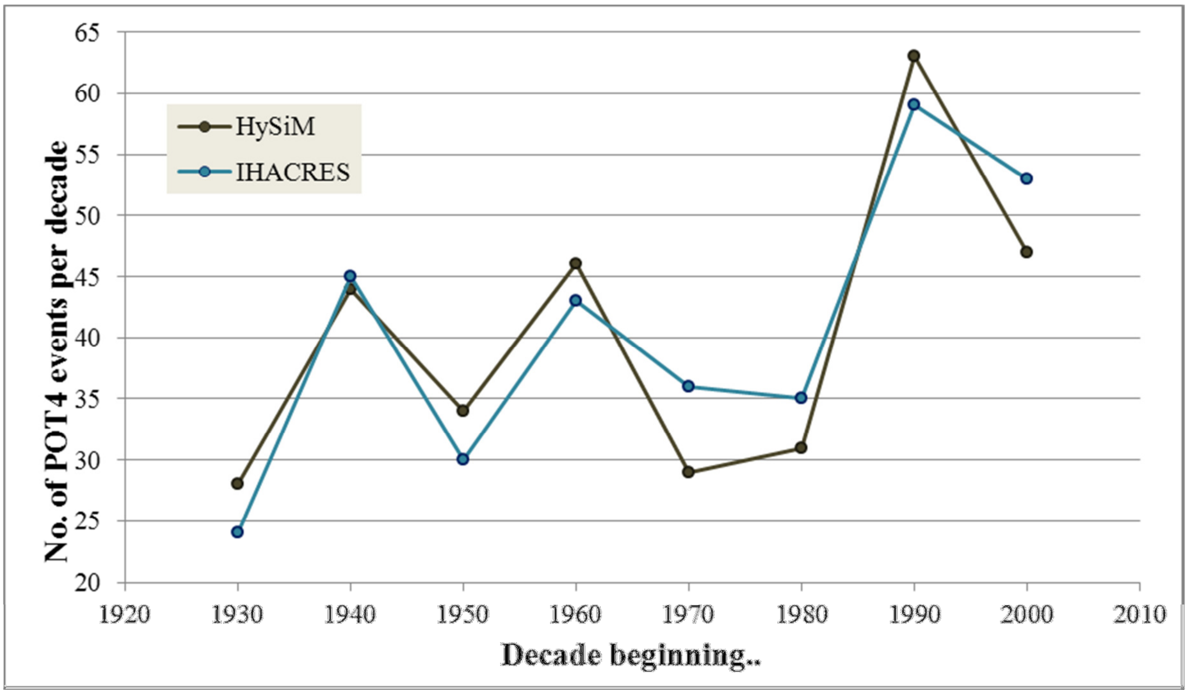


Figure 6.19 Decadal number of POT4 flood events.

6.14 Flood Frequency Analysis

Current methods of flood frequency analysis are based on the assumption of stationarity in the data being examined. While the examination of studies on how to deal with non-stationarity is outside the scope of this study it was nevertheless decided to perform a flood frequency analysis on the reconstructed flow data in order to illustrate the effect of the period of record on flood rarity estimates.

In order to calculate the flow of a given return period (Q_T) we must first know two items of information. The first is the magnitude of the index flood, and the second is the growth factor for the specified return period. For the upcoming update of the Flood Studies Report (NERC, 1975) known as Flood Studies Update (FSU) for Ireland, the index flood is taken to be the median of the annual maximum flood series at a site. Therefore for any given return period (T), the corresponding flow is given by:

$$Q_T = Q_{med} * X_T$$

Q_{med} is calculated from the annual maximum (Amax) flow series at the gauge, and X_T is calculated from a growth curve. The growth curve is the statistical distribution that best fits the data at the site. In order to produce the growth curve, the Amax series for the site is first arranged in order of increasing value, and then transformed using a pre-specified "plotting position" formula applied to the ranks of each value in the series. The choice of plotting position formula is dependent on the type of distribution be fitted to the data, and decides the values of the x coordinate for plotting the data. The abscissa (y-coordinate) is given predefined functions that also relate to the distribution being examined. These are known as Extreme Value (EV) plots.

In the Flood Studies Update, a total of six statistical distributions are supported for the purposes of producing growth curves (Das, 2010) made up of 3 no. two parameter, and 3 no. three parameter distributions as follows:

Two parameter distributions

- Extreme Value Type 1 distribution (EV1)
- Logistic Distribution (LO)
- 2-Parameter Lognormal distribution (LN2)

Three parameter distributions

- Generalised Extreme Value distribution (GEV)
- Generalised Logistic distribution (GLO)
- 3-Parameter Lognormal distribution (LN3)

The Amax series produced by the HYSIM model was used for flood frequency analysis to assess the effects of period of record effects on the estimating the return period of specific floods. The guidance given in the final report of FSU Work Package 2.2 “Flood Frequency Analysis” states that when using at site (single site) analysis, the maximum return period flood that can be calculated is 2N, where N is the number of years of Amax record at the site. The 1:100 year return period flood was chosen as the return period for which the comparison would be carried out seeing as it is a commonly used design criterion. The distribution that was chosen as the best fit to the data from the HYSIM model was the 2-parameter lognormal (LN2) distribution. The extreme value plot for the LN2 distribution applied to the 1926-2009 Amax series is shown in Figure 6.20. The LN2 distribution was chosen because when the flow data is plotted against the normal reduced variate it best approximates a straight line, and ‘snakes’ around the best fit line.

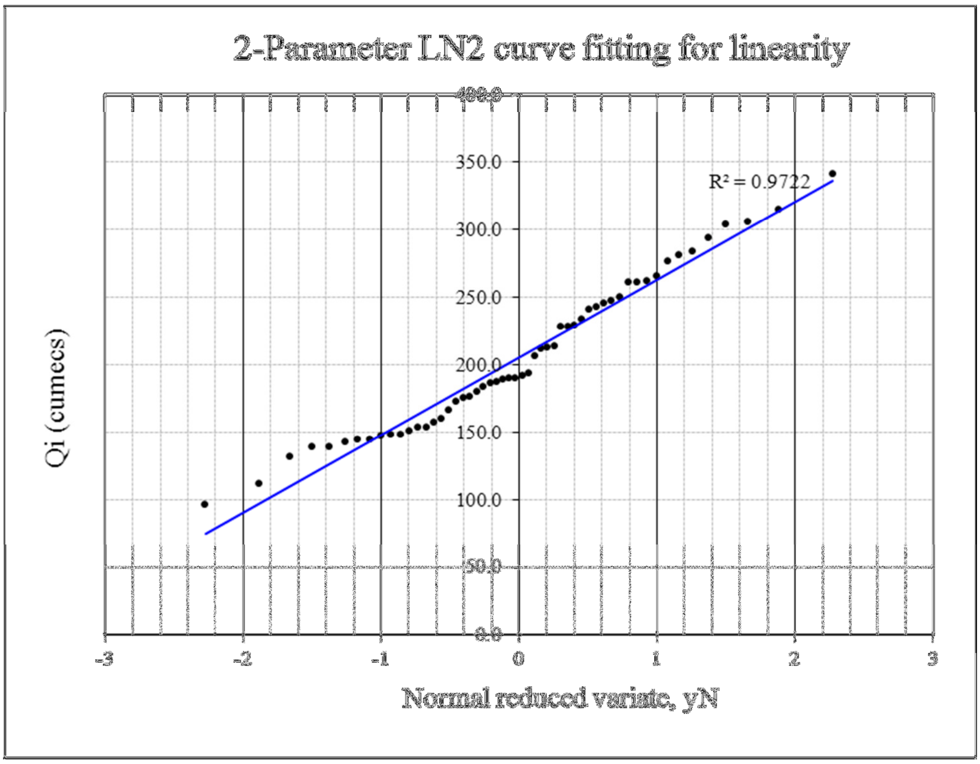


Figure 6.20 Extreme value plot for the LN2 distribution applied to the reconstructed data

The flood frequency curve for the site was constructed using the 1956-2009 Amax series and the Amax series for the extended period of 1926-2009. The two differing curves produced are as shown in Figure 6.21.

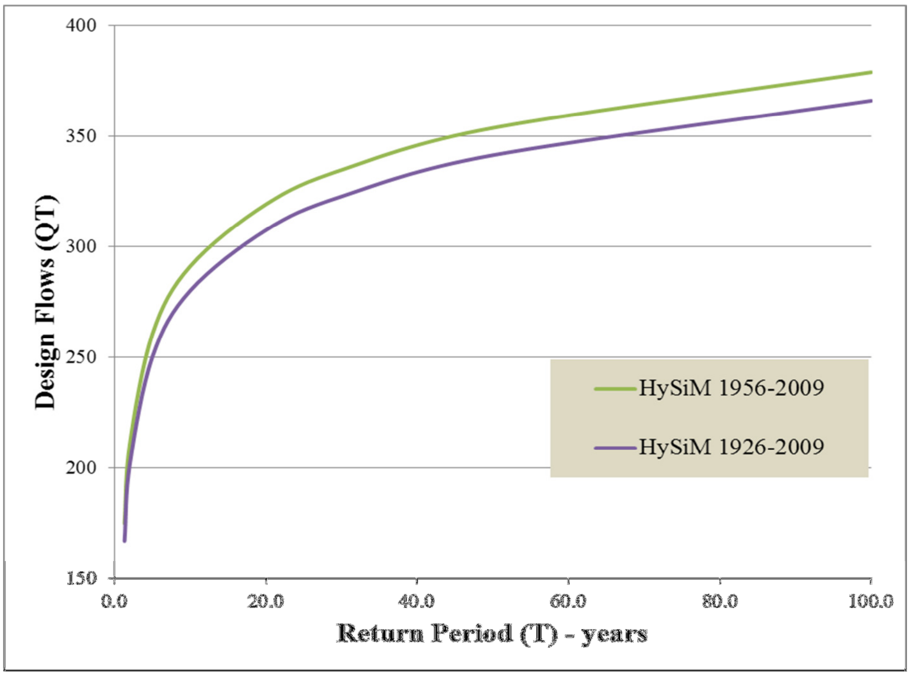


Figure 6.21 Design Flows up to the 100-year return period flow based on the LN2 Growth Curve.

The 1:100 year flood based on the 1956-2009 Amax series is estimated to be 379 m^3/s, whereas the same measure calculated using the longer 1926-2009 Amax series is 366 m^3/s. This puts the November 1941 flood event (471 m^3/s) and the 7th December 1978 (387 m^3/s) as being well in excess of the 1:100 year flood, and thus beyond that which could be estimated per the FSU guidance. Using the flood frequency curve to assess the return period of the event of the 12th August 1946 (350m^3/s) we find that the event is approximately a 1:65 year event when using the curve based on the extended series whereas if based on the shorter series the return period of the August 1946 flood is the 1:45 years flood.

The shallower growth curve produced by using the full series from 1926-2009 seems to reflect the proclivity towards fewer extreme floods in the earlier part of the series prior to 1956. Similar to testing for trend, assigning rarities (return periods) to flood events can be strongly dependent on the period of record used. The example of the August 1946 event is proof of this. The 100-year flood obtained from using the extended flow series is 366 m^3/s. If using the growth curve based on data after 1956 this flow is only found to be the 1:73 year flood.

This large discrepancy would lead to the suggestion that when quoting return periods of a given flood, or estimating Q_T, the period of data (start and end dates) on which the growth curve is based should also be quoted. Furthermore it also goes towards disproving the assumption of stationarity in the flood data for the Kilavullen catchment.

Rarity estimates of the largest daily rainfall data can also be inferred from the depth duration frequency (DDF) model for Ireland described in Met Éireann's Technical Note no. 61 Estimation of point rainfall frequencies. The data used in the analysis for the DDF model was based on the data from all available Met Éireann daily and sub-daily rain gauges between 1941-2004 This model allows estimation of design rainfall depths for a range of frequencies and durations at any point in Ireland. The range of depths for all the 1-day duration rainfalls within the Kilavullen catchment were calculated for each return period, and the growth curve for the catchment was plotted after applying the appropriate areal reduction factor to the average catchment design rainfalls.

Return Period	Point Rainfall Depth	Catchment Areal Rainfall
(years)	(mm)	(mm)
2	48.73	43.23
5	62.16	55.14
10	71.69	63.59
20	81.76	72.52
30	88.08	78.13
50	96.60	85.69
100	109.32	96.97
150	117.63	104.34
200	123.93	109.93

Table 6.14 24-hour duration rainfall growth factors for the Kilavullen catchment

Table 6.14 sets out the design rainfalls for each return period. By plotting these values, we can construct the rainfall growth curve for the Kilavullen catchment, and this can be seen in Figure 6.22.

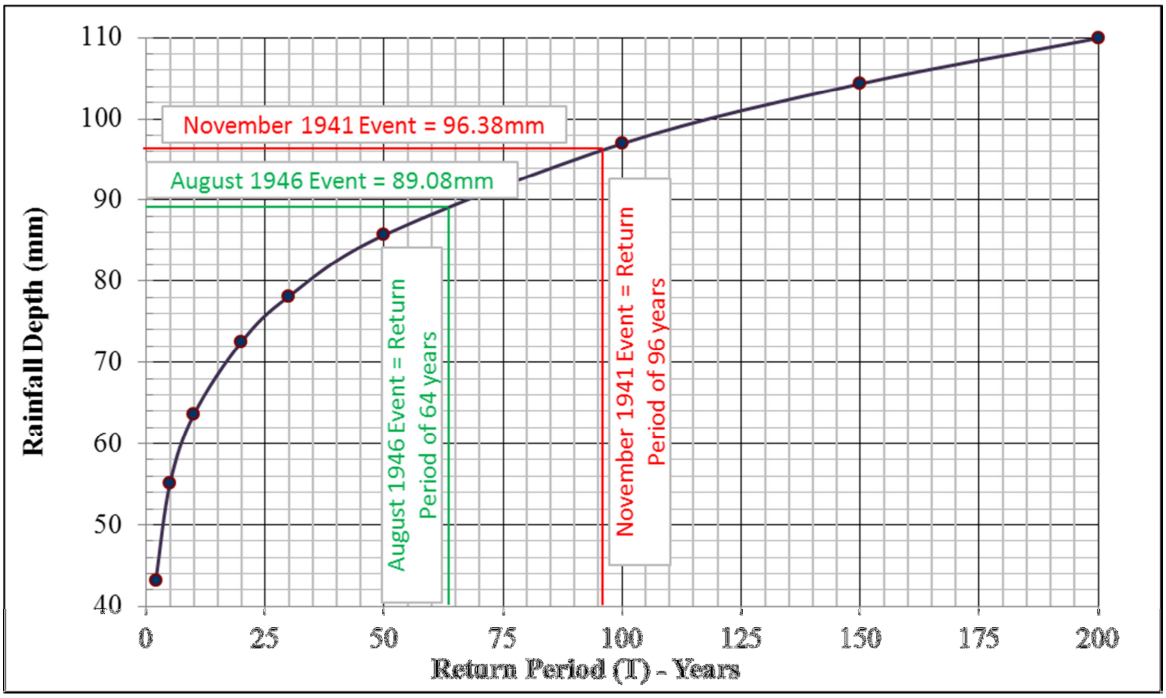


Figure 6.22 24-hour duration rainfall growth curve for the Kilavullen catchment

The largest single daily average rainfall over the catchment occurred on the 9th November 1941 and amounted to 96.38mm. This has been estimated as being a 1:96 year event. The second largest single daily rainfall amount was 89.08 on the 11th August 1946. This has been estimated as being a 1:64 year event. It is interesting to note that even though the Munster Blackwater catchment has such a long history of extreme floods, even at its most extreme, it has still not yet experienced a 24-hour duration rainfall of return period greater than 100 years.

6.15 Trend and frequency analysis conclusions

This chapter has detailed the procedures that were employed in order to test for trends in the average temperatures, annual rainfalls and reconstructed flow series for the Kilavullen catchment between 1926 and 2009. Tests for gradual trend in the annual average temperature and annual total rainfall series showed a strong persistent trend in both series. Three tests for gradual trend were applied to the annual average flow data which all showed a persistent statistically significant trend in the flows over the period of record. By delving deeper into the flow series for the Kilavullen gauge it was found that springtime flows are the main driver behind the trend signal in the catchment, and of the three spring months, March is the month that primarily drives the trend behaviour of the spring flows. The summer flows were seen to contribute the least to the overall trend in average annual flows. Statistical tests for step change on annual rainfalls and flows showed that clear change points occurred in 1980/81, 1987/88 and 1992/93 which were all more or less driven by corresponding changes in the North Atlantic Oscillation.

It was also found that the winter and spring NAO indices are positively correlated with the flows of all seasons, and that the summer and autumn flows tend to be negatively correlated to the flows in each season. The analysis of the time to detect trend in the annual average flows in the Kilavullen catchment showed that a record length of between 44 and 94 years of annual average flow data would be required to successfully detect the presence of trend. This is the flow index that would yield the earliest detection time. Of the four seasons, winter yields the shortest detection time of between 65 and 104 years. Analysis of the peaks-over-threshold series for the catchment indicates that over the latter half of the record, the number of flood events increased by almost 16%. This trend is also evident in the number of POT4 events recorded per decade, with the 1990s being identified as the most flood rich period in the flow series. This increase in flood events seems to be distributed between the months from October to February and corresponds to a decrease in the number of flood events occurring in September and March.

The flood frequency analysis applied to short and long series of annual flows showed the importance of the period of record that is used for flood frequency analysis. The more flood prone period from 1956-2009 shows a steeper growth curve than that produced by using flood series from 1926-2009 (which includes the flood poor years of the earlier part of the record). By proxy, this also highlights the changing characteristics of floods in the catchment.

7 CONCLUSIONS

7.1 Introduction

This research sought to examine the changing long term characteristics of flows in the Munster Blackwater catchment in order to add to the current state of knowledge of change in hydrological systems in Ireland. This was achieved through a number of subtasks that were primarily motivated by the need for a robust model of the catchment.

In the earlier part of the research, hydrometeorological time series for the Kilavullen catchment were examined with the intention of producing the best possible dataset for use in rainfall runoff modelling. During the review of this data the deficiencies associated with the raw data were identified and recorded. This work was important and highlights that data which is assumed to be fully quality controlled will still contain errors that may lead to erroneous model results, and hence a full quality control assessment of all data is necessary before proceeding.

A number of methods for adjusting the data into a form that was fit for use in rainfall runoff modelling were explored, and resulted in some useful discoveries, especially in the application of a method for calculating Potential Evapotranspiration for catchments that did not contain synoptic stations that could provide such data. This also resulted in the realisation that the method proposed by Oudin et al. showed superior performance when applied to rainfall runoff models.

Perhaps the most notable result from this research was the development of a method that used historical gauged data to generate time series for use in hydrological modelling of the Kilavullen catchment. There is no evidence of such a study being carried out previously in Ireland that possessed such a long record of reconstruction of flows. The application of historical data can be shown to have uses in assessing the impacts of climate change on river flows and can be easily applied to other catchments in Ireland.

7.2 Reconstruction of River Flows 1926-1955

The two models developed for the reconstruction of river flows in the Kilavullen catchment have proven the usefulness of both the HYSIM and IHACRES models in hindcasting of flows, with both showing excellent performance in reproducing observed flows as evidenced by the high objective function scores obtained from both models, most notably the Nash-Sutcliffe efficiencies. However, despite their good performance, neither model was perfect across the range of flows with both underestimating the highest annual flows and HYSIM in particular failing to capture the summer flows. Importantly, the flows that were reconstructed showed no evidence of step change at the interface between the gauged and ungauged periods within the catchment indicating that the data used for reconstruction were suitable for such purposes. The reconstructed flows highlight the importance of long records of river flows in the detection of trend signals in Irish rivers, as well as providing information on the changing seasonality of the flows in the Munster Blackwater.

7.3 Trend Analysis

The results of the analysis of trend in the Kilavullen catchment confirmed that there is significant positive trend present in the flows for the catchment, most of which is attributable to the unprecedented large rainfall amounts witnessed in the past two decades. The behaviour of annual flows was shown to be correlated to the North Atlantic Oscillation Index. The annual trends in flows were found to be dominated by the changes derived for spring and to a lesser extent, winter flows. The trend exhibited by spring flows was furthermore attributed to the trend in flows for the month of March. The significance of trends was found to decrease in the last number of decades and even become non-significant and emphasises the importance of long record lengths in conducting trend analysis. It is obvious that trends derived from short records, may thus give misleading results.

The POT4 analysis on reconstructed flows was used to show that the number of large flood events occurring in the catchment have greatly increased between the first and second half of the period examined. The analysis of the flood frequency curve for the site also showed the importance of record length in defining the 100-year return period flow. When the period of analysis includes flood poor periods the flood growth curve shows a much reduced flow for the 100 year flood as compared to using a flood rich period for the analysis.

The trend analysis also highlighted the strong trends that also exist in temperature and rainfall measurements with the period since 1990 being shown to be among the warmest and wettest periods on record. Trends in temperature are particularly driven by increases in the minimum temperatures.

Much research has concluded that the detection of trend is heavily dependent on the period of record available, and that at least 50 years of data is required for the analysis of climate driven trends in river flows. Based on results derived here such as suggestion would seem to be conservative. The detection times for climate change scenarios for the catchment indicate that changes will not be detectable within the time frame they are simulated to occur. Within this research it was found that the length of record of annual average flows required to detect a significant trend would range between 44 and 94 years of data. This would represent the flow index that would yield the earliest trend detection time. Of the four seasons, winter exhibits the shortest detection time of between 65 and 104 years.

Statistical tests for step change on annual rainfalls and flows showed that clear change points occurred in 1980/81, 1987/88 and 1992/93 which were all more or less driven by corresponding changes in the North Atlantic Oscillation.

It was also found that the winter and spring NAO indices are positively correlated with the flows of all seasons, and that the summer and autumn flows tend to be negatively correlated to the flows in each season.

7.4 Policy Implications

Flood policy in Ireland over the next few years will depend on the ability to quantify the expected increase in flood magnitudes due to climate change. It is therefore of great interest that a means of detecting trend in river flows in a timely manner is developed so that its effects in the future may be quantified as early as possible, and the necessary steps be taken to protect people and property. The research presented here would suggest that the period of record that is used to define flood growth curves strongly influences the results of such an analysis. Flood risk management policy in the future should reflect the realisation that the assumption of stationarity in flood data is no longer true, and more sophisticated techniques for non-stationary flood frequency analysis should be adopted.

Flood risk management policy into the future should also take into account how the flow gauging network is to be organised. A network of early indicator stations should be identified that will be maintained far into the future so that detection of trend in river flows can be accommodated.

7.5 Suggestions for future research

In this research the method developed for reconstructing historic flows is proposed as a best practice for such a study, and future research in this area of study should attempt to build on the findings presented in this research. The extension of this method to other catchments should be identified as a pressing need for understanding the long term variability of river flows. This would play an important role in placing changes from shorter term records for the observed network in context. The sources of data unearthed as part of this research, and the success obtained in their use mean that this approach could be easily reproduced for other catchments.

During the course of the research the following possibilities for future research were identified:

- Assessment of the behaviour influence exerted by the NAO on annual, seasonal and monthly flows. If a methodology for relating NAO Indices to periods of high flow were possible, it would have wide applications in the field of water management and flood forecasting.

- Historical data across the country should be digitised for use in future work of this kind. Not only would this assist in reconstructing historic flood flows, but it could be used to reconstruct historic drought conditions as well.

- Further research into examining the use of monthly rainfalls for hindcasting. In this study, daily rainfall values only were used. Many early historic rainfall records were recorded on a monthly basis and it is highly likely that the models developed in this study could be used to hindcast monthly flows even further back in time. Such an analysis would aid the development of seasonal and annual mean series that could theoretically be developed back to the 1880s, or event earlier in some cases.

- This work has examined the persistence of trend over time to overcome the challenges of fixed periods of analysis. The approach taken in the analysis of persistence, while it allows a fuller appreciation of the evolution of trends, is limited in that the end of the record remains unchanged. Across Ireland, river flow and precipitation records both show high extremes at the end of the record. Future work should aim at developing methods that can allow a fuller analysis of the role of extremes in the development of trends.

This research has clearly shown the value of historic records in putting current climate conditions in a historical context. It also raises the awareness of the existence of such data that can be used by other researchers in this field. The methodology for reconstructing historic flood flows presented here can be used as a starting point, and further refinement to the methodology will allow for a speedier more widespread use of the method across Ireland. The application of the method will further the efforts of identifying a network of gauging stations for the detection of climate change in the long term behaviour of Irish catchments.

8 BIBLIOGRAPHY

Acreman, M. (1985) Effects of afforestation on the flood hydrology of the upper Ettrick valley. *Scottish Forestry,* 39, 89-99.

Adamowski, K. and C. Bocci. (2001) Geostatistical regional trend detection in river flow data. *Hydrological. Processes,* 15, 3331-3341.

Arnell, N.W., (2003) Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: future streamflow in Britain. *Journal of Hydrology,* 270, *195–213.*

Babtie Group (2003) *Munster Blackwater River (Fermoy) Drainage Scheme – Hydrology Report*. Report for the Office of Public Works. pp-70.

Bailey, A.D. and Bree, T. (1981) Effect of improved land drainage on river flow. In: *Flood Studies Report: 5 Years On. Thomas Telford, London, 131-42.*

Bayliss A.C. and Reed D.W. (2001) *The use of historical data in flood frequency estimation. Report to MAFF*, Wallingford: CEH Wallingford.

Barnett, T.P, Pierce, D.W., Hidalgo, H.G., Bonfils C., Santer, B.D., Das, T., Bala, G., Wood, W.A., Nozawa, T., Mirin, A.A., Cayan, D.R., and Dettinger, M.D. (2008) Human Induced Changes in the Hydrology of the Western United States. *Science,* 139, 1080-108.

Bastola, S., Murphy, C and Sweeney, J. (2011) The role of hydrological modelling uncertainties in climate change impact assessments for Irish river catchments. *Advances in Water Resources,*34(5), 562-576.

Beven, K. and Binley, A., (1992) The future of distributed models: model calibration and uncertainty prediction. *Hydrological Processes,* 6, 279–298.

Beven, K.J. (2000) *Rainfall-Runoff Modelling: the Primer*. Chichester: Wiley.

Beven, K.J., (2002) Towards a coherent philosophy for modelling the environment. *Proceedings of the Royal Society of London,* 458, 2465 – 2484.

Brázdil, R., Kundzewicz, Z.W., and Benito, G., (2006) Historical hydrology for studying flood risk in Europe, *Hydrological Sciences Journal*, 51(5), 739-764

Bree, T. and Cunnane, C. (1979) The effect of arterial drainage on flood magnitude. *Casebook of scientific project 5.1 of the International Hydrological Programme: Assessment of changes in the hydrological regime of river basins due to human activities. UNESCO*, 116-126.

Brooks, R.H. and Corey, A.T. (1964) Hydraulic properties of porous media. *Hydrological Papers* (Colorado State University), 3, 27 pp.

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

Cargill, A., and Price, D.J., (2001) *Comparison of FEH and FSR estimates of design flood magnitudes in Scotland*. In: Proceedings 36th DEFRA Conference of River and Coastal Engineers, Keele University, June 2001, 06.4.1 – 06.4.8.

Casella, G., and Berger, R.L. (1990) *Statistical Inference*.Pacific Grove, California: Wadsworth and Brooks/Cole.

Charlton, R. and Moore, S. (2003) The impact of climate change on water resources in Ireland. In: Sweeney, J. et al. *Climate Change, Scenarios and Impacts for Ireland*, Wexford, Ireland: Environmental Protection Agency, Johnstown Castle Estate,. 81–102.

Chiew, F. H. S., and McMahon, T.A., (1993) Detection of trend or change in annual flow of Australian rivers, *International Journal of Climatology*, 13, 643–653,

Chow, V.T. (1959) *Open Channel Hydraulics*. New York: McGraw-Hill.
Commission on Geosciences, Environment and Resources (CGER) (1999) Improving American River Flood Frequency Analyses. Washington D.C., National Academy Press.

COST Secretariat (2009) *Memorandum of Understanding for the implementation of a European Concerted Research Action designated as COST Action ES0901: European procedures for flood frequency estimation (FloodFreq): COST 229/09*. Brussels 11June 2009. [online] Available at:
http://w3.cost.eu/fileadmin/domain_files/ESSEM/Action_ES0901/mou/ES0901-e.pdf

Dai, A., Trenberth, K.E., and Qian, T. (2004), A global data set of Palmer drought severity index for 1870– 2002: Relationship with soil moisture and effects of surface warming, *Journal of Hydrometeorology,* 5, 1117–1130.

Das, S. (2009) *Examination of flood estimation techniques in the Irish context*. Unpublished PhD Thesis, National University of Ireland, Galway

Dettinger, M.D., Cayan, D.R., Meyer, M.K., and Jeton, A.E. (2004) Simulated hydrological responses to climate variations and change in the Merced, Carson, and American river basins, Sierra Nevada, California, 1900-2099. *Climate Change,* 62, 283-317.
Dixon, F.E. (1987) Early Irish weather records. Pages 59-61 in: Shields, L (ed.) *The Irish Meteorological Service. The First Fifty Years 1936-1986.* The Stationery Office, Dublin.
Douglas, E.M., Vogel, R.M., and Kroll, C.N. (2000) Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology*, 240, 90-109.

Fowler, H. J., and R. L. Wilby (2010) Detecting changes in seasonal precipitation extremes using regional climate model projections: Implications for managing fluvial flood risk, *Water Resources Research*, 46, W03525.

Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C., and Stott, P.A. (2006), Detection of a direct carbon dioxide effect in continental river runoff records, *Nature*, 439, 835–838.

Gosain, A.K., Mani, A., Chandramauli, D., (2009) *Hydrological modelling Literature Review Report No.1*, Climawater Research Project.

Grubb, H., and Robson, A., (2000) Exploratory/visual analysis. In: Kundzewicz, Z.W., and Robson, A., eds. (2000) *Detecting Trend and other changes in Hydrological Data*, World Climate Programme – Water, World Climate Programme Data and Monitoring, WCDMP-45, WMO/TD no. 1013, Water Meteorological Organisation, Geneva, Switzerland. 19-48

Guowei, L. & Jingping, W. (1999) A study of extreme floods in China for the past 100 years. In: Gottschalk, L., Olivry, J-C., Reed, D. & Rosbjerg, D. (eds) (1999) *Proceedings IAHS Symposium. Hydrological extremes: understanding, predicting, mitigating*., Birmingham, July 1999. *IAHS Publication No. 255*, 109-119.

Hannaford, J., Laize, C.L.R., and Marsh, T.J. (2005) *An assessment of runoff trends in undisturbed catchments in the Celtic regions of North West Europe*
Presented at: The Fourth Inter-Celtic Colloquium on Hydrology and Management of Water Resources. Guimaräes, Portugal, July 11-14, 2005.

Hannaford, J., and Harvey, C.L., (2010) *UK Seasonal river flow variability in near-natural catchments, regional outflows and long hydrometric records*. Presented at: BHS Third International Symposium, Managing Consequences of a Changing Global Environment, Newcastle 2010.

Harrigan, S. (2010) *Detection of Climate Change in Irish Streamflow Records*. Unpublished masters thesis. National University of Ireland, Maynooth.

Helsel, D.R., and Hirsch, R.M. (1992) *Statistical Methods in Water Resources*, Amsterdam 1992: Elsevier.

Huntington, T. G. (2006) Evidence for intensification of the global water cycle: Review and synthesis, *Journal of Hydrology,* 319, 83– 95.

Hurrell, J.W. (1995) Decadal Trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science,* 269, 676-679

Institute of Hydrology (1985) *Flood Studies Supplementary Report 16 – The FSR rainfall-runoff model parameter estimation equations updated*. Wallingford: Institute of Hydrology.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., Qin, D., Manning, M., Marquis, M., Chen, Z., Averyt, K.B., Tignor, M., and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA. 996 pp.

IPCC (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel* *on Climate Change,* Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E., (eds.), Cambridge University Press, Cambridge, UK, and New York, USA. 976pp.

Irish Newspapers Archive website Available at:(www.irishnewsarchive.com/)

Jakeman A.J., Littlewood I.G., and Whitehead P.G. (1990) Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments,
Journal of Hydrology, 117, 275-300.

Jaksic, V. (2004) Observations and modelling of carbon dioxide and energy fluxes from an Irish grassland for a two year campaign. Unpublished Masters Thesis, University College Cork, Cork

Jones, P.D. and Lister, D.H. (1998) Riverflow reconstructions and their analysis on 15 catchments over England and Wales, *International Journal of Climatology*, 18, 999-1013.

Jones, P.D., Lister, D.H., Wilby, R.L. and Kostopoulou, E., (2006) Extended river flow reconstructions for England and Wales, 1865 – 2002. *International Journal of Climatology*, 26, 219–231.

Jones, P.D., Lister, D.H., Wilby, R.L., and Kostopoulou, E. (2006) Extended riverflow reconstructions for England and Wales, 1865–2002, *International Journal of Climatology*, 26, 219-231.

Kiely, G. (1999) Climate change in Ireland from precipitation and streamflow observations. *Advances in Water Resources,* 23, 141–151.

Kiely, G., (2000). *Flood Study of the Blackwater River at Fermoy.* Cork, Ireland: Cork County Council.

Kiely, G. *et al*. (2010) Extreme Weather, Climate and Natural Disasters in Ireland. Johnstown Castle, Wexford, Ireland: EPA

Kundzewicz, Z. and Robson, A.J. (2004) Change detection in hydrological records – a review of the methodology. *Hydrological Sciences Journal,* 49 (1), 7 – 19.

Kundzewicz, Z.W., Graczyk, D., Maurer, T., Pinskwar, I., Radziejewski, M., Svensson, C., and Szwed, M. (2005) Trend Detection in river flow series: 1. Annual maximum flow.
Hydrological Sciences Journal, 50(5), 797-810

Law, F., Black, A.R., Scarrott, R.M.J., Miller, J.B., and Bayliss, A.C. (1998)
Chronology of British Hydrological Events [online].
Available at: http://www.dundee.ac.uk/geography/cbhe/

Legates, D.R. and McCabe, G.J., (1999) Evaluating the use of "goodness of fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research,* 35(1), 233–241.

Lindström, G. (1997) A simple calibration routine for the HBV Model. *Nordic Hydrology,* 28(3), 153-168.

Lins, H. F., and J. R. Slack (1999), Streamflow trends in the United States, Geophysical Research Letters, 26, 227– 230.

McGrath, R., Lynch, P., Dunne, S., Hanafin, J., Nishimura, E., Nolan, P., Venkata Ratnam, J., Semmler, T., Sweeney, C., and Wang, S.,. (2008) *Ireland in a Warmer World. Scientific Predictions of the Irish Climate in the Twenty-First Century: Final report of C4I*, Dublin.

Manley, R.E., 1978. Calibration of Model using Optimization. *Journal of the Hydraulics Division,* ASCE, 104 (2), 189-202

Manley, R.E. (2006) *HYSIM Reference Manual*. Cambridge: R.E. Manley and Water Resource Associates Ltd.: Cambridge.

McElwain, L. and Sweeney, J. and (2007) *Key Meteorological Indicators of Climate Change in Ireland.* Johnstown Castle, Wexford, Ireland: Environmental Protection Agency.

McWilliams, B.E. (ed) (1991) *Climate Change: Studies on the Implications for Ireland*. Dublin, Ireland: Stationery Office.
Met Éireann (2007) *Our History* [online]. Available at: http://www.met.ie/about/our-history.asp?prn=1 (accessed 12 December 2011)

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

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W. Lettenmaier, D.P., Stouffer, R.J. (2008) Stationarity Is Dead: Whither Water Management?, 319 *Science* 319, 573-574.

Montanari, A., (2005) Large sample behaviours of the generalized likelihood uncertainty estimation (GLUE) in assessing the uncertainty of rainfall-runoff simulations, Water Resources Research, 41, W08406.

Monteith, J.L. (1965) *Evaporation and environment*. pp. 205-234. In: G.E. Fogg (ed.) Symposium of the Society for Experimental Biology, *The State and Movement of Water in Living Organisms*, Vol. 19, Academic Press, Inc., NY.

Mountain, N.C., Jones, J.A.A. (2006) Reconstructing extreme flows using an airflow index based stochastic weather generator and a hydrological simulation model, *Catena*, 66, 120-134.

Mulvaney, T. J. (1851) On the use of self-registering rain and flood gauges, in making observations of the relation of rainfall and flood discharges in a given catchment. *Proceedings of the Institute of Civil Engineers of Ireland*, 4, 18-31.

Murphy, C., Charlton, R., Sweeney, J. and Fealy, R., (2006) The reliability of an “off-the-shelf” conceptual rainfall runoff model for use in climate impact assessment: uncertainty quantification using Latin Hypercube sampling. *Area,* 38(1), 65–78.

Murphy, C. and Charlton, R. (2008) “*Climate Change and Water Resources in Ireland*”. In: Sweeney, J. (ed.) Climate Change: Refining the Impacts. Environmental Protection Agency, Johnstown Castle, Wexford, Government Publications.

Murphy, C. (2009) *Work Package 2.3 of the Flood Studies Update – Estimation of the Index Flood at ungauged locations*. FSU-WP2.3

Murphy, E.W.M. (1926) *The Rainfall of Ireland*. Clonmel, Ireland: The Chronicle Newspaper and Printing Works.

Naden, P. S. and Polarski, M. (1990) Derivation of river network variables from digitised data and their use in flood estimation. Report to Ministry of Agriculture, Fisheries and Food; Institute of Hydrology, Wallingford, UK.

NERC (1975) *Flood Studies Report,* Volumes I-V, Natural Environment Research Council, London, UK.

NOAA (2011) *National Climatic Data Center, State of the Climate: Global Analysis for Annual 2011* [online], available at: http://www.ncdc.noaa.gov/sotc/global/2011/13. (accessed 31 January 2012)

Office of Public Works (2005) *Flood Hazard Mapping* [online]. Available at: http://www.floodmaps.ie (accessed 20 January 2011)

Olsen, R., Kiang, J., and Waskom, R. (eds.) (2010) *Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management*. January 13-15, 2010 Boulder, Colorado Colorado Water Institute Information Series No. 109

O’Sullivan, G. (ed.) (1994) *CORINE Land Cover Project (IRELAND)*. Project Report, December 1994. Dublin: Ordnance Survey and Belfast: Ordnance Survey of Northern Ireland.

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andrèassian, V., Anctil, F., and Loumagne, C. (2005) Which potential evapotranspiration input for a lumped rainfall–runoff model? Part 2—Towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling, *Journal of Hydrology,* 303, 290–306.

Ove Arup, (2003) Munster Blackwater (Mallow) Drainage Scheme - Hydrology Report. Report for the Office of Public Works, Dublin Ireland: Office of Public Works.

Pilling, C.G. and Jones, J.A.A., (1999) High resolution climate change scenarios: implications for British runoff. *Hydrological Processes*, 13, 2877–2895.

Pilon, P. (2000) Criteria for the selection of stations in climate change detection network. In: Kundzewicz, Z.W., and Robson, A., eds. (2000) *Detecting Trend and other changes in Hydrological Data*, World Climate Programme – Water, World Climate Programme Data and Monitoring, WCDMP-45, WMO/TD no. 1013, Water Meteorological Organisation, Geneva, Switzerland. 121-132.

Porter J.W. and McMahon T.A. (1971) A model for the simulation of stream flow data from climatic records, *Journal of Hydrology*, 24, 121-134

Price D.J., Kaya Y. and Tingle S. (2000) Land-use change and flood attenuation - the predicted potential benefits of semi-natural woodland. In: Proceedings of 35th MAFF Conference of River & Coastal Engineers, Keele, July 2000

Price, D., Toth, M., Janes, A. (n.d.) Application of the UK Flood Estimation Handbook pooling group approach to the Munster Blackwater River [online] Available at: http://www.engineersireland.ie/EngineersIreland/media/SiteMedia/groups/societies/water-enviro/Application-of-the-UK-Flood-Estimation-Handbook-pooling-group-approach-to-the-Munster-Blackwater-River.pdf?ext=.pdf (accessed December 2011)

Radziejewski, M. and Kundzewicz, Z. W. (2004) Detectability of changes in hydrological records. *Hydrological. Sciences Journal,* 49(1), 39–51.

Refsgaard, J.S., and Knudsen, J., (1996) Operational validation and intercomparison of different types of hydrological models. *Water Resources Research,* 32 (7), 2189–2202.

Robinson, M. (1986). Changes in catchment runoff following drainage and afforestation. *Journal of Hydrology*, 86, 71-84.

Robinson, M. Cognard-Plancq, A-L., Cosandey, C. David, J., Durnad, P., Fuhrer, H-W., Hall, R., Hendriques, M. O., Marc, V., McCarthy, R., McDonnell, M., Martin, C., Nisbet, T., O'Dea, P., Rodgers, M. and Zoller, A. (2003) Studies of the impact of forests on peak flows and base flows: a European perspective. *Forest Ecology and Management*, 186, 85-97.

Robson, A. (2002) Evidence for trends in UK flooding. *Philosophical Transactions of the Royal Society,* 360, 1327-1343.

Robson, A. and Reed, D. (1999). *Flood Estimation Handbook, Vol. 3: Statistical procedures for flood frequency estimation*. Wallingford, Oxfordshire, UK: Institute of Hydrology.

Sefton, C.E.M. and Howarth, S.M. (1998) Relationship between dynamic response characteristics and physical descriptors of catchments in England and Wales. *Journal of Hydrology*, 211, 1-16.

Sheridan, T. (2001) *Analysis of trends at some Irish rainfall stations*, Technical Note 59, Dublin, Ireland: Met Éireann.

Steele-Dunne, S., Lynch, P., McGrath, R., Semmler, T., Wang, S., Hannifin, J and Nolan,

P. (2008) The impacts of climate change on hydrology in Ireland. *Journal of Hydrology,* 356, 28-45.

Sturm, K., Glaser, R., Jacobeit, J., Deutsch, M., Brázdil, R., and Pfister, C., (2001) Hochwasser in Mitteleuropaseit 1500 und ihre Beziehung zur atmosphärischen Zirkulation. *Petermanns Geographische Mitteilungen*, 145, 18–27

Sullivan, M., (1986). *The Floods of Mallow Part 1*, Mallow: Mallow Field Club Journal.

Sullivan, M., (1988). *The Floods of Mallow Part 2*, Mallow: Mallow Field Club Journal.

Svensson, C., Kundzewicz, Z.W., and Maurer, T., (2005) Trend detection in river flow series: 2. Flood and low-flow index series, *Hydrological Sciences Journal*, 50(5), 811-824.

Sweeney, J. (ed.) (2003) Climate Change: Refining the Impacts. Environmental Protection Agency, Johnstown Castle, Wexford: Government Publications.

Thiessen, A.H. (1911) Precipitation for large areas. *Monthly Weather Review*, 39, 1082-1084.

Trigo, R.M., Pozo-Vázquez, D., Osborn, T.J., Castro-Díez, Y., Gámiz-Fortis, S., and Esteban-Parra, M.J., (2004) North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian peninsula, *International Journal of Climatology, 24, 925-944*

Villarini, G; Smith, J.A., Serinaldi, F. and Ntelekos, A.A. (2011). Analyses of seasonal and annual maximum daily discharge records for Central Europe. *Journal of Hydrology,* 399, 299-312

Wagener, T., Wheater, H.S. and Gupta, H. (2004) *Rainfall-Runoff Modelling in Gauged and Ungauged Catchments.* London: Imperial College Press.

Wilby, R. L. (2006), When and where might climate change be detectable in UK river flows?, *Geophysical. Research Letters,* 33 (19), L19407.

Wilby, R.L., Beven, K.J. and Reynard, N.S. (2008) Climate change and fluvial flood risk in the UK: More of the same? *Hydrological Processes,* 22, 2511-2523

Wilby, R.L. and Dessai, S., (2010) Robust adaptation to climate change. *Weather,* 65(7),
180-185.

Wilkinson, J. (2005). "*Reconstruction of historical stormwater flows in the Adelaide metropolitan area.*" ACWS Technical Report No. 10 prepared for the Adelaide Coastal Waters Study Steering Committee, September 2005. Department of Environmental Health, Flinders University of SA

Williams A., and Archer D., (2002) The use of historical flood information in the English Midlands to improve risk assessment, *Hydrological Sciences Journal*, 47(1), 67-76

Yue, S., Wang, C.Y., 2004. The Mann–Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resource Management,* 8(3), 201–218.

Zhang, X., Harvey, K.D., Hogg, W.D., and Yuzyk, T.R., (2001) Trends in Canadian streamflow. *Water Resources Research*, 37, 987–998.

Ziegler, A.D., Maurer, E.P., Sheffield, J., Nijssen, B., Wood, E.F., and Lettenmaier, D.P. (2005) Detection time for plausible changes in annual precipitation, evaporation and streamflow in three Mississippi river sub-basins, *Climatic Change*, 73, 17-36.

Glaser, R. and Stangl, H. (2003) Historical floods in the Dutch Rhine Delta. *Natural Hazards and Earth System Sciences,* 3, 605–613.

OPW, (2003) Munster Blackwater Modelling report (unpublished)

9 APPENDICES

9.1 Appendix A: Rain Stations Used in the Rainfall Analysis

Station no.	Station Name	River Catchment	Height	Start	End	Record Length (Yrs)
1504	RATHDUFF G.S.	MARTIN-BLARNEY	138	21/10/1942	31/12/2009	67.2
1704	BALLYVOURNEY G.S.	SUILLANE	129	27/10/1942	31/08/1985	42.8
2004	MACROOM (GLENDAV FOREST)	FOHERISH-SUILLANE	287	01/11/1942	30/09/1974	31.9
2204	CARRIGNAVAR G.S.	BOHREEN-GLASHABOY	116	12/07/1944	30/04/1966	21.8
2504	BALLINAGREE (HORSEMOUNT)	LANEY	162	01/02/1948	31/07/1977	29.5
2804	DONOUGHMORE	DRIPSEY	200	02/02/1948	31/12/2009	61.9
2904	BALLINAGREE (MUSHERA)	LANEY	351	19/10/1948	30/06/2005	56.7
4104	CARRIGNAVAR COLL.	GLASHABOY	107	01/10/1966	31/05/1973	6.7
5204	MACROOM (CURRALEIGH)	FOHERISH-SULLANE	229	01/12/1977	31/12/2009	32.1
6404	COOLEA (MILLEENS)	BARDINCH-SULLANE	198	01/05/1999	31/01/2009	9.8
9804	M.BALLYVOURNEY (KNOCKACOMMEEN)	AUGHBEG-SUILLANE	415	Null	Null	Null
1205	CASTLEISLAND (COOM)	SHANOWEN-MAINE	157	01/06/1944	03/08/2009	65.2
2005	CASTLEISLAND (GLOUNTAINE)	GLANTAINE-BROWN FLESK	241	17/05/1950	31/08/2004	54.3
2105	FARRANFORE (SCARTAGLIN)	BROWN FLESK-MAINE	213	17/05/1950	30/04/1971	21.0
2205	FARRANFORE (CLOUNLEA)	DOGUE-BROWN FLESK	177	18/05/1950	31/08/2005	55.3
2505	BARRADUFF G.S.	OWNEYKEAGH-FLESK	113	12/10/1951	31/10/1984	33.1
3605	BAWNASKEHY CASTLEISLAND	MAINE	52	01/04/1982	31/12/2009	27.8
4905	CASTLEISLAND (KILMURRY)	SHANOWEN-MAINE	107	01/11/1998	31/05/2010	11.6
106	KANTURK (CASTLECOR)	AWBEG-BLACKWATER	107	Null	Null	Null
406	RATHCOOLE G.S.	RATHCOOLE-BLACKWATER	99	11/07/1944	31/12/1950	6.5
706	MALLOW (HAZELWOOD)	BLACKWATER	94	01/01/1941	04/05/2006	65.3
806	MILLSTREET CONVENT	FINNOW	126	01/01/1941	31/05/1988	47.4
906	RATHMORE G.S.	BLACKWATER	162	01/11/1941	29/02/1984	42.3
1006	BALLYDESMOND G.S.	BLACKWATER	198	01/01/1942	31/12/1963	22.0
1206	BOHERBUE G.S.	BROGEEN	201	05/06/1944	30/06/1971	27.1
1306	NEWMARKET G.S.	DALUA	157	05/06/1944	30/09/1985	41.3
1406	KANTURK (VOC.SCH.)	DALUA	104	06/06/1944	31/12/2009	65.6
1506	MEELIN G.S.	DALUA	238	06/06/1944	31/03/1971	26.8
1606	BUTTEVANT G.S.	AWBEG	96	08/06/1944	31/01/2000	55.6
1706	DONERAILE G.S.	AWBEG	79	08/06/1944	31/07/1985	41.1
2206	BANTEER G.S.	BLACKWATER	75	10/07/1944	31/01/1970	25.6
2306	GLANTAINE G.S.	BLACKWATER	94	11/07/1944	31/07/1984	40.1
2406	GLENVILLE G.S.	GLASHANABRACK	152	12/07/1944	31/03/1996	51.7
2906	MALLOW (SUGAR FACTORY)	BLACKWATER	52	15/04/1950	31/01/1985	34.8
3006	BARNA	YELLOW	226	17/05/1950	30/04/1985	35.0

Table 9.1: List of daily rainfall stations with data supplied by Met Eireann in digital form

…continued

Station no.	Station Name	River Catchment	Height	Start	End	Record Length (Yrs)
3506	MILLSTREET G.S.	BLACKWATER	126	23/04/1952	30/04/1974	22.0
3906	BALLYDESMOND (EAST) G.S.	BLACKWATER	207	01/01/1964	31/12/1967	4.0
4306	BALLYDESMOND (TURREENGARRIVE)	YELLOW-BLACKWATER	299	Null	Null	Null
4606	RATHMORE CONVENT	CULLAVAW-BLACKWATER	168	01/09/1969	31/01/1979	9.4
5106	BALLYDINEEN DONERAILE	CARRIG-BLACKWATER	143	01/10/1982	31/07/1984	1.8
5206	NEWMARKET BALLINATONA P.H.	DALUA	192	01/09/1982	31/12/2009	27.3
5706	CASTLEMAGNER	AWBEG-BLACKWATER	98	01/01/1985	31/12/2005	21.0
5806	FREEMOUNT PUMPING STATION	ALLOW	137	01/11/1984	31/12/2009	25.2
5906	BOHERBOE	BROGEEN	183	01/03/1985	31/10/1990	5.7
6006	BALLYDESMOND	BLACKWATER	201	01/03/1985	31/12/2009	24.8
6106	CASTLETOWNROCHE (NAGLESBOROUGH)	AWBEG-BLACKWATER	67	01/07/1985	30/04/1986	0.8
6206	LOMBARDSTOWN (DROMPEACH)	DUVGLASHA-BLACKWATER	134	01/07/1985	31/12/2009	24.5
6306	BANTEER LYRE	GLEN-BLACKWATER	267	01/07/1985	31/05/2010	24.9
6506	MILLSTREET SEWAGE WORKS	STREAM-FINNOW	101	01/10/1986	30/04/2010	23.6
6606	MALLOW (SEWAGE TREATMENT WORKS)	BLACKWATER	55	01/05/1988	31/12/2009	21.7
6906	MILLSTREET (COOMLOGANE)	FINNOW-BLACKWATER	113	01/05/1991	31/12/2009	18.7
7206	GLENVILLE (GLENASACK)	STREAM-CROM RIVER	201	01/08/1993	30/06/1997	3.9
7306	NEWMARKET (NEW STREET)	DALUA	152	01/11/1993	31/12/2009	16.2
7406	MALLOW (SPA HOUSE)	BLACKWATER	61	01/08/1996	31/12/2009	13.4
7506	BANTEER (GLENSOUTH)	GLEN-BLACKWATER	161	01/05/1997	31/12/2009	12.7
7906	BALLYHOOLY (CASTLEBLAGH)	BLACKWATER	140	01/02/2001	31/12/2009	8.9
8306	SHANBALLYMORE	AWBEG	75	01/03/2002	31/12/2009	7.8
9906	M.MALLOW FOREST	CASTLEPOOK	229	Null	Null	Null
210	ROCKCHAPEL G.S.	FEALE	198	01/11/1941	31/12/1950	9.2
1310	TOURNAFULLA G.S.	ALLAGHAUN	160	01/10/1943	30/11/1992	49.2
1610	BROSNA (MT.EAGLE)	CLYDAGH	238	11/11/1947	31/01/2004	56.2
1710	BROSNA	CLYDAGH	134	11/11/1947	30/09/1992	44.9
2410	ROCKCHAPEL (CAPPAPHAUDEEN)	BREANAGH FEALE	256	01/08/1982	31/12/2008	26.4
2710	KNOCKNAGOSHEL (MEINLEITRIM)	OWVEG	183	07/10/1992	31/12/2009	17.2
711	DRUMCOLLOGHER G.S.		121	01/10/1943	27/12/1945	2.2
3611	MILFORD G.S.	DEEL	140	08/10/1951	30/04/1987	35.6
5511	MILFORD G.S. II	DEEL	107	01/04/1987	31/01/2000	12.8
6011	SPRINGFIELD CASTLE	BUNOKE	110	01/07/1994	31/12/2009	15.5

Table 9.1: List of daily rainfall stations with data supplied by Met Eireann in digital form (cont'd)

9.2 Appendix B: Thiessen Polygons for subperiods of analysis

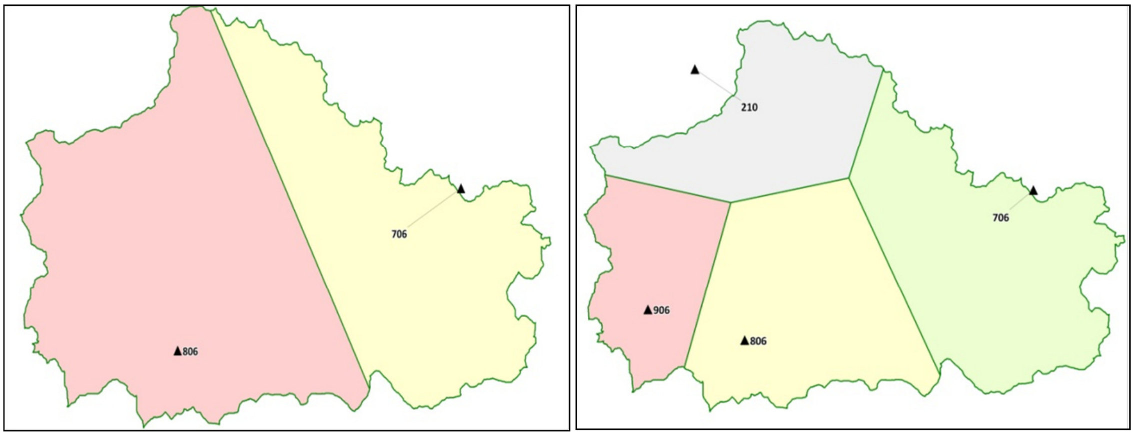


Figure 9.1 Polygons for 01/01/1941-31/10/1941 and /11/1941 – 31/12/1941

Figure 9.2 Polygons for 01/01/1942 – 20/10/1942 and 21/10/1942 – 30/09/1943

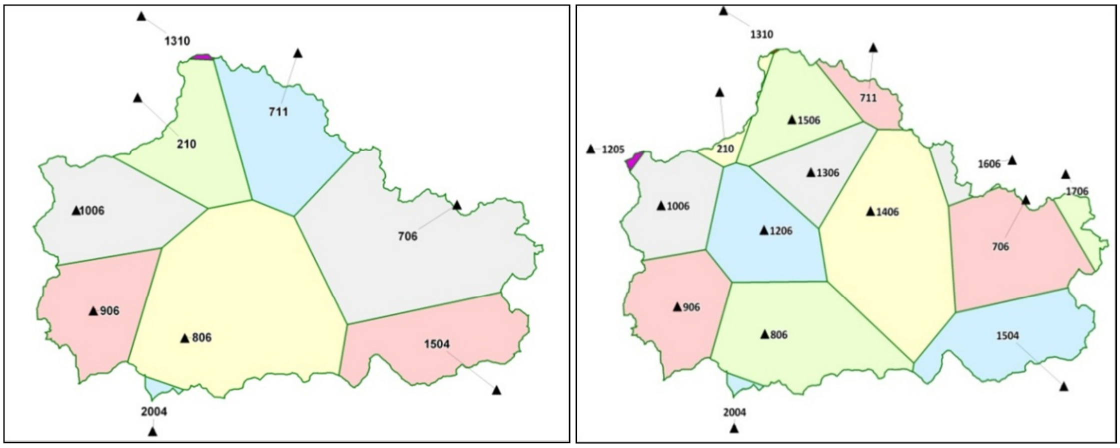


Figure 9.3 Polygons for 01/10/1943 – 31/05/1944 and for 01/06/1944 – 09/07/1944

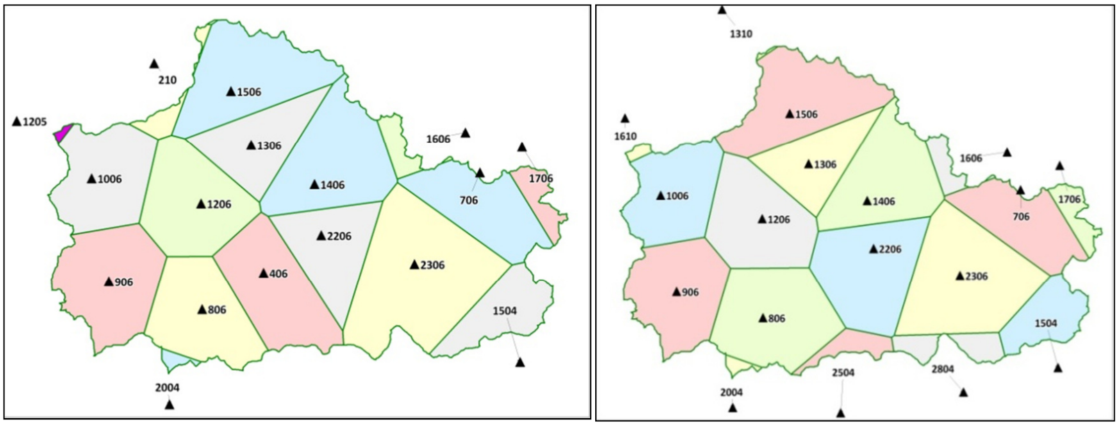


Figure 9.4 Polygons for 10/07/1944 – 31/01/1948 and 01/02/1948 – 14/04/1950

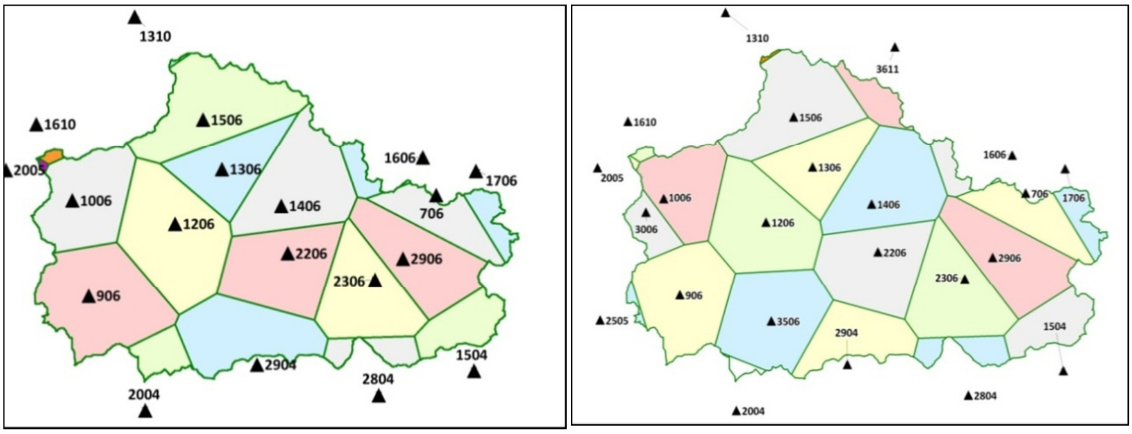


Figure 9.5 Polygons for 15/04/1950 – 22/04/1952 and 23/04/1952 – 31/12/1963

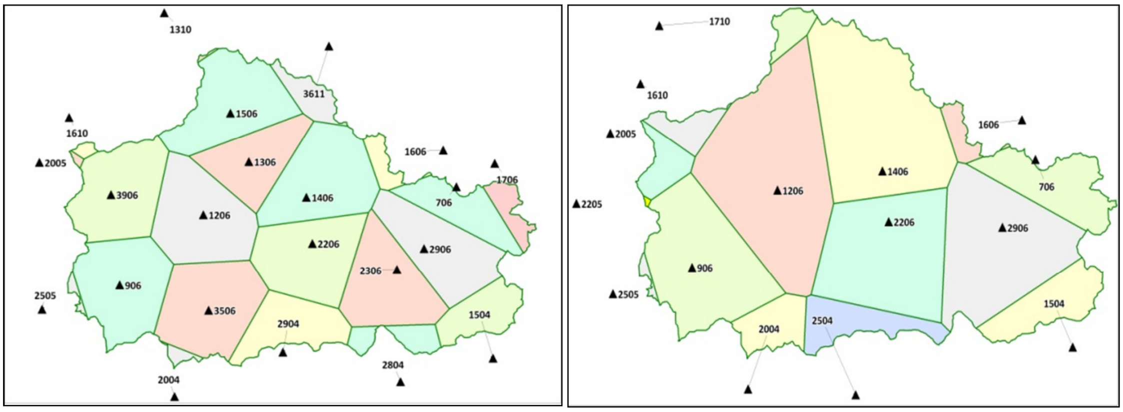


Figure 9.6 Polygons for 01/01/1964 – 31/12/1967 and 01/01/1968 – 31/01/1970

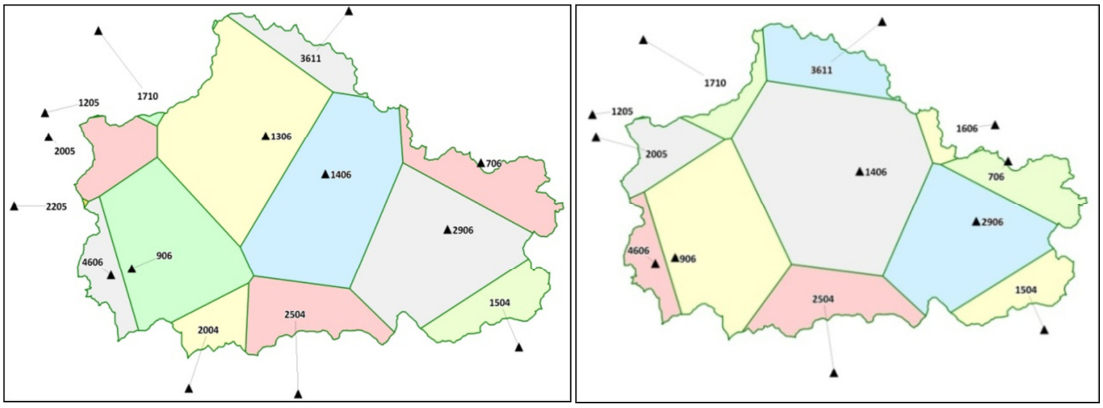


Figure 9.7 Polygons for 01/02/1970 – 31/05/1973 and 01/06/1973 – 30/09/1974

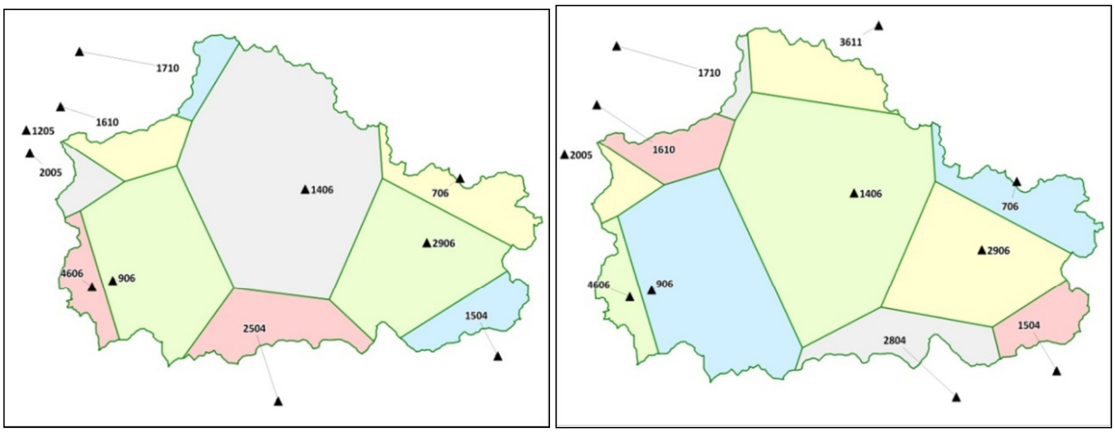


Figure 9.8 Polygons for 01/10/1974 – 31/07/1977 and 01/08/1977 – 31/01/1979

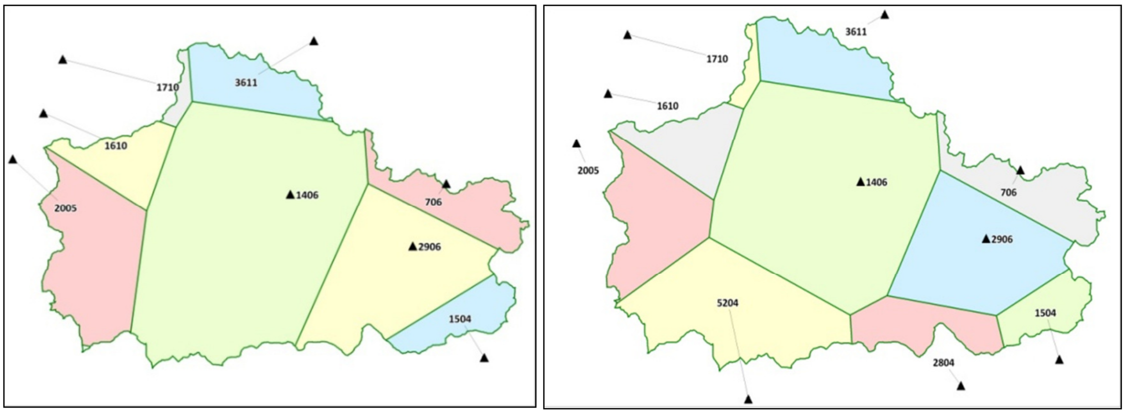


Figure 9.9 Polygons for 01/02/1979 - 31/03/1982 and 01/04/1982 – 31/10/1984

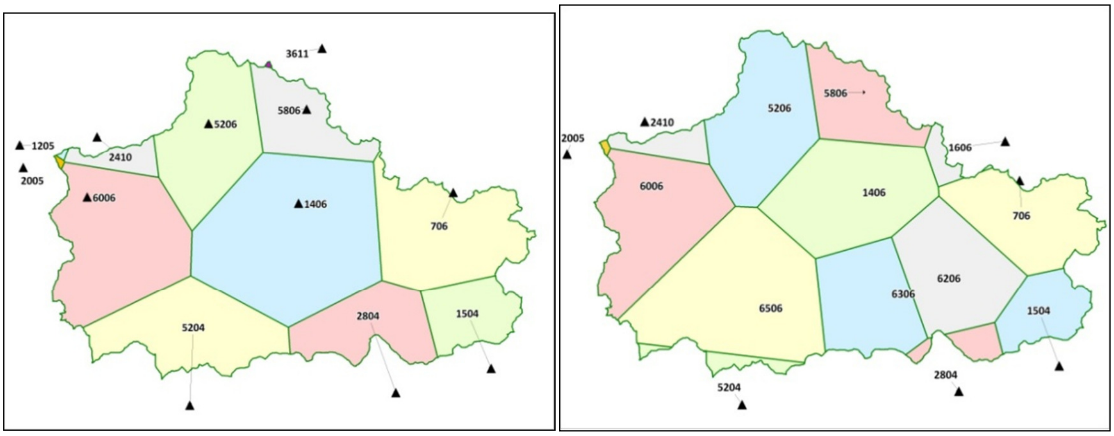


Figure 9.10 Polygons for 01/11/1984 – 30/04/1987 and 01/05/1987 – 30/04/1988

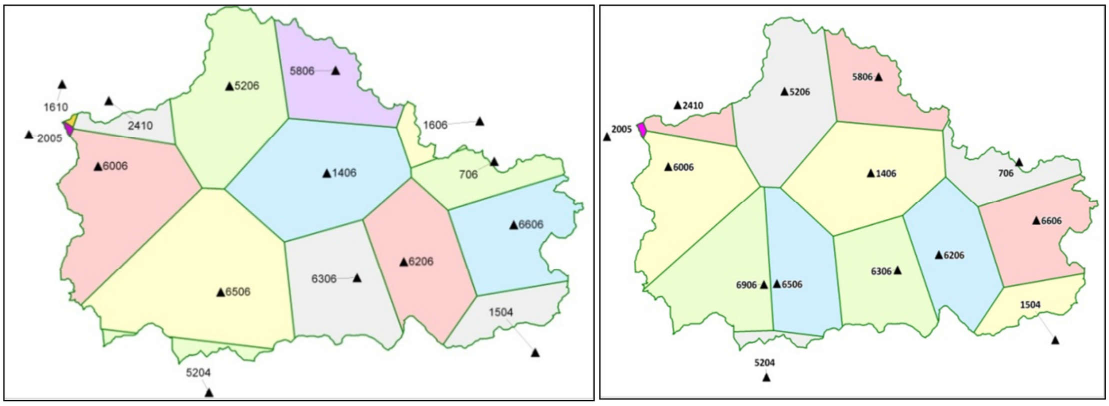


Figure 9.11 Polygons for 01/05/1988 – 30/04/1991 and 01/05/1991 – 31/10/1993

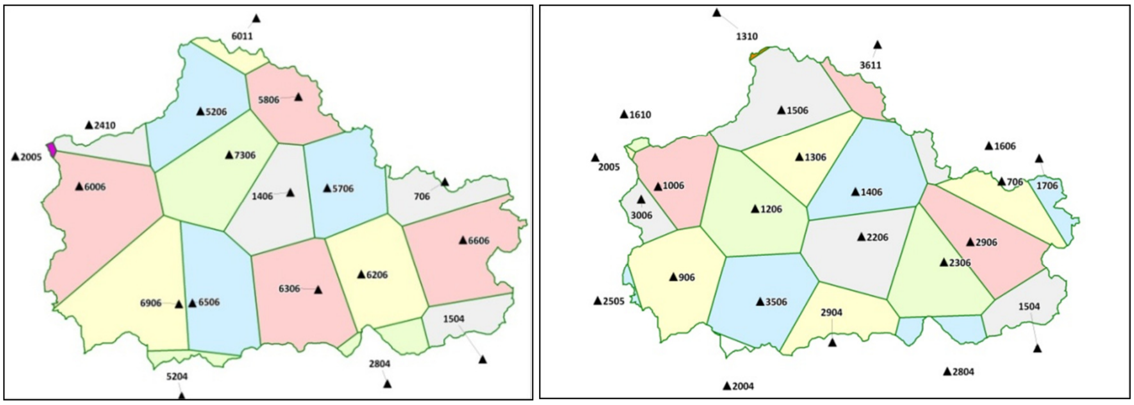


Figure 9.12 Polygons for 01/11/1993 – 30/04/1997 and /05/1997 – 28/02/2002

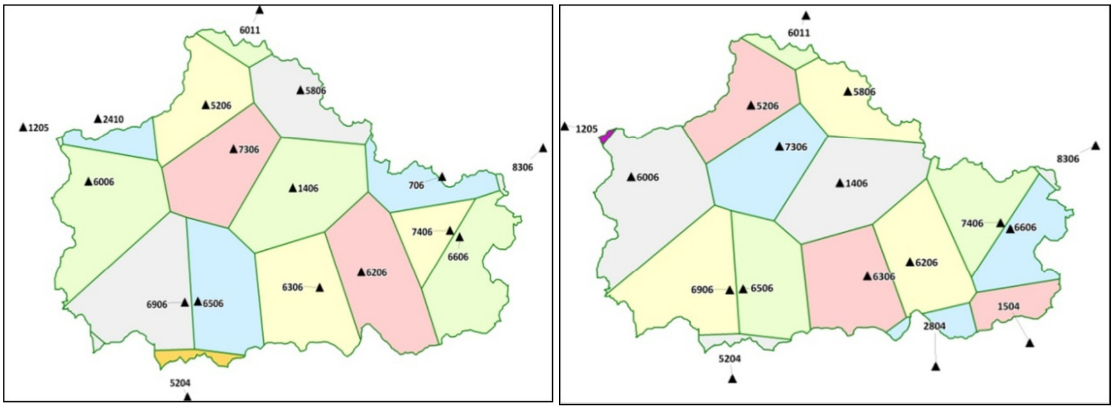


Figure 9.13 Polygons for 01/03/2002 – 04/05/2006 and 05/05/2006 – 31/12/2009

9.3 Appendix C: Database of Flood Events in the Munster Blackwater Catchment

MALLOW FLOOD EVENTS

General Flood Information

General Mallow Report 01:

Source:- Sullivan, 1988

Further evidence has been taken from the town of Mallow where level measurements have been taken at Golden's Bar (Sullivan, 1988). These level measurements suggest that the largest event experienced on the Blackwater on record occurred in 1853 with a level of 3.85m and that the 1948
event (1.62m) was greater than that experienced in 1916 (1.54m). The exact level of the 1853 event should be treated with caution due to the age of the source material and changes in the channel and structures over time. There is also very little difference in recorded levels between the 1948 and 1916 events, probably within measurement accuracy achievable at that time

General Mallow Report 02:

Event	Level at Golden's Bar (m)
1853	3.85
1948	1.62
1916	1.54
1980	1.4
1988	1.0

Table 9.2 Estimated historic flood levels (Mallow Field Club Journal)

Event	Level (mOD Malin)
1853	52.5
1948	50.25
1916	50.15
1980	50
1988	49.5
1986	49
1995	49
1969	48.9
1996	48.6

Table 9.3 Estimated flood levels of the largest floods on record

1578

1578 Mallow Report 01:

Source:- The Mallow Field Club Journal

Reports of someone who was delayed a considerable period at Mallow by a Summer flood in the Blackwater

1600 February

1600 Mallow Report 01:

Source:- The Mallow Field Club Journal
Reports of a traveller at the time illustrates that the town bridge was impassable ……."This day past, the Blackwater, which, by reason of the greatness and height thereof, he was not able before this time to pass."

1628 September

1628 Mallow Report 01:

Source:- The Mallow Field Club Journal
"The river suddenly rose eight feet higher than was ever seen by the oldest living man. It carried away the Bridge at Mallow."

1853 November 2nd

1853 Mallow Report 01:

Source:- OPW, Munster Blackwater Drainage Scheme Hydrology and Hydraulic Modelling report

Further evidence has been considered from the town of Mallow where level measurements have been recorded (Sullivan, 1986: Sullivan, 1988). These measurements suggest that the largest recorded event occurred in 1853 and that the 1948 event was marginally greater than that experienced in 1916; probably within measurement accuracy achievable at the time. The 68 years from 1916 back to 1853 provides additional time for natural changes to occur to the channel and its flowing floodplain such as increased vegetation; this reduces confidence in the 1853 event so its estimate should be treated with caution.

1853 Mallow Report 02:

Source:- The Mallow Field Club Journal
Extreme flood where it was reported that "The bridge was almost totally swept away by a flood event."
»»»
"The Blackwater began to flood the Town Park at around midnight, and began to flood Bridge Street at 1:00 am, having sufficient force to carry away large household objects. The river was observed to rise 10 feet in 40 minutes, with the peak occurring at about 06:30am. At the peak of the flood, the lower streets were beneath 12 feet of water, so that the only upper stories of houses were visible. Water receded from the floodplain at about 7pm that evening. The town was subjected to severe damage, including destruction of the bridge."

1853 Mallow Report 03:

Source:- OPW, Blackwater Hydrologic and hydraulic modelling report., 2003
The event of 2nd November 1853 occurred during the "Little Ice Age", and therefore, this may have been a combined rainfall and snowmelt event.

1853 Mallow Report 04

Source:- Anglo Celt 10th November 1853 Page 2
On the arrival of the train at Mallow, we were informed of the death by drowning of a whole family occupying a cottage on the bank of the Blackwater, which also overflowed. Not yet has it been ascertained how many lives were lost.

1869 December 31st

1869 Mallow Report 01:

Source:- The Irish Times , 31st December 1869
Text was written on the Thursday before at 3 o clock.

Great Flood At Mallow
Since the great flood which took place here on the 1st November 1853, and did great damage to life and property, such a flood as that of this day has not been witnessed in this town.

A thaw set in yesterday and rain began to fall. From the time it commenced raining yesterday at four o' clock there was one continuous downpour until twelve o clock this day.
A very high wind was blowing all the time and has done great injury. The different tributaries of the Blackwater near the town have all overflowed their banks . The lower part of the town of Mallow is completely flooded up to the entrance to the steam mills, Bridge Street, and Gallows hill lane. The Spa Walk and Norcotts Lane are one sheet of water, and the flood has done considerable damage. The poor of the districts that were flooded have suffered very much. As I write, the water is still rising

1875 January

1875 Jan Mallow Report 01

Source:- The Freemans Journal 18th January 1875
Written on the Sunday Before

A Flood at Mallow
Owing to the very heavy rain which fell during the past week the Blackwater overflowed its banks on Friday morning, and forced its way into several houses in Bridge Street, the occupants of these houses were accordingly compelled to betake themselves to the upper attics. After a few hours it fell rapidly. The weather still continues here very wet and severe.

1875 September 26th

1875 Mallow Report 01:

Source:- The Mallow Field Club Journal
Reported as disastrous floods causing extensive damage to houses household goods, shops, cattle and crops.

1875 Mallow Report 02:

Source:- OPW, Blackwater Hydrologic and hydraulic modelling report., 2003
The size of the 1875 event is unknown, although the description of the event is very similar to that of the 1916 event, with damage to the railings of the bridge being described. This suggests that the 1875 event may have been larger than the 1980 event, this would make the 1980 event the sixth largest since 1853.

1876 31st December (approx.)

1876 Mallow Report 01
Source:- The Irish Times, 1st January 1877
Severe Floods were also experienced yesterday at Mallow and Belfast. At the former place still more dangerous inundations are apprehended.

1876 Mallow Report 02
Source:- The Irish Times, 1st January 1877
Written on the Sunday Before.

The recent heavy rains accompanied by very high winds, have overflowed the river Blackwater and the small rivers in the neighbourhood.
, and all the low lying grounds in this neighbourhood, and all the low lying grounds in this neighbourhood are completely submerged. The waters have got into the houses in Lower Bridge Street and the Spa Walk. During the Last two nights ………………

1878 14th May (approx..)

1916 November 17th

1916 Mallow Report 01:
Source:- The Mallow Field Club Journal
Reported as "disastrous flooding causing extensive damage".
»»»
Flood waters rose rapidly, and by 4:00am Bridge Street, Bridewell Lane, St. Josephs Rd., Spa Walk, and Spa Terrace were flooded, along with the lower portions of Ballydaheen and Broom Lane on the South Bank. Water was 4.5 feet deep in Bridge St., with water reportedly running through the upper stories of the lower houses. Significant flow occurred across the bridge deck, such that pillars supporting the railings were torn up.

1916 Mallow Report 02:
Source:- Cork Examiner, Nov. 18th 1916
Floods in Mallow
Large tracts of land around Mallow flooded to 6-9 ft. Town flooded: Clockhouse, Mallow Bridge, Lower Bridge St., flooded to 4-5 ft. Impossible to cross the river at Mallow. Most railway lines flooded and out of action. Crops damaged, Cattle drowned.

1916 Mallow Report 03:
Source:- Cork Examiner, Nov. 21st 1916
Flood Distress
Flood relief funds opened.

1925 January 13th

1925 Mallow Report 01:
Source:- Limerick Leader, January 07, 1925
"A portion of the embankment on the Mallow-Killarney railway line collapsed due to heavy rains and recent flooding. Railway line also found to have subsided."

1925 Mallow Report 02:
Source:- Cork Examiner, January 14, 1925
River Blackwater overflowed at Mallow causing some flood damage to houses in the town.

1941 November 10th

1941 Mallow Report 01:
Source:- Evening Echo, November 10th, 1941
Extensive Damage by Floods
Mallow town under several feet, rivers sweep away livestock, many roads impassable, Skibbereen area inundated with flood water & high tide (highest in 20 years), especially Townsend St. Caravan residents, Carrigrohane road, rescued.

1941 Mallow Report 02:
Source:- Evening Echo, November 10th, 1941
The Flood Damage
Sheep rescued, UCC grounds, 6' at Mardyke, roads impassable, Mallow @ Bridge St. & Spa Walk, Blackwater Inches cattle lost,

1941 Mallow Report 03:
Source:- Cork examiner, November 11th, 1941
The Floods
In Mallow isolated, Bridge St & Spa completely under water & impassable, William's Mills damaged . Many Macroom roads flooded, Livestock drowned, lost or isolated

1941 Mallow Report 04:
Source:- Cork Examiner, November 11th, 1941
Amazing Scenes
Mallow evacuations, Fermoy flooded to several feet, worst since 1916, Bantry area flooded. Evacuations from Kilocrim & Ennismore, 4 houses destroyed, Brick & Lixnaw valleys a lake, Listowel Island bridge swept away, 6' nearby

1941 Mallow Report 05:
Source:- The Irish Times,, November 11th, 1941
Extensive flooding in the south
Worst flooding in 25 years Cork, 50 years Kerry, evacuations in Bridge St area of Mallow, & 50 people from Kilorcrin/Ennismore. Many cattle sheep drowned on Blackwater. Part bridge washed away in Listowel, county resembles a lake. NCR.

1941 Mallow Report 06:
Source:- Cork Examiner, November 11th, 1941

Enormous damage done by floods in Munster area
Mallow houses flooded, as bad as 1916, Bandon water came through sewers and flood many streets to 1', highest since Nov 1917. Feale valley a lake, Abbeyfeale area impassable. Macroom worst in 50 years, Fermoy extensive damage.

1941 Mallow Report 07:
Source:- Irish Independent, November 12th, 1941
Roofs as a refuge from floods in south
Listowel 50 people evacuated to hospital, 4 houses destroyed, some spent night on top of hay barns, Cork 26 people rescued from caravans, Inagh overflows into Ennistymon & low lying lands

1941 Mallow Report 08:
Source:- Cork Examiner, November 14th, 1941
Flood aftermath
Flood has subsided, description of relief work, £2,000 grain damaged. Worst since 12 Nov 1916 which was 2' higher, greatest flood on record was 1853

1941 Mallow Report 09:
Source:- Kerryman, November 15th, 1941
Old Mallow floods recalled
Mallow evacuations, livestock swept away, Red Cross relief, £2,000 grain damage, not as bad as Nov 12 1916 & 1853. Fermoy worst since 1916 when 2 soldiers lost their lives. Now flooding of premises, sheep lost Kilmurry, Fermoy floods 3 hours after Mallow.

1941 Mallow Report 09:
Source:- Kerryman, November 15th, 1941
Flooding in Cork and Limerick
Extensive coverage for Limerick, lands & houses flooded, animals rescued, Deel worst for 30 years.

1946 August 12th

1946 Mallow Report 01:
Source:- The Mallow Field Club Journal
During the early morning, houses on Spa Walk were flooded as the Spa glen(“the canal”) overflowed. At 4pm the town was flooded, with Bridge Street being inundated by several feet of water. Water reached an average height of 12 feet on the racecourse. By 7am the following morning the water had receded.

1948 December 2nd

1948 Mallow Report 01:
Source:- Application of the UK Flood Estimation Handbook pooling group approach to the Munster Blackwater River By David Price, Manuela Toth, Alison Jane, (Jacobs Babtie, 95 Bothwell St., Glasgow)

Further evidence has been considered from the town of Mallow where level measurements have been recorded (Sullivan, 1986: Sullivan, 1988). These measurements suggest that the largest recorded event occurred in 1853 and that the 1948 event was marginally greater than that experienced in 1916; probably within measurement accuracy achievable at the time. The 68 years from 1916 back to 1853 provides additional time for natural changes to occur to the channel and its flowing floodplain such as increased vegetation; this reduces confidence in the 1853 event so its estimate should be treated with caution.

1948 December 2nd - Mallow Report 02:
Source:- The Mallow Field Club Journal
The Town Park flooded to a depth such that the water reached the height of the crossbars of the hurling goalposts, suggesting a depth of flooding in the park of 2.5 metres.

1948 December 5th

1948 December 5th Mallow Report 01:
Source:- OPW, Blackwater Hydrologic and hydraulic modelling report., 2003

Bridge Street flooded at 7pm, to a greater depth than had occurred on the 2nd December. The Spa Glen Flooded during this event, increasing water levels in Bridge St. By midnight the flow across the bridge was so high that attempts to cross the bridge by boat had to be abandoned. Navigation Road was closed to traffic during the flood. Flooding occurred again the following day following a large thunderstorm, with houses in Ballydaheen being flooded up to 4 feet deep.

1948 December 5th Mallow Report 02:
Source:- Irish Independent, December 6th 1948, Page 7

In Mallow the low lying eastern portion of the town was completely isolated by flood waters resulting from the overflowing of the Blackwater. In Bridge Street the water rose to a depth of more than four feet. A house in the street partially collapsed. The back wall falling out into the town park, which was covered to a depth of between six and seven feet. The house was occupied by a Mill worker, Mr. J O'Keeffe, who, with his family was rescued by boat. A man named murphy was being swept away when he was pulled into a boat by Messrs' G. and J. Bolster.

1949 October 25th

1949 Mallow Report 01:
Source:- Cork Examiner, October 26th 1949.
Ireland swept by rainstorm
Many streets in the centre of Cork temporarily flooded due to high tides and heavy rainfall, Town park in Mallow flooded, flooding outside Millstreet along the Blackwater river. Continued on page 7

1949 Mallow Report 02:

Source:- Cork Examiner, October 27th 1949.
Floods follow storm
Parts of Mallow flooded to a depth of 3 feet, shops flooded in Fermoy, river Ilen flooded inundating large areas of farm land. Continued on page 9

1966 October

1966 Mallow Report 01:

Source:- Flood Warning Systems in Cork County.

1969 January 10th

1969 Mallow Report 01:

Source:- OPW, Blackwater Hydrologic and hydraulic modelling report., 2003

The flood of the 10th January 1969 was detailed in "The floods of Mallow, Part 2". It is listed as a "major winter event".

1980 November 2nd

1980 Mallow Report 01:

Source:- *OPW, Blackwater Hydrologic and hydraulic modelling report., 2003*
The Town Park was flooded by 10 a.m. and at 11:30 the water level began to rise rapidly and flooded the lower parts of the town within 30 minutes. The peak level occurred soon after 3pm, and it was not possible to cross the Bridge due to the strength of the flow crossing it.. The flood reached to the cinema on the north side, and almost to the post office on the south side. The streets were passable by midnight. Bridge Street was flooded to depths of more than 2.5m. During the 1980 flood, the level recorder at the sugar factory gauge was overtopped and the Peak Level was estimated using debris marks (EPA, 1999).

1986 August 6th

1986 Mallow Report 01:

Source:- Hand written report from the Flood Hazard mapping website (may be a technicians report)

"A flood mark was noted and marked on right bank downstream of bridge. This can be levelled if an ordnance datum level is required. On visiting Mallow on Thursday 6th August, there was no remaining water on the streets, but from the newspaper reports, flooding was severe and extensive in Mallow. According to the Corkman Newspaper water was a foot high on many private houses and business premises. The townspark relief road was flooded to a depth of four feet and some other roads were flooded to a lesser degree."

1986 Mallow Report 02:

Source:- Cork Co. Co, Flood Study of the River Blackwater and Spa Glen
Flooding affecting properties and roads in Bridge Street and Spa walk.

1986 Mallow Report 03:
Source:- *OPW, Blackwater Hydrologic and hydraulic modelling report., 2003*

1988 October 11th

1988 Mallow Report 01:
Source:- Cork Co. Co, Flood Study of the River Blackwater and Spa Glen

Flooding affecting properties and roads in Bridge Street and Spa walk.

1988 October 21st

1990

1990 Mallow Report 01:
Source:- Cork Co. Co, Flood Study of the River Blackwater and Spa Glen

Flooding affecting properties and roads in Bridge Street and Spa walk.

1995

1995 Mallow Report 01:
Source:- Cork Co. Co, Flood Study of the River Blackwater and Spa Glen

Flooding affecting properties and roads in Bridge Street and Spa walk

1998 December 30th

1998 Mallow Report 01:
Source:- Cork Co. Co, Flood Study of the River Blackwater and Spa Glen

Flooding affecting properties and roads in Bridge Street and Spa walk
In December 1998, Bridge Street was flooded to a depth of 0.4 metres, and as much as 2.2 metres in the Town Park. The 1998 flood was peculiar in that it had two flood peaks which resulted in the Town Park and Park road being inundated for over two days.

1999

1999 Mallow Report 01:
Source:- Cork Co. Co, Flood Study of the River Blackwater and Spa Glen

The Town Park and Park road in Mallow were flooded twice in December 1999. The Spa walk was also flooded twice in 1999.

2000 November

2000 Mallow Report 01:
Source:- EPA Hydrometrics

Water levels recorded at hydrometric stations in the period 01 November 2000 to 5th December 2000.

Three floods were recorded at station 18006 CSET Mallow.

Date	Time	Level (m)
06/11/00	12:00	4.85
26/11/00	12:00	4.49
01/12/00	01:15	4.83

The 6th November flood was the fifth severest in the period July 1977 to September 2000. (Mallow CSET started recording in 1977).

2008

Source:- Arup Consulting Engineers, Paper presented to Engineers Ireland Cork Region on 10th February 2009. "Design and Implementation of the Mallow Flood Relief Scheme

- Bridge Street was flooded twice

FERMOY FLOOD EVENTS

GENERAL FLOOD INFORMATION

General Fermoy Report 01:

Source:- Application of the UK Flood Estimation Handbook pooling group approach to the Munster Blackwater River By David Price, Manuela Toth, Alison Jane, (Jacobs Babtie, 95 Bothwell St., Glasgow)

Fermoy Rank	Date
1	1853
2	1948
3	1916
4	1946
5	1980

Table 9.4: Ranking of Fermoy using indirect evidence

General Fermoy Report 02:

Source:- Babtie Group, Munster Blackwater River (Fermoy) Drainage Scheme – Hydrology Report

Date	Grand Hotel	Brian Boru Square	Promenade	Mart Mill Rd.	Courthouse	Waste Water Treatment Plant
08/12/1916	---	---	---	---	26.69	---
02/11/1980	26.83	---	---	---	26.12	---

11/08/1986	26.09	25.79	---	---	---	25.35
13/01/1988	25.97	25.74	25.53	25.25	25.25	25.25
02/02/1988	25.69	25.39	25.25	24.97	---	24.93
12/10/1988	25.72	25.50	25.30	24.97	---	25.07
22/10/1988	26.83	26.78	26.46	26.10	26.08	26.07
06/02/1990	---	25.74	---	---	---	---
10/03/1995	---	26.34	---	---	---	---
30/12/1998	26.47	26.55	26.18	25.73	---	25.76

Table 9.5: Flood Levels at points in and around Fermoy.

The ranking of floods at Fermoy were most similar to those at Kilavullen. Hand-written level records of the 09:00 values at Kilavullen were available for the period 1940 to 1955. These records identify that there were substantial events in 1946 and 1948.

Event	Rank at Fermoy	Rank at Kilavullen	Rank at Ballyduff
08/12/1916	1	---	---
02/11/1980	2	1	6
22/10/1988	3	3	2
30/12/1998	4	5	4
10/03/1995	5	4	---
11/08/1986	6	6	---
13/01/1988	7	---	---
06/02/1990	8	---	---
12/10/1988	9	---	---
02/02/1988	10	---	---

Table 9.6: Comparisons of Flood Rankings

1626 – Timber Bridge Built across the Blackwater at Fermoy

1626 channel change:

Source:- Michael Barry, “A Brief History of Fermoy”

A timber bridge was built over the Blackwater in Fermoy in 1626 by the 1st Earl at a cost of around five hundred pounds. The Cistercians operated a ferry prior to the building of the bridge and the Earl had an income from this of twenty five pounds per annum.

1628

1628 Fermoy Report 01:

Source:- Michael Barry, “A Brief History of Fermoy”

The timber bridge was swept away in 1628 following "an extraordinary flood".

1687

1687 channel change:

There was no immediate replacement and while provision was made in the Earl's Will in 1642 for the erection of a new bridge, it wasn't until 1687 that the provision could be put into effect. This was a bridge described by the historian Smith 6O years later as "A large stone bridge of thirteen arches".

1853 November 2nd

1853 Fermoy Report 01 - 2nd November:

Source:- History of Fermoy flooding (original sources OPW, Babtie Grp hydrology report) – report by Donal O Lochlainn that appeared in the Avondhu on 8th March 2007.

The 1853 flood happened on 2nd November, the same day that Loreto Convent opened. In the history of Loreto Convent, this flood is described as causing enormous damage in Fermoy.

1853 Fermoy Report 02 - 2nd November:

Source:- Sr. Consiglio Murphy Loreto Fermoy -how it came into being

The school opened on November 2, the Feast of All Souls, the year the river swelled to such a height, the flood caused dreadful destruction in the town. Conditions in the convent were so bad one of the nuns inspired by necessity to write to her sister in Dublin, a Miss Deane, telling her of the distressed state of the community and imploring her to send and to beg of her Aunts to send down any spare articles of furniture, table ware, carpets or other household necessities that they could dispense with.

1886 August 20th

1886 Fermoy Report 01:

Source:- http://newtownsandes.jimdo.com/some-06-notes/

Kerry Sentinel of August 20th 1886 reports that on Thursday last after thunderstorm the Feale in Listowel turned black.

1916 August

1916 Fermoy Report 01:

Source:- Ireland and the Easter Rising 1916

Keywords:- 2/5 Leicesters War Diary

“At Fermoy the battalion underwent training in trench warfare using specially constructed trenches. Live ammunition was used and there was instruction in wiring and 'reliefs'. The gorse laden hill called Corrin Mountain was used for battle practise. It was also during August 1916 that Fermoy suffered a serious flood as the River Blackwater burst its banks.

1916 November 18th

1916 Fermoy Report 01 – 18th November:

Source:- History of Fermoy flooding (original sources OPW, Babtie Grp hydrology report) – report by Donal O Lochlainn that appeared in the Avondhu on 8th March 2007.

The 1916 flood occurred on 8th December. Earlier that year on 18th November two soldiers, members of the 2nd and 5th Leicester's, were swept away from the bridge and lost their lives. They were Corporal Bertie Smith, North Luffenham, Rutlandshire and Private Hedley Jewell, Appleby Magna, Leicestershire. Both are buried in the Fermoy Military Graveyard.

The levels recorded in Fermoy for the 1916 flood put the flood level at Brian Boru Square at approximately the top of the window on what is now the Flower Shop, Deerpark Florist (about 2.2 meters). The predicted flood level for the 100-year flood is 2.5 meters at the same point.

1916 December 8th

1916 Fermoy Report 01 – 8th December:

Source:- Application of the UK Flood Estimation Handbook pooling group approach to the Munster Blackwater River By David Price, Manuela Toth, Alison Jane, (Jacobs Babtie, 95 Bothwell St., Glasgow)

The severity of a number of events in Fermoy has been recorded with level measurements taken at different locations throughout the town. These data were collated by Jack O'Keefe of Cork County Council and John McCarthy of Murphy McCarthy Consulting Engineers, Cork and was reproduced in the UCC report (2000).
These records suggested that the worst event during the 20th century occurred on 8 December 1916 and the second worst on 2 November 1980.

1916 Fermoy Report 02 – 8th December:

Source:- History of Fermoy flooding (original sources OPW, Babtie Grp hydrology report) – report by Donal O Lochlainn that appeared in the Avondhu on 8th March 2007.

The 1916 flood occurred on 8th December. Earlier that year on 18th November two soldiers, members of the 2nd and 5th Leicester's, were swept away from the bridge and lost their lives. They were Corporal Bertie Smith, North Luffenham, Rutlandshire and Private Hedley Jewell, Appleby Magna, Leicestershire. Both are buried in the Fermoy Military Graveyard.

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1946 August 12th

1946 Fermoy Report 01:

Source:- Unknown

A local Fermoy flooding report (reference unknown) identified the 1946 event as 18 inches lower than the 1916 event in Fermoy. This report included photographs of the event in the town. From this direct evidence this flood has been ranked between the 1916 and 1980 events. In an attempt to better understand the relative magnitudes of the 1948 and 1946 events historic daily rainfall records were provided by OPW. High rainfall totals were evident for the 11 August 1946 with a notable maximum of 115.1mm recorded in the Cork area. The 1946 event was in August and one may assume it was characterised by intense rainfall and runoff from a dry catchment.

1946 Fermoy Report 02:
Source:- http://newtownsandes.jimdo.com/some-06-notes/

Floods: 11th August 1946 big flood in Finuge and elsewhere, no hay saved; August 1916 floods in Fermoy and the Blackwater burst its banks;

1948 December 5th

1948 Fermoy Report 01:
Source:- History of Fermoy flooding (original sources OPW, Babtie Grp hydrology report) – report by Donal O Lochlainn that appeared in the Avondhu on 8th March 2007.

Flood levels were not recorded for the 1948 event, however we know from levels recorded elsewhere, that the 1948 event was probably worse than the 1916 event in Fermoy.

1948 Fermoy Report 02:
Source:-Unknown
The 1948 event alternatively was in December. The main peak of the event occurred on the 5 December but the maximum daily rainfall totals were recorded on the 1st December

1980 November 2nd

1980 Fermoy Report 01:
Source:- Application of the UK Flood Estimation Handbook pooling group approach to the Munster Blackwater River By David Price, Manuela Toth, Alison Jane, (Jacobs Babtie, 95 Bothwell St., Glasgow)

The severity of a number of events in Fermoy has been recorded with level measurements taken at different locations throughout the town. These data were collated by Jack O'Keefe of Cork County Council and John McCarthy of Murphy McCarthy Consulting Engineers, Cork and was reproduced in the UCC report (2000).
These records suggested that the worst event during the 20th century occurred on 8 December 1916 and the second worst on 2 November 1980.
»»»

Following the methodology advocated by Bayliss and Reed (2001), the Gringorten plotting position for both sets of rankings estimated the 1980 event to have a return period of 45 +/- 10 years. Corresponding historical analysis at Mallow undertaken by Ove Arup (2003) gives a similar return period to the 1980 event

1986 – August 11th

1986 Fermoy Report 01:

Source:- Hand written report from the Flood Hazard mapping website (may be a technicians report)

"A flood mark was noted and marked on the right bank upstream of road bridge and this can also be labelled if an ordnance datum level is required. There was no visible flooding on visiting Fermoy and the Cork Examiner states that there was only minor flooding on Brian Boru square, but otherwise the town had a lucky escape".

1988 October 22nd

1988 Fermoy Report 01:

Source:- History of Fermoy flooding (original sources OPW, Babtie Grp hydrology report) – report by Donal O Lochlainn that appeared in the Avondhu on 8th March 2007.

Keywords: flood risk in Fermoy

"There were four floods in 1988, however the worst of that year was the fourth, on the 22nd October. The flood level was approximately waist deep at the Avondhu Bar.

University College Cork and the OPW have ranked the five worst floods since 1853 in order of magnitude: they are 1853 (worst) 1948, 1916, 1946 and 1980.

KILAVULLEN FLOOD EVENTS

1946 August 12th

1946 Kilavullen Report 01:

Source:- Application of the UK Flood Estimation Handbook pooling group approach to the Munster Blackwater River By David Price, Manuela Toth, Alison Jane, (Jacobs Babtie, 95 Bothwell St., Glasgow)

In addition to the automated sub-daily monitoring at Kilavullen, manually read daily level records were also available from the OPW for the period 1940 to 1955. These records identify that there were substantial events in 1946 and 1948. A local Fermoy flooding report (reference unknown) identified the 12 Aug 1946 event as 18 inches lower than the 1916 event in Fermoy. This report included photographs of the event in the town. From this direct evidence this flood has been ranked between the 1916 and 1980 events.

»»»

High rainfall totals were evident for the 11th of August 1946 with a notable maximum of 115.1mm recorded in the Cork area. With the event being
in August, one may speculate that it was characterised by intense rainfall and runoff from what was likely to have been a relatively dry catchment
»»»

1948 December 5th

1946 Kilavullen Report 01:

Source:- Application of the UK Flood Estimation Handbook pooling group approach to the Munster Blackwater River By David Price, Manuela Toth, Alison Jane, (Jacobs Babtie, 95 Bothwell St., Glasgow)

In addition to the automated sub-daily monitoring at Kilavullen, manually read daily level records were also available from the OPW for the period 1940 to 1955. These records identify that there were substantial events in 1946 and 1948. A local Fermoy flooding report (reference unknown) identified the 12 Aug 1946 event as 18 inches lower than the 1916 event in Fermoy. This report included photographs of the event in the town. From this direct evidence this flood has been ranked between the 1916 and 1980 events.
»»»
The 1948 event was, on the other hand, in December with the main peak of the event occurring on 5th but the maximum daily rainfall totals were recorded on the 1st December. Anecdotal evidence from Mallow (Sullivan, 1986) suggests that there was an initial flood event on the 2 December and therefore the rainfall required for the main event could have been relatively small, since it would have been falling on a saturated catchment. Unfortunately, a definitive ranking of these events cannot be achieved from this rainfall data alone

1980

1980 Kilavullen Report 01

Source:- Application of the UK Flood Estimation Handbook pooling group approach to the Munster Blackwater River By David Price, Manuela Toth, Alison Jane, (Jacobs Babtie, 95 Bothwell St., Glasgow)

The Kilavullen 1980 "best estimate" value of 525 m3/s [+/- 70 m3/s (Babtie Group, 2003)] has a return period of approximately 80 years based on the single site flood frequency analysis of the site. Although not conclusive, the historic evidence may point toward a lower return period for the 1980 event at Kilavullen than the "best estimate" value obtained from the revised rating curve (which attempts to account for the bypassing flows). However the robustness of the single site curve for return periods beyond 0.5N (where N is the number of years in the record, which for Kilavullen is 46 years) is likely to be poor. For example if the Hydrometric Stations at Kilavullen and Ballyduff had not been installed then the investigation would conclude that the 1980 flood was about a 45-Year event (based on the historic evidence).

1986 August

1986 Kilavullen Report 01:

Source:- Hand written report from the Flood Hazard mapping website (may be a technicians report)

"As this recorder did not have a reversible spindle the peak of the flood was not recorded. From flood marks in the area, the maximum flood would have coincided with a staff gauge reading of 5.47m.
The flood marks also clearly showed that the water had crossed the road on the Fermoy side of the gauge and just approximately a half mile further on the flood marks on both sides of the road were approximately four feet above the road level.
A flow measurement was done at any average staff gauge reading of 2.35m."

1916

Report 01:

Source:- Application of the UK Flood Estimation Handbook pooling group approach to the Munster Blackwater River By David Price, Manuela Toth, Alison Jane, (Jacobs Babtie, 95 Bothwell St., Glasgow)

DOWNING BRIDGE FLOOD EVENTS

1986 August

Report 01:

Source:- Hand written report from the Flood Hazard mapping website (may be a technicians report)

The maximum staff gauge reading was 1.74m at 14:30 on Wednesday 07/08/'86.
After Downing bridge we continued into Kilworth, turning right in the town at the T-junction and after a further four miles we turned left onto the main road for Ballyduff. From there into Ballyduff there was extensive flooding on the right hand side and two miles before Ballyduff the road was flooded.

BALLYDUFF FLOOD EVENTS

1986 August 6th

1986 Ballyduff Report 01:

Source:- Hand written report from the Flood Hazard mapping website (may be a technicians report)

"The maximum staff gauge reading was 3.50m at 10am on 06/08/'86."

1853 November 3rd

1853 Ballyduff Report 01:

Source:-The Mallow Field Club Journal
On 3rd November 1853, major flooding damaged bridges in counties Cork and Waterford. The wooden structure at Ballyduff, some four miles from Lismore, was completely carried away in the torrent. Lismore bridge was badly damaged too, yet Thomas Ivory's main arch spanning the river endured, and in 1858 sections of the bridge were rebuilt. The inscription on the plaque misleadingly gives the impression that the whole bridge had to be reconstructed, and reads: "1858 / Lismore Bridge / Rebuilt / C.H. Hunt and E.P. McGee Contractors / Charles Tarrant Engineer." The Waterford Co. Council report on bridges, 1918 records that "Lismore Bridge was 24ft. and 4in. wide overall" and had seven arches. The main arch, Thomas Ivory's 1775 original, incorporates distinctively different masonry from the rebuilt 1858 land arches, and this evidence of different stone being used in separate projects is clearly evident in the parapet and spandrel walls. Ivory's arch remains today a remarkable and noteworthy example in the history of Irish masonry bridges.

MOYEDA FLOOD EVENTS

1986 August

1986 Moveda Report 01:
Source:- Hand written report from the Flood Hazard mapping website (may be a technicians report)

"As the chart had been changed, the peak could not be read. When the chart was changed at 17:30 on Wednesday was 1.84m and the trace was falling at that stage. The recorder was reading correctly."

KANTURK FLOOD EVENTS

1702

1702 Kanturk Report 01:
The original Kanturk Bridge was a timber structure. In 1702 there was a confluence of the rivers above and below the bridge owing to heavy flooding.

1712

1712 Kanturk Report 01:
Ten years later the flooding was again very heavy and again the bridge (Kanturk Br.) suffered much damage. More repairs were required in 1720. Forty years later, the present stone bridge was built.

1926

1926 Kanturk Report 01:
Source:- www.kanturk.ie/map.html

The bridge (Dalua Bridge) was severely damage by a 1926 flood as a result of which its timber superstructure was replaced with concrete. The removal of the bridge was part of proposed flood prevention works following severe flooding in the town in 1980, but local objections saved the structure.

1946 August 12th

1946 Kanturk Report 01:

Source:- Cork Co. Co, Flood Study of the River Blackwater and Spa Glen

The railway bridge at Ballymaquirk (near Kanturk) was washed away in the flood of August 12 1946 (Doheny, 1997).

1980

1980 Kanturk Report 01:

Source:- Cork Co. Co, Flood Study of the River Blackwater and Spa Glen

In 1980, a flood with a return period of about 30 years occurred on the Blackwater. Total flood damage and losses in the catchment were estimated at over £2.5 million. The severity of the 1980 flood with losses in Kanturk estimated at £370,000 prompted the Kanturk flood study. The subsequent flood alleviation scheme on the Allow River (a tributary of the Blackwater, was carried out by Cork County Council in 1987.

1986 August

Report 01:

Source:- Hand written report from the Flood Hazard mapping website (may be a technicians report)

Included are cuttings from the cork examiner of Thursday, August 7th. In it, it says that in the Blackwater Valley, around Mallow and Kanturk were the worst affected.

BALLINAMONA FLOOD EVENTS

1986 August

Report 01:

Source:- Hand written report from the Flood Hazard mapping website (may be a technicians report)

"The maximum staff gauge reading was 1.26m at 10 a.m. on Wednesday 06/08/1986."

LISMORE FLOOD EVENTS

1853 November 3rd

1853 Lismore Report 01:

Source:-

Lismore bridge was badly damaged too, yet Thomas Ivory's main arch spanning the river endured, and in 1858 sections of the bridge were rebuilt. The inscription on the plaque misleadingly gives the impression that the whole bridge had to be reconstructed, and reads: "1858 / Lismore Bridge / Rebuilt / C.H. Hunt and E.P. McGee Contractors / Charles Tarrant Engineer." The Waterford Co. Council report on bridges, 1918 records that "Lismore Bridge was 24ft. and 4in. wide overall" and had seven arches. The main arch, Thomas Ivory's 1775 original, incorporates distinctively different masonry from the rebuilt 1858 land arches, and this evidence of different stone being used in separate projects is clearly evident in the parapet and spandrel walls. Ivory's arch remains today a remarkable and noteworthy example in the history of Irish masonry bridges.

1853 Lismore Report 02:
Source:- http://www.irelandbyways.com/ireland-routes/byroute-3/byroute-3-co-cork/

Lismore Bridge spans the **River Blackwater** at the junction with its tributary ***Abh na Shead***. A ferry used to cross the river at this point until 1775, when the 5th Duke of Devonshire commissioned the bridge from **Thomas Ivory**. Partially destroyed by floods in 1853, it was rebuilt to the original elegant design.

2004 October 28th

1853 Lismore Report 01:
Source:-Waterford Co. Co. Memo
N72 – road impassable due to flooding between cappoquin and Lismore at Salterbridge and Canal.

R666 – Road impassable due to flooding between Lismore Bridge and Ballyduff, and also between Ballyduff and County boundaries.

9.4 Appendix D: Statistical Tests for Trend

9.4.1 Mann Kendall Test

This method tests whether there is a trend in the time series data. It is a non-parametric test (Kendall, 1938). The n time series values ($x_1, x_2, x_3, \ldots, x_n$) are replaced by their relative ranks ($r_1, r_2, r_3, \ldots, r_n$) (starting at 1 for the lowest up to n).The test statistic S (Kendall's sum) is:

$$S = \sum_{i=1}^{n-1}\left[\sum_{j=i+1}^{n} sign(r_i - r_j)\right]$$

Where:

$$sign(r_i - r_j) = 1 \text{ For } (r_i - r_j) > 0$$
$$sign(r_i - r_j) = 0 \text{ For } (r_i - r_j) = 0$$
$$sign(r_i - r_j) = -1 \text{ For } (r_i - r_j) < 0$$

Mann (1945) and Kendall (1975) have documented that if the null hypothesis H_0 is true then for $n \geq 8$, the statistic S is approximately normally distributed with the mean and the variance as follows:

$$\text{Mean: } E(S) = 0$$

$$\textbf{Variance:} \quad V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18}$$

where: t_i is the number of ties of extent i.

The standardised test statistic Z_{MK} is computed by:

$$Z_{MK} = \begin{cases} for\ S > 0 \ldots\ldots \dfrac{S-1}{\sqrt{Var(S)}} \\ for\ S = 0 \ldots\ldots\ldots\ldots\ldots 0 \\ for\ S < 0 \ldots\ldots \dfrac{S+1}{\sqrt{Var(S)}} \end{cases}$$

The standardized Mann-Kendall statistic Z follows the standard normal distribution with mean of zero and variance of one. The P-value of the Mann-Kendall statistic (S) of sample data can be estimated using the normal Cumulative Distribution Function,

$$P = 0.5 - \Phi(|Z|)$$

$$\Phi|Z| = \frac{1}{\sqrt{2\pi}}\int_{-0}^{-|Z|} e^{-t^2/2}\,dt$$

If the P-value is small enough, the trend is quite unlikely to be caused by random sampling. At the significance level of 0.05, if $p \leq 0.05$ then the existing trend is considered to be statistically significant.

Critical test statistic values for various significance levels can be obtained from normal probability tables (refer to Appendix C). A positive value of S indicates that there is an increasing trend and vice versa.

9.4.2 Spearman's Rho Test

This is a rank-based test that determines whether the correlation between two variables is significant. In trend analysis, one variable is taken as the time itself (years) and the other as the corresponding time series data. Both variables are replaced by their ranks. If the time series consists of n distinct values, the ranks will be the numbers from 1 to n, with n corresponding to the highest value in the series, n-1 to the second highest, and so on. If there are ties (equal values) in the series, each value in the tie group is assigned the same (mean) rank.

Given a sample data set{x_i, i=1,2,…,n}, the null hypothesis H_0 of the Spearman's Rho test against trend tests is that all the x_i are independent and identically distributed; the alternative hypothesis is that x_i increases or decreases with i, that is, trend exists. The test statistic 'D' is given by (Sneyers, 1990)

$$D = 1 - \frac{6\sum_{i=1}^{n}[R(x_i) - i^2]}{n(n^2 - 1)}$$

where R(x_i) is the rank of i-th observation x_i in the sample of size n. Under the null hypothesis, the distribution of 'D' is asymptotically normal with the mean and variance as follows (Lehmann, 1975; Sneyers, 1990).

$$E(D) = 0$$

$$V(D) = \frac{1}{n-1}$$

The P-value of the D of the observed sample data is estimated using the normal cumulative distribution function (CDF) as its statistics are approximately normally distributed with mean of zero and variance of V(D) for the Spearman's Rho statistic. Using the following standardisation,

$$Z_{SR} = \frac{D}{\sqrt{V(D)}}$$

the standardised statistics Z follows the standard normal distribution Z ~ N(0,1).
The P-value of the Spearman's Rho statistic (D) of sample data can be estimated using the normal CDF,

$$p = 0.5 - \Phi(|Z_{SR}|)$$

Where: $$\Phi(|Z_{SR}|) = \frac{1}{2\pi}\int_{0}^{|Z|} e^{-t^2/2}\,dt$$

If the P-value is small enough, the trend is quite unlikely to be caused by random sampling. At the significance level of 0.05, if $p \le 0.05$, then the existing trend is considered to be statistically significant.

For large samples, the quantity $r_s\sqrt{n-1}$ is approximately normally distributed with mean of 0 and variance of 1 (critical test statistic values for various significance levels therefore can be obtained from normal probability tables). This test is particularly useful for the detection of gradual change in time series.

9.4.3 Mean-weighted Linear Regression test (parametric test for trend)

This is a parametric test that assumes that the data come from EV1 distribution. It tests whether there is a linear trend by examining the relationship between time (*x*) and the variable of interest (*y*). The regression gradient is estimated by:

$$b = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

The Y-Axis intercept is given by $a = \bar{y} - b\bar{x}$

The test statistic S is given by:

$$S = \frac{b}{\sigma}$$

Where:

$$\sigma = \sqrt{\frac{12\sum_{i=1}^{n}(y_i - a - bx_i)}{n(n-2)(n^2-1)}}$$

The test statistic S follows a Student-t distribution with n-2 degrees of freedom under the null hypothesis (critical test statistic values for various significance levels can be obtained from Student's t statistic tables).

The linear regression test assumes that the data are normally distributed and that the errors

(deviations from the trend) are independent and follows the same normal distribution with

zero mean. For large samples, the quantity b_s / σ is approximately normally distributed.

9.4.4 Distribution-free CUSUM (non-parametric test for step jump in mean)

This method tests whether the means in two parts of a record are different (for an unknown time of change). This is a rank-based test in which successive observations are compared with the median of the series (Chiew & McMahon, 1993; McGilchrist & Woodyer, 1975). The test statistic is the maximum cumulative sum (CUSUM) of the signs of the difference from the median (i.e. the CUSUM of a series of plus or minus ones) starting from the beginning of the series.

Given a time series data ($x_1, x_2, x_3, \ldots\ldots, x_n$), the test statistic is defined as:

$$V_k = \sum_{i=1}^{k} sgn(x_i - x_{median})$$

$$sgn(x_i - x_{median}) = 1 \text{ For } (x_i - x_{median}) > 0$$

$$sgn(x_i - x_{median}) = 0 \text{ For } (x_i - x_{median}) = 0$$

$$sgn(x_i - x_{median}) = -1 \text{ For } (x_i - x_{median}) < 0$$

x_{median} is the median value of the x_i dataset.

The distribution of V_k follows the Kolomogorov-Smirnov two sample statistic (KS = (2/n) max|V_k|) with the critical values of max|V_k| given by:

$\alpha = 0.10$ $1.22\sqrt{n}$

$\alpha = 0.05$ $1.36\sqrt{n}$

$\alpha = 0.01$ $1.63\sqrt{n}$

A Negative Value of V_k indicates that the latter part of the record has a higher mean than the earlier part and vice versa.

9.4.5 Cumulative Deviation (parametric test for step jump in mean)

This method tests whether the means in two parts of a record are different (for an unknown time of change). The cumulative deviation test (Buishand, 1982) is based on the rescaled cumulative sum of the deviations from the mean. The test is relatively powerful in comparison with other tests (e.g. Worsley likelihood ratio test; Buishand, 1982) for a change-point that occurs towards the centre of the time series. The test assumes that the data are normally distributed. The purpose of this test is to detect a change in the mean of a time series after m observations:

$$E(x_i) = \mu \qquad i = 1, 2, 3, \ldots m$$

$$E(x_i) = \mu + \Delta \qquad i = m+1, m+2, m+3, \ldots, n$$

Where μ is the mean prior to the change and Δ is the change in the mean. The cumulative deviations from the means are calculated as:

$$S_o^* = 0 \qquad S_k^* = \sum_{i=1}^{k} [(x_i - \bar{x}])$$

And the rescaled adjusted partial sums are obtained by dividing the S_k^* values by the standard deviation:

$$S_k^{**} = S_k^* / D_x$$

$$D_x^2 = \sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n}$$

The test statistic Q is:

$$Q = \max|S_k^{**}|$$

and is calculated for each year, with the highest value indicating the change point.

Critical values of $Q/\sqrt{n}$ are given in table 6.1 below. A negative value of S_k^* indicates that the latter part of the record has a higher mean than the earlier part and vice versa.

N	Q/√n at significance level

	α = 0.10	α = 0.05	α = 0.01
10	1.05	1.14	1.29
20	1.10	1.22	1.42
30	1.12	1.24	1.46
40	1.13	1.26	1.50
50	1.14	1.27	1.52
100	1.17	1.29	1.55
∞	1.22	1.36	1.63

Table 9.7 critical values of Q/√n

9.4.6 Turning Points (non-parametric test for randomness)

This non-parametric test is based on counting "turning points" in the series, i.e. triplet sets of subsequent values x_{i-1},x_i,x_{i+1} such that $x_{i-1}<x_i>x_{i+1}$ or $x_{i-1}>x_i<x_{i+1}$.

If $x_{i-1}<x_i>x_{i+1}$ the n time series are assigned a value of 1 and

If $x_{i-1}>x_i<x_{i+1}$ the n time series are assigned a value of 0

The number of times that 1 appears in the series (m^*) is approximately normally distributed with:

$$\mu = 2(n-2)/3$$

$$\sigma = (16n-29)/90$$

The Z-statistic is therefore : $Z_{TP} = |m^* - \mu|/\sigma^{0.5}$

Under the null hypothesis of independent, equally distributed values, this test statistic is normally distributed with mean 0 and variance 1 (Srikanthan and MacMahon, 1983).

9.4.7 Rank Difference (non-parametric test for randomness)

This is a nonparametric test. It involves computing differences between the ranks of subsequent values in the series. If U denotes the sum of absolute values of such rank differences then the test statistic is

The n time series values are replaced by their relative ranks starting at 1 for the lowest up to n.

The statistic U is the sum of the absolute rank differences between successive ranks:

$$U = \sum_{i=2}^{n} |r_i - r_{i-1}|$$

For large n, U is normally distributed with:

$$\mu = (n + 1)(n - 1) / 3$$

$$\sigma = (n - 2)(n + 1)(4n - 7) / 90$$

The z-statistic is therefore (critical test statistic values for various significance levels can be obtained from normal probability tables):

$$Z = | U - \mu | / \sigma^{0.5}$$