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Development and Examinations of Flood Warning Systems for the Munster Blackwater at Mallow

By

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Abstract

The town of Mallow on the river Blackwater, in the south west of Ireland, experiences flooding on an annual basis. Severe economic losses due to flooding as well as traffic disturbances have affected Mallow and Fermoy on many occasions including: 15th of November 2003; the 1st of February 2002; and the 5th of November 2000. As part of this project two river level monitoring stations on the river Blackwater have been upgraded: one at Duarrigle, 38 km upstream of Mallow; and the second at Dromcummer 19 km upstream of Mallow. These stations now record the water level every 15 minutes and transfer this data to a base station at University College Cork every two hours. The water levels are used to give warning of imminent floods for Mallow. A live website of continuous river levels at both stations has been implemented, providing information to the general public and relevant authorities involved in flood management.

New concepts in flood warning as well as the existing flood warning system were examined. Four separate flood warning systems were evaluated: a river level threshold flood warning system; a rate of rise flood warning system; an atmospheric pressure flood warning system; and a neural network flood warning system.

The river level threshold flood warning system is based on river heights exceeding a pre-determined threshold and provides approximately five hours flood warning for Mallow. The system predicted 86% of the floods from 20 years of historical data. This rate of rise system examines the rate at which the river rises during flood events. The rate of rise flood warning system has potential to improve the warning time by approximately an additional 3 hours. The third system examines the levels of atmospheric pressure and the rate of change of atmospheric pressure, prior to a flood event. The atmospheric pressure system has the potential to improve the flood warning time but success in predicting a flood is lowered. Further research is necessary to improve the accuracy.

A new artificial neural network model was developed using the *matlab* neural network toolbox. The neural network flood warning system provides at least ten hours flood warning. The neural network model is trained to recognise patterns of the river heights (of the 20 year database) and predict future river heights based on these patterns. The neural network model predicts the river level height accurately.

The threshold flood warning system is in place providing a 5 hour warning time and proves to be robust and reasonably accurate. Integration of the neural network model into the website would enhance the current flood warning system, thereby giving accurate flood warnings at least 10 hours ahead.

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Chapter 1
Introduction

1.1 Background

The driver of flooding is rainfall or more appropriately excess rainfall onto lands and areas unable to allow absorption and thereby facilitating large runoff to streams and rivers. Flooding of agricultural land, though important, is seen as less significant than flooding of urban areas. Many rivers that flow through relatively flat land flow through areas called flood plains. In times of heavy rainfall these rivers can burst their banks; water then spreads throughout the flood plain. Flooding deposits silt on the flood plain, improving its fertility which attracts agriculture and other developments.

Flooding in Ireland is a problem in several catchments. Ireland is saucer-shaped with an elevated maritime rim and a flat low central plain. As a result many rivers with their sources on the inland side of the maritime rim follow long winding courses to the sea, which consequently leads to slow flowing inland rivers. Due to this Ireland's river systems frequently flood in urban areas and agricultural land.

Two possible types of solutions to flooding are: structural solutions and non-structural solutions. Structural solutions are mainly preventative. Structural solutions attempt to eliminate flooding using different methods such as the building of flood control dams, excavating ditches, the building of canals, the cleaning and widening of river beds and compound channelling (McKeogh et al. 1991). This could however result in adverse environmental, hydrologic, economic, ecological and geologic consequences. Non-structural solutions include: flood forecasting systems; flood warning systems; focussed regulations (for example curtail floodplain developments). Non-structural solutions tend to have less environmental impact, but also may not be as successful.

Flood forecasting systems use methods such as rainfall runoff modelling to determine if a flood is going to occur. Flood warning systems recognise an imminent flood and provide warnings. Information gathering; information appraisal and action are core to a successful flood forecasting or flood warning system..

This project deals with the information gathering and information appraisal of a number of flood warning systems, i.e. how the data are measured and how the data are analysed

1.1.1 History of Global Flooding

Throughout the developed world, rivers prone to flooding are managed carefully. Many structural solutions are used to prevent rivers from bursting their banks, such as levees, bunds, reservoirs, and weirs.

The most devastating flood in U.S. history occurred in the summer of 1993 (Mississippi River Flood, 1998). The Mississippi river flooded St. Louis Missouri for 144 days between April 1 and September 30 1993. Roughly 3 billion cubic meters of water overflowed from the Mississippi river onto the flood plain downstream of St Louis. Seventeen thousand square miles of land were covered by floodwaters in a region covering all or parts of nine states (North Dakota, South Dakota, Nebraska, Kansas, Missouri, Iowa, Wisconsin, Minnesota, Illinois). Close to 50 people died as a result of the flooding with 26,000 people being evacuated and 56,000 homes damaged. The economic losses due directly to the flood totaled almost $10 billion

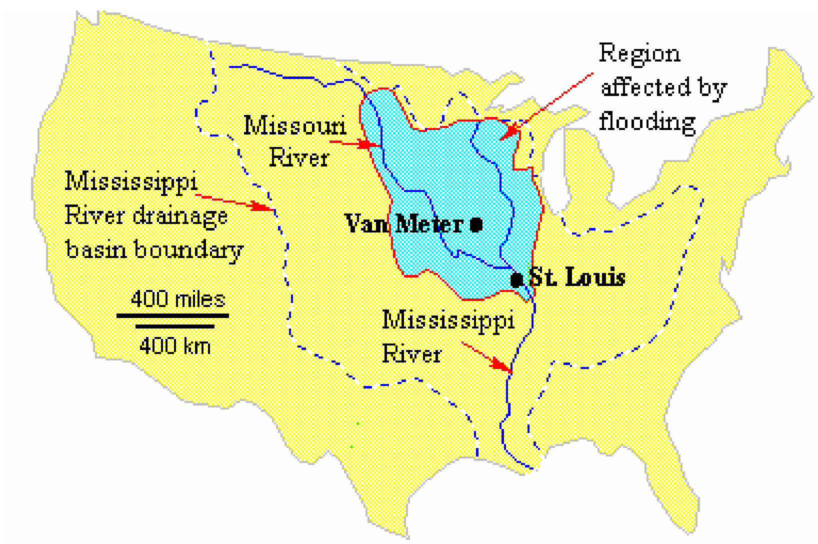

Figure 1-1 Extent of region of U.S. affected by flooding (Mississippi River Flood, 1998)

In August 2002 parts of Europe experienced the worst flooding in 150 years (World Socialist Website, 2002). Almost 100 people died in Austria, Russia, Romania, the Czech Republic, Germany, Northern Italy and Rome. Approximately 60 of these people died in the villages close to the Russian Black Sea. The River Elbe in Dresden eastern Germany reached a river height of 9.4 m which was the highest ever recorded. 70,000 people in Prague needed to be evacuated. In Germany flooding caused approximately €23 billion worth of damage.

Planning laws have been used to limit building on flood plains, particularly in some flood-prone areas near high population density locations, such as Holland and parts of England. (Wikipedia, 2004).

Some of the most historic global floods are listed below:

•1963 October 9th. Italy, Alps, Vaiont Dam: landslide into the water reservoir caused a shockwave which over-topped the wall of the dam. Five villages (Longarone, Fae, Pirago, Codissago, Castellavazzo) were severely damaged, at least 2,000 people died.

•1993 August 1st.USA, Midwest / Mississippi: worst flooding in recorded history, 38,000 homes damaged or destroyed, 20 million acres of farmland under water

•1998 Bangladesh: worst flood in the century, two-thirds of the country were submerged for more than three months, 500,000 homes were damaged and about 1,000 people died.

•1999 December 19th. Venezuela, Caracas: massive floods due to torrential rainfall, at least 10,000 people died, more than 150,000 became homeless

(Emergency Management, 2002)

1.1.2 History of Flooding of the Munster Blackwater

The Munster Blackwater catchment suffers from flooding when the Blackwater River overflows its banks in or near the towns of Mallow and Fermoy (See Figure 2-2). These towns have had major floods in 1853, 1875, 1916, 1946, 1948, 1969 and 1980. The railway bridge over the Blackwater at Ballymaquirke (near Kanturk) was washed away in the flood of August 12, 1946 (Doheny, 1997). On November 2nd 1980, a flood with a return period of about 30 years occurred on the Blackwater. Flood damage and losses in the catchment on this occasion were estimated at over £2.5 million (Doheny, 1997).

Mallow experiences some flooding every year, due to the River Blackwater, or due to the Spa Glen stream, which is a small tributary of the Blackwater that flows through Mallow Town Center. Serious flooding affecting properties and roads in Bridge Street and in the Spa Walk occurred in 1986, 1988, 1990, 1995 and 1998. The Town Park and the Park Road in Mallow were flooded twice in December 1999 (Steinmann, 2004).

According to records, the most disastrous flood occurred in 1853 leaving the lowest street under 3.6 m of water. In 1980 the fourth largest recorded flood occurred where the water level reached 2.5 m in some houses. In November 1998, Bridge Street, Mallow was flooded to a depth of

0.4 m and as much as 2.2 m in the town park (Steinmann, 2004). Figure 1-2 and Figure 1-3 shows an example of this flood, notice the river height compared to the truck.

Figure 1-2 Flooding at Mallow Bridge December 30, 1998

Figure 1-3 Flooding at the Town Park Road, Mallow 14:30 December 30, 1998

The town park in Mallow is flooded several times a year to depths as high as 2.2 m. Near Longsfield Bridge, adjacent to the beet factory, the road is affected by flooding several times a year (Doheny, 1997)(see Figure 1-4). The depth of water that can appear on this road can be very misleading and at least two mishaps have occurred in the past decade. To prevent accidents both ends of this road are closed when a flood has been detected. It is therefore vital that a flood warning is put in place to prevent potential fatalities at this location.

Figure 1-4 1998 Flooding of Longsfield Bridge near the Beet Factory, Mallow December 30, 1998

1.2 Literature Review

Flooding is a recurring global problem and seemingly getting worse due to climate change (Emergency Management, 2002). In the last forty years the world has experienced some of the worst floods in history (Mississippi River Flood, 1998, World Website, 2002). Climate change is considered to be influencing the global weather and thought to be instrumental in the recent trends of extremes of climate e.g. extremes of rainfall. It has been shown that since 1975 in the western half of Ireland there has been an increase in the annual precipitation which has an impact on flood frequency and flood magnitudes (Kiely, 1999).

Warnings and emergency planning for flooding are based on the principle that no matter how thorough the investigation and flood prevention efforts through engineered structural works or land use management, some risk will always remain (Handmer, 2001). Due to this persistent risk of flooding, flood alleviation methods have been used throughout the world (Moray Flood Alleviation, 2004). There are many benefits to flood alleviation schemes such as the decrease in damage caused by flooding, the decrease in injuries caused by flooding and the saving of lives (Penning-Rowsell, 1977).

Flood alleviation schemes require some method of flood warning (Clonmel Nationalist, 2004). Such flood alleviation systems have been implemented successfully in England (Moray Flood Alleviation, 2004). There are flood warning systems in use throughout England, Scotland and Wales.

The English and Welsh flood warning systems use flood warning phone numbers, which the public can call to learn of the risk of flooding in their area. The Welsh system uses a flood warning website (www.environment-agency.gov.uk) which the public can access to view information on their area. Similar flood systems are in place in the US, Canada and in New Zealand. An added benefit of flood warning website in New Zealand is the use of the website by anglers checking the suitability of the rivers for fishing. The Scottish flood warning system has proven to be successful (BBC News, 2000). The Scottish flood warning system also uses a flood warning website, which can be seen at http://www.sepa.org.uk/flooding/warnings/index.aspx.

The flood alleviation scheme designed for Mallow includes temporary flood walls which will be put in place subsequent to a flood warning. Such a system requires an efficient, robust and reliable flood warning system. The current flood warning system is a river threshold system i.e. once the water exceeds a predetermined threshold at a point upstream of Mallow, a warning is given. The current system provides a five hour flood warning with moderate accuracy (Steinmann, 2004). For the proposed flood alleviation scheme a larger flood warning time is required.

For the 1980 flood of the Blackwater catchment an estimate of the damages and losses in the towns affected was stated by the Blackwater Flood Association to exceed £2.5 million (Moore, 1992). It was then decided by Cork County Council that a flood alleviation scheme was required to reduce the damage caused by repeated flooding. A flood alleviation scheme was designed and implemented for one of the towns on the Blackwater, Kanturk, in 1986 and this scheme which utilized compound channel works has operated successfully for the past 18 years, (Kiely, 1985). For Mallow and Fermoy a flood warning system for the Munster Blackwater was set up in 1982. However this flood warning system failed due to lack of mechanical/ electrical expertise and lack of maintenance (Steinmann, 2004). A manual flood warning system has been in place since 1982. The County Council area engineer in Millstreet, Mr. Martin Corcoran has been observing the Blackwater levels near Millstreet since 1975 and he advises his colleagues in Mallow of impending floods. This is a labour intensive exercise and automatic computational systems can now assist. In 2003 in collaboration with Ott-hydrometry and UCC, the Cork County Council installed two new automatic river level monitoring devices, reviving the 1982 automatic flood warning system. (Steinmann, 2004). Existing flood warning systems, even with their obvious deficiencies, can be effective in the alleviation of flood damage. It is very likely that if they are recast in terms of completeness, carefully planned, well run and maintained, their effectiveness can be amplified considerably (Keys, 1997). It was therefore decided that the existing flood warning system as well as a number of additional flood warning concepts should be analysed to increase the effectiveness of the flood warning system of the Munster Blackwater for Mallow (and by association, Fermoy).

The river level threshold method of flood warning has proven to be successful in many other parts of the world (Minnesota DNR, 2003). The key to an efficient river level threshold flood warning system is choosing the correct thresholds (Steinmann, 2004). It was therefore decided that different thresholds should be analysed to determine the most suitable river level threshold at which a flood would occur.

A news release in Harrisburg, PA recommended monitoring the rate of rise of the river height as an improvement in a flood warning system (Obleski, 2002). Since the river height during a flood increases rapidly, the rate of rise before a flood would be quite large. It would be beneficial to a flood warning system to analyse the rate of rise of the river level. It was therefore decided that this method of flood warning system be analysed for the Munster Blackwater catchment.

Bosak observed "if the pressure is falling slowly, rain will occur within a day and if it is falling rapidly, it will rain within a few hours and wind speeds will increase" (Bosak, 1991). As rainfall is related to atmospheric pressure and flooding is proportional to rainfall, atmospheric pressure could perhaps be used as a prediction of flooding. This method of flood warning was also examined for the Munster Blackwater catchment.

Artificial Neural Networks are used to recognise patterns and relationships in long time series of river height or flow data (Laio, 2003). Artificial Neural Networks can therefore be used to recognise patterns in the change in river heights and relationships between the river heights at different points on a river. Artificial Neural Networking was analysed by Laio for multivariate flood forecasting and good results were obtained (Laio, 2003). It was decided that this form of flood forecasting/warning would be analysed for the Munster Blackwater catchment as part of this project.

A flood warning system should not only be accessible to the relevant authorities (County Council, Fire Brigade, Gardai etc) but should also be accessible to the general public (Handmer, 2002). This would give the general public some responsibility in the protection of their homes and businesses from flooding. There are a number of methods of delivering this warning such as a phone line (Floodline in England) or a website (http://www.sepa.org.uk/flooding/warnings). It was decided for ease of use that an Irish website would be the best approach and this also formed part of this project.

1.3 Objectives

The main objective in this project is to improve the current basic flood warning system of the Munster Blackwater. This objective was carried out as follows:

- Analyse the existing basic flood warning system, i.e. the river level threshold flood warning system (see Section 4.2)
- In addition analyse a number of other flood warning systems: the rate of rise flood warning system; the atmospheric pressure flood warning system and the neural network flood warning system. These methods were analysed in order to improve the existing basic flood warning system.
- Integrate a flood warning system web based module into the existing flood warning system.

An improved flood warning system is one that will predict all floods and produce less false warnings, and one with a large prediction time.

1.4 Methods

The Munster Blackwater flood warning system was optimized in a number of ways. The existing river level threshold flood warning system was examined and optimized. Optimization included calculating more accurate thresholds. These thresholds were calculated by examining historical floods. The optimized thresholds were then tested for accuracy (see Section 6.2

Other flood warning systems were then examined. The rate of rise flood warning system, the atmospheric pressure flood warning system and the neural network flood warning system were developed and tested, and accuracies and prediction times for these flood warning systems were measured. These accuracies and prediction times were then compared to the optimized river level threshold flood warning system to see if it would be advantageous to integrate these systems into the existing system.

A flood warning system website was created to optimize the existing flood warning system. This website was tested for accuracy and uploaded to the internet. The website provides a relatively accurate flood warning to the general public at www.irishfloodwarning.com. That is giving the public direct access to a flood warning system.

1.5 Previous Work

The first flood warning system in the Munster Blackwater catchment was installed in 1980. This system lasted only 3 months due to the unreliability of the system installed, the lack of maintenance and the lack of the technological skills within the Council to repair and maintain the equipment. The existing flood warning system installed in the Summer of 2003 is more robust. However the reliability of the system was questionable. (Steinmann, 2004)

Prior to this project began were no live flood warning websites available anywhere in Ireland. To date the only flood warning website available is the website created by the author during the course of this project and is found at www.irishfloodwarning.com.

1.6 Layout of Thesis

Chapter 2 describes the Munster Blackwater catchment, which is the catchment used during the course of the research project. Chapter 2 also describes the equipment used for the research project. Chapter 3 details the data used in the optimization of the flood warning system. Chapter 4 explains the methods used to optimize the existing flood warning system and how the new flood warning systems were developed and analysed. Chapter 5 describes the creation and layout of the flood warning system website. Chapter 6 gives the results of the analysis of the different flood warning systems. Chapter 7 contains a discussion and analysis of the results of chapter 6. Chapter 8 presents the conclusions and recommendations and makes suggestions for continuing research.

Chapter 2

Site Description

2.1 Catchment Location

The Munster Blackwater catchment is located in the southwest of Ireland (see Figure 2-1). The catchment is primarily within North West County Cork, Mid Cork and East Cork. The total area of the catchment is 3324km^2 which is almost 4% of the total land area of Ireland (Doheny, J. 1997). The Munster Blackwater catchment drains most of the Northern Division of County Cork and a large part of east County Waterford. The project's interest is in flooding of Mallow (known as the *flood focal point*), which is located about midway in the catchment. Therefore the area of interest is the western half of the catchment (i.e. west of Mallow)

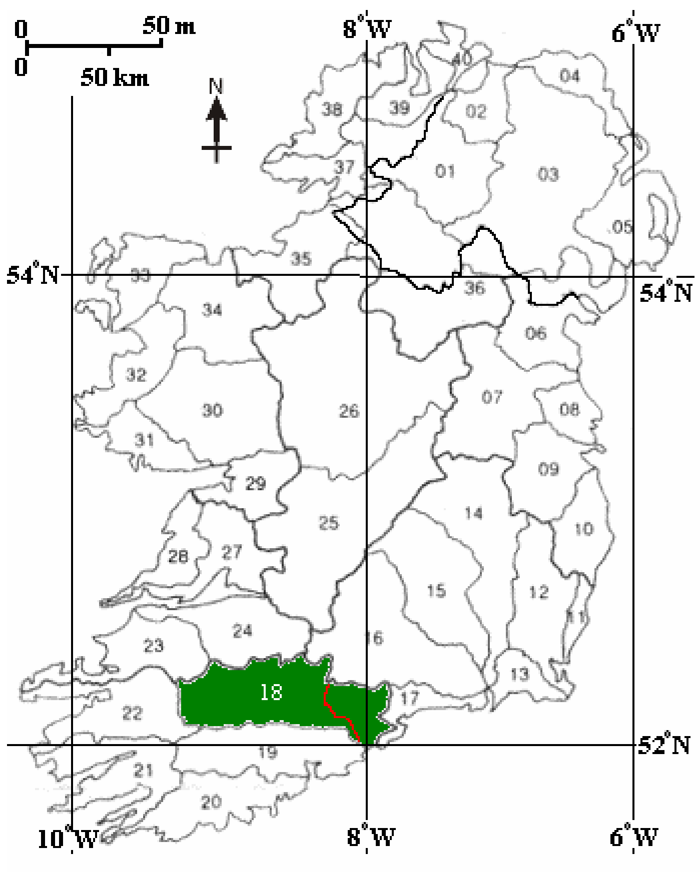

Figure 2-1 The Munster Blackwater Catchment is shown shaded and given a catchment No.18 by the Office of Public Works (OPW)

2.2 Catchment Description

The Munster Blackwater rises in the foothills of the Mullaghareirk Mountains at Knockanefune in County Kerry (see Figure 2-2). The river flows due south to Rathmore along the Cork and Kerry border. At Rathmore the river turns and flows due east passing near Millstreet and Kanturk and then through Mallow and Fermoy into County Waterford. At Cappoquin the river turns to flow due south and enters the sea at Youghal. There are 29 tributaries running into the Blackwater the main ones being the Bride, close to Cappoquin, the Awbeg, between Fermoy and Mallow, the Allow, which is close to Kanturk, and the Owentaraglin which is close to Duarrigle. The river is tidal for a distance of approximately 20km upstream to Cappoquin.

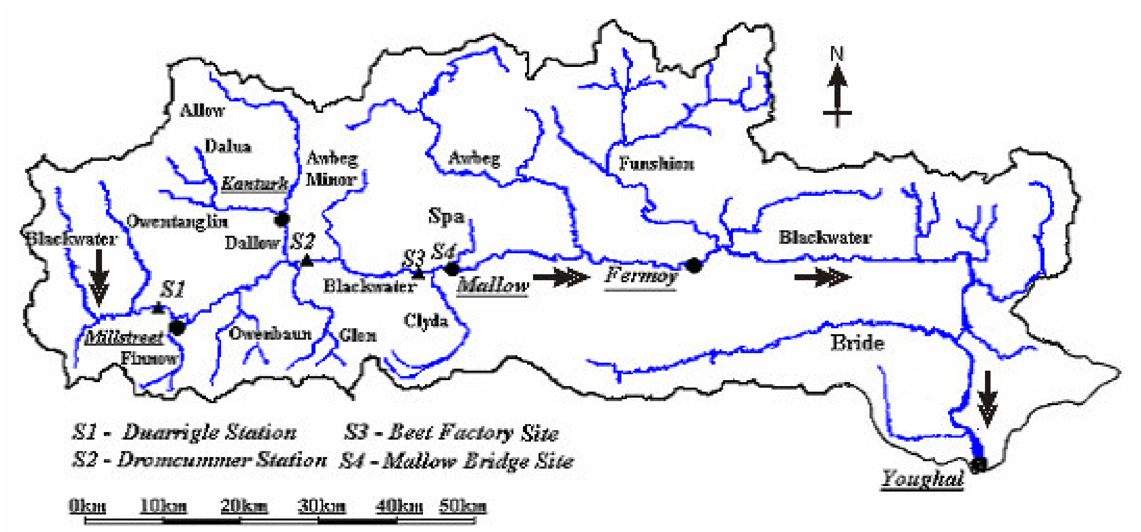

Figure 2-2 Outline of Munster Blackwater Catchment showing major towns, tributaries and sites.

The general pattern of river flow in the Munster Blackwater is a temperature oceanic river regime, influenced by year round rainfall with evaporation losses only during the summer months of May to September (Doheny, J. 1997). The annual average rainfall is about 1200 mm with about 300 to 400 mm for evapotranspiration.

Agriculture is the dominant land use in the catchment, with greater than 90% being grassland. Increasing amounts of land are being used for forestry on higher ground (See Figure 2-3). It can be seen from Figure 2-3 that a large percentage of the catchment is represented by pastures and arable land.

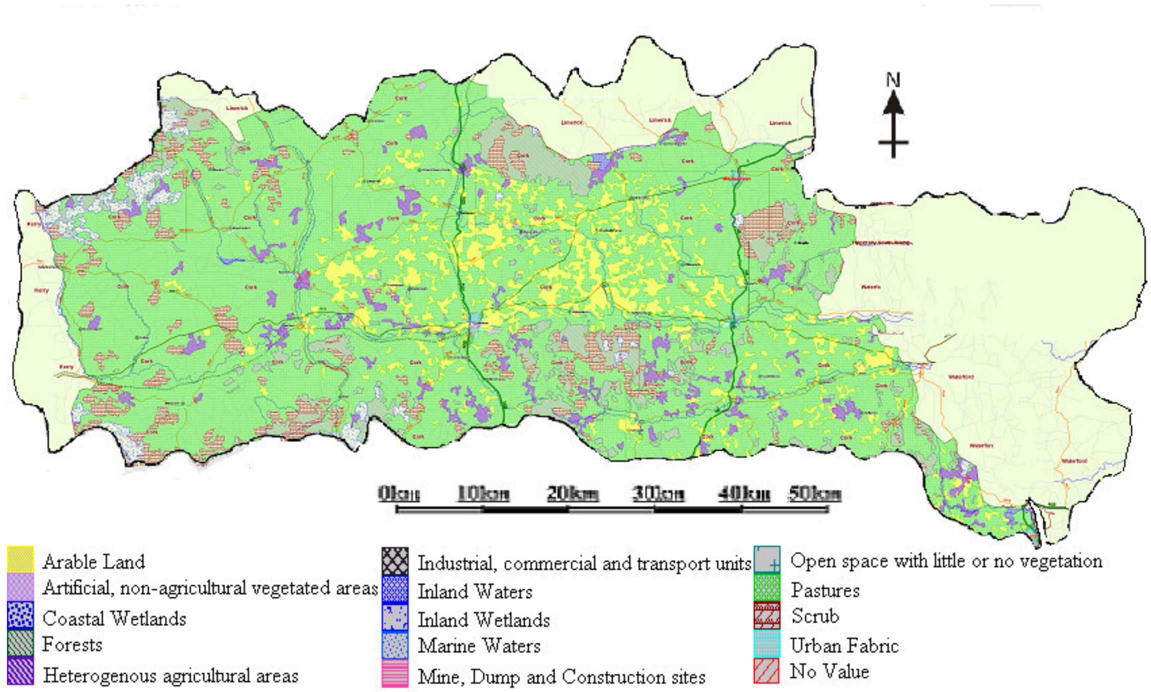

Figure 2-3 Map of Catchment showing land use

2.2.1 Sub Catchments

As the projects main area of interest is towards the west of Mallow, it is these western tributaries (the Allow, the Owentaraglin, the Finnow, the Glen, the Owenbaun and the Awbeg Minor) that are of key interest. These include: the upper Blackwater(1); the Finnow (2); the Owenbaun (2); the Allow (3); the Dromcummer Mallow (4); the Glen (5); the Awbeg (6); the Beet Factory (7); Fermoy (9) and the Clyda (9) (See Figure 2-4)

Table 2-1 Sub Catchment Areas and Slopes

Catchment	Area [km^2]	length [km]	Slope - S1085
Blackwater to Duarrigle	248	33	3.9
Blackwater to Dromcummer	868	55	2.7
Blackwater to Beet Factory	1058	71	2.3
Blackwater to Mallow Bridge	1186	75	2.1
Blackwater to Fermoy	1762	106	1.3
Blackwater to Youghal	3324	163	0.9
Allow to Riverview	306	33	4.0
Allow to Blackwater	311	35	4.1
Clyda	113	16	6.7
Glen	77	14	9.6
Awbeg	369	50	1.6

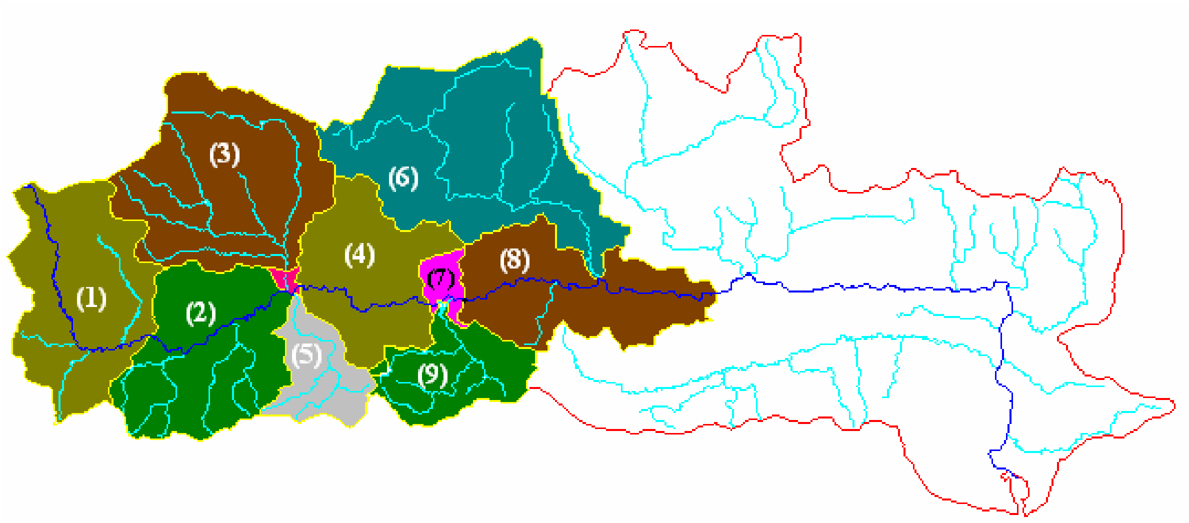

Figure 2-4 Munster Blackwater Catchment divided into its Sub Catchments

The main towns in these catchments are Mallow, and Fermoy, which are most affected by flooding of the Munster Blackwater. The total flood damage and losses in the Blackwater catchment due to the flooding in October 1980 amounted to over £2.5 million (UCC Flood Studies Group, 2000). Table 2-2 shows the main centres of population in the catchment, the rivers serving them and their respective populations.

Table 2-2 Catchment areas and populations for the main towns (Doheny, J. 1997)

Town	Population	River	Catchment Area [km2]
Millstreet	2700	Finnow	31
Kanturk	2500	Allow	274
Fermoy	5040	Blackwater	1795
Youghal	6300	Blackwater (Estuary)	3324
Mallow	8650	Blackwater	1196

2.3 Topography

The Munster Blackwater runs through a broad valley bounded by mountain ranges, on the north by the Knockmealdown, Kilworth, Galtee, Ballyhoura and Mullaghareirk Mountains, and on the south by the Boggeragh range. On the South and East the watershed between the Blackwater and its main tributary (the Bride) is bounded by the Nagles Mountains and a range of hills running east-west from Drum Hills near Villierstown to Fermoy (See Figure 2-5).

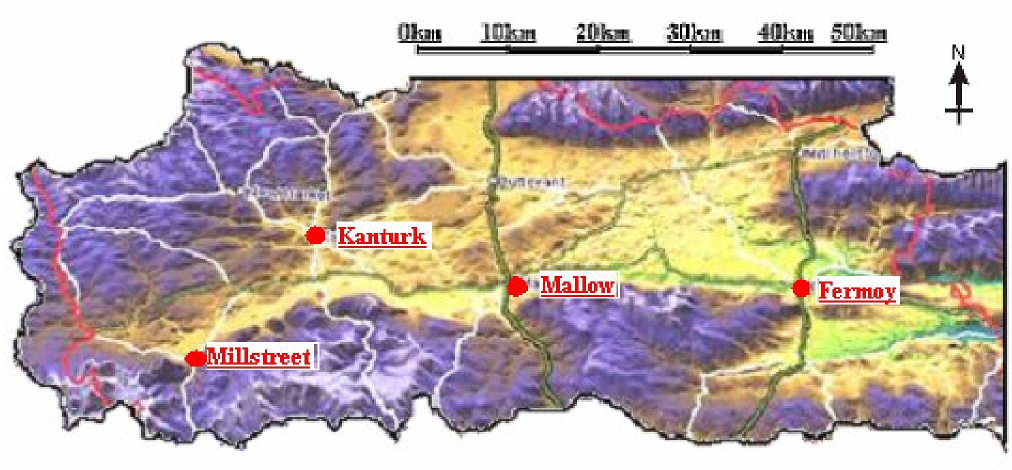

Figure 2-5 Topography of the Munster Blackwater Catchment

2.4 Catchment Geology

2.4.1 Soils

As can be seen in Figure 2-6 the soils to the south of the catchment are mainly brown podzolics and peaty podzols and the soils to the north of the river are mostly gleys and acid brown earths (Gardner & Radford, 1980). The dominant soil type of the catchment being gleys and brown podzolics.

Podzols are normally poor soils with high lime and fertilizer requirements. Brown podzolics are similar although are less depleted of nutrients than the podzols. Podzols are usually formed in hill and mountainous areas, whereas brown podzolics are often devoted to farming, the addition of lime and fertilizer overcomes their low nutrient status.

Gleys are soils which have developed under the influence of permanent or intermittent water logging, which may be due to a high water table or run off from hills and mountains (Gardner & Radford, 1980). This soil type is mostly unsuitable for cultivation or intensive grassland farming. Acid brown earths are relatively mature, well drained mineral soils possessing a rather uniform profile. They are amongst the most extensively cultivated soils within the catchment (Gardner & Radford, 1980).

The dominant soil type to the west of the catchment is gleys. To the north of the Blackwater valley this soil type changes from gleys to minimal grey brown podzolics to acid brown earth and brown podzolics, moving from west to east along the catchment. To the south of the river the dominant soil types are brown podzolics and peaty podzols.

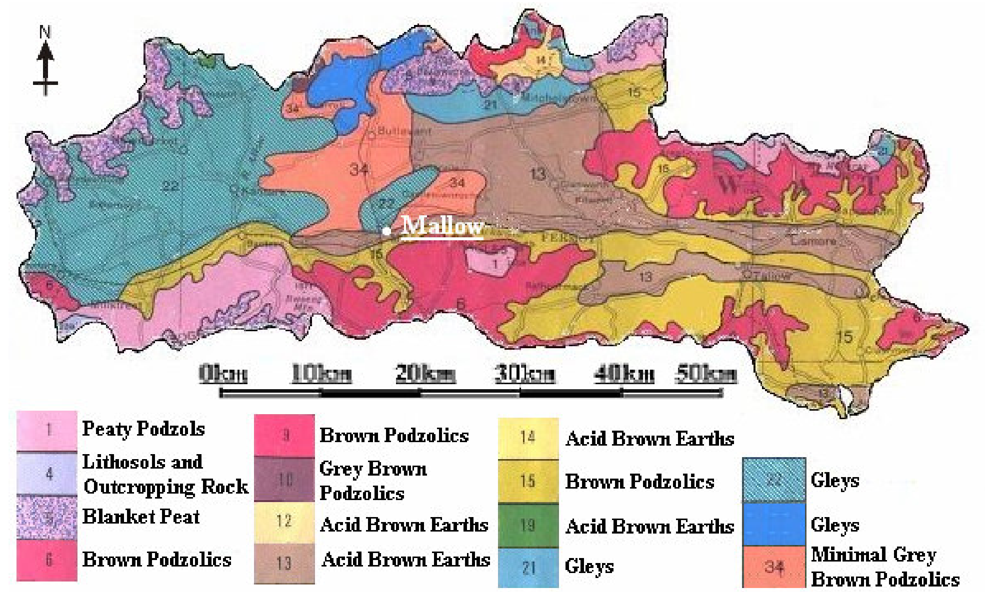

Figure 2-6 Catchment soil types (Gardner & Radford, 1980)

2.4.2 Bed Rock

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 (Figure 2-7) (Geological Survey of Ireland, 2004)

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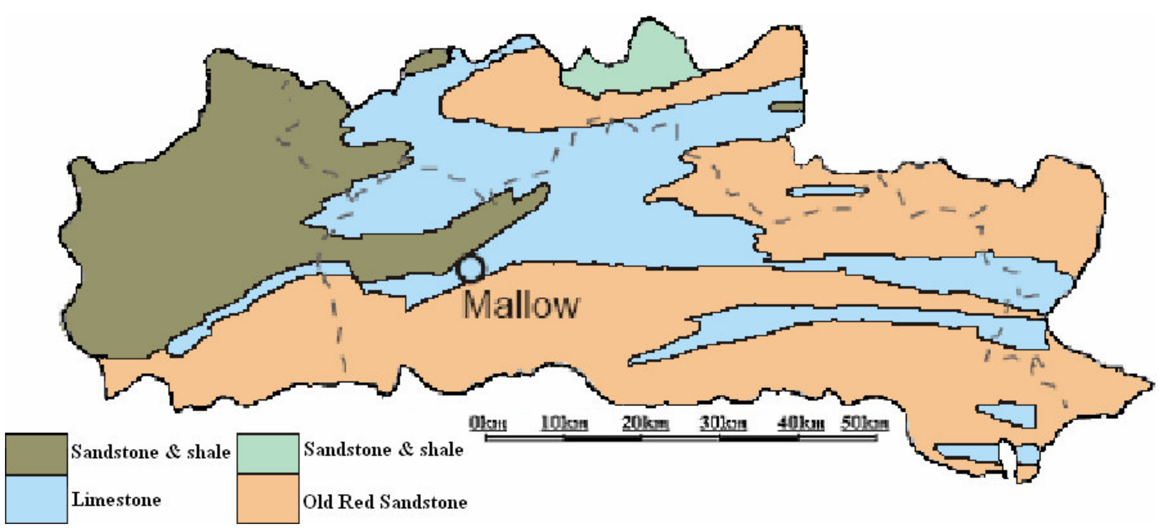

Figure 2-7 Catchment rock types (Geological Survey of Ireland, 2004)

2.5 Climate

The climate is mild and humid due to the influence of the warm Gulf Stream. Daily air temperatures have a small range of variation during the year, going from a maximum of 20ºC to a minimum of 0ºC, with an average of 15ºC in summer and 5ºC in winter (Jaksic, 2004). Figure 2-8 is a wind rose for a meteorological station near the boundary of the catchment Donoughmore (which is assumed to be representative of the Blackwater catchment). The prevailing wind direction is from the southwest (See Figure 2-8).

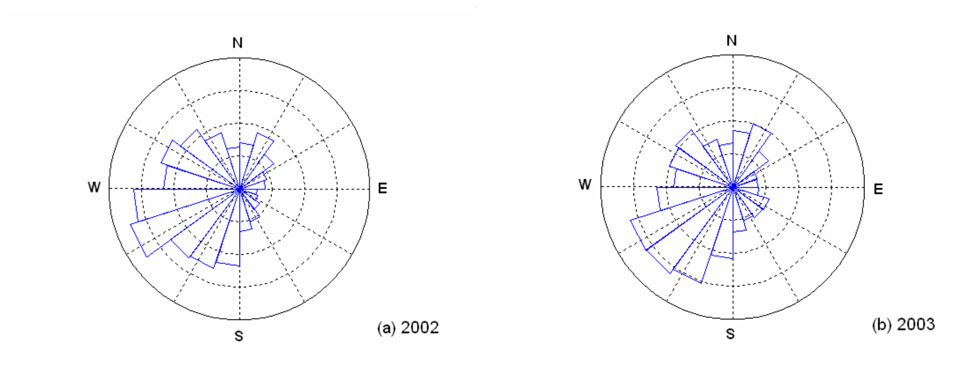

Figure 2-8 Wind rose: (a) for 2002 and (b) for 2003 (Jaksic, 2003)

From a hydrological and flooding perspective, precipitation, in this case for the most part rainfall is the most important climactic factor. The rainfall regime is characterized throughout the year by long duration events of low hourly intensity. Short duration events of high intensity are more seldom and mostly occur in summer (See Figure 2-9).

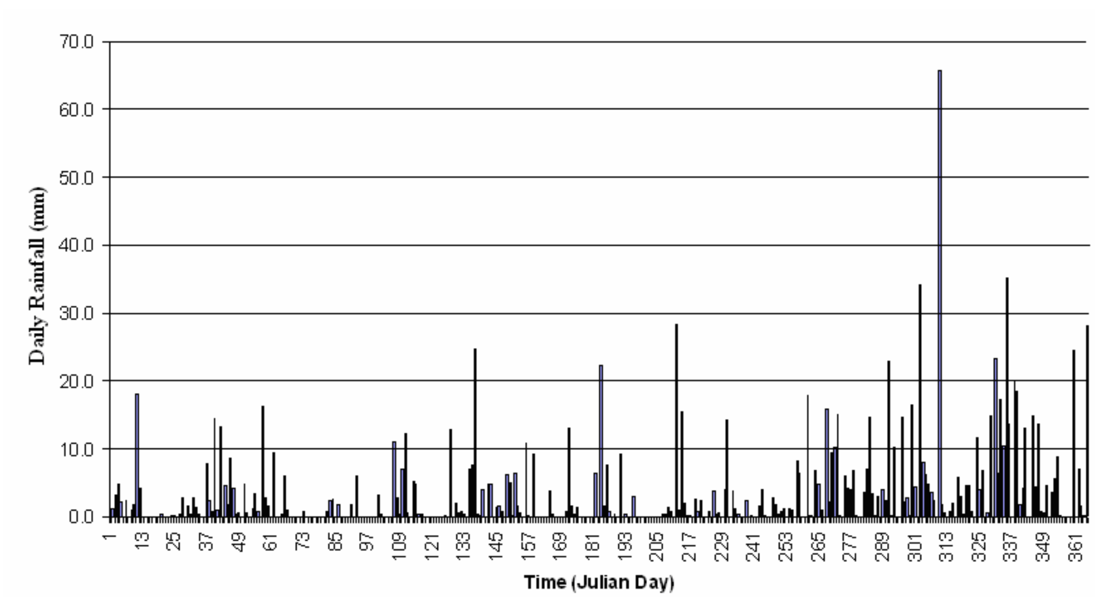

Figure 2-9 Daily Rainfall for the year 2000 at Mallow

The rainfall for the Munster Blackwater Catchment varies from 980 mm per year at Doneraile (the centre of the catchment) to 2000 mm per year at Caherbarnagh to the south west of the catchment (SeeTable 2-3) (Doheny, J. 1997).

Table 2-3 Catchment areas and average rainfall for the main stations (Doheny, J. 1997)

Station Name	Tributary	Catchment Area [km^2]	Long Average rainfall 1941-1970 [mm]
Mogeely	Bride	335	1202
Ballyduff	Blackwater	2338	1159
Killavullen	Blackwater	1258	1216
Ballynamona	Awbeg	324	1064
Downing Bridge	Funshion	363	1190
Mallow Beet Factory	Blackwater	1058	1303
Riverview	Allow	316	1230
Allen's Bridge	Dalua	88	1344
Duncannon Bridge	Blackwater	113	1465
Dromcummer	Blackwater	881	1356
Duarrigle	Blackwater	245	1456

2.6 River Monitoring Sites - Description

The aim of this project is to develop an improved flood warning system for the River Blackwater for Mallow. For this reason it was required to have a number of water level sensors on the river to measure the heights of the river on a continuous basis.

From Figure 2-10 the locations of the three monitoring stations used for this project are shown. Two of these stations are live (telemetrically) stations and are located in Duarrigle (S1) and Dromcummer (S2). Duarrigle is near Millstreet and is approximately 38 km upstream of Mallow. Dromcummer is near Kanturk and is approximately 19 km upstream of Mallow At these two sites there are two height sensors: an OTT-Hydrometry Kalesto water height sensor and Thalimedes water height sensor. These sensors are described in Section 2.7 . Two sensors are used so that the system is still operational if one fails. At the Beet Factory (S3) (approximately 3 km up river of Mallow town) there is a stand alone Ott-Hydrometry Thalimedes water height sensor without telemetry. At Mallow Bridge (S4) there is also a Thalimedes water height sensor without telemetry. The National Grid References for the four sites are given in Table 2-4.

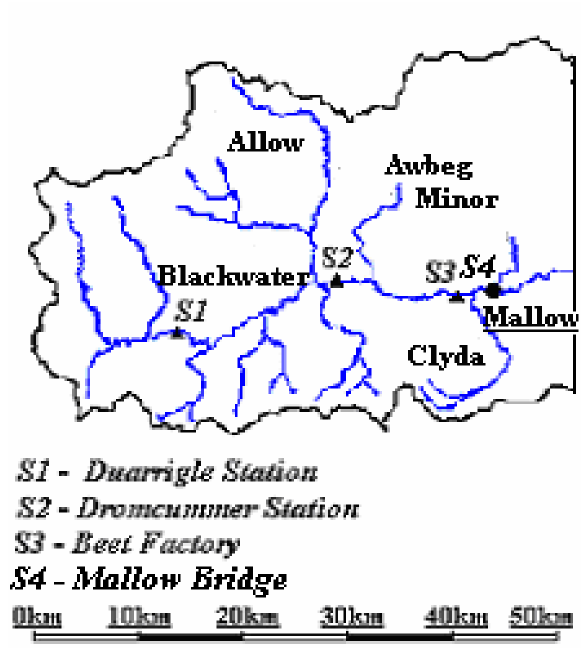

Figure 2-10 Map of the relevant sites and stations.

Table 2-4 Station Grid References and Types

Station Name	National Grid Reference	Gauge Type
Duarrigle	W 249 943	OTT-Hydrometry Kalesto and Thalimedes
Dromcummer	W 398 993	OTT-Hydrometry Kalesto and Thalimedes
Beet Factory	W 525 973	OTT-Hydrometry Thalimedes
Mallow Bridge	W 561 981	Thalimedes

2.6.1 Duarrigle (S1)

The station at Duarrigle is approximately 38km upstream of Mallow. Its catchment area is 245 km^2. This is approximately 20% of the catchment area to Mallow. Historically this was used as the main river monitoring site, with the help of Martin Corcoran (Area Engineer – Millstreet), who monitored the river heights when he suspected a flood was imminent.

In general, high flows in Duarrigle should represent high flows in Mallow, but this is not always the case due to additional tributaries such as the Allow, the Glen and the Clyda which enter the Blackwater downstream of Duarrigle but upstream of Mallow. The area between the Duarrigle station and Mallow may be too large to provide the necessary accuracy. Rainfall on this area may be different compared to the rainfall on the Duarrigle catchment. It is possible that a flood may occur at Mallow even though no flood occurs at Duarrigle.

2.6.2 Dromcummer (S2)

The Dromcummer station is approximately 19 km upstream of Mallow Bridge and is a much more significant monitoring station due to the fact that it is the last main catchment before Mallow. It has a catchment size of 868 km^2 which is about 75% of the catchment area to Mallow. This site gives a far greater idea of what heights and flows will occur in Mallow, which is discussed in Chapter 4 The Awbeg Minor and the Clyda are the two main tributaries that enter the Blackwater between Dromcummer and Mallow.

2.6.3 The Beet Factory (S3)

Mallow Sugar Beet Factory is situated approximately 3 km up river of Mallow town. Due to its proximity to Mallow town, it gives a good representation of river heights in Mallow town itself, which can be seen in Chapter 4 . This site is managed by the office of public works and contains an OTT-Hydrometry Thalimedes water height sensor but currently contains no telecommunications. Although the warning time from the Beet Factory is less than 1 hour its main use is its suitability in predicting the peak and time of a flood for Mallow.

2.6.4 Mallow Bridge (S4)

Mallow Bridge is situated in the heart of Mallow towards the east of the town. If a flood occurs at Mallow Bridge it impacts parts of Mallow Town. The monitoring site at Mallow Bridge is managed by the office of public works and contains a Thalimedes water height sensor but currently contains no telecommunications.

2.7 Instrumentation

The instrumentation used at Duarrigle, Dromcummer and the Beet Factory was provided by Ott-Hydrometry. The equipment is robust and easy to use.

2.7.1 Sensors

Two water level recording sensors were used at the sites, Dromcummer and Duarrigle. The second sensor was used to provide a back up system in case one device failed. The devices were chosen to best suit the site requirements. The two sensors that were used were the Ott-Hydrometry Thalimedes Shaft Encoder (See Figure 2-11) (Ott-Hydrometry, 2002) and the Ott-Hydrometry Kalesto Radar Sensor (See Figure 2-12) (Ott-Hydrometry, 2002)

2.7.1.1 Thalimedes Shaft Encoder

The float-operated Thalimedes Shaft Encoder with integral data logger (See Figure 2-11) is designed for continuous, unattended monitoring of water level in ground and surface waters. In the case of changing water level, the smooth running float pulley is put into motion via the float and the float cable, a potentiometer inside the pulley records the change and represents the change as a change in the height on the LCD display. The change is also recorded by the inbuilt data logger. The Thalimedes was a cost effective upgrade from a mechanical system to digital technology and was installed at Duarrigle and Dromcummer in September 2003. The inbuilt buffered data logger offers many features like event controlled recording, 1 minute to 24 hour storage interval etc. Data downloading or configuration can easily be done in the office or at site directly via IBM-compatible notebooks, palmtops or with the rugged VOTA Multifunctional Field Unit. In this project the data downloading is done in the office.

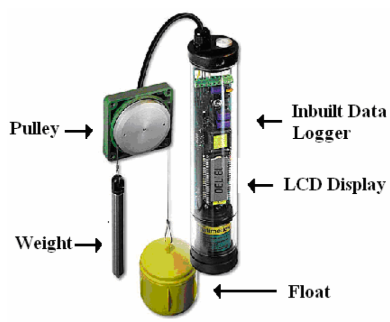

Figure 2-11 Thalimedes shaft encoder. (Ott-Hydrometry, 2004)

2.7.1.2 Kalesto Radar Sensor

The Kalesto Radar Sensor (See Figure 2-12) is designed for continuous unattended monitoring of surface water level. Compared with conventional level measuring systems (pressure probes, float operated or ultrasonic systems) the installation and handling of a Radar Sensor is cost and time effective. The Kalesto sends radar waves (microwaves) perpendicular to the water surface. These waves are then mixed with the signals reflected on the surface. The distance travelled is then calculated within the Kalesto and sent to the data logger.

As no stilling well or inlet pipe are required, it is ideal for rivers containing a lot of sediments and debris. It is also ideal for sites where construction work would damage a hydraulic system. Compared to the Thalimedes Shaft Encoder this sensor can be easily moved.

Figure 2-12 Kalesto Radar Sensor (Ott-Hydrometry, 2004)

Figure 2-13 shows the operation of the Kalesto radar sensor, a wave is sent from the Kalesto to the surface of the water and the distance x is measured. Height y can be calculated by subtracting height x from height b, which has been measured previously.

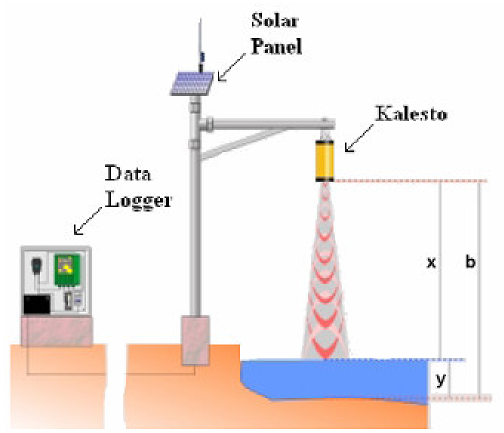

Figure 2-13 Operation of the Kalesto Radar Sensor (Ott-Hydrometry, 2004)

2.7.2 Data Logger

The data logger used in this project is the Ott-Hydrometry Hydrosens Multi-Channel Data Logger (See Figure 2-14). It is designed for the continuous, unattended monitoring of numerous parameters in hydrometry, meteorology, and environmental protection. In this case the Hydrosens logger is used to monitor and record the river levels read from the two sensors. Data can be read directly from the Hydrosens or transmitted in a number of ways.

- Using a VOTA for site download, the rugged alternative to a notebook or palmtop, which carries out a vast array of functions in the fields of acquisition, data readout, configuration and management as well as evaluation of measured values.
- Using a laptop with Infra Red attachment and a software program called hydras 3 designed specifically for Ott-Hydrometry equipment.

- Using a modem, the Hydrosens may be directly connected to an ordinary modem or GSM modem, and can be dialled into for data download or in the case of an emergency (flooding) can dial specific emergency numbers. This was the method used for the duration of this project at the two sites, Dromcummer and Duarrigle.
-

Power to the data logger is supplied by a 12V DC power supply and the low power consumption enable sensor operation for several days even when there is a loss in the mains power supply. A 12 Volt back up battery supply is also connected. This is an invaluable source of back up and has been used several times in this project when mains power fails.

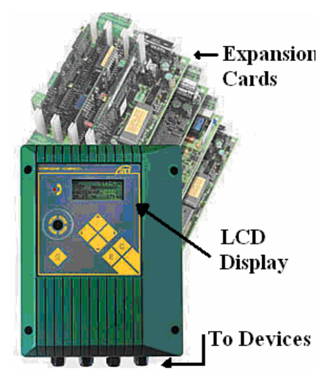

Figure 2-14 Hydrosens Multi-Channel Data Logger

2.8 Power and Telecommunications

The two stations, Duarrigle and Dromcummer, are supplied with mains power and a telephone line. In the case of mains failure the 12v back up battery is used. The Hydrosens can automatically switch between mains supply and battery supply. Once the mains supply has been reconnected the Hydrosens will then recharge any power lost in the battery. The battery can last between three to five days depending on how the data is transmitted and how often the transmission occurs.

The telecommunications have proved to be quite stable as seen in Figure 2-15 but it was decided that a GSM modem should be installed as back up. This means that in the case of a broken land line, the system would automatically choose the GSM modem ensuring data transfer.

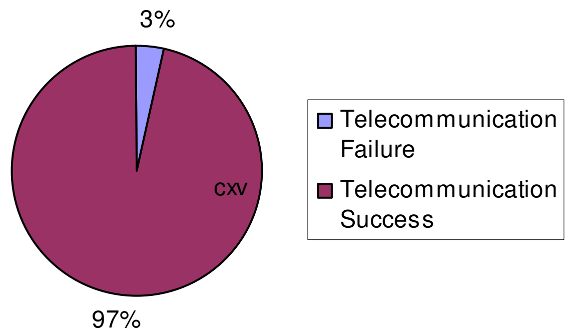

Figure 2-15 Pie Chart of Telecommunication Successes and Failures

2.9 Base Station

The base station is a simple system that may be set up anywhere, it consists of a Desktop Computer (or laptop) with the software package Hydras 3 and modem (or GSM Modem). The system installed in UCC consists of a desktop computer with software package Hydras 3 Pro and a Siemens TC35 GSM modem. The system proved to be both efficient and robust. Layout of the system is shown in Figure 2-16.

The system dials both Dromcummer and Duarrigle stations every four hours and this can be changed depending on how often the user requires, for example in times of bad weather the period has been changed to an hour.

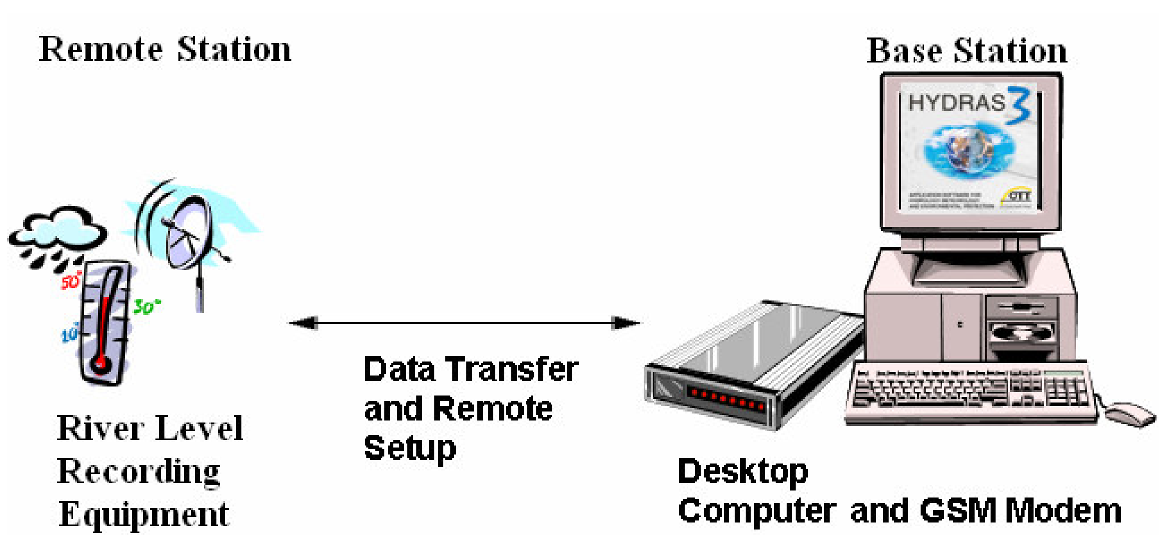

Figure 2-16 Orientation of Base Station

2.10 Communications Software

The Hydras 3 Pro software package is a user friendly package, produced by Ott-Hydrometry, that has a number of useful functions. Apart from the automatic dialling of the stations, its graphical facility can be used to display time series and water level heights. It can alert the user to a faulty sensor, or dial/text/email certain numbers when certain alarms are triggered (see Figure 2-17). Efficient, configurable import and export functions integrate Hydras 3 into a broad range of external applications and work environments.

Apart from these features, Hydras 3 Pro comes with its own script editor (based on a version of Perl) which enables the user to write scripts which adds more functionality to the program, without changing the core of the program itself. For example scripts have been written for this project to automatically export *html* tables of the river level heights for that day.

These scripts have many applications for example enabling the user to create higher quality graphics for the internet, sending data to a different server, converting data to a different value, creating web pages and tables, exporting data to another networked computer (see Figure 2-17). This procedure was used to create the live web pages of water levels at the two sites as described in 0.

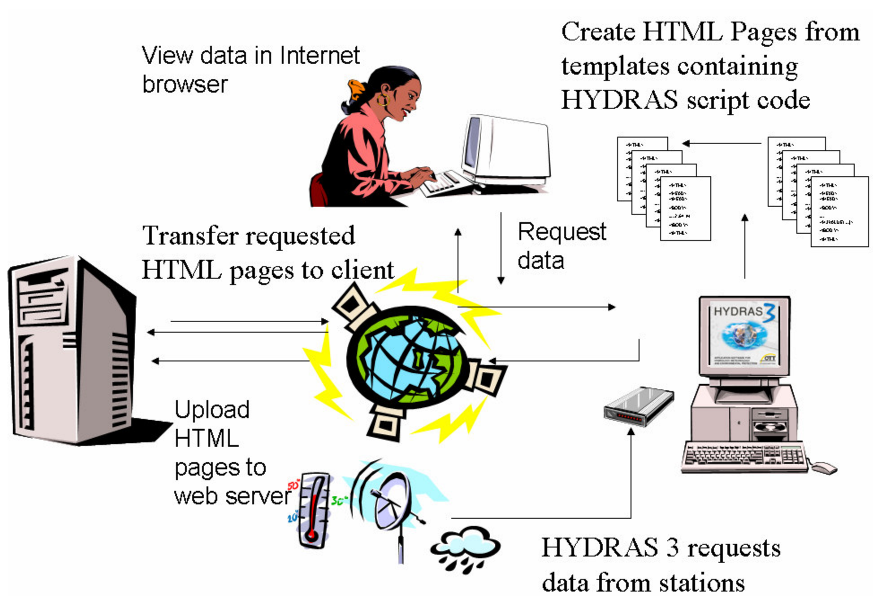

Figure 2-17 Functionality of Hydras

Chapter 3
Raw Data of River Heights at Four Stations

3.1 Introduction

The data required for this research project were time series of river heights at the four river sites on the Munster Blackwater, and the mean sea level air pressure for the catchment. The sources of the data are the Cork County Council, the Environmental Protection Agency, the Office of Public Works and the Meteorological Service.

3.1.1 Original Data Sets

Cork County Council and the Environmental Protection Agency (EPA) supplied the river height data for three of the sites: Duarrigle (S1); Dromcummer (S2) and the Beet Factory (S3). This data was in comma delimited file format. Data sets contained the following headings; year, month, day, hour minute, second, river height, 1 + julian day for the year, julian day for the year and total julian day (See Table 3-1).

Table 3-1 Example of beet factory data set provided by the Cork County Council

Year	Month	Day	Hour	Minute	Second	River Height	1+Julian Day	Julian Day	Total Julian Day
2000	1	1	2	45	0	1.481424	1.1146	0.1146	729131.115
2000	1	1	6	7	0	1.480403	1.2549	0.2549	729131.255
2000	1	1	8	7	0	1.474907	1.3382	0.3382	729131.338
2000	1	1	12	29	0	1.429478	1.5201	0.5201	729131.52
2000	1	1	18	2	0	1.376787	1.7514	0.7514	729131.751
2000	1	2	0	36	0	1.330499	2.025	1.025	729132.025
2000	1	2	7	8	0	1.304519	2.2972	1.2972	729132.297
2000	1	2	16	25	0	1.264122	2.684	1.684	729132.684
2000	1	2	21	38	0	1.245876	2.9014	1.9014	729132.901
2000	1	3	1	36	0	1.23589	3.0667	2.0667	729133.067

Julian days represent the days of the year in an incremental fashion, January 1st being Julian day 1 and December 31st being Julian day 365 (In non-leap years). Total Julian day is the same as Julian day except the starting date is January 1st 0000. For example 1st of February 2004 in Julian day format is 731978.

As can be seen from Table 3-2 the records for the three sites begin at different periods.

Table 3-2 Start date of records for Duarrigle, Dromcummer and the Beet Factory

Site	Start Data Date
Duarrigle (S1)	January 1982
Dromcummer (S2)	October 1981
Beet Factory (S3)	January 1978
Mallow Bridge (S4)	June 2001

Atmospheric pressure data from Cork Airport was supplied by Met Eireann. This data is the hourly mean sea level pressure for the years 1995 through to 2000.

3.1.2 Data Interpolation

The river heights for the three sites up to and including 1999 were not all recorded at equal time intervals. The intervals of the recording of data were irregular, for example the river height at Duarrigle on the 19th of September 1990 was recorded at 13:30, the next value was recorded at 17:04 and the next value was recorded at 20:13. Originally data was logged onto paper tape and subsequently digitised by the EPA.

This irregular time step of data needed to be converted into a form that would have a fixed interval between every data point for subsequent analysis. Matlab code was written to convert the random interval into a 15 minute interval using linear interpolation. Figure 3-1 shows there are three river heights recorded before interpolation while after interpolation in Figure 3-2 it can be seen that there are 31 river heights recorded.

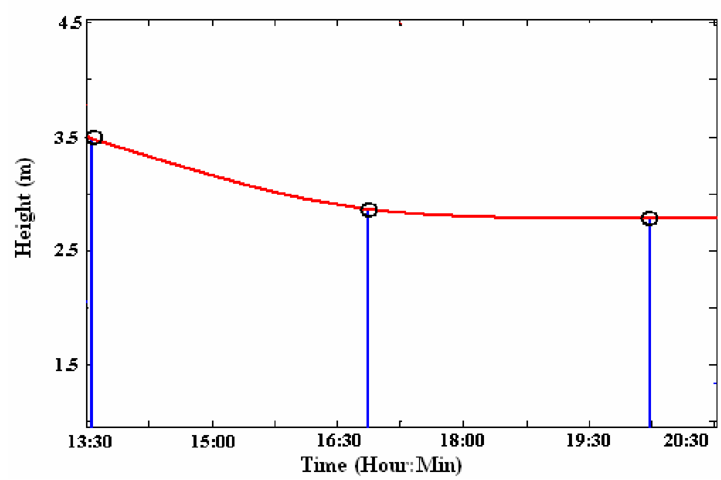

Figure 3-1 River Height before interpolation

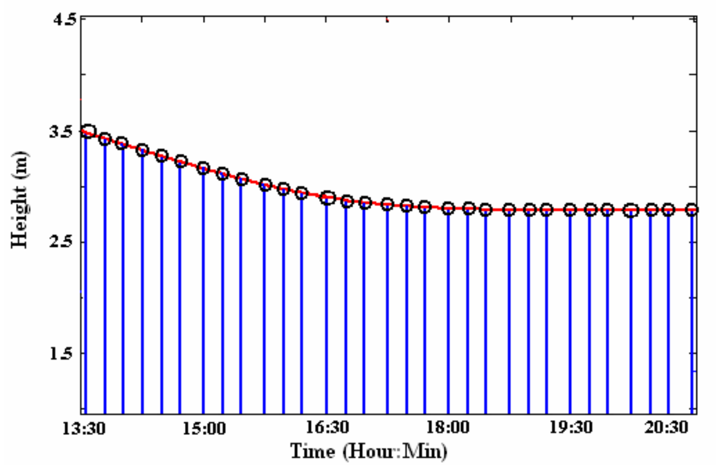

Figure 3-2 River Height after interpolation

The method of interpolation used was linear interpolation. This form was used as it is a quick and easy method. Even though there was an irregular interval between the values the intervals were typically still quite small. Because of this it was safe to use the linear form of interpolation. Since there were extra river heights and times created using the interpolation command, a matlab program was used to convert the extra times created to Julian day format using the Matlab function *datenum* (Mathworks, 2004). For example 1990 June 2nd 13:15 was converted into 153.5521 Julian Days. Data for the years 2000 through to 2003 already had a fixed interval of 15 minutes between each data point. It was not required to interpolate this data.

3.1.3 Final Data Sets

Two river height data sets for each site are formed as a result of programming, A large file for each site containing the river height data for the full period (approximately 20 years), and a file for each site containing the river height data for each year. As the different sites contained different amounts of historical data (see Table 3-2) it was decided that the analysis would be limited to the common period 1982 to 2002.

River height data sets for each year contain year, month, day, total minutes, total Julian day, Julian day for that year and height (See Table 3-3). Matlab code was used to format similar data sets for the data supplied by the Office of Public Works (the Mallow Bridge site). The data files contained year, month, day, total Julian day, Julian day for that year and mean sea level pressure. Matlab code was used to form similar data sets to the river height data sets for mean sea level pressure. The data files contained year, month, day, total Julian day, Julian day for that year and mean sea level pressure (Table 3-4).

Table 3-3 Example of final data set for river heights at the Beet Factory

Year	Month	Day	Minute	Total Julian Day	Julian Day	River Height
2000	1	1	0	730486	1	1.481424
2000	1	1	15	730486	1.010417	1.481348
2000	1	1	30	730486	1.020833	1.481272
2000	1	1	45	730486	1.03125	1.481197
2000	1	1	60	730486	1.041667	1.481121
2000	1	1	75	730486.1	1.052083	1.481045
2000	1	1	90	730486.1	1.0625	1.480969
2000	1	1	105	730486.1	1.072917	1.480893
2000	1	1	120	730486.1	1.083333	1.480818
2000	1	1	135	730486.1	1.09375	1.480742

Table 3-4 Example of final data set for the atmospheric pressure

Year	Month	Day	Minute	Total Julian Day	Julian Day	Atmospheric Pressure
2000	1	1	0	730486	1	1023.2
2000	1	1	15	730486	1.010417	1023.25
2000	1	1	30	730486	1.020833	1023.3
2000	1	1	45	730486	1.03125	1023.35
2000	1	1	60	730486	1.041667	1023.4
2000	1	1	75	730486.1	1.052083	1023.45
2000	1	1	90	730486.1	1.0625	1023.55
2000	1	1	105	730486.1	1.072917	1023.7
2000	1	1	120	730486.1	1.083333	1023.9
2000	1	1	135	730486.1	1.09375	1024

3.2 Height Data at Duarrigle

The Duarrigle river height data set includes data from 1982 to 2002. For that period of monitoring the maximum recorded height of the River Blackwater at Duarrigle was 3.82 m on the 21st of October 1988. The minimum recorded height of the River Blackwater at Duarrigle was 0.06 m on the 11th of October 2001. An example of one year's data is shown in Figure 3-3. This presents the river height at Duarrigle for the year 2002 and contains 35040 data points (i.e. 15 minute intervals for 1 year).

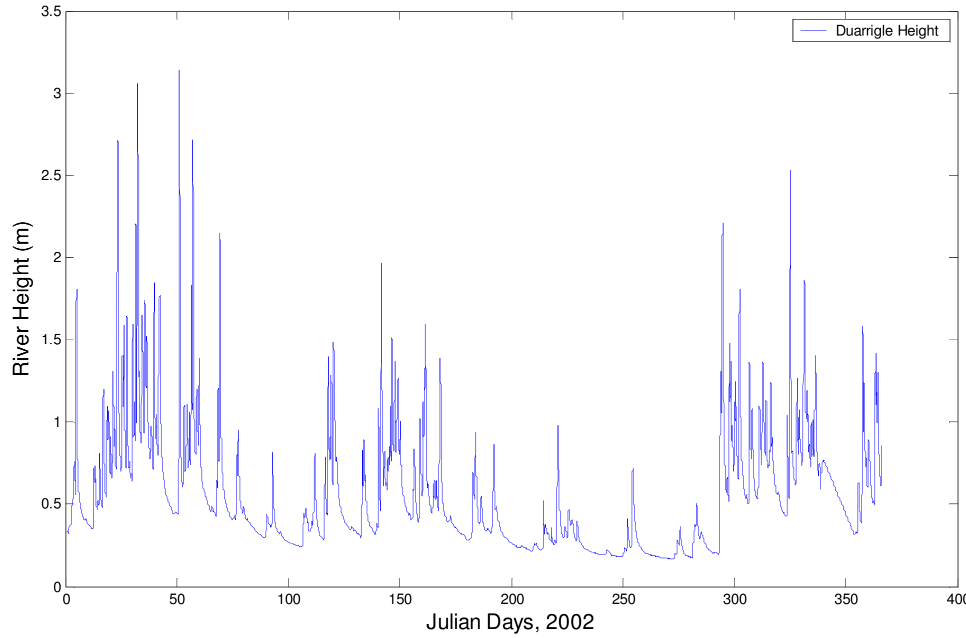

Figure 3-3 River Height data for the year 2002 at Duarrigle (No Missing Data)

An example of a flood event at Duarrigle can be seen in Figure 3-4 and shows that a flood occurred between the 19th and 21st of February 2002 (Julian Day 50 to 52). It can be seen that the river rises from 0.44 m to 3.14 m in approximately 11.4 hours, in this example the river rose at a rate of approximately 0.24 m hr $^{-1}$.

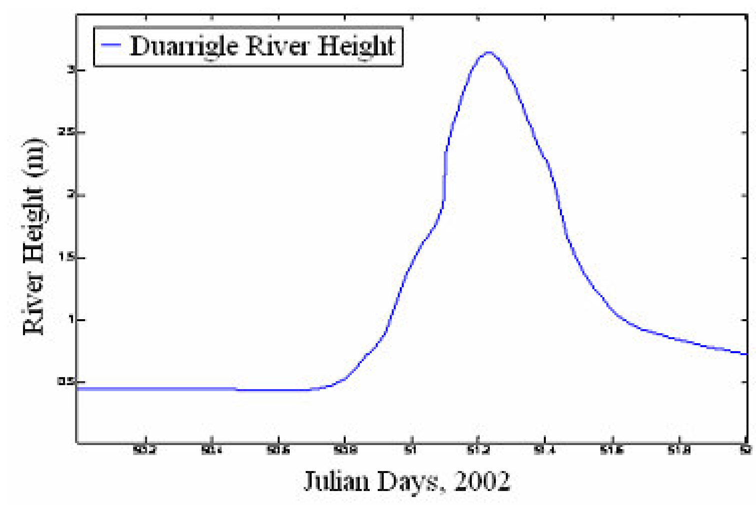

Figure 3-4 A 2 Day Flood Event at Duarrigle – Feb 19 to 21, 2002

3.3 Height Data at Dromcummer

The Dromcummer river height data set includes data from 1982 to 2002. For that period of monitoring the maximum recorded height of the River Blackwater at Dromcummer was 3.02 m on the 5^{th} of August 1986. The minimum recorded height of the Blackwater at Dromcummer was 0.11 m on the 24^{th} of September 2000.

In Figure 3-5 an example of the River heights of the Blackwater at Dromcummer for the year 2002 can be seen. The data ranges from a maximum of 2.67 m in February to a minimum of 0.16 m towards the end of September.

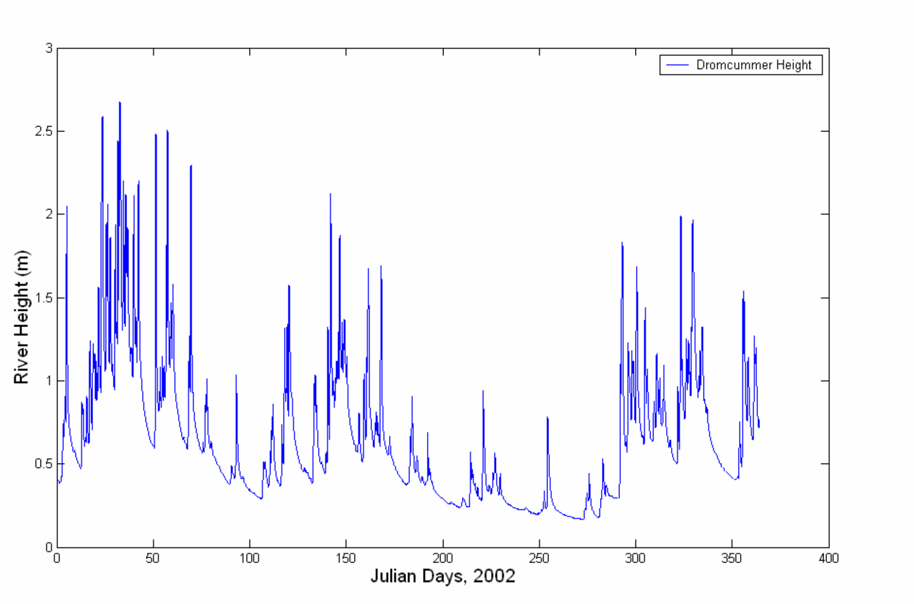

Figure 3-5 River Height data for the year 2002 at Dromcummer (No Missing Data)

An example of a 2 day flood event recorded at Dromcummer can be seen in Figure 3-6. The flood occurred between the 19^{th} and 21^{st} of February 2002 (Julian Day 50 to 52). It can be seen that the river rises from 0.59 m to 2.48 m in approximately 7.6 hours. In this example the river rose at a rate of approximately 0.25 m hr $^{-1}$.

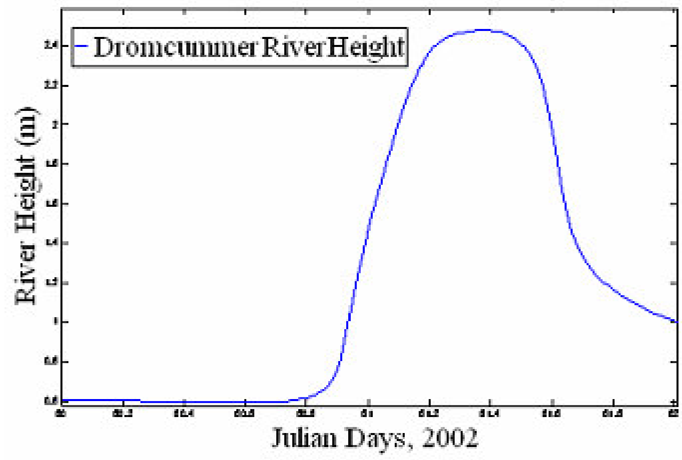

Figure 3-6 A 2 Day Flood Event at Dromcummer – Feb 19 to 21, 2002

It is noted from Figure 3-6 that there is a longer duration of peak at Dromcummer than at Duarrigle, it is also noted that the rate of rise of the river heights is the same for both sites.

3.4 Height Data at Beet Factory

The Beet Factory river height data set includes data from 1982 to 2002. For that period of monitoring the maximum recorded height was 5.14 m on the 21st of October 1988. The minimum recorded height of the River Blackwater at the Beet Factory was 0.26 meters on the 10th of September 1989. In Figure 3-7 an example of the River heights of the Blackwater at the Beet Factory for the year 2002 can be seen. The data ranges from a maximum of 4.51 m in February to a minimum of 0.41 m towards the end of September.

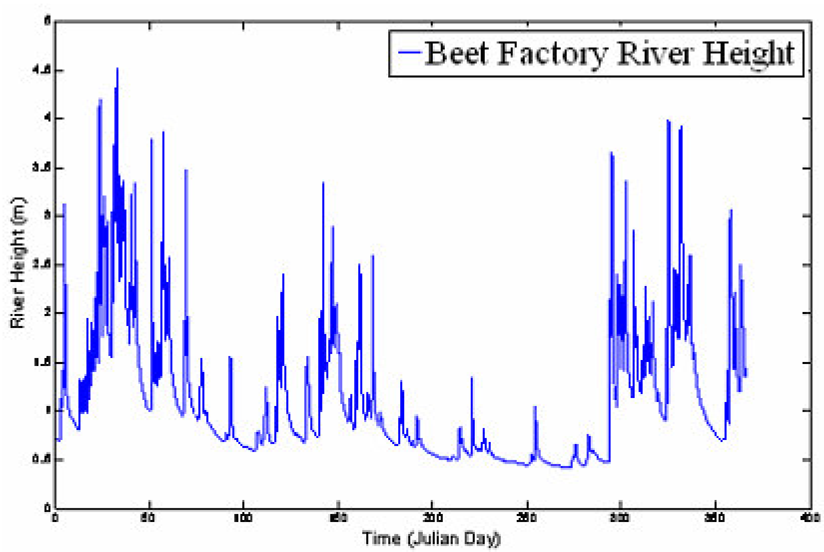

Figure 3-7 River Height data for the year 2002 at the Beet Factory (No Missing Data)

An example of a 2 day flood event recorded at the Beet Factory can be seen in Figure 3-8. The flood occurred between the 19th and 21st of February 2002 (Julian Day 50 to 52). It can be seen that the river rises from 0.99 m to 3.79 m in approximately 7.4 hours. In this example the river rose at a rate of approximately 0.38 m hr $^{-1}$.

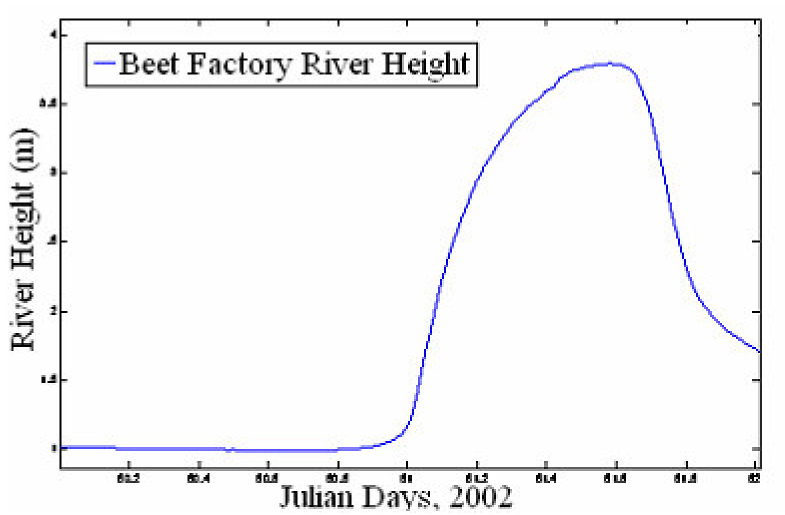

Figure 3-8 A 2 Day Flood Event at the Beet Factory – Feb 19 to 21, 2002

3.5 Height Data at Mallow Bridge (Upstream Face of Bridge)

The Mallow Bridge river height data set includes data from June 2001 to the end of 2003. During this period the maximum recorded height of the River Blackwater at Mallow Bridge was 4.6 m on the 2nd of February 2002. The minimum recorded height of the River Blackwater at Mallow Bridge was 1.27 m on the 25th of October 2003.

In Figure 3-9 an example of the River heights of the Blackwater at Mallow Bridge for the year 2002 can be seen. The data ranges from a maximum of 4.66 m in February to a minimum of 1.31 m towards the end of September.

It should be noted that during this period the Beet Factory river height data and the Mallow Bridge river height data appear to be very similar.

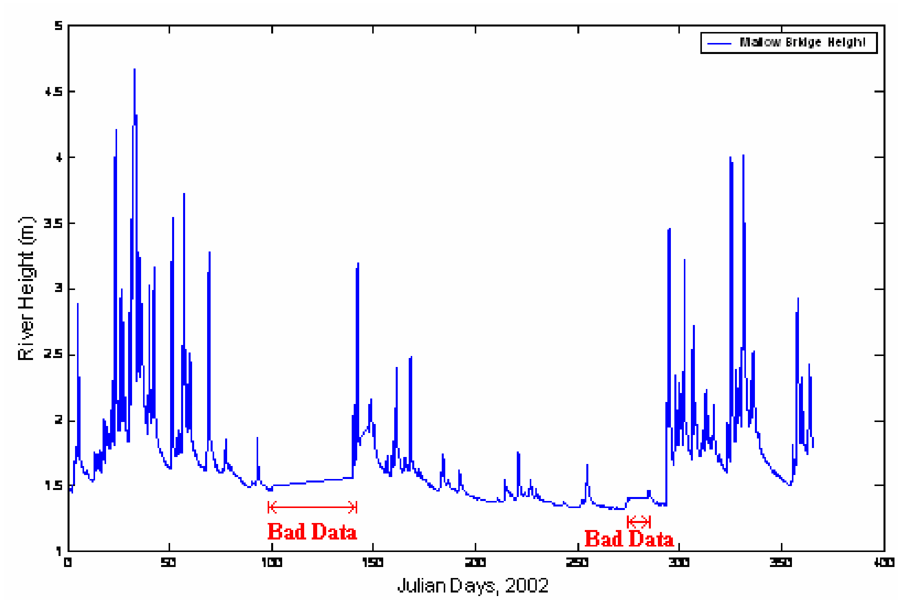

Figure 3-9 River Height data for the year 2002 at Mallow Bridge

An example of a 2 day flood event recorded at Mallow Bridge can be seen in Figure 3-10. The flood occurred between the 19th and 21st of February 2002 (Julian Day 50 to 52). It can be seen that the river rises from 1.62 m to 3.54 m in approximately 10.43 hours. In this example the river rose at a rate of approximately 0.18 m hr $^{-1}$.

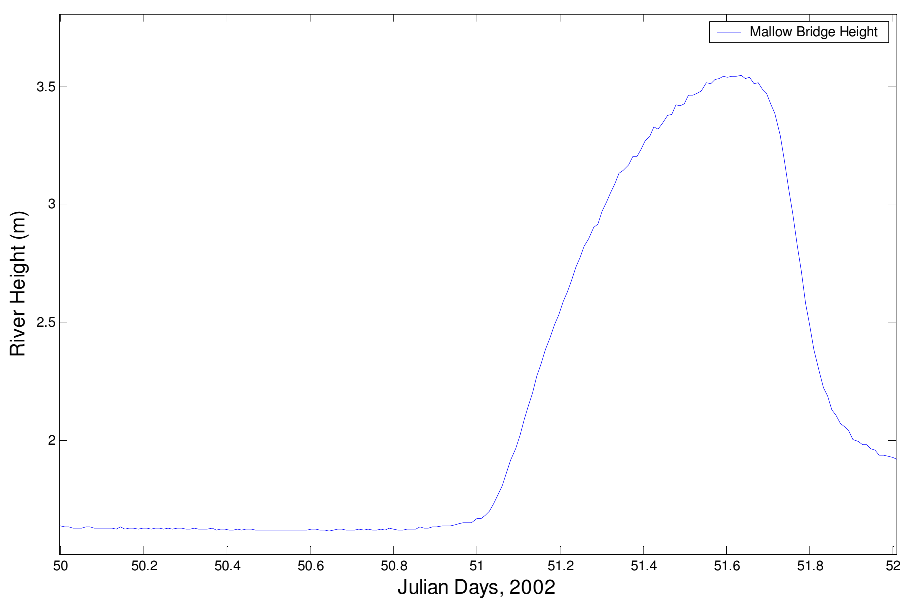

Figure 3-10 A 2 Day Flood Event at Mallow Bridge – Feb 19 to 21, 2002

3.6 Data Comparison of Flood Event (Feb 19 to 21, 2002)

Figure 3-11 compares the flood event at the four sites, It is seen that the flood event occurs first in Duarrigle, then 3.5 hours later in Dromcummer, and after another 4 hours at the Beet Factory and finally an hour later at Mallow Bridge. It is shown that the flood peak at Duarrigle is much narrower than the flood peaks at the other three sites. It is also clear that the normal river levels for the four sites vary considerably. (This is a function of the river geometry at each site, which is different)

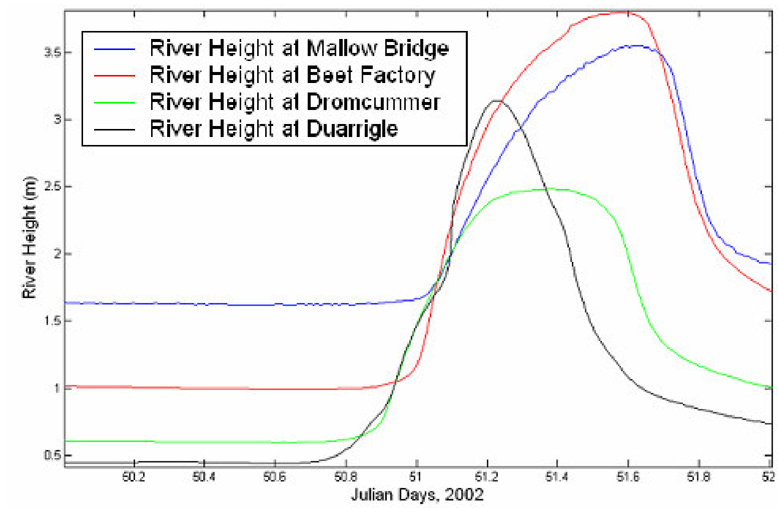

Figure 3-11 Comparison graph of a 2 Day Flood Event

3.7 Data Reliability

The river height data used in this project appear to be reliable, apart from some minor gaps in the time series. In the Duarrigle river height data, there was a large gap in 1987 where data for the month of June was missed. At Dromcummer data for the month of June 1987 was lost as well as half of the month of August 1982. The Beet Factory river height data and Mallow Bridge river height data proved to be the most reliable data with no gaps of any importance. The gaps in Duarrigle and Dromcummer river height data appeared in times of low river heights. Since the project is based on flood events, that is high river levels; the fact that a small amount of low height data was omitted is unimportant. Due to the fact that there was such a large volume of data, there was no need to incorporate any gap filling methods to replace the omitted data as can be seen in Figure 3-12.

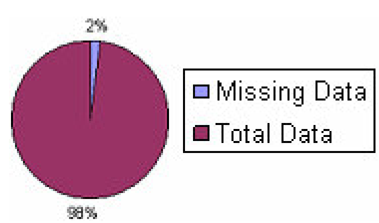

Figure 3-12 Pie Chart of Missing Data vs. Total Data for Dromcummer River Heights

Chapter 4
Flood Warning Methods

4.1 Introduction

The project examines a number of flood warning system concepts and applies these concepts to the river Blackwater. They include: the river level threshold flood warning system; the rate of rise flood warning system; the atmospheric pressure flood warning system and the neural network flood warning system. The following chapter will explain how each flood warning system works and the advantages and disadvantages of each system. Two measures of success are used to compare the systems: the accuracy of the system and the flood warning time provided by the system. In Figure 4-1, the relative warning time and relative accuracy of each system is noted.

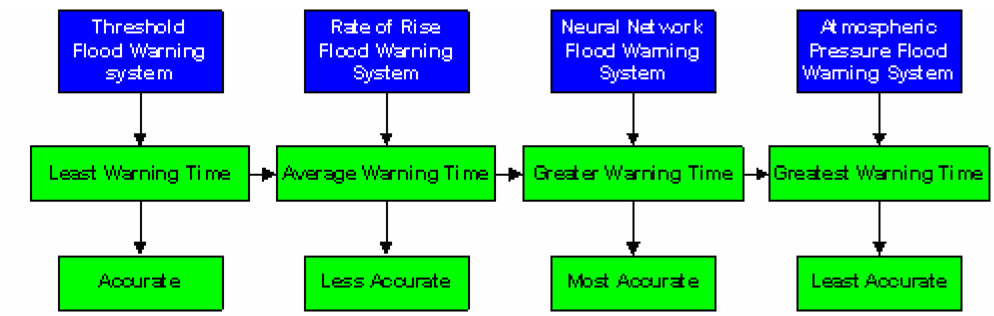

Figure 4-1 Description of Flood Warning Systems

These different flood warning systems may be connected together to form one overall complex flood warning system. The flow chart of this overall flood warning system is outlined in Figure 4-2. The layout and function of each flood warning system will be discussed in the following chapter.

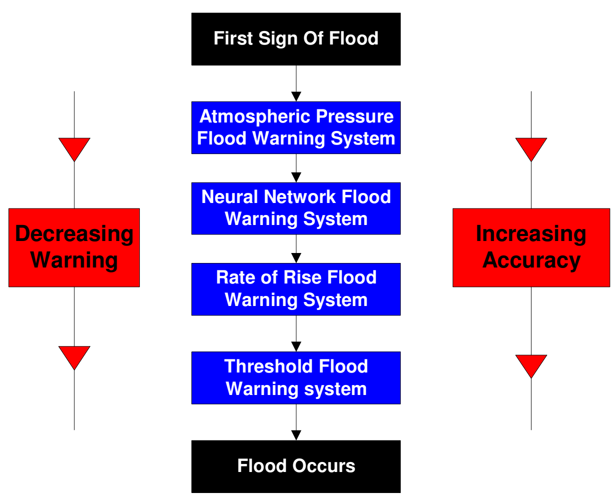

Figure 4-2 Flow Chart of Overall Flood Warning System

The flood warning time is both a function of the distance between the monitoring station and the flood focal point, and the type of flood warning system used.

4.2 Threshold Flood Warning System (TFWS)

4.2.1 Introduction

The river water level threshold flood warning system a basic form of flood warning. The principle is that if a flood level exceeds a certain river height (threshold) at S2, then after a certain time period (Δt) the flood peak will make its way downstream and the flood peak will pass the flood focal point downstream (e.g. S4) (See Figure 4-3). When this flood is recognized at S2 a warning is issued of the imminent flood for S4.

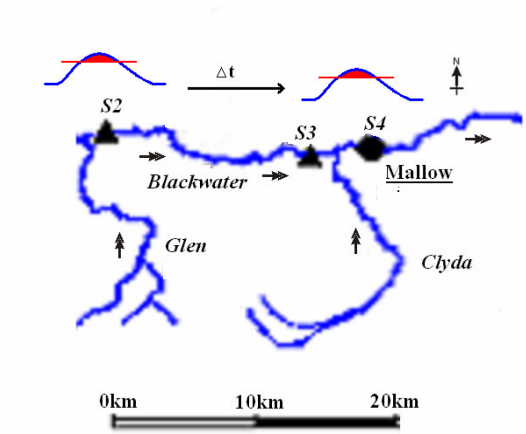

Figure 4-3 Threshold Flood Warning System

This basic warning system is in widespread use, with or without monitoring stations. The simplest system being where an engineer observes the river heights at an upstream point and based on his experience of river heights, he is then in a position to predict a flood and so issue a warning.

The advantages of this system are:

- The system can be accurate.
- The system is technologically simple, as it only needs a river level recording device and a device for communication.
- The system is easy to calibrate. Once a number of past floods have been recorded, it is easy to calculate the threshold level at which a flood will occur.
- The system is easy to maintain and can be set up anywhere. With the development of low power level recording equipment and GSM[1] modems the system can be set up without the need for an external power supply or telecommunications line.

[1] GSM: Global System for Mobile communication.

There are also a number of disadvantages

- The warning time afforded by the threshold flood warning system depends on the distance between the stations. There is a trade off between warning time and distance from site and accuracy. The greater the distance, the less the accuracy but the greater the warning time.
- There is still the risk of flash floods i.e. floods generated in the catchment downstream of the river level recording station (S2).
- There is a risk of Flood Warnings being issued unnecessarily. That is a flood may pass a certain point up stream but on some occasions it may not pass the focal point downstream as the flood may have attenuated over the intervening floodplain.

There is a trade off when developing a threshold flood warning system between accuracy and warning time as can be seen in Section 6.2 . The flood warning time is proportional to the distance of the river level recording site from the flood focal point. That is the greater the distance the site is from the flood focal point the greater the prediction time (See Figure 4-4).

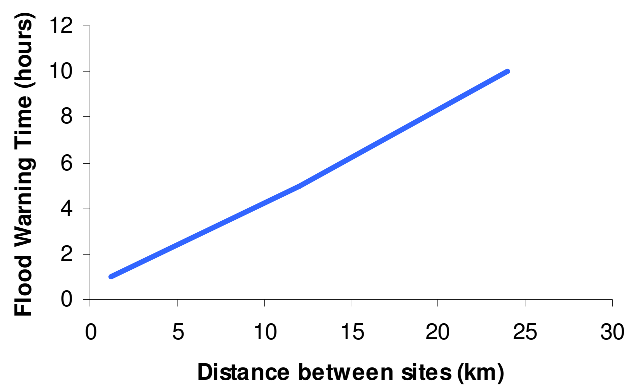

Figure 4-4 Typical relationship between sites and Flood Warning Time, (data from Section 6.2)

Increased prediction times are gained at the expense of accuracy (i.e. degree of successful predictions) (See Figure 4-5). This is due to the fact that there is an increasingly large catchment area between the recording site and focal point.

A GSM modem is a modem that works a lot like a mobile phone, no landline is required.

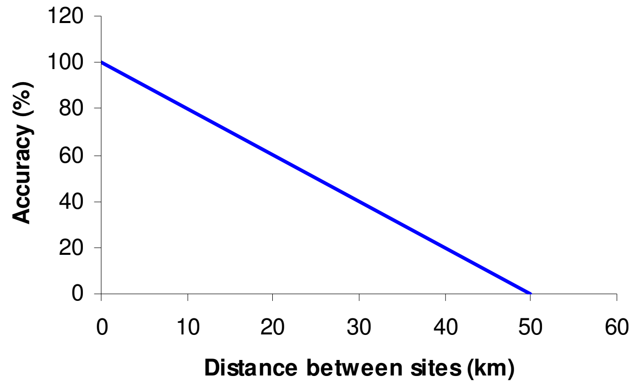

Figure 4-5 Typical relationship between Accuracy of Flood warning system and Distance between sites, from data (Section 6.2)

4.2.1.1 History of Application

The water level threshold system has been in use on the River Blackwater intermittently for over 20 years. In November of 1980 there was a severe flood which caused extensive damage throughout the catchment. After this, a flood plan was developed by Cork County Council in Mallow for the Blackwater Catchment.

Two river water level stations at Duarrigle and Dromcummer were built in 1981 containing automatic remote water level recorders. These automatic remote sensors monitored the river for a certain threshold to be crossed. Once this threshold was crossed a warning was transmitted. But this first flood warning system broke down after a few months and was never repaired. The technical expertise to maintain the system was not employed by the local authorities.

Before this system was set up, people relied on Mr. Martin Corcoran (Area Engineer – Millstreet) to observe the river heights at Duarrigle. Mr. Corcoran has intimate knowledge of the heights of the River Blackwater at Duarrigle; he knew the river heights which were likely to cause flooding in Mallow. Once the threshold height was exceeded Mr. Corcoran would inform the correct authorities (the Gardai and Fire Service) and a flood warning would be given. After the break down of the automatic flood warning system, there was no other option but to return to the manual system of river monitoring by Mr. Corcoran.

As a result of collaboration between Ott-hydrometry and UCC, in 2002 the Cork County Council installed two new automatic river level monitoring devices: one at Duarrigle and the second at Dromcummer. The data was collected via modem in the Cork County Council Office in Mallow. The data was analysed by Hydras 3 (see Section 2.10) and if a threshold level was crossed the program issued certain warnings. This is the current system (October, 2004).

4.2.1.2 Current Applications

As part of this project a base station was set up in UCC by this author and is discussed in Section 2.9 This system monitors the river levels at both stations. This system is proving to be more robust than the system set up in Mallow due to the fact that, the UCC system uses a GSM modem rather than a land line, and the technical expertise for maintenance is at UCC.

A website has been set up by this author, www.irishfloodwarning.com, This gives a live indication of the river levels at the two sites; the website also gives warnings of flooding. There are two categories of warning: an Orange warning for road and field flooding and a red warning for street flooding and flooding of buildings. A flood warning system is now available for the people of Mallow as well as the responsible agents. The river heights as well as warnings are available twenty four hours a day and accessible to all from a home pc. Having a web page as a warning system empowers the public while decentralizing some of the responsibilities away from the local authorities.

4.2.2 Observations

One objective is to estimate thresholds for the two sites. Following consultation with Cork County Council and the Office of Public Works it was decided to have three flood warning stages for the Mallow Area.

Flood Stage 1 – Blue Warning

Flooding occurs at Longsfield Bridge (3km upstream of Mallow Bridge). For very minor flooding, the road in the vicinity of Longsfield Bridge would have to be closed

Flooding Stage 2 – Orange Warning

Flooding occurs in the town park and at the Park Road, Mallow. In moderate floods the Park Road would have to be closed

Flooding Stage 3 – Red Warning

Flooding occurs on Bridge Street, Mallow with a risk of flooding to the Spa area. The action is to close several streets to traffic and assist businesses and homes to protect their properties.

4.2.3 Estimation of Thresholds

To estimate the required thresholds for the three stages of flooding, the time series of river height data at the three sites are examined. The significant floods at Mallow and the corresponding times and peaks at the upstream sites for these occasions were examined. The water levels (or thresholds) at Duarrigle and Dromcummer, that produce flooding in mallow for the three stages of flooding (see Section 4.2.2), were then examined.

4.2.4 Accuracy

The Accuracy of the system is measured in two ways:

- The number of false floods predicted by the system. That is the number of warnings given when no flood occurred.
- The number of floods missed by the system. That is the number of floods which occurred when no flood warning was given.

The accuracy was estimated for the two sites: Duarrigle and Dromcummer. Equations were developed to determine the accuracy for each method of flood warning. There are two forms of inaccuracy, missed floods and false floods. Therefore two equations for accuracy were required. The definition for accuracy of the system in relation to false flooding is based on equation [4-1]. Where A_{false} represents false accuracy and N_{false} represents the number of false floods and N_{total} represents the total number of floods. The definition for accuracy of the system in relation to missed flooding is based on equation [4-2]. Where A_{missed} represents miss accuracy and N_{missed} represents the number of missed floods and N_{total} represents the total number of floods.

$$A_{false} = 1 - N_{false} / N_{total} \qquad [4\text{-}1]$$

$$A_{missed} = 1 - N_{missed} / N_{total} \qquad [4\text{-}2]$$

An assessment of the accuracy for both sites is carried out in Section 6.2

4.3 Rate of Rise Flood Warning System (RRFWS)

4.3.1 Introduction

The principle behind the rate of rise flood warning system is as follows. During a flood the river level will rise at a certain rate (m/s). There is a certain rate of rise and a certain river level at which a flood is likely occur (see Figure 4-6). Combining the rate of rise threshold with the threshold system improves the accuracy of the flood warning system.

In Figure 4-6 it can be seen that when the hydrograph is rising the rate of rise is positive, and when the hydrograph is falling the rate of rise is negative. The rate of rise (on the positive side) varies from 0 t0 15 m/day.

Similar to calculating the threshold for the threshold flood warning system, the main interest is defining the thresholds for the rate of rise flood warning system. During a flood the river will start to rise which will increase the rate of rise. Once the rate of rise threshold is broken, the river height is frequently monitored. Once the river height threshold is broken, a flood is imminent and the flood alarm is raised.

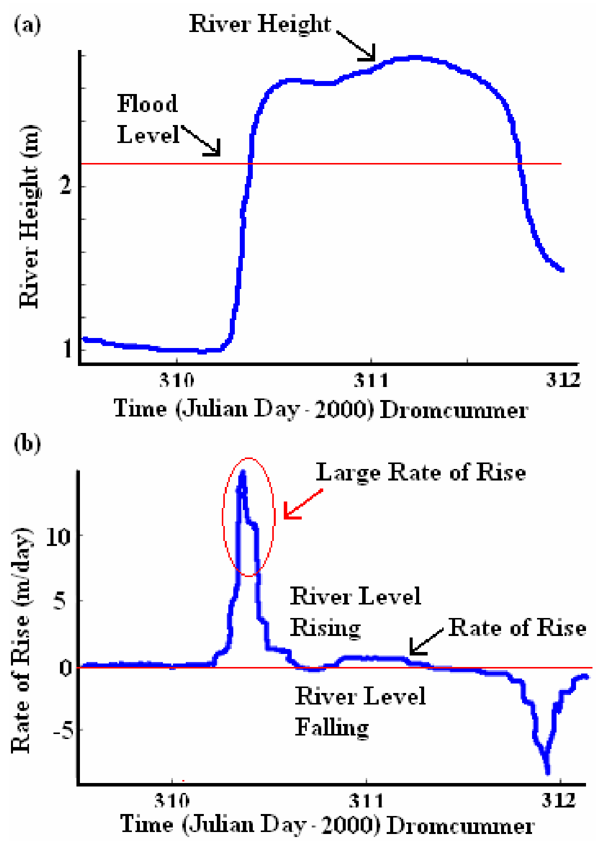

Figure 4-6 (a) River Height vs. Time (b) Rate of River Rise vs. Time

The river height threshold used in the RRFWS will be lower than the river height threshold used by the TFWS. As can be seen in Figure 4-7 t_1 occurs much earlier than t_2. This means that an earlier flood warning will be provided.

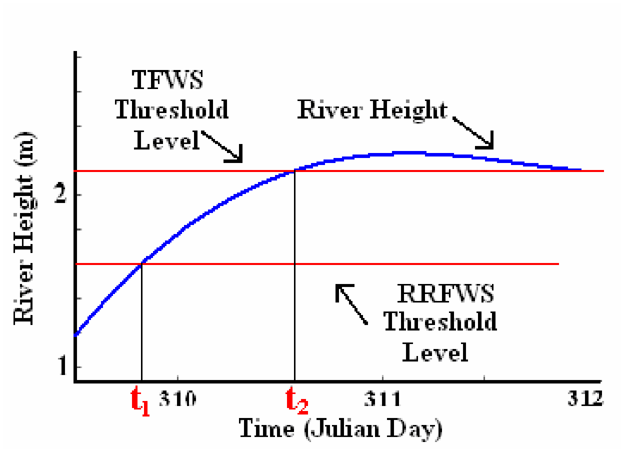

Figure 4-7 Time difference between RRFWS threshold and TFWS threshold

There are a number of advantages to this system

- There is an increased warning time compared to the simple method of river level threshold flood warning.
- No new equipment is needed to incorporate this form of flood warning. The rate of rise can be calculated easily through the software package Hydras 3.
- The system is relatively easy to calibrate, once there is enough historical data to analyse.

However there are a number of disadvantages to this system of flood warning.

- There is still the risk of flash floods flooding the area without a warning from the rate of rise flood warning system.
- There is a risk of flood warnings being issued unnecessarily. That is a flood may pass a certain point up stream but on rare occasions it may not pass the prediction point downstream.

In this case there is a trade off between flood warning time and accuracy. If a large rate of rise is chosen as a threshold, this will enable a low river height to be chosen. If a low height is chosen this will mean that an earlier flood warning will be given. But since some floods rise slowly the system will not detect this low rate of rise and no warning will be given. Therefore a suitable rate of rise threshold must be chosen to detect all floods, while still providing an adequate flood warning time.

4.3.2 Observations

There are three separate flood events that may occur in Mallow, as discussed in Section 4.2.2 , Stage 1, Stage 2 and Stage 3. The Rate of Rise method of flood warning could be used on all three stages. It was decided for this research project that one stage should be chosen and the rate of rise flood warning system be calibrated to this. The stage chosen was Stage 1 due to the fact that if the system detects this type of flood it will by definition detect the other two more serious types of flood.

It was decided that since Duarrigle has already proven to be a less accurate flood warning station due to longer upstream distance, that the rate of rise flood warning system should be configured on the Dromcummer station alone.

4.3.3 Calculation

A suitable rate of rise threshold and river height threshold was chosen. By observation it was decided that the rate of rise method of flood warning should give a prediction time of the order of ten hours (by comparison with the five hours from the simple river height system). The rates of rise and river heights in Dromcummer, ten to fifteen hours before a flood event were then examined. An average was calculated for the two thresholds. These average values were tested and adapted to calculate the most suitable rate of rise threshold and river height threshold.

4.3.4 Accuracy

There is a trade off when calibrating the thresholds. The trade off is between predicting too many floods, (i.e. giving warnings of floods that never occur), and calculating too few floods, (i.e. not recognizing certain floods). This is the principle of measuring the accuracy of the rate of rise flood warning system.

4.4 Atmospheric Pressure Flood Warning System (APFWS)

4.4.1 Introduction

When atmospheric pressure is falling slowly, rain will usually occur within a day. When atmospheric pressure is falling rapidly, it will rain within a few hours and wind speeds will increase (Bosak, 1991). This is the basis for the next method of flood warning. If the atmospheric pressure and the rate of change of pressure are monitored then rainfall may be predicted (See Figure 4-8). If the onset of rainfall can be predicted then an improvement in flood prediction can be implemented.

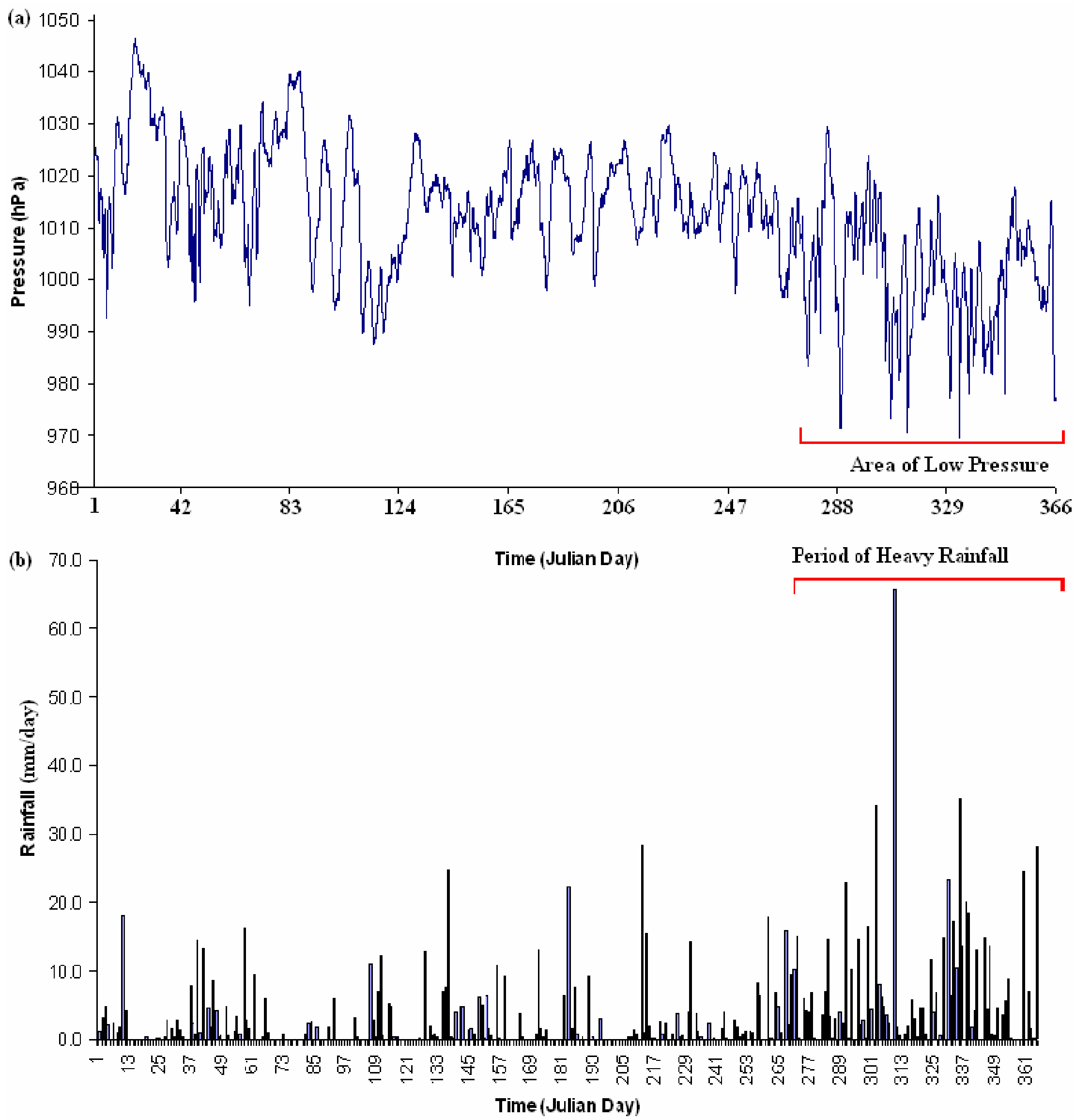

Figure 4-8 (a) Rainfall vs. Time for the year 2000 at Mallow

(b) Plot of Pressure vs. Time for the year 2000 at Mallow

There are two thresholds required for this method of flood prediction, a rate of change in atmospheric pressure threshold (hPa/day) and an atmospheric pressure threshold (hPa) (See Figure 6-29). This method of flood warning can predict a flood earlier, but due to seasonal changes, soil moisture and different water tables it may not prove to be as accurate as the other systems. Ideally this system might be incorporated into a rainfall runoff model.

The advantages of this method of flood warning are as follows.

- The pressure flood warning system has a longer prediction time than the threshold flood warning system or the rate of rise flood warning system
- The system is easy to set up, as it only needs an atmospheric pressure sensor and communication device.
- The system is easy to calibrate, once historical floods and pressure have been recorded.
- The system is easy to maintain and can be set up anywhere. Atmospheric pressure recorders are relatively inexpensive and consume little power.

The disadvantages of this method of flood warning are as follows.

- The pressure flood warning system is less accurate than the threshold flood warning system or the rate of rise flood warning system
- Extra equipment (an atmospheric pressure recorder) is needed.

4.4.2 Observations

The atmospheric pressure flood warning system does not take into account river heights. This may have advantages and disadvantages. An advantage would be that this system could be duplicated to predict flooding in other catchments due to the fact that little equipment is required to set up the Pressure Flood Warning System.

Another advantage would be that the system could be used as a form of back up, and keeping the two systems completely independent of each other would be ideal. A disadvantage of not incorporating the river heights is the lack of accuracy. For example if the river height is very low, and the pressure falls rapidly, a predicted flood event might not necessarily occur. There is the option of incorporating pressure and river heights to improve the accuracy. A rate of decrease in atmospheric pressure threshold and a river height threshold could be used to predict floods more accurately. However it was decided that on inspection that the accuracy of the flood prediction using atmospheric pressure alone should be examined in this thesis.

4.4.3 Calculations

To calculate the correct rate of decrease in atmospheric pressure or to calculate the level of atmospheric pressure threshold a number of floods were examined. The rates of decrease in atmospheric pressure during the period of the flood were calculated and examined. Initial thresholds were based on visual examination. These thresholds were tested and calibrated to calculate the most suitable level of atmospheric pressure threshold and rate of decrease in atmospheric pressure threshold.

4.4.4 Accuracy

As discussed this method of flood warning is not as accurate as the previous two methods. But the longer prediction time is attractive. Perhaps a solution would be to use both methods in flood prediction. Once the system is set up for the river level flood warning methods, incorporating an atmospheric pressure recorder would be inexpensive and easy. Another method of flood warning should be to lengthen the flood prediction time without minimizing the accuracy.

4.5 Artificial Neural Network Flood Warning System (NFWS)

4.5.1 Introduction

An artificial neural network is a powerful data modelling tool that is able to capture and represent complex input/output relationships. It is a computer program that can recognise patterns in a given collection of data and produce a model for that data. Neural networking is a method of designing a model to "learn". That is data is entered into a model and the model tries to recognize patterns and predict future outcomes.

An artificial neural network is modelled on how the human brain acquires knowledge through learning. An artificial neural network's "knowledge" is stored within its synaptic weights (See Figure 4-9), That is the inter neuron connections similar to the way the human brain stores its knowledge within junctions called synapses

4.5.1.1 Multilayer Perceptron (MLP)

Multilayer perceptrons are feed forward artificial neural networks trained with the standard back propagation algorithm. They learn how to transform input data into a desired response, so they are widely used for pattern classification. With one or two hidden layers, they can approximate virtually any input-output map. Most neural network applications involve MLPs. A multilayer perceptron model was used for this project. A multi layer perceptron model can be seen in Figure 4-9.

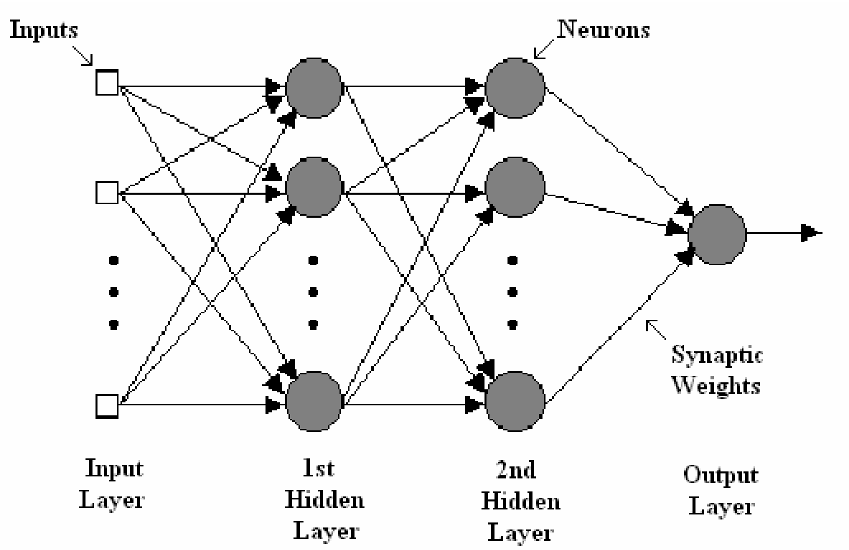

Figure 4-9 A graphical representation of a Multilayer Perceptron

As can be seen from Figure 4-9 a multi layer perceptron comprises of the following.

- An input layer containing input neurons
- Synaptic weights joining the corresponding neurons.
- Hidden layers
- An output layer.

4.5.1.2 Neuron

The neuron is the basic processor in neural networks. Each neuron has a summing function as well as an activation function to produce one output from any number of inputs. This can be seen in Figure 4-10.

The summing function (Σ) adds all the weighted inputs together to produce one output. The activation function is generally some form of non linear function. To model a non linear system a non linear activation function must be used, such as the logarithmic function or the tan sigmoid function. The activation function normalizes the output of the summing function to convert it to a value between 0 and 1.

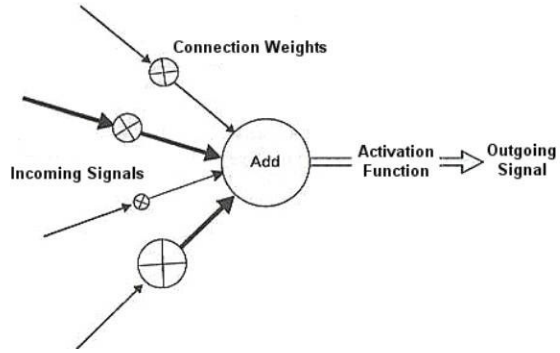

Figure 4-10 A single node and its functions

4.5.1.3 Training

For the artificial neural network model to "learn", inputs and a corresponding output are fed into the model. The synaptic weights or connection weights (See Figure 4-10) within the model are then changed accordingly to produce a similar output to the output supplied. This is called training. The model is trained repeatedly until the output produced is as similar to the supplied output as it can be.

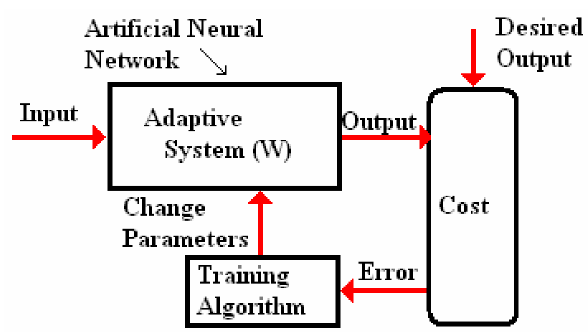

Figure 4-11 Model of how an artificial neural network works

As we can see from the model (Figure 4-11) there are a number of steps involved in the set up of an artificial neural network.

- The data is presented to the network via input and desired output,
- The network or adaptive system then computes an output.
- This output is measured against the desired output.
- An error is calculated.
- This error is entered into a training algorithm.
- The parameters (weights) are then changed accordingly
- This process is repeated until there is little or no error.

4.5.1.4 Advantages of Artificial Neural Networks

- Universal function approximation
- Deal with non-linearity
- Handle noisy data
- Work with large numbers of variables or parameters

4.5.1.5 Limitations of Artificial Neural Networks

- Lacks explanation capacities as the model is hidden (not process based).
- Bad input, bad output.
- Over fitting data
- Work better when the data set is sufficiently large
- Neural networks require extensive amounts of training time (i.e. years of continuous time series)
- Lack of portability, a new model required for each catchment.

4.5.2 Methods

The creation of an artificial neural network is relatively straight forward. There are a number of factors which must first be decided upon.

- The number of inputs
- The number of outputs
- The type of network
- The training function
- The number of layers
- The number of neurons per layer
- Transfer functions

The number of inputs and outputs are determined by the specific system in question, in this case there are three sites, Duarrigle, Dromcummer and the Beet Factory, with three different river heights. This means three inputs. The output required is the river height at the Beet Factory a specific time in the future.

However the number of inputs can change. It is possible that the use of historical data, That is the heights for the previous four to five hours, could be of benefit to the accuracy of the network. For example the system could use 9 inputs which would be the river heights at the three sites and the river heights at the three sites 3 hours ago and the river heights at the three sites 6 hours.

The numbers of inputs are therefore decided based upon trial and error. The model is tested with three inputs, then six, then nine and then twelve. The output with the lowest error is then selected. As there are limitless combinations of possibilities the other factors were decided on a trial and error basis.

4.5.3 Calculations

Once the model is built, the input and output data are split into two Sections, a training set and a testing set (as in traditional hydrological modelling). The artificial neural network works most efficiently with normalised data, so the data are then normalised. The training set data as well as the test set are then normalised.

The training set is then entered into the model; the model is then trained on this data. The weights of the model are adjusted until the most satisfactory error is obtained. The model is then tested on the testing set.

4.5.4 Accuracy

It can be seen that the artificial neural network model is the most accurate form of flood warning (See Chapter 6). The flood warning time provided by the model can be adjusted. To increase the accuracy of the data more historical data must be entered. This means more inputs and more data to compute. The main problem being the processing of the data. The artificial neural network model needs a great deal of processing power and time to train. Including more inputs increases the amount of data being processed. Unfortunately there is a limit to the amount of data a computer can process which limits the amount of inputs that can be added which limits the accuracy of the system.

Chapter 5

Flood Warning System Website

5.1 Overview

One of the tasks of this project was to develop a flood warning system website (FWSW) to enable the people of Mallow as well as the civil protection agency direct access to the river heights and flood warnings. This form of website although the first in Ireland has been used in other countries (Agency, 2003).

In Figure 5-1 a flow chart of a typical flood warning system can be seen. After a warning is given of a flood, the flood warning agency then notifies the civil protection authorities, the media and the public. The civil protection agency and media also notify the public.

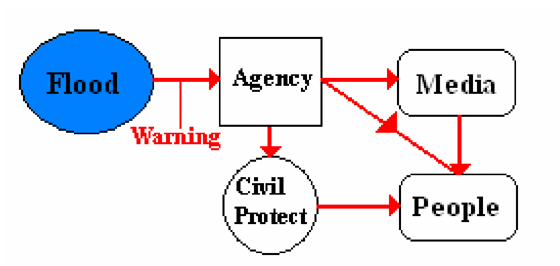

Figure 5-1 Flow Chart for Typical Flood Warning System

In Figure 5-2 a flow chart for a flood warning system incorporating a website can be seen, the automated areas are shaded in yellow. After a warning is given, the original flood warning system steps are taken, but the warning is also sent via the base station to the internet. The advantages of this system are as follows:

- The automation removes the need for 24 hour monitoring by personnel
- The automation removes human error
- There is a direct link between the flood warning system and the public.
- Gives the public more accessibility.

There are disadvantages to the system including:

- Danger of communicating false warnings to the public
- What happens if the system fails?

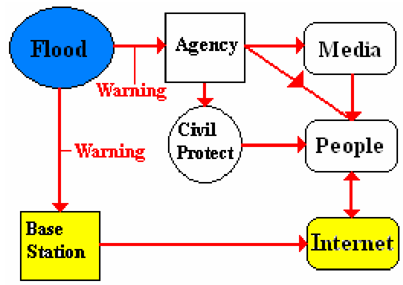

Figure 5-2 Flow Chart of Flood Warning System Incorporating Website

There is a principle for creating any website, which includes three steps: design; implementation; and testing.

5.2 Design

Creating an impressive cover page is the key to a successful website. An impressive cover page is one that has many links to as many Sections and services as possible without appearing cluttered. All the important information must be right in front of the user or one click away. Therefore the important information for the flood warning system website (FWSW) must be pre-planned.

The first step was to decide what is required of the FWSW, i.e. what data the user would like use and see. The main role of the website is flood warning; therefore the main information must be the flood warning itself. Another role of the website is to provide river levels. Therefore the river levels at each of the river sites must be easily accessible on the website. Another role of the website is to provide historical river levels for the two sites. The proposed hierarchy of the website can be seen in Figure 5-3. The website is not to be a database for other data users, but simply a visual presentation of current and past river levels at the monitoring stations.

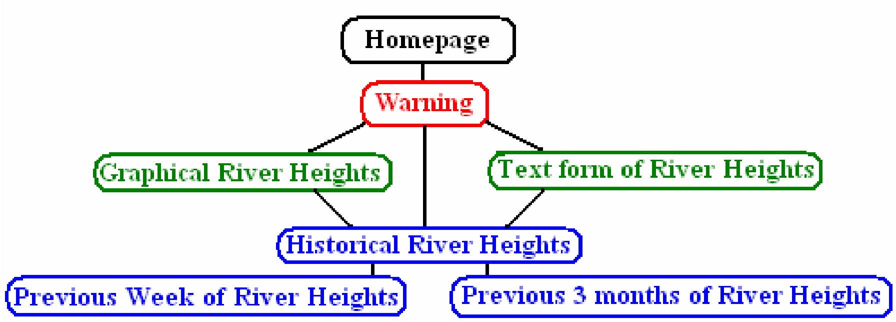

Figure 5-3 Hierarchy of Website

5.2.1 Layout

The main purpose of the website should be displayed in the homepage as discussed in section 5.1 . It was therefore decided that the homepage should contain the current flood warning for the catchment in question.

The next step in the hierarchy is displaying the current river height. Therefore the next page should contain the current river height either graphically or in text form. Since there are two sites connected to the flood warning system website, Dromcummer and Duarrigle, an option should be provided to view the river heights at either site. Since there are two sensors at each site an option should be provided to view the river heights from each sensor.

An extension to viewing the river heights from each site should be the option to compare the river heights at one site to the river heights at another site. The final step in the hierarchy is displaying the historical data. The next webpage of the website should then contain the historical river height data either in graphical or textual form. A layout of the website can be seen in Figure 5-4

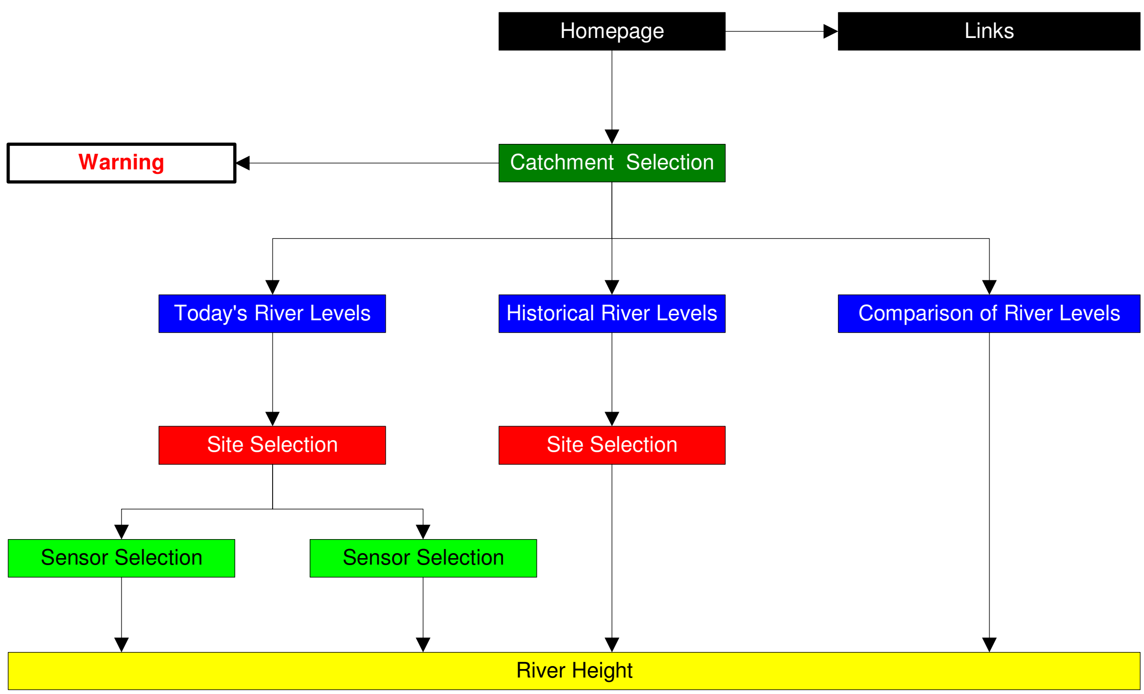

Figure 5-4 Layout of Website

5.2.2 Usability

The website was set up with its goal being to create an Irish flood warning system. Eventually it is hoped to incorporate more and more catchments throughout Ireland into the website. Because of this the homepage should incorporate all of Ireland and have the option of selecting a catchment of interest to the user. This can be seen in Figure 5-4 where the green box in the hierarchy represents the option to choose different catchments.

5.3 Implementation

Having decided upon the layout and requirements of the website the requirements must now be implemented. Each Section is implemented separately. When all Sections have been created they are combined to create the website.

5.3.1 Homepage

It was decided that the frame method of web design would be incorporated into this website. This method enables three webpages to be viewed as one. When the website is loaded, three pages appear: One at the side, the sidebar, one at the top, the header, and the main page, the main page (See Figure 5-5). If a link is selected on the side bar the page opens in the main window.

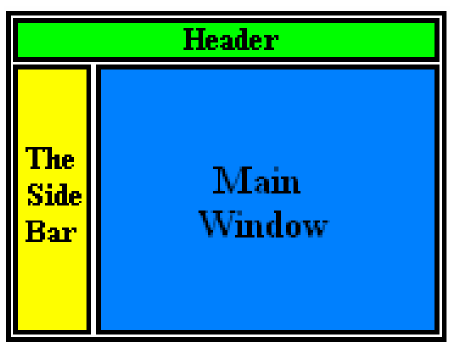

Figure 5-5 Example of a website using frames

There are many advantages to using the frames method.

- If changes are needed to be made to the entire site, such as adding new links, these only need to be made in one page, for example the side bar. Instead of having to make the changes to every page of the site.
- The header will remain static in the website.
- Links to other parts of the site will always be available to the user.
- Other websites can be opened in the main page. The sidebar and header will remain, leaving the links to the original website.

However there are some disadvantages to using frames

- Search engines do not work well with frames.
- Frames do not support printing features well.
- There are refresh and reload problems with frames

5.3.1.1 The Side Bar

The side bar will contain the links to the different pages of the site. The following links have been included:

- Home Page Main page of the website
- About Us Gives details of the project and the developers of the website.
- Map Page Gives a map of the active catchments
- Site List Gives a list of the active catchments
- Publications Gives details of the publications of the developers of the website.
- Reports Gives details of the relevant reports of the project
- Contacts Gives contact details of the developers
- Links Gives links to other relevant sites
- Flood Photos Gives examples of previous floods

5.3.1.2 Header

Figure 5-6 shows the graphic for the header frame of the webpage. This logo was designed to show how the website is dedicated to flooding throughout Ireland.

Figure 5-6 Header Graphic for Webpage

5.3.1.3 Main Page

The main page contains the homepage. The homepage contains information on the flood warning system as well as links to different parts of the site. The homepage contains a map of all the catchments in Ireland (See Appendix A Screen Shot of Irish Flood Warning Website). The map of catchments is used to enable the user to select different catchments, as well as displaying the current flood warning status of each catchment. This feature will be discussed in Section 5.3.2

5.3.2 Catchment Selection

A map of Ireland similar to Figure 2-1 is used. This map is used in two ways. To find the river height of a certain catchment a user simply has to click on the catchment in question and the user will be brought to the webpage containing the river heights for that catchment. This is made possible using the javascript[2] command *onMouseClick*. This command recognises when the mouse is over a certain catchment and if the left mouse button is clicked the user will be directed to the webpage dealing with that catchment.

---

[2] Javascript: Designed by Sun Microsystems and Netscape as an easy-to-use scripting language of Java programming. JavaScript code can be inserted into standard HTML pages to create interactive documents.

To find the warning relating to a certain catchment the user simply has to position the cursor over the catchment. A box will pop up displaying the warning. This is made possible using the javascript command *onMouseOver* and a hidden layer. The javascript command *onMouseOver* recognises when a mouse is over a certain area of the map and performs an action when it is over this area. In this case the action is to reveal a hidden layer (See Figure 5-7).

A layer is an area that can be hidden in a webpage, it can be positioned anywhere in the page and can contain anything a normal webpage can contain. In this case the layer contains a graphic displaying the appropriate flood warning. A layer can be revealed by a user if certain actions are performed, in this case *onMouseOver*.

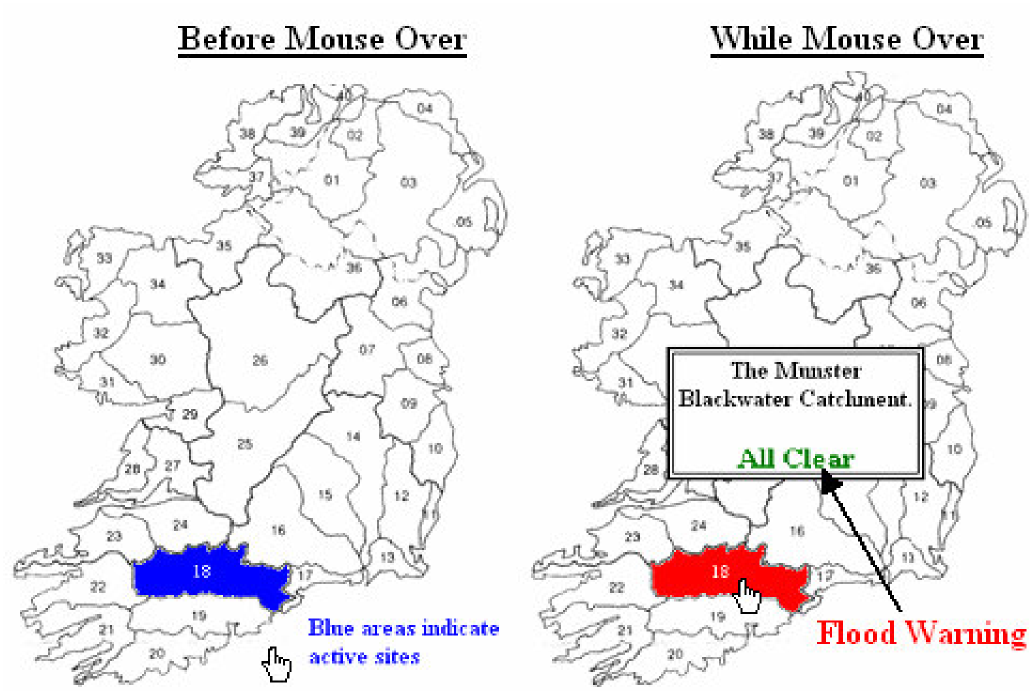

Figure 5-7 Map of Ireland showing flood warning after mouse over

5.3.3 River Height

The river heights for both stations are displayed in two forms, graphically (See Figure 5-9) and in text form (See Figure 5-11). Both forms are created by the scripting program in Hydras 3 Pro (See Section 2.10). Code was written to create several graphics for the website (see Appendix B Sample of html code used in design of website) the following graphics were created by the code.

- Graph of today's river heights at Dromcummer using Thalimedes sensor.
- Graph of today's river heights at Dromcummer using Kalesto sensor.
- Graph of this week's river heights at Dromcummer using Kalesto sensor.
- Graph of last three month's river heights at Dromcummer using Kalesto sensor.
- Graph of today's river heights Duarrigle using Thalimedes sensor.
- Graph of today's river heights at Duarrigle using Kalesto sensor.
- Graph of this week's river heights at Duarrigle using Kalesto sensor.
- Graph of last three month's river heights at Duarrigle using Kalesto sensor (See Figure 5-8).

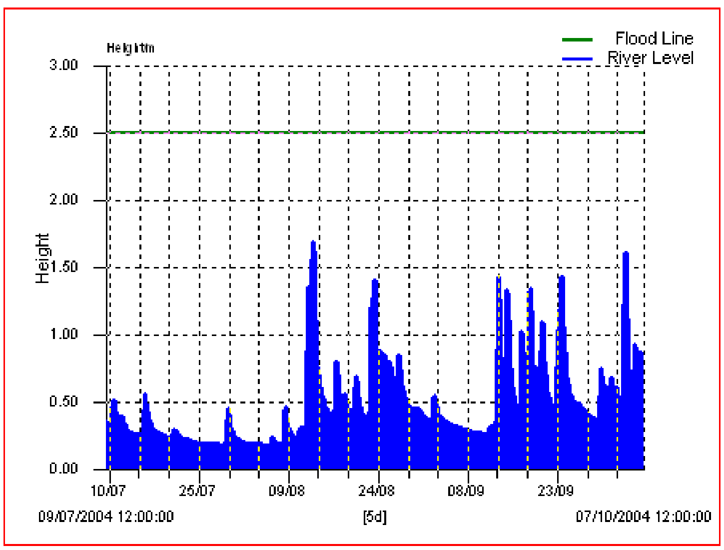

Figure 5-8 Example of graph of last three months of river height data

- Graph of today's river heights at Dromcummer compared to today's river heights at Duarrigle (See Figure 5-9).

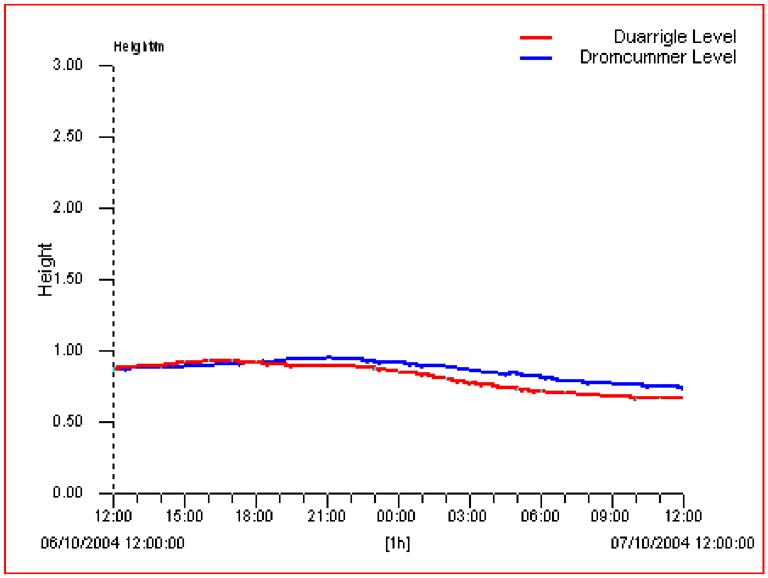

Figure 5-9 Example of graph of today's river heights at Dromcummer compared to Duarrigle.

- Graphic of flood warning (See Figure 5-10).

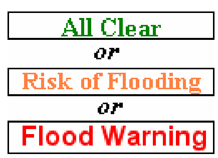

Figure 5-10 Choice of Graphic for Flood Warning

- Graphic of river height in text form (See Figure 5-11).

Figure 5-11 Example of Graphic or River Height in text form

These graphics were created by Hydras 3 and then uploaded to the internet. The scripts used to create these graphics were executed every time data was recorded by hydras 3. If the data is recorded every four hours by hydras 3, the online figures would be updated every four hours. As discussed in Section 2.9 the interval for recording data is adjustable, in this case the interval was four hours during good weather and one hour during bad weather.

5.3.4 Today's River Levels

Today's river levels webpage uses another frame set, in this page there are three frames, one for sites of the catchment on the left, one for the map of the catchment in the middle and one for sensors of the site on the right (See Figure 5-12).

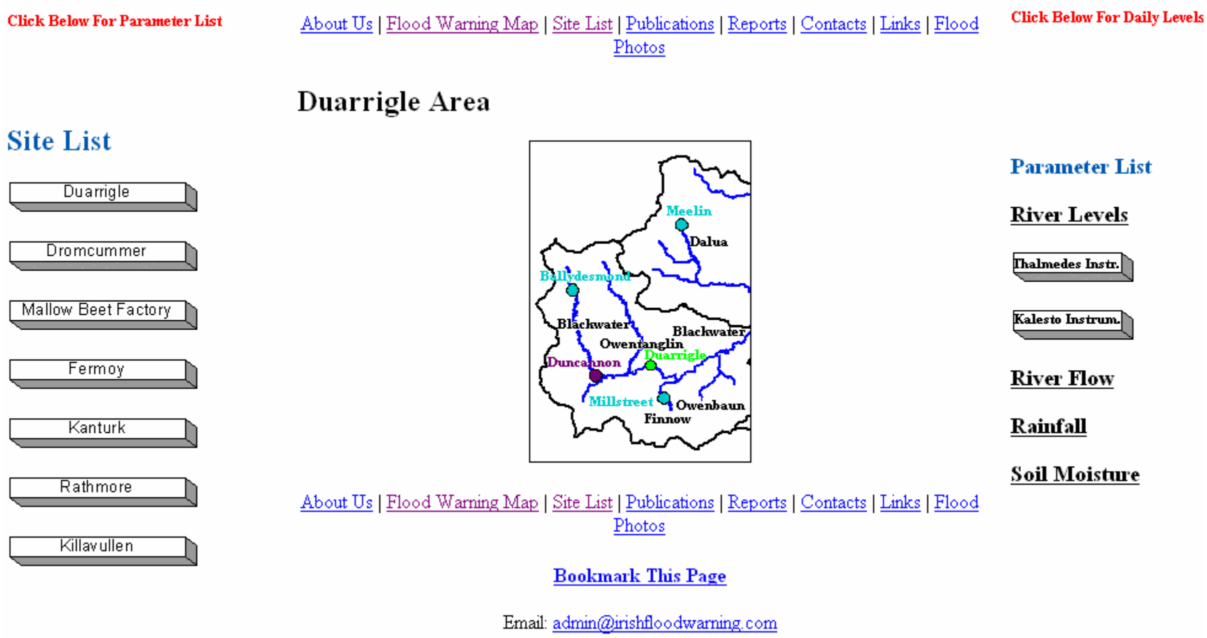

Figure 5-12 Screenshot of Today's River Levels Page

The user first selects the monitoring site on the left. The map then changes in the middle to show a close up of that site. The sensor/parameter list on the right also changes to show the current active sensors of that site. The user can then select the required sensor and a window will open showing today's river levels for that site (See Figure 5-13).

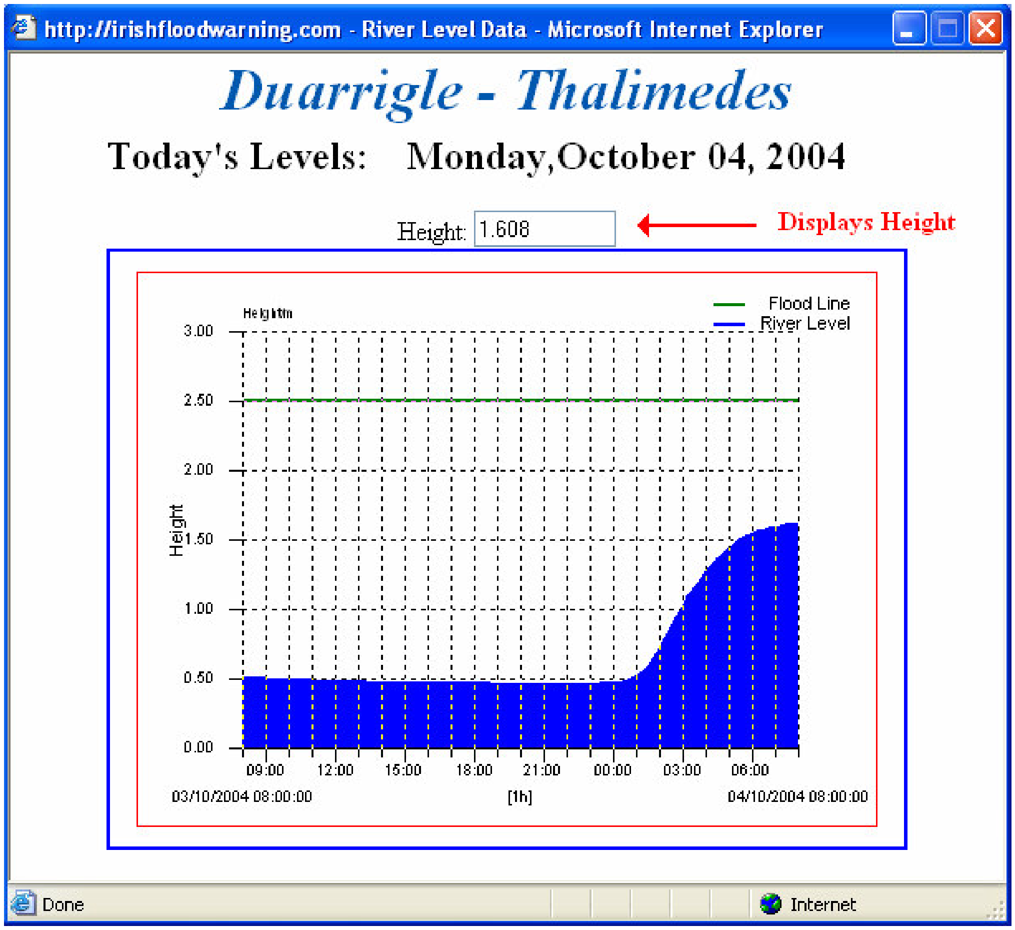

Figure 5-13 Webpage displaying today's river height.

It can be seen from Figure 5-13 that there is a box displaying the height at any point in the graph, this is useful for checking the height at very specific points.

5.3.5 Historical River Levels

The historical river levels page is created in a different manner. It was decided that it would be useful to see the heights of the river at the two sites without having to read the heights off a graph. A map of the catchment is shown on the page (See Figure 5-14), if the user positions the cursor over certain sites, which are the live sites, the height of the river at that time will appear. The user can click on one of these sites to then view the historical data of the site. The historical data is represented by three graphs (See Figure 5-9 for example) giving the river heights of the selected site for the last day, week and three months, respectively.

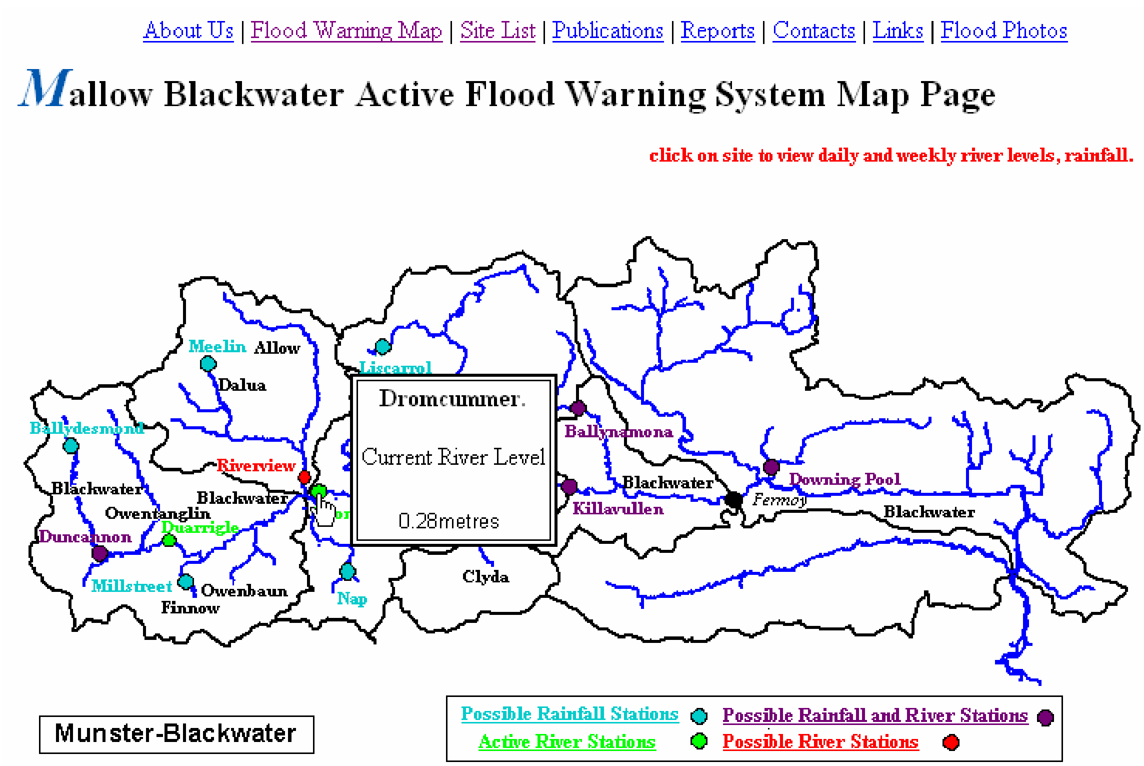

Figure 5-14 Webpage displaying river height data in text form

It should be noted that the river level height in text form appears in a hidden layer similar to the hidden layer appearing in Section 5.3.2 In this way a full view of the catchment can be seen when all hidden layers are hidden.

5.4 Testing

The website was built and uploaded onto a server for testing. A week was spent removing the bugs from the system. Once the webpage worked correctly for a number of days the site was transferred to an online server. The domain name www.irishfloodwarning.com was purchased and attached to the site. There have been very few glitches in the system and the website has proved to be a great success.

Chapter 6

Results

6.1 Introduction

The results of the flood warning system are presented in this chapter. As the Beet Factory is only 3 km upstream of Mallow, the river levels at the Beet Factory will be used to represent the levels at Mallow. This is necessary to test the results of the flood warning systems. Mallow Bridge is situated in the centre of Mallow and represents the river levels for Mallow town itself. As can be seen in Figure 6-1 the Mallow Bridge river height is very similar to the Beet Factory river height. It can also be noted from Figure 6-1 that the flood peaks in Mallow approximately one hour after it peaks at the Beet Factory.

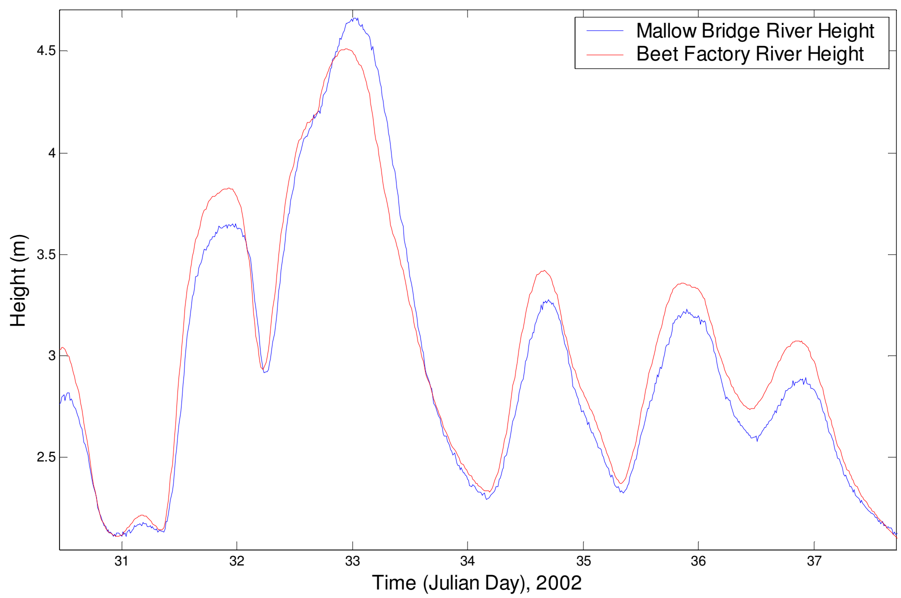

Figure 6-1 Mallow Bridge river height and Beet Factory river height vs. time for julian day 31 to 38, 2002

The relationship between river heights at Mallow Bridge and river heights at the Beet Factory (3 km upstream from Mallow Bridge) can also be seen in Figure 6-2. There is correlation between the river heights at Mallow Bridge and the river heights at the Beet Factory. The relationship is given in equation 6-1 where Y_{bf} represents the river height at the beet factory and x_{mb} represents the river height at Mallow Bridge.

$$Y_{bf} = 0.035x_{mb}^{3} - 0.64x_{mb}^{2} + 3.97x_{mb} - 3.8 \qquad [6\text{-}1]$$

The R^2 value [3] for this fit is approximately 0.964 and the Sum Squared Error [4] for this fit is approximately 622.1 m^2

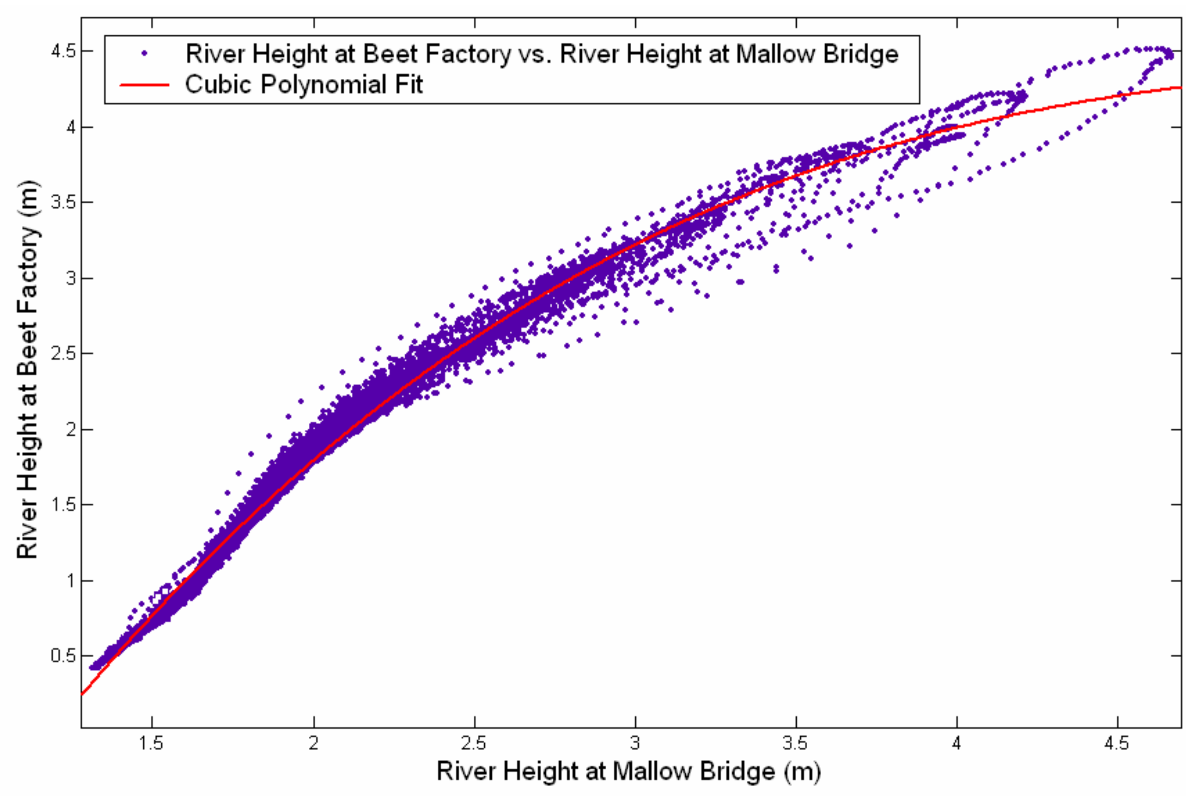

Figure 6-2 River height at Beet Factory vs. river height at the Mallow Bridge for 2002

6.2 Threshold Flood Warning System Results

The following analysis examines the results of the threshold flood warning system for the Munster Blackwater catchment. The river levels were examined and threshold levels were calculated. The thresholds were then tested for accuracy.

---

[3] R^2 Value: This is a statistical term saying how good one term is at predicting another, a higher R^2 value means that you can better predict one term from another.

[4] Sum Squared Error: This is the sum of the differences between simulated outputs and actual outputs squared, $SSE = \Sigma (u - \hat{u})^2$ where u is the actual output and û is the simulated output.

6.2.1 River Levels

The river levels between the three sites must first be compared. It will be determined what kind of relationship exists between the river levels at each site. A typical flood can be seen in Figure 6-3 It can be seen that the flood peaks at Dromcummer and the flood peaks at Beet Factory correspond with some lag period (about 5 hours).

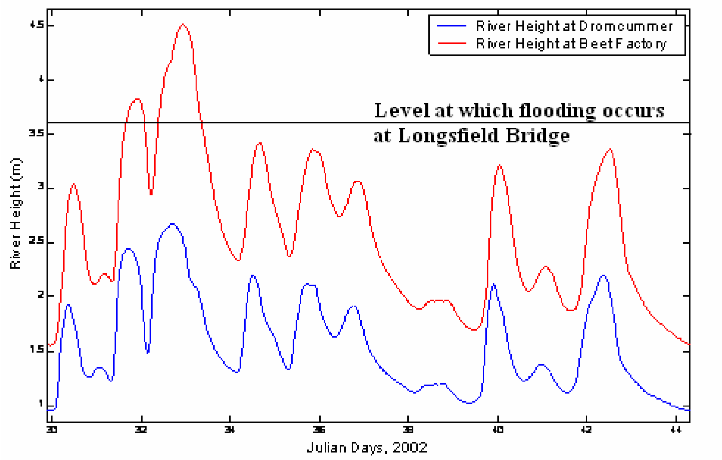

Figure 6-3 Typical time series at Dromcummer and the Beet Factory

The lag time is not always the same. It can be seen in Figure 6-4 that the lag time for the first flood (day 31) is 5 hours and the lag time for the second flood (day 32) is 7 hours. In Figure 6-4 a more detailed set of data for a single flood comparison between Dromcummer and the Beet Factory.

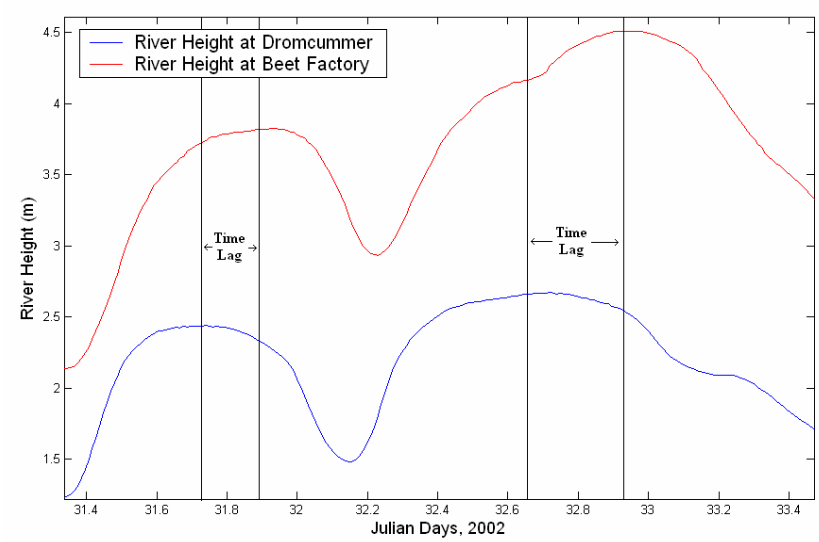

Figure 6-4 Typical flood event levels at Dromcummer and Duarrigle

In Figure 6-5 a comparison of data at Dromcummer and the Beet Factory at the same time are presented. There is some relationship between the river heights. The relationship is better at the lower river heights than in times of flooding. The R^2 value in this case is 0.96 and the sum squared error is 164.3 m^2

The red line in Figure 6-5 represents a relationship between the river heights at the two sites. Equation [6-2] is the equation which represents this line. Where Y_{dm} represents the river height at Dromcummer and x_{bf} represents the river height at the beet factory.

$$Y_{dm}=0.03446x_{bf}^3 - 0.2618\ x_{bf}^2 + 1.15\ x_{bf} - 0.2716 \qquad [6\text{-}2]$$

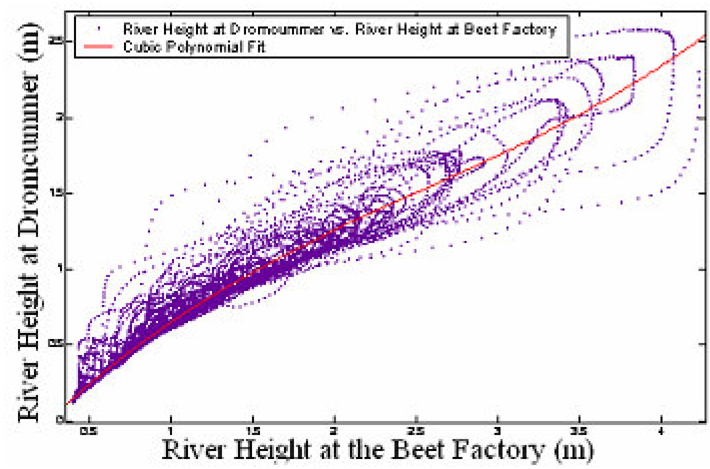

Figure 6-5 River height at Dromcummer vs. river height at Beet Factory for 2002

In Figure 6-6 it can be seen that the relationship between the river height at Duarrigle and the river height at the Beet Factory is less clear. This is due to the large catchment area between the two sites. The R^2 value in this case is 0.82 and the sum squared error is 795.8 m^2.

The red line in Figure 6-6 represents the closest cubic relationship between the river heights at the two sites, Duarrigle and the Beet Factory. equation [6-3] is the equation which represents this line. Where Y_{dr} represents the river height at Duarrigle and x_{bf} represents the river height at the beet factory.

$$Y_{dr} = 0.0057x_{bf}^3 - 0.066x_{bf}^2 + 0.6366x_{bf} - 0.06726 \qquad [6\text{-}3]$$

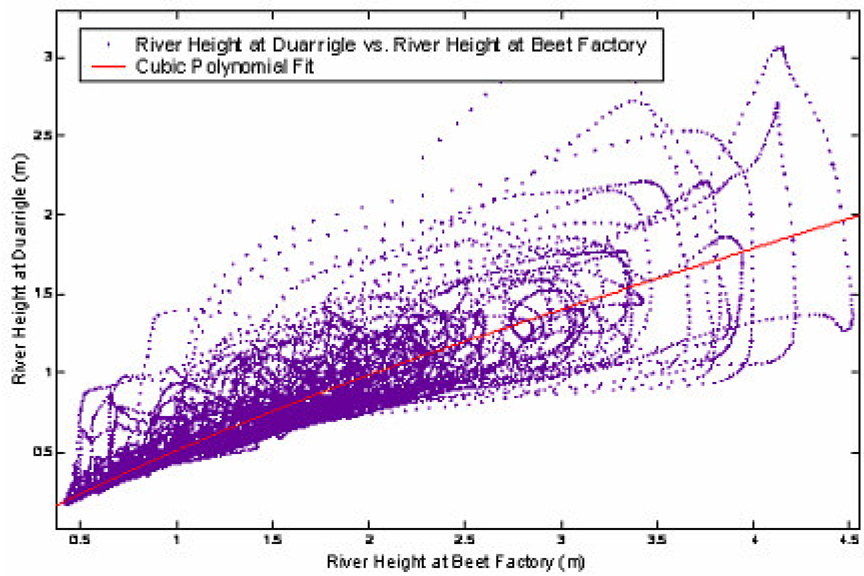

Figure 6-6 River height at Duarrigle vs. river height at Beet Factory for 2002

It is clear from equation [6-3] that the relationship between the river height at Duarrigle and the river height at the beet factory appears linear, due to the contribution of the very small coefficients of x^3 and x^2 (0.0057, 0.066 respectively). It can be seen in Figure 6-7 that a linear relationship exists between the two sites but the sum squared error of 816 m^2 and the R^2 value of 0.82 shows the inaccuracy of this fit. Equation [6-4] represents this linear fit, where x_{bf} represents the river height at the Beet Factory and Y_{dr} represents the river height at Duarrigle.

$$Y_{dr} = 0.4719x_{bf} + 0.02263 \qquad [6\text{-}4]$$

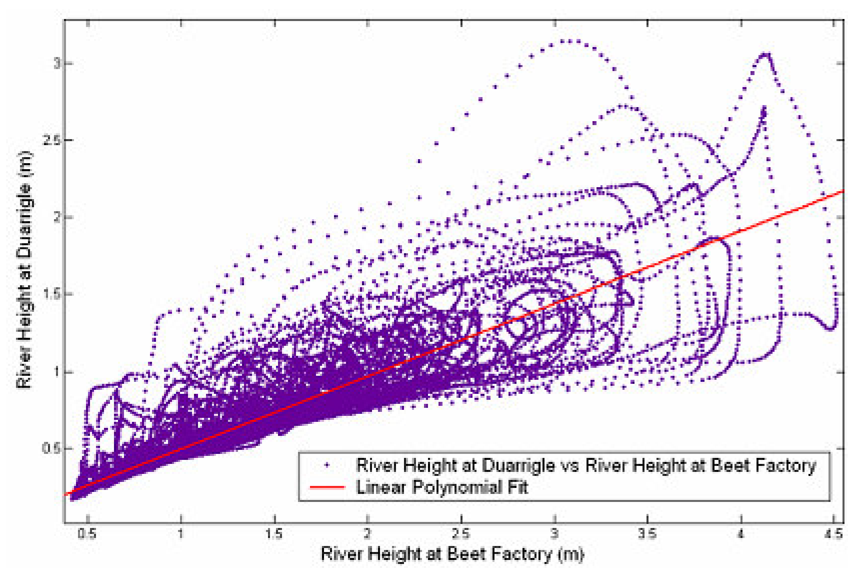

Figure 6-7 River height at Duarrigle vs. river height at Beet Factory for 2002

In Figure 6-8 and Figure 6-9 it can be seen that there is a clear relationship between the river heights at Duarrigle and at the Beet Factory. Due to this relationship it was decided that the Duarrigle river height data would be incorporated into the threshold flood warning system. On the basis of the relative strengths of these relationships more emphasis is placed upon the better relationship between Dromcummer and the Beet Factory.

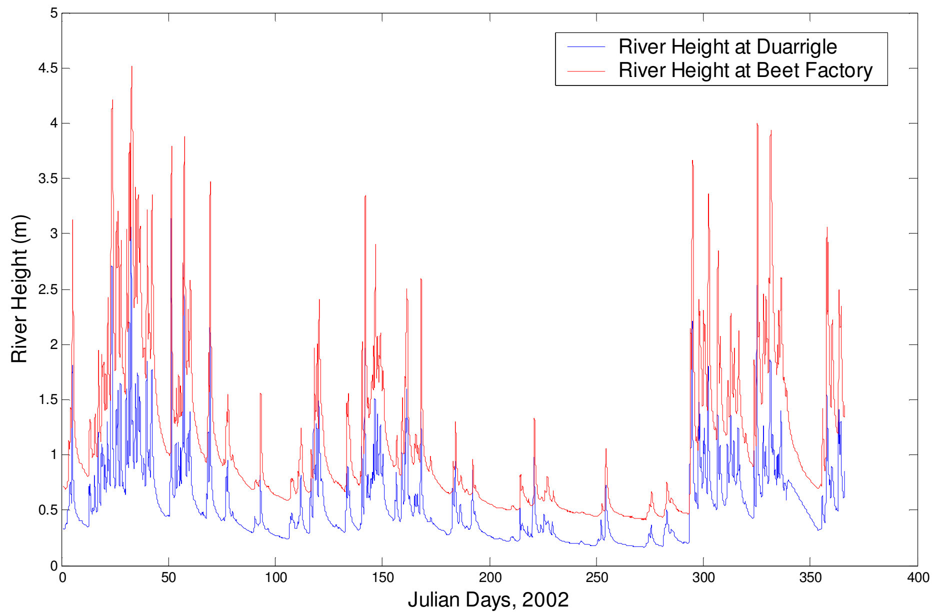

Figure 6-8 Duarrigle river height and Beet Factory river height vs. Time

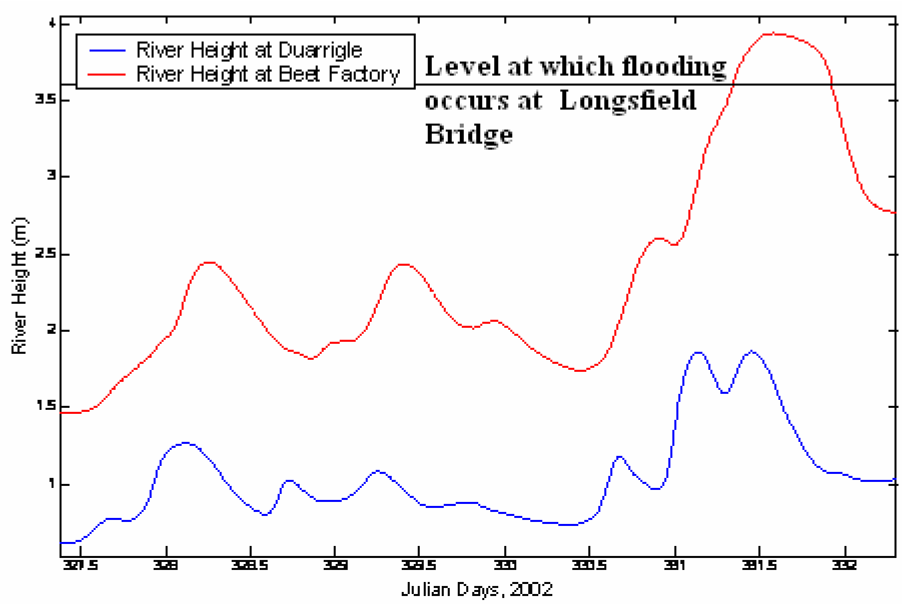

Figure 6-9 Duarrigle river height and Beet Factory river height vs. Time showing sample flood

6.2.2 Threshold Levels

As discussed in Section 4.2.2 there are three flood stages involved in the Threshold Flood Warning System: Stage 1, flooding of Longsfield Bridge; Stage 2, flooding of the town park and town park road; and Stage 3, flooding of Bridge St.

Events of these different types of flood were then studied and the times when the flood first occurred were noted. The river levels at the Beet Factory at this time were examined. In Table 6-1 the times and heights of the specific floods can be seen.

Table 6-1 River heights at the Beet Factory for types of flood.

Flood Type	Year	Month	Day	Hour	Minute	River Height (m)
Stage 1	2003	11	14	17	45	3.618
Stage 2	2002	1	23	14	30	4.084
Stage 3	2003	11	15	4	0	4.127

These heights are the flood heights for the Beet Factory, the corresponding river heights at Dromcummer and Duarrigle must now be found. Flood events in Mallow which reach those heights are found which allows the corresponding river heights in Dromcummer and Duarrigle to be established, i.e. to find flood events that peak at 3.618 m, 4.084 m and 4.127 m in Mallow and then find the corresponding peaks at the other two sites.

Using Figure 6-10 a river height at Dromcummer of 2.1 m was initially estimated for Stage 1 flooding (corresponding to the beet factory river height = 3.6 m). The corresponding river height at Duarrigle was estimated to be 2.3 m. These thresholds were tested for accuracy (equation [6-5] and [6-6]) and adjusted. A full table of the flood levels and thresholds can be seen in Table 6-2.

Figure 6-10 shows how changing the flood warning threshold by ten centimetres can change a flood warning output by a large amount. A threshold level at Dromcummer of 2.1 m produces a flood warning for floods that never occur while a threshold level of 2.3 m will miss several floods. Choosing 2.2 m as the threshold level gives the most suitable trade off between the numbers of floods missed by the flood warning system and the number of false flood warnings given by the system.

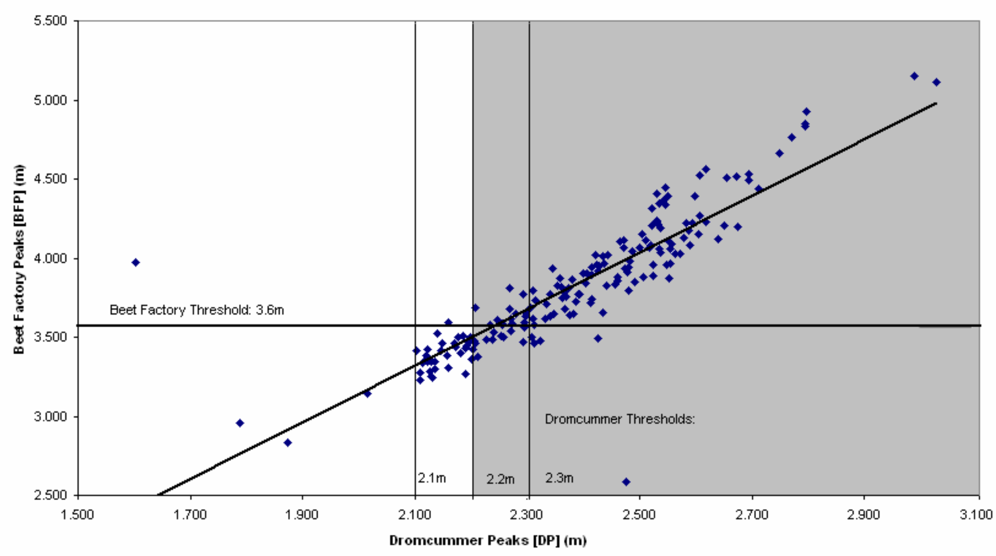

Figure 6-10 Stage 1 Flood thresholds: Dromcummer vs. Beet Factory river levels

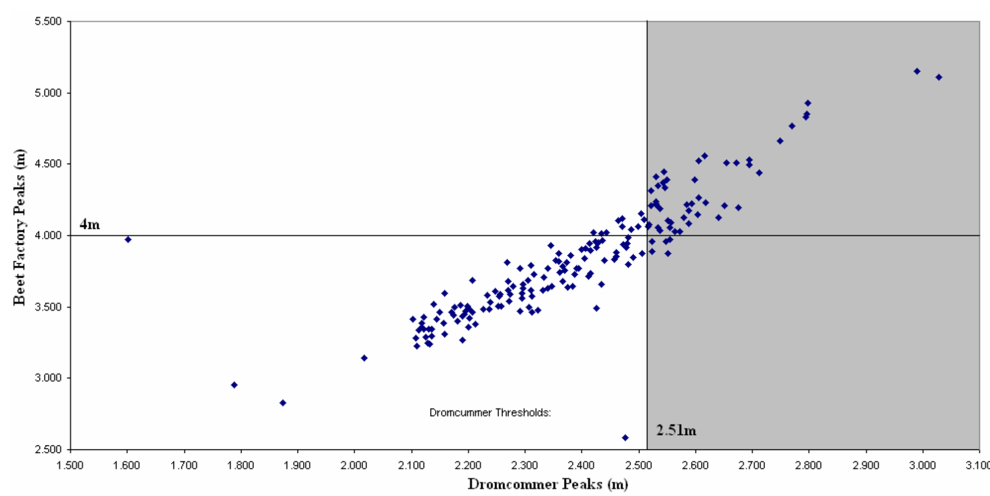

Figure 6-11 Stage 2 Flood thresholds: Dromcummer vs. Beet Factory river levels

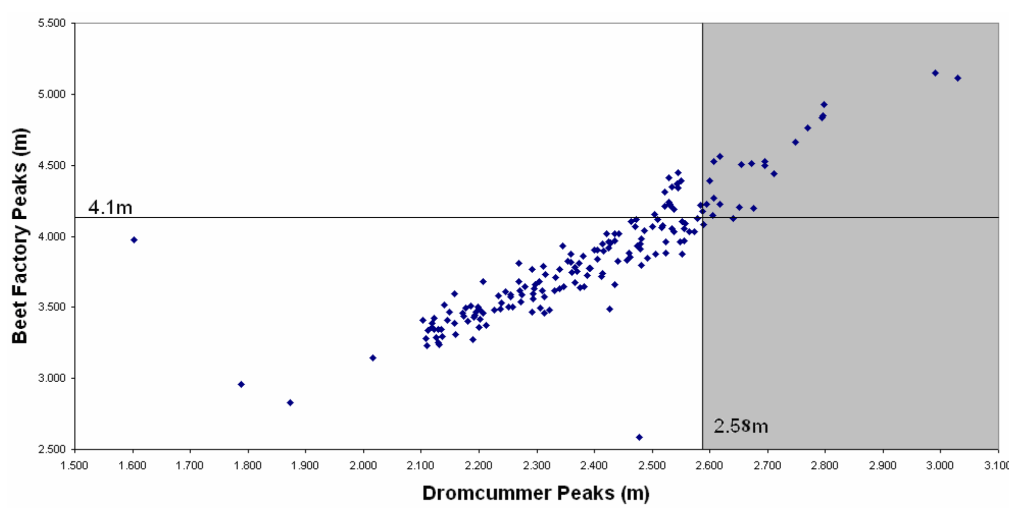

Figure 6-12 Stage 3 Flood thresholds: Dromcummer vs. Beet Factory river levels

The 6 thresholds were obtained and can be seen in Table 6-2. The warning times for the different thresholds were then calculated and the accuracy was measured. These thresholds are shown graphically in Figure 6-10, Figure 6-11 and Figure 6-12.

Table 6-2 Thresholds for the Threshold Flood Warning System

	Stage 3 Flooding	Stage 2 Flooding	Stage 1 Flooding
Beet Factory River Flood Height	4.12	4.08	3.61
Duarrigle River Threshold	2.97	2.6	2.32
Dromcummer River Threshold	2.58	2.51	2.13

6.2.2.1 Warning Time

Figure 6-13 shows a typical flood event (Feb. 19 to 21, 2002) that occurs on the river Blackwater. It can be seen that the flood peaks first at Duarrigle, then 3.5 hours later at Dromcummer and finally 4 hours after that at the Beet Factory. Using the threshold flood warning system in this example, results in two *positive* flood warning times.

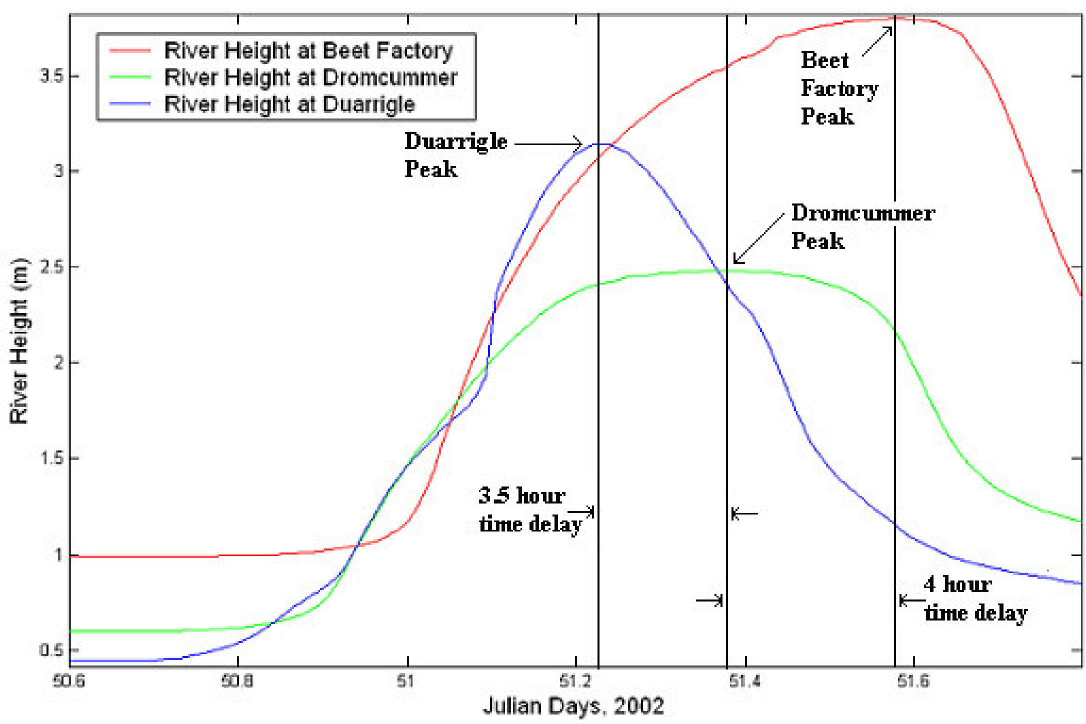

Figure 6-13 Comparison graph of a 2 Day Flood Event

Figure 6-14 shows another flood event which occurred on the river Blackwater (Nov 6 to 8, 2000), it can be seen that the flood peaks in this figure are different compared to Figure 6-13. It can be seen that the first flood peaks at Duarrigle (Duarrigle peak (a)). This flood peak is roughly 2.5 m which represents a stage 1 flood event. The next peak occurs at Dromcummer three and a half hours later. This flood peaks at 2.75 m which represents a stage 3 flood event and finally the flood peaks at the Beet Factory 6 hours later at a river height of 4.8 m which also represents a stage 3 flood. Therefore it can be seen that the flood warning system at Duarrigle would predict a stage 1 flood, whereas at Dromcummer the flood warning system would predict a stage 3 flood. This would lead to a missed flood prediction from Duarrigle.

However there is a second peak of 3 m at Duarrigle 4 hours after the first flood peak at the beet factory representing a stage 3 flood event. This flood peak attenuates before it reaches Dromcummer and the Beet Factory, therefore giving a false flood warning.

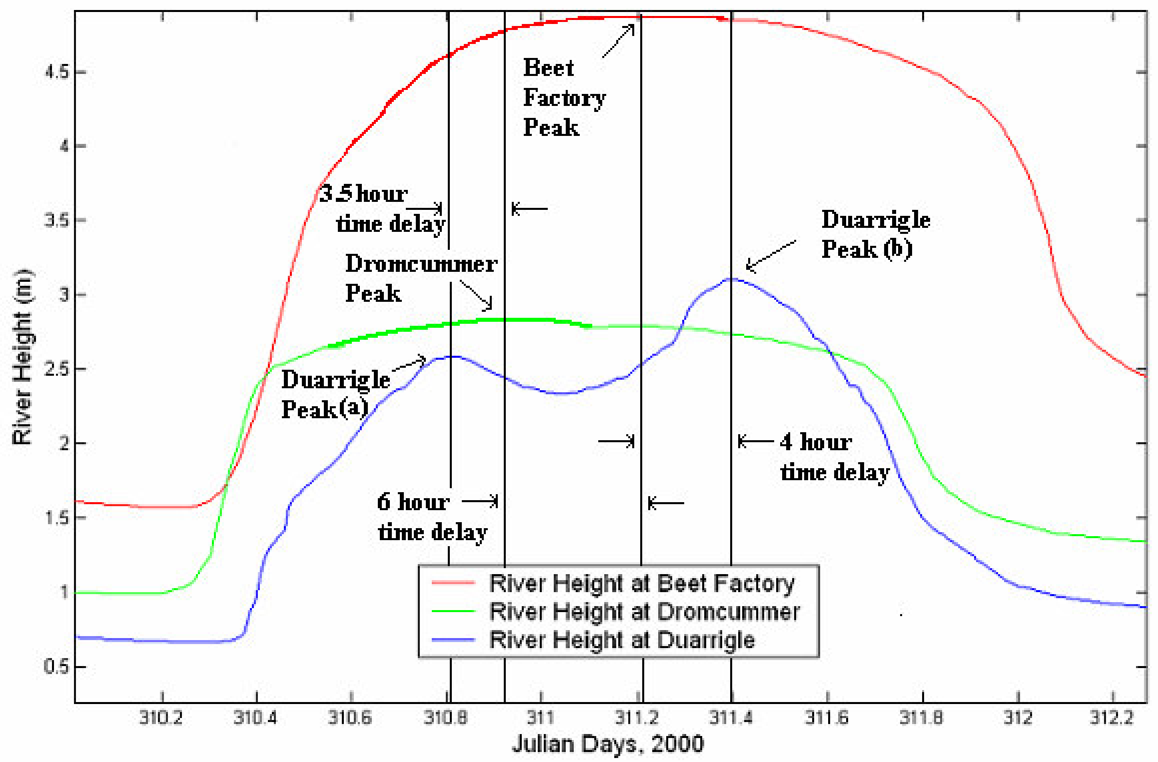

Figure 6-14 Comparison graph of a 2 1/2 Day Flood Event

Table 6-3, Table 6-4 and Table 6-5 show the times in Julian days at which stage 1, stage 2 and stage 3 thresholds were exceeded for a selection of historic floods. S1 time, S2 time and S3 time represent the times at which the thresholds were exceeded at Duarrigle, Dromcummer and the Beet Factory respectively.

The tables also show the time difference between when the thresholds were broken. The time difference represents the flood warning time given by both sites (i.e. Duarrigle and Dromcummer). The last two columns show the flood warning time for the two sites, Dromcummer and Duarrigle in hours.

Table 6-3 Stage 1 flood warning times for sample Stage 1 Floods

Flood Date	S3 Time	S2 Time	S1 Time	S3 – S2	S3 - S1	Flood Warning Time Dromcummer	Flood Warning Time Duarrigle
19 Feb '82	50.94	50.86	51.14	0.28	0.19	6.75	4.75
5 Aug '86	217.03	216.97	217.13	0.15	0.10	3.75	2.50
11 Jan '88	11.42	11.43	11.69	0.26	0.27	6.25	6.50
21 Feb '95	52.61	52.69	52.77	0.07	0.15	1.75	3.75
17 Jun '82	168.10	168	168.33	0.33	0.22	7.99	5.49
24 Aug '86	236.81	236.61	236.90	0.29	0.09	7.00	2.25
1 Dec '00	335.57	335.36	335.48	0.12	-0.08	3.00	*-2.02 **
Average Flood Warning Time						**5.00**	**4.2**

Table 6-4 Stage 2 flood warning times for sample Stage 2 Floods

Flood Date	S3 Time	S2 Time	S1 Time	S3 – S2	S3 - S1	Flood Warning Time Dromcummer	Flood Warning Time Duarrigle
20 Feb '82	51	51	51.14	0.14	0.14	3.50	3.50
11 Jan '88	11.52	11.62	11.69	0.07	0.17	1.75	4.25
28 Oct '00	301.26	304.02	304.22	0.20	2.96	5.00	71.25 **
1 Dec '00	335.66	335.45	335.61	0.15	-0.05	3.75	*-1.25 **
17 Jun '82	168.16	168	168.33	0.33	0.16	7.99	3.99
31 Jan '88	31.69	31.79	31.85	0.06	0.15	1.50	3.75
16 Nov '97	320.93	320.93	321.38	0.44	0.44	10.75	10.75
Average Flood Warning Time						**4.53**	**5.25**

Table 6-5 Stage 3 flood warning times for sample Stage 3 Floods

Flood Date	S3 Time	S2 Time	S1 Time	S3 – S2	S3 - S1	Flood Warning Time Dromcummer	Flood Warning Time Duarrigle
20 Feb '82	51.05	51.05	51.14	0.09	0.09	2.25	2.25
17 Jun '82	168.22	168.00	168.33	0.33	0.10	7.99	2.4
5 Aug '86	217.21	217.07	217.13	0.06	-0.08	1.50	*-1.99 **
17 Nov '97	321.14	320.96	321.38	0.41	0.23	10.00	5.75
7 Nov '00	311.33	310.50	310.70	0.20	-0.62	4.99	*-15.00 **
1 Dec '00	335.66	335.45	335.61	0.15	-0.05	3.75	*-1.25 **
Average Flood Warning Time						**5.78**	**3.5**

* It should be noted that there are several negative warning times from the Duarrigle site for the stage 3 flood event. In reality these negative times represent two different flood events; a flood missed by the flood warning system and a false flood warning given by the system after the flood has occurred. This is due to the large catchment area between the two sites as discussed in Section 4.1

** The large flood warning time provided is another combination of a false flood warning and a missed flood. The warning given by the system in Duarrigle represents a false flood warning, that is the flood event recognised by the system never occurs in Mallow and the later flood event that does occur in Mallow is missed by the system in Duarrigle. It should be noted that these values were not used in the calculation of a flood warning time for the system.

6.2.2.2 Accuracy

The definition of a missed flood and false flood can be seen in Table 6-6.

Table 6-6 Definition of False and Missed Floods

Missed Flood	A missed flood is a flood missed by the flood warning system. This flood has never been counted by the flood warning system.
False Flood	A false flood is a flood which is counted by the flood warning system but never actually occurred.

As discussed in Section 4.2.4 there are generally two equations used to calculate the accuracy of a system, the false flood equation, (equation [6-5]) and the missed flood (equation [6-6]). Where A_{false} represents false accuracy, A_{missed} represents miss accuracy, N_{false} represents the number of false floods, N_{missed} represents the number of missed and N_{total} represents the total number of floods.

$$A_{false} = 1 - N_{false} / N_{total} \qquad [6\text{-}5]$$

$$A_{missed} = 1 - N_{missed} / N_{total} \qquad [6\text{-}6]$$

These two equations will be used to calculate the accuracy of the system for the 3 flood events, stage 1, stage 2 and stage 3. Table 6-7, Table 6-8 and Table 6-9 show the miss accuracy and the false accuracy for the three flood events.

Table 6-7 Accuracy of Flood Warning System for Stage 1 Flooding

	Dromcummer	Duarrigle
Total Number of Stage 1 Floods	127	127
Total Number of Predicted Floods	125	79
Total Number of Missed Floods	2	54
Total Number of False Floods	25	6
Accuracy % (Missed Floods)	98	59
Accuracy % (False Floods)	80	96

Table 6-8 Accuracy of Flood Warning System for Stage 2 Flooding

	Dromcummer	Duarrigle
Total Number of Stage 2 Floods	55	55
Total Number of Predicted Floods	51	41
Total Number of Missed Floods	9	22
Total Number of False Floods	5	5
Accuracy % (Missed Floods)	91	60
Accuracy % (False Floods)	84	84

Table 6-9 Accuracy of Flood Warning System for Stage 3 Flooding

	Dromcummer	Duarrigle
Total Number of Stage 3 Floods	36	36
Total Number of Predicted Floods	24	20
Total Number of Missed Floods	13	19
Total Number of False Floods	1	3
Accuracy % (Missed Floods)	66	52
Accuracy % (False Floods)	98	98

From Table 6-7 above it is seen that the flood warning system in place in Dromcummer misses 2% of the stage 1 floods, although one out of every five flood warnings given will be a false flood warning. The system will recognise almost every flood but on certain occasions a flood warning will be given but no flood will occur in Mallow.

Table 6-7 also shows that the flood warning system in Duarrigle missed 54 floods out of 127 compared to the flood warning system in Dromcummer which missed only 2. But of the floods predicted in Duarrigle only 6 of those floods proved to be false floods whereas 25 of the floods predicted in Dromcummer proved to be false floods.

Table 6-8 and Table 6-9 show that as the stages of flooding increase the accuracy of the flood warning systems to missed floods decreases. In other words that it is harder to predict the floods of higher volume. Table 6-8 and Table 6-9 also show that as the stages of flooding increase the number of false flood warnings given by the system decreases.

From this investigation it is seen that with further research the accuracy of the system to missed stage 2 and stage 3 floods may be improved. It is also seen that with further research into sensitivity analysis and optimisation, the accuracy of the flood warning systems to false flood warnings may also be improved.

6.3 Rate of Rise Flood Warning System Results

The following analysis examines the results of the rate of rise flood warning system for the Munster Blackwater. The rate of rise system could be used on any of the flood stages (Stage 2 and Stage 3 floods are subsets of Stage 1 floods) (see Section 4.3), and it was decided that the rate of rise system would be analysed on the stage 1 floods only. The rates of rise of the river heights were examined and threshold levels were calculated for the rate of rise of the river and river height for a stage1 flood. These thresholds were then tested for accuracy for the site at Dromcummer only.

6.3.1 Rate of Rise

The rate of rise of the river Blackwater was calculated using equation [6-7] where H represents the river height and T represents the time at which it was recorded.

$$\Delta H / \Delta T = H_t - H_{t-1} / T_t - T_{t-1} \qquad [6\text{-}7]$$

Figure 6-15 (a) shows the rate of rise of the river Blackwater for the year 2000, positive values represent the river height increasing and negative values represent the river height decreasing. Figure 6-15 (b) shows the corresponding river heights at Dromcummer for the same year. It can be seen from the figure that the periods of high river level correspond to the periods of high rate of rise.

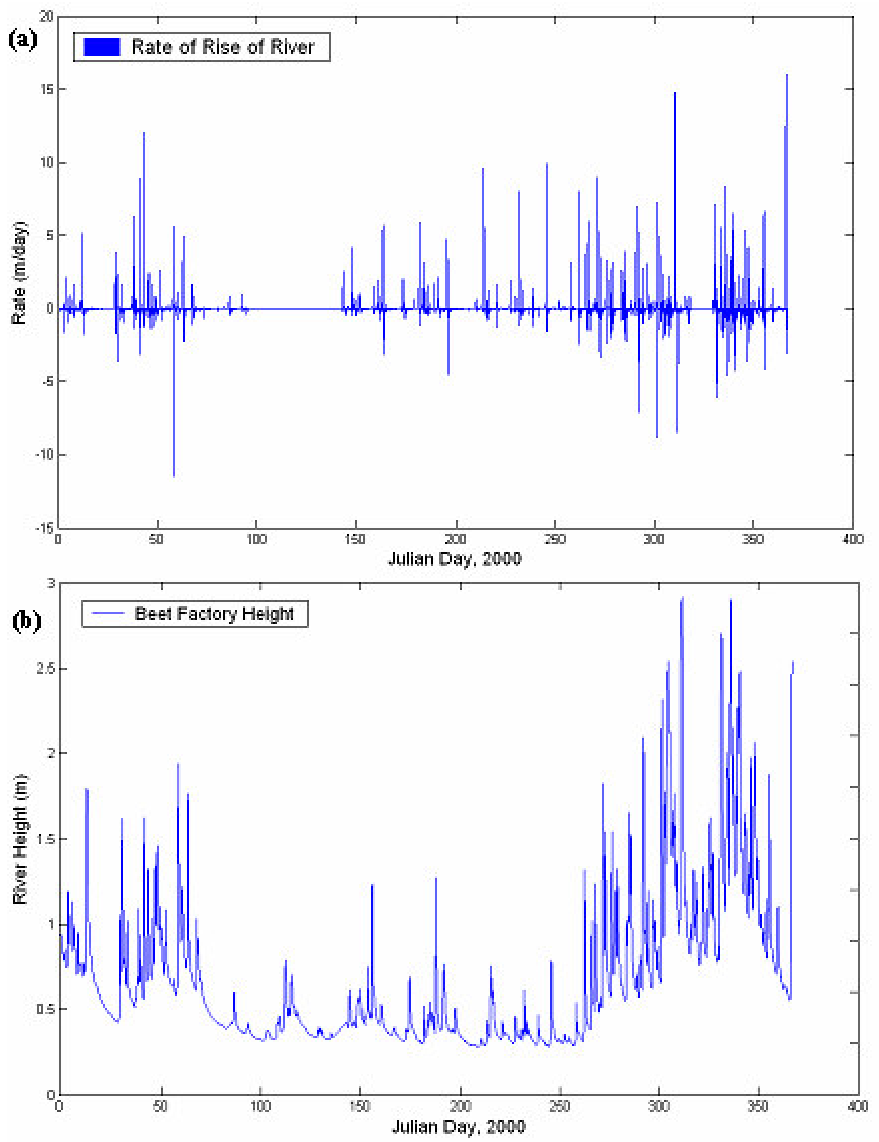

Figure 6-15 (a) Rate of rise of river at Dromcummer for the year 2000

(b) River height at Dromcummer for the year 2000

6.3.2 Estimation of thresholds for Rate of Rise (Dromcummer only)

It was decided that the rate of rise and river height 4 hours and 5 hours before the threshold being reached should be examined. In Figure 6-16 the plot of rate of rise for 26 flood events can be seen, and show that 4 to 5 hours before a flood the river rises at a rate of approximately 4.5 m/day. In Figure 6-17 it can be seen that the height of the river 4 to 5 hours before a flood is on average 2 m.

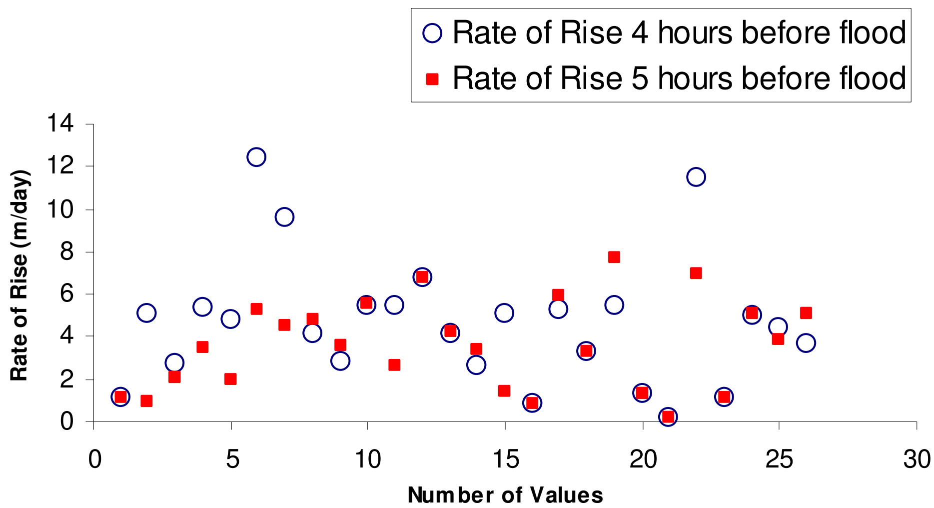

Figure 6-16 Rate of rise 4 and 5 hours before flooding

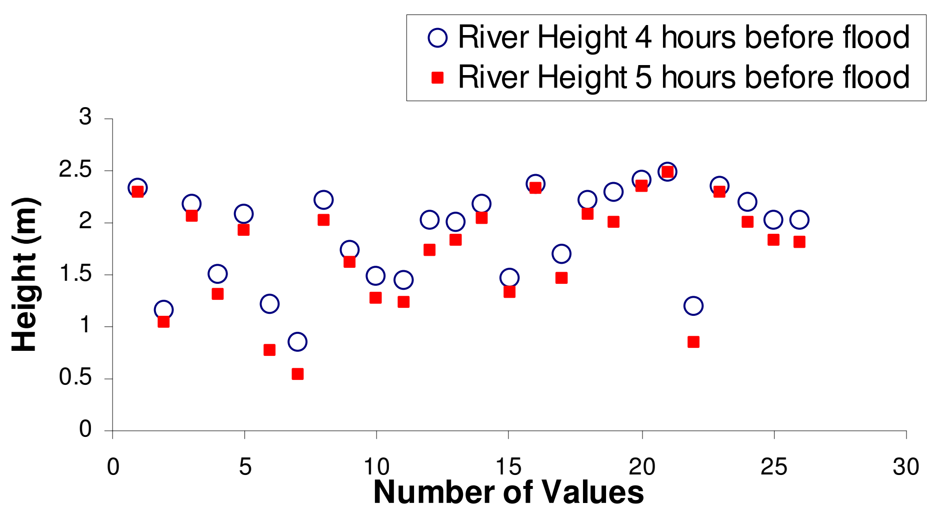

Figure 6-17 River height 4 and 5 hours before flooding

It is noted that in some cases the rate of rise of the river exceeds 10 m per day, which appears to be a relatively large rate of rise. In reality the river height does not increase by this amount during the day. This is due to the fact that the rate of rise is calculated over 15 minute intervals. That is a 10 m per day rate of rise represents a rise of approximately 10 cm in that 15 minutes.

The initial thresholds chosen were a rate of rise of 4 m/day and a river height of 2 m. These thresholds were tested and calibrated to determine the number of floods missed by the system and the number of false flood warnings given by the system. See Table 6-10, and Figure 6-18

Table 6-10 Missed floods & False flood warnings using rate of rise of 4m/day and river height of 2m

Flood Type	1997	1998	1999	2000	2001	2002	Total
Flood	11	13	12	12	4	8	60
Missed	5	10	5	5	2	2	29
False	0	0	0	0	0	2	2

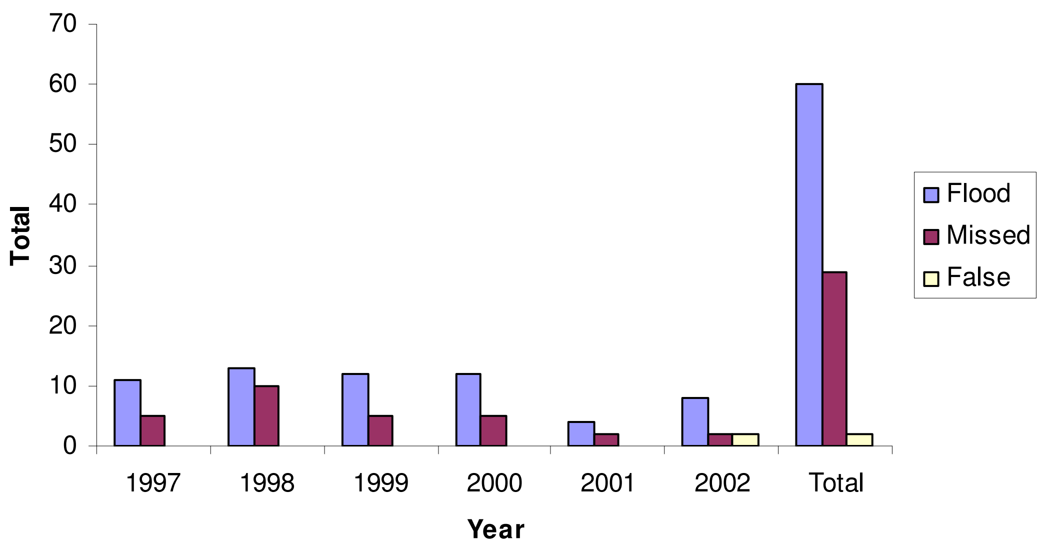

Figure 6-18 Missed floods & False flood warnings using rate of rise of 4m/day and river height of 2m

The thresholds of 4 m/day and 2 m height have a success rate of providing a flood warning of approximately 50% (Figure 6-18). The results are then examined for a rate of rise threshold of 4.4 m/day and a river level threshold of 1.5 m to improve on accuracy.

Table 6-11 Missed floods & False flood warnings using rate of rise of 4.4m/day and river height of 1.5m

Flood Type	1997	1998	1999	2000	2001	2002	Total
Flood	11	13	12	12	4	8	60
Missed	5	4	4	7	1	3	24
False	2	2	0	7	4	4	19

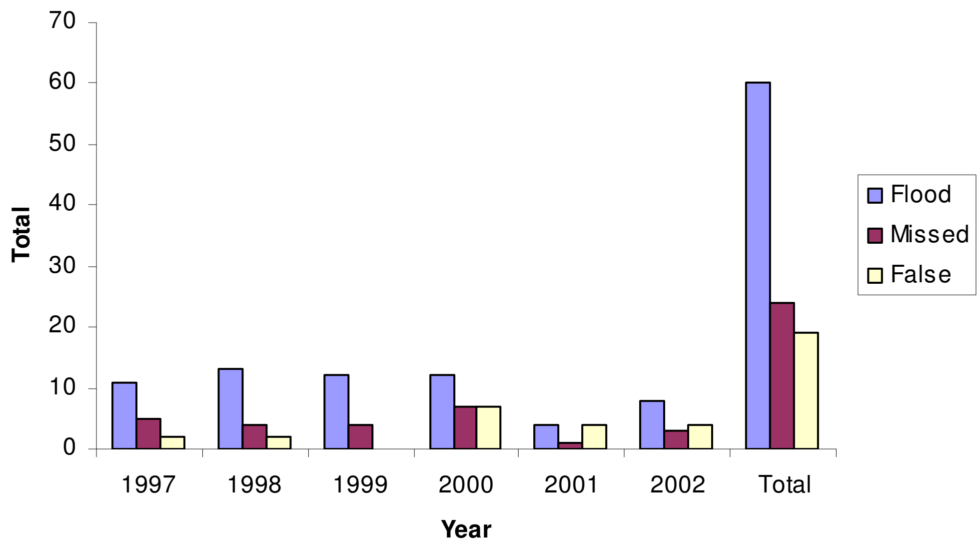

Figure 6-19 Missed floods and False flood warnings using rate of rise of 4.4 m/day and river height of 1.5 m

It can be seen that there has been a decrease in the number of missed floods but an increase in the number of false floods. The rate of rise is then decreased more as can be seen in Figure 6-20 and Table 6-12.

Table 6-12 Missed floods & False flood warnings using rate of rise of 2.7m/day and river height of 1.5m

Flood Type	1997	1998	1999	2000	2001	2002	Total
Flood	11	13	12	12	4	8	60
Missed	1	4	2	5	0	2	14
False	3	9	6	9	9	6	42

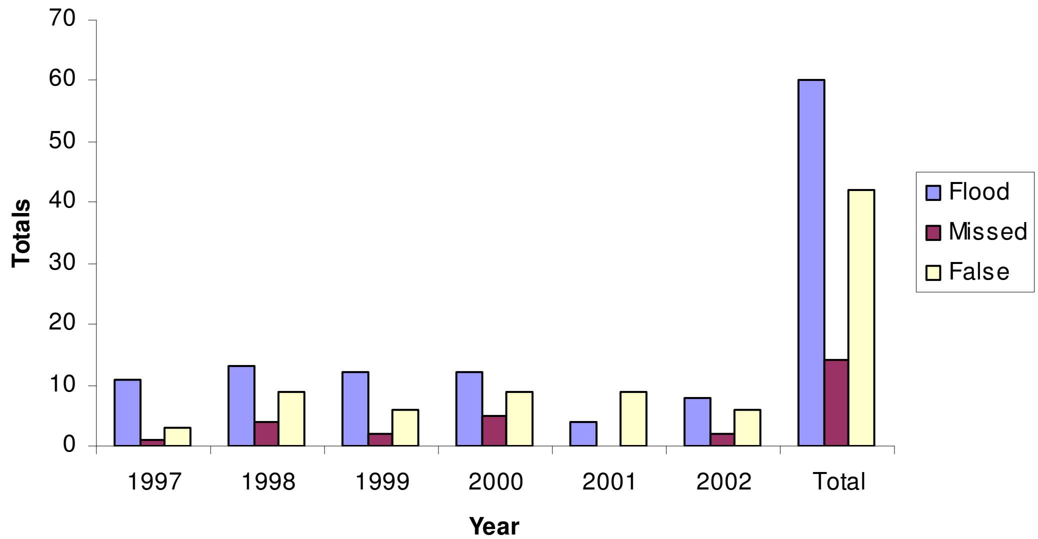

Figure 6-20 Missed floods and False flood warnings using rate of rise of 2.7 m/day and river height of 1.5 m

There is a large number of false floods predicted by the system (approximately 66%) the rate of rise and river height threshold is then increased as can be seen in Figure 6-21 and Table 6-13.

Table 6-13 Missed floods & False flood warnings using rate of rise of 3.6m/day and river height of 1.64m

Flood Type	1997	1998	1999	2000	2001	2002	Total
Flood	11	13	12	12	4	8	60
Missed	2	3	2	2	1	1	11
False	0	3	1	6	3	5	18

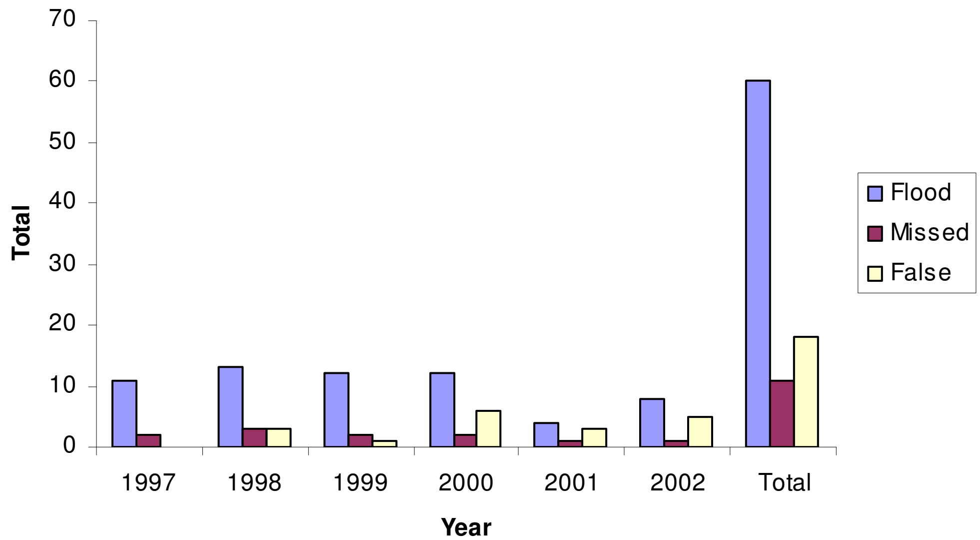

Figure 6-21 Missed floods and False flood warnings using rate of rise of 3.6 m/day and river height of 1.64 m

From this very preliminary analysis it is seen that combining the rate of rise with height is not as successful as expected. However, it is suggested that this concept may have potential and future research should focus on more rigorous analysis (e.g. sensitivity and optimization)

6.3.3 Increased Warning Time of Rate of Rise System

The increased warning time is estimated by subtracting the warning time given by the threshold flood warning system from the time given by the rate of rise flood warning system. The increase in warning time is noted in Table 6-14. The increase in warning time is represented in Figure 6-22 where there is an increase of 1.5 hours on the original warning given by the threshold flood warning system. It can be seen in Figure 6-22 (b) that once the rate of rise of river height threshold is broken an observation period of the river height begins. If in Figure 6-22 (a) the rate of rise of the river height exceeds the rate of rise in height threshold a flood warning is then given, as shown in the figure. Figure 6-22 (a) also shows the original threshold flood warning system threshold and the time at which the flood warning is given by this system. On average the threshold flood warning system gives a flood warning period of 5 hours (See Section 6.2.2.1). The average increase in flood warning time is 3 hours (Table 6-14) thus the rate of rise flood warning system will give an average flood warning time of approximately 8 hours.

Table 6-14 Increase in flood warning times using the rate of rise flood warning system

Year	1997	1998	1999	2000	2001	2002	Average
Increase in Warning Time (Hrs)	2.285	3.225	2.361	4.999	2.125	2.428	3

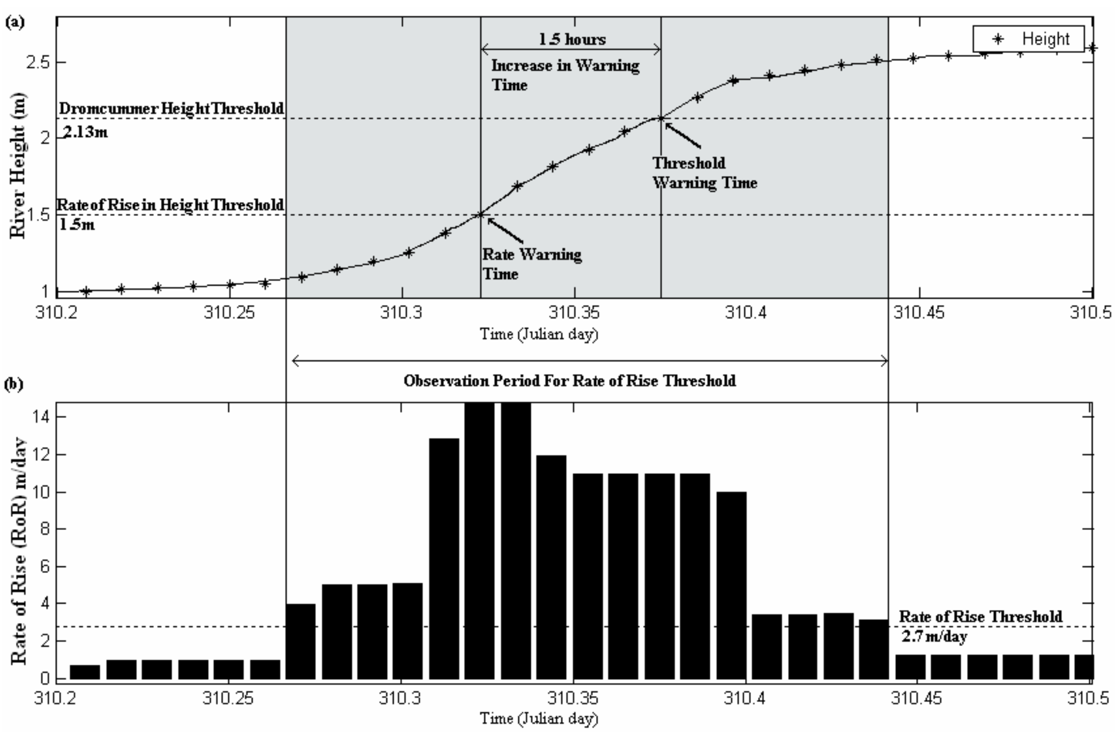

Figure 6-22 (a) River Height for typical flood event (6 Nov, 2000)

(b) Rate of Rise of River Height for typical flood event (6 Nov, 2000)

6.3.4 Accuracy

Equation [6-5] and equation [6-6] were used to calculate the accuracy of the rate of rise flood warning system, the accuracy for each year can be seen in Table 6-15.

Table 6-15 Accuracies for the Rate of Rise Flood Warning System

Year	1997	1998	1999	2000	2001	2002	Total
Flood	11	13	12	12	4	8	60
Missed	2	3	2	2	1	1	11
False	0	3	1	6	3	5	18
Miss Accuracy (%)	81	76	83	83	75	87	81
False Accuracy (%)	100	76	91	50	25	37	70

From Table 6-15 it is shown that the accuracy of the system in relation to missed floods is 81%, that is that the rate of rise flood warning system misses one out of five floods. This is a drop of 17% in accuracy compared to the threshold flood warning system. The accuracy of the system in relation to false flood warnings is 70%, in other words three out of the ten floods predicted by the system never occur downstream. This is a drop of 10% in the accuracy compared to the threshold method of flood warning.

The main advantage of the system can be seen in the flood warning time given by the system as seen in Table 6-14. There is on average an increase of 3 hours on the flood warning time provided by the threshold flood warning system, giving on average an overall flood warning time of 8 hours.

6.4 Results for Atmospheric Pressure Flood Warning System

The following analysis examines the results of the atmospheric pressure flood warning system for the Munster Blackwater catchment. Thresholds for the atmospheric pressure and for the rate of decrease of atmospheric pressure were examined during several flooding periods. Suitable thresholds for rate of decrease in pressure and pressure level were then estimated. These levels were tested and adjusted to improve on the accuracy of the system.

6.4.1 Atmospheric Pressure and Rate of Decrease in Pressure

The rate of decrease in atmospheric pressure was calculated using equation [6-8] where P represents the atmospheric pressure and T represents the time at which it was recorded.

$$\Delta P / \Delta T = P_t - P_{t-1} / T_t - T_{t-1} \qquad [6\text{-}8]$$

Figure 6-23 (a) shows the atmospheric pressure for the year 2000 and Figure 6-23 (b) shows the rate of change of atmospheric pressure for the year 2000. It can be seen from the figures that the peak rates of change of atmospheric pressure are found in the months commonly prone to flooding, i.e. October, November and December. It can also be seen that the lowest levels of atmospheric pressure can be seen in the months commonly prone to flooding.

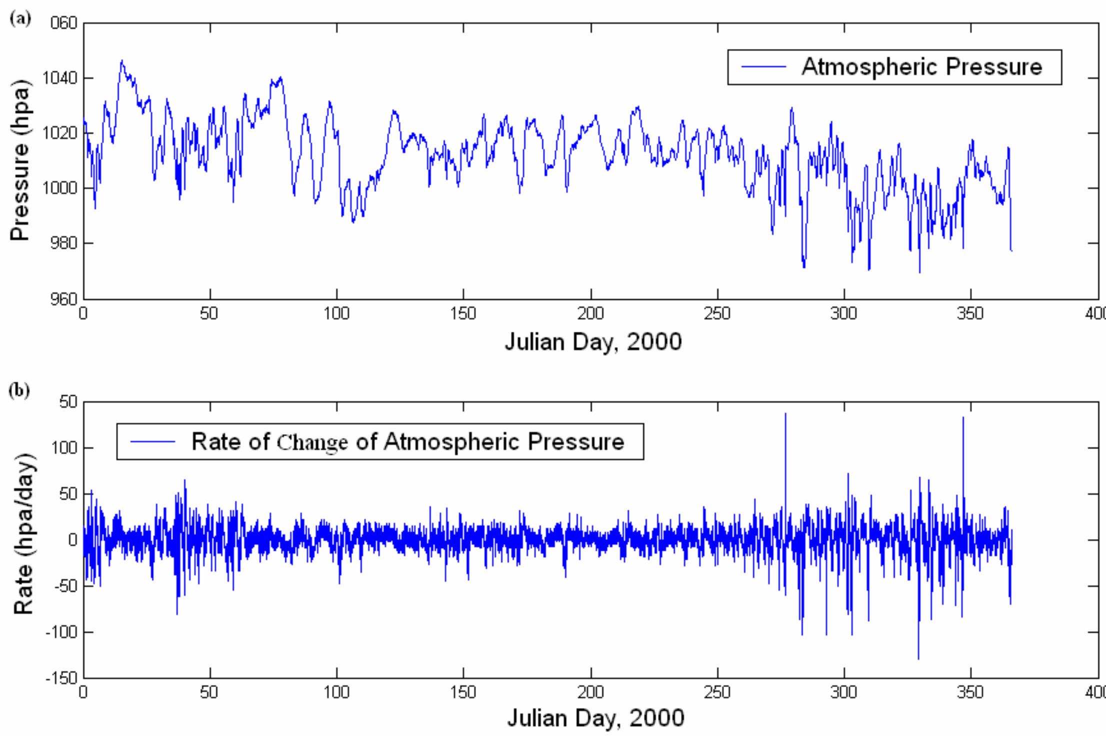

Figure 6-23 (a) Atmospheric pressure for the year 2000

(b) Rate of change of atmospheric pressure for the year 2000

6.4.2 Estimation of thresholds for Atmospheric Pressure System

Figure 6-24 (a) shows the atmospheric pressure during a flood event. Figure 6-24 (b) shows the rate of change of atmospheric pressure during a flood event. Figure 6-24 (c) shows the river height at the beet factory during a flood event. As shown in Figure 6-24 (a) the atmospheric pressure is low (983 hpa) a number of hours before the flood event. It is also noted that the rate of change of atmospheric pressure is a large negative value (-86 hpa/day) a number of hours before the flood event. It can be seen from this that a combination of the two low levels may indicate a flood event.

The rates of change of atmospheric pressure for 10 flood events were calculated, the lowest rate of change during that period was measured and an average obtained. the atmospheric pressure during the same 10 flood periods was also examined, the lowest atmospheric pressure was recorded and an average was obtained. These averages were used as the initial thresholds for the flood warning system.

An average rate of change of atmospheric pressure of -80 hpa/day was identified as well as a threshold atmospheric pressure of 985 hpa. These levels were tested and adjusted to obtain the most accurate pressure flood warning system. (See Table 6-16 and Figure 6-25)

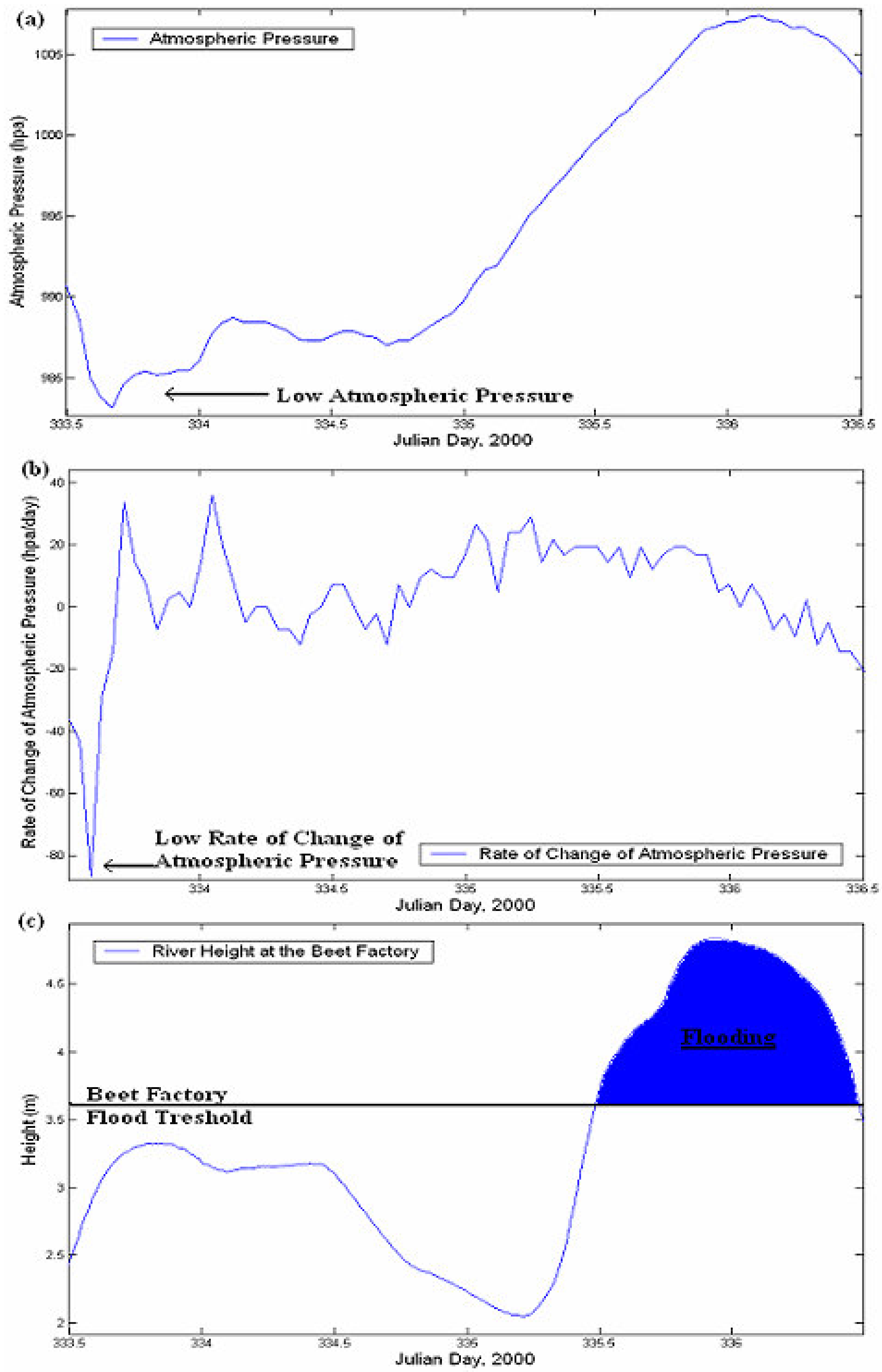

Figure 6-24 (a) Atmospheric pressure for a flood period (30 Nov – 2 Dec, 2000 (b)Rate of change off atmospheric pressure for a flood period (30 Nov – 2 Dec, 2000 (c) River height for a flood period (30 Nov – 2 Dec, 2000)

Table 6-16 Missed floods and False flood warnings using rate of change of pressure of -80hpa/day and atmospheric pressure of 995hpa

	2000	1999	1998	Total
Flood	7	9	9	25
Missed Floods	5	8	7	20
False Flood Warnings	3	1	2	6

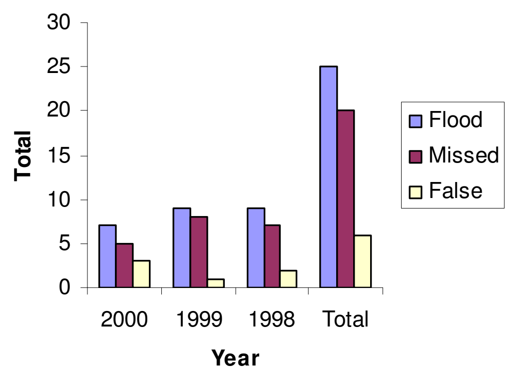

Figure 6-25 Missed floods and False flood warnings using rate of change of pressure of -80hpa/day and atmospheric pressure of 995hpa

It can be seen from Figure 6-25 that there are a large number of missed floods (Approximately 80%), the rate of change of pressure threshold is then changed to -70hpa/day and the atmospheric pressure threshold is increased by 5hpa from 985hpa to 990hpa (See Figure 6-26 and Table 6-17)

Table 6-17 Missed floods and False flood warnings using rate of change of pressure of -70hpa/day and atmospheric pressure of 990hpa

	2000	1999	1998	Total
Flood	7	9	9	25
Missed Floods	3	8	7	18
False Flood Warnings	4	1	1	6

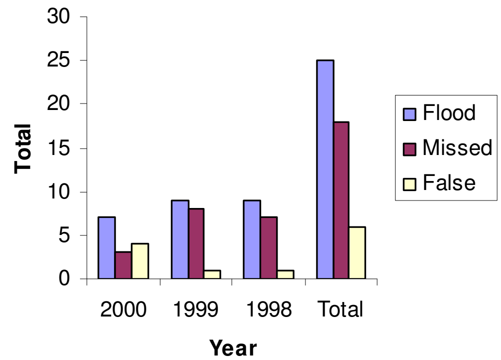

Figure 6-26 Missed floods and False flood warnings using rate of change of pressure of -70hpa/day and atmospheric pressure of 990hpa

The number of missed floods in Figure 6-26 is still quite large so the atmospheric pressure threshold is increased by 10hpa to 1000hpa (See Table 6-18 and Figure 6-27)

Table 6-18 Missed floods and False flood warnings using rate of change of pressure of -70hpa/day and atmospheric pressure of 1000hpa

	2000	1999	1998	Total
Flood	7	9	9	25
Missed Floods	1	7	5	13
False Flood Warnings	3	1	2	6

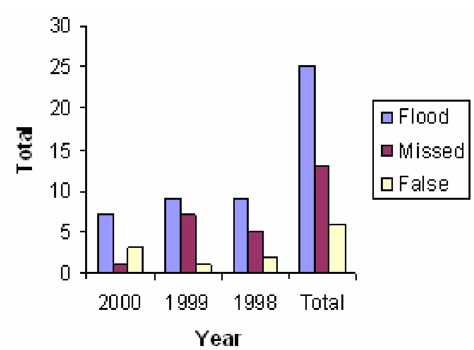

Figure 6-27 Missed floods and False flood warnings using rate of change of pressure of -70hpa/day and atmospheric pressure of 1000hpa

There is a significant drop in the number of missed floods (See Figure 6-27) but the number of missed floods must decrease further. The rate of change of pressure threshold is increased to -50hpa/day and the atmospheric pressure threshold is returned to 990hpa (See Table 6-19 and Figure 6-28).

Table 6-19 Missed floods and False flood warnings using rate of change of pressure of -50hpa/day and atmospheric pressure of 990hpa

	2000	1999	1998	Total
Flood	7	9	9	25
Missed Floods	0	3	4	7
False Flood Warnings	4	5	3	12

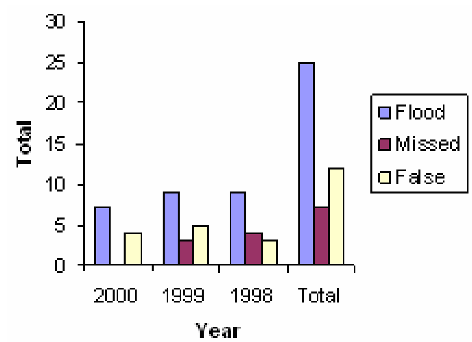

Figure 6-28 Missed floods and False flood warnings using rate of change of pressure of -50hpa/day and atmospheric pressure of 990hpa

The atmospheric pressure flood warning system therefore uses an atmospheric pressure threshold of 990 hpa and a rate of change of atmospheric pressure of – 50 hpa / day. It can be seen from the results in Table 6-19 that the flood warning system misses 7 out of 25 floods, that is almost 25% of the floods. It can also be seen that the system predicts 12 floods that never occur, therefore one in every two floods predicted never occurs. This system has a poor performance compared to the threshold flood warning system and the rate of rise flood warning system. Due to the fact that 50% of the warnings given are false, the system should not be relied on as heavily as the other two systems.

6.4.3 Warning Time of the Atmospheric Pressure Flood Warning System

The warning time is calculated by recording the time at which a flood warning is given by the atmospheric pressure flood warning system and subtracting the time at which the flood occurs at the beet factory (See Figure 6-29). As shown in Figure 6-29 when the rate of change of atmospheric pressure is exceeded an observation of the atmospheric pressure begins. If the atmospheric pressure breaks the atmospheric pressure threshold (i.e. decreases below 990 hpa) a flood warning is given.

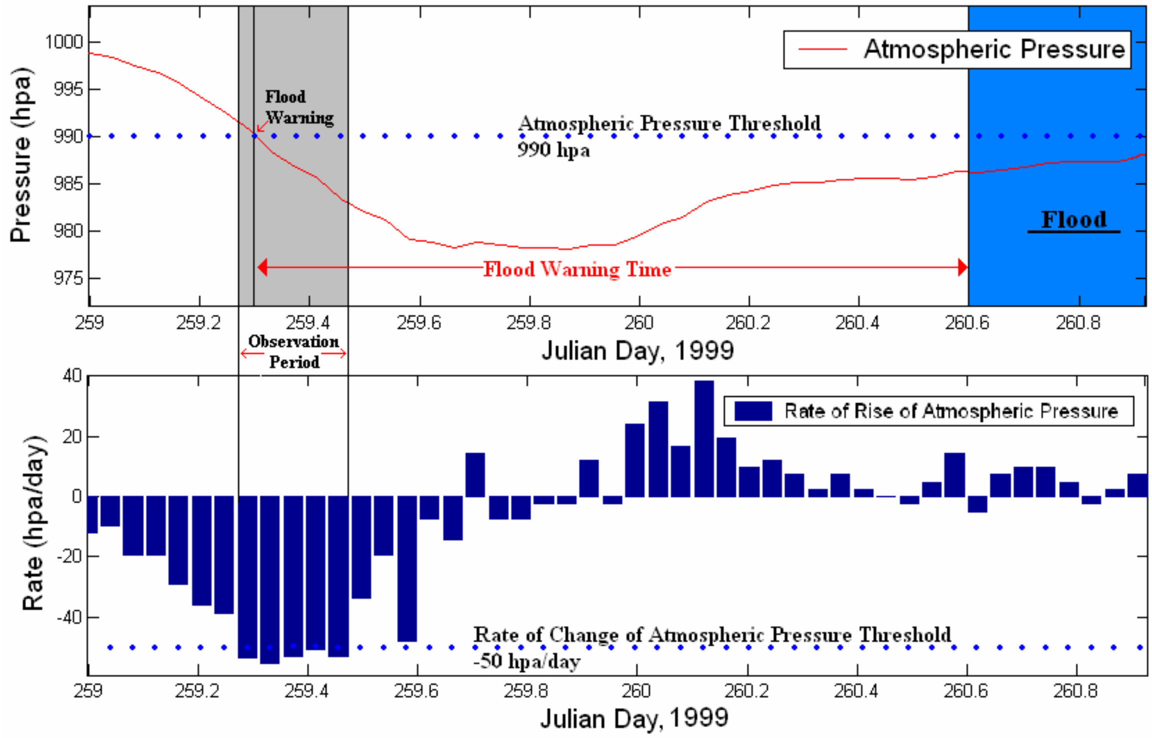

Figure 6-29 Example of flood warning period using pressure flood warning system

The average flood warning time is shown in Table 6-20. The average flood warning time provided by the system in this case is almost 19 hours, which is an increase of more than 100% on the flood warning time provided by the rate of rise flood warning system. There is an obvious trade off here between flood warning time provided and accuracy, as the accuracy of the system is relatively low compared to the other flood warning systems whereas the flood warning time is relatively large in comparison to the other flood warning systems.

Table 6-20 Flood warning times using the atmospheric pressure flood warning system

Year	1998	1999	2000	Average
Warning Time (Hrs)	20.16	10.83	24.79	18.59

6.4.4 Accuracy

Equations [6-5] and [6-6] were used to calculate the accuracy of the pressure flood warning system, the accuracy for each year can be seen in Table 6-21.

Table 6-21 Accuracies for the Rate of Rise Flood Warning System

	2000	1999	1998	Total
Flood	7	9	9	25
Missed	0	3	4	7
False	4	5	3	12
Miss Accuracy (%)	100	66	56	72
False Accuracy (%)	43	45	66	52

The accuracy of the system is lower than the previous two systems (26%). From this initial analysis it is seen that introducing the atmospheric pressure flood warning system is not as successful as first thought. However it does still provide a back up system to the river level recording systems such as the threshold flood warning system and rate of rise flood warning system. It is recommended that this concept should be examined using different methods such as incorporating rain gauges and modelling.

6.5 Results for Neural Network Flood Warning System

The artificial neural network model described in section 4.5 is trained on river height data and the results are analysed to develop a suitable neural network flood warning system. To determine the most suitable number of neurons, inputs, hidden layers, the transfer function, the performance function, training function and prediction time the neural network model is initially trained using one year's river height data of the three sites.

The historical data is then tested on the neural network; this historical data is split into two, a first data set to train the neural network and a second data to test the trained neural network. This network is then analysed for accuracy. It should be noted that during analysis the normalised sum square error was used, which is the same as the sum squared error (See Section 6.1 apart from the fact that the data is normalised).

6.5.1 Selection of Neural Network Model Variables

While one variable was being tested the other remained constant. In the process of selecting the optimum number of neurons was being selected the number of inputs remained constant. Default settings are then chosen before any values are adjusted. The default settings for the artificial neural network are given below.

Table 6-22 Default Settings for Artificial Neural Network

Network Type	Feed-Forward backprop
Training Function	Trainlm
Number of Layers	2
Number of Neurons	5
Transfer Function	(1) Log (2) Tan
Number of Inputs	6

To select the correct value for each variable the data is trained and tested over the same year. The data is trained and a network is generated, the same data is then entered into the network and the simulated output is plotted against the observed output. The accuracy of this network is then checked using the sum squared error. The lower the sum squared error, the better the result.

It should be noted that river height data while being used in the network is normalised (convert the values from 0 m to 5 m to from 0 to1 m) the sum squared error shown is therefore the normalised sum squared error.

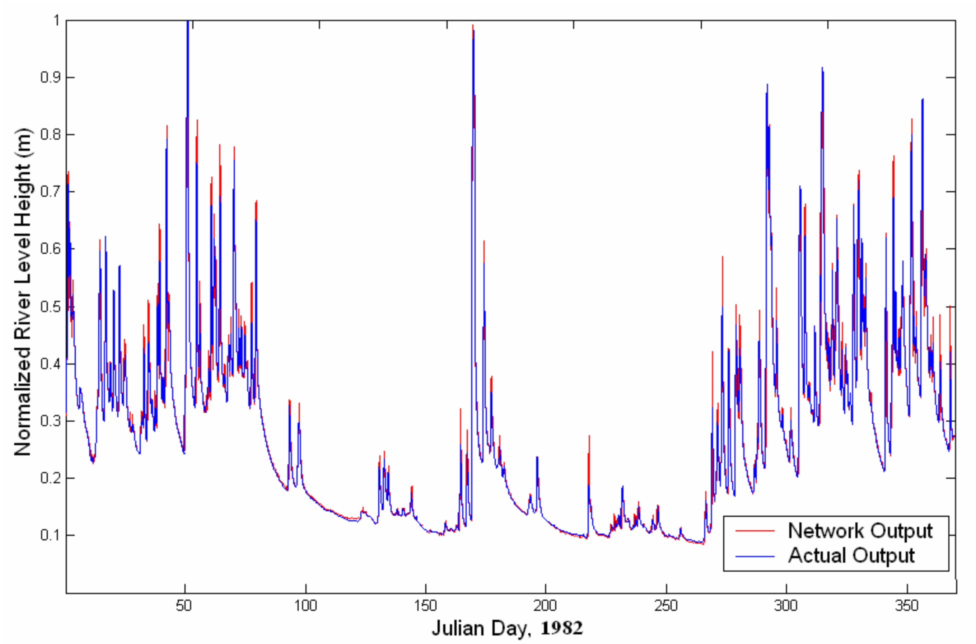

Figure 6-30 Artificial Neural Network simulated height and actual height vs. time

Figure 6-30 shows the simulation output of an artificial neural network when it is trained using the default settings. There is good agreement between the two plots due to the fact that this neural network has been trained on the river heights for 1982 and tested on the same data. The similarities between the two can be seen again in Figure 6-31. The sum squared error for this model is 21.56 m^2. That is sum of the square of the errors in the normalized data is 21.56 m^2.

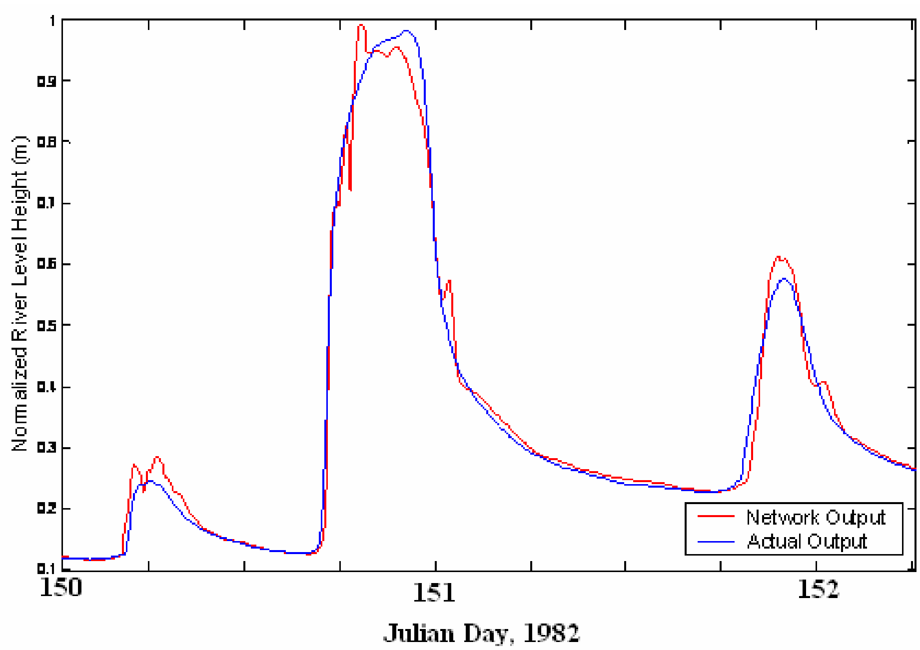

Figure 6-31 Close up of plot of Neural Network simulated output against the actual normalised river level height for julian day 150 to 152, 1982

6.5.1.1 Selection of number of neurons

The default number of neurons is five in the first and only hidden layer. Neural networks of varying numbers of neurons were then trained on a year's river height data and tested on the year's data to check for accuracy.

Table 6-23 The Sum Squared Error of a Neural Network for varying number of neurons

Number of Neurons	5	6	7	8	9	10	11
Sum Squared Error (m^2)	21.56	13.304	12.48	12.92	12.67	17.76	14.833

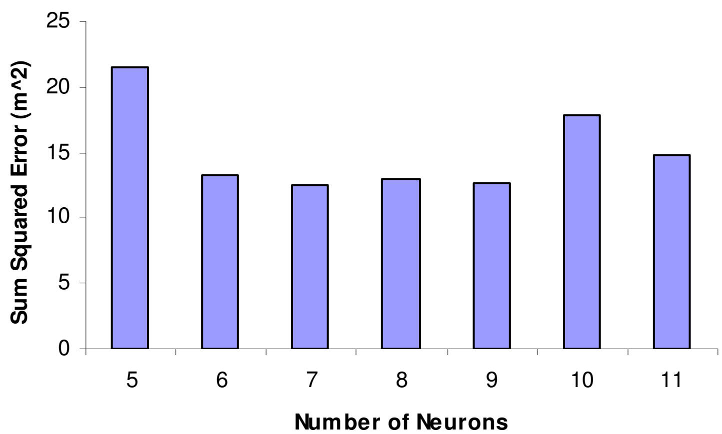

Figure 6-32 Sum Squared Error of a Neural Network vs. number of neurons

It can be seen from Table 6-23 and Figure 6-32 that the ideal number of neurons for a neural network with 6 inputs is 7 neurons. The ratio of n inputs: n +1 neurons will be used throughout the modelling, that is if there are 9 inputs, there should be 10 neurons.

6.5.1.2 Selection of number of layers

There are now seven neurons in the first layer (Layer A), the number of layers must now be adjusted to decrease the sum squared error. It can be seen in Table 6-24 that by adding another hidden layer to the model the sum squared error is first increased, but by adjusting the number of neurons in the second hidden layer the sum squared error is decreased.

Table 6-24 The Sum Squared Error of a Neural Network for varying number of layers and neurons

Number of Layers	2	3	3	3	3	3	4	4	4
Number of Neurons Layer A	7	7	7	7	7	7	7	7	7
Number of Neurons Layer B	1	8	7	6	5	4	6	6	6
Number of Neurons Layer C	0	1	1	1	1	1	6	5	4
Number of Neurons Layer D	0	0	0	0	0	0	1	1	1
Sum Squared Error (m^2)	12.48	14.9	11.2	10.7	13.2	13.9	14.4	13.4	2000

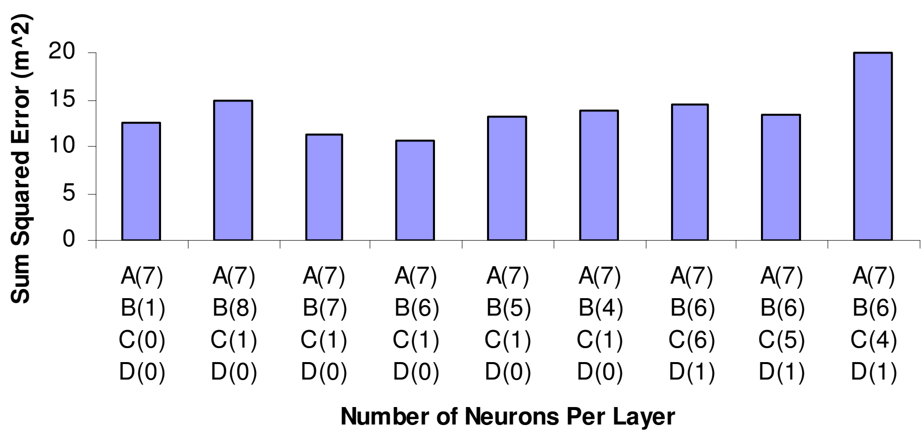

Figure 6-33 Sum Squared Error of a Neural Network vs. varying number of neurons

It can be seen from Figure 6-33 that by adding another layer (that is having 3 hidden layers) does not lower the sum squared error. It was therefore decided that the model will contain 2 hidden layers with seven neurons in the first and six neurons in the second.

6.5.1.3 Selection of transfer functions.

The transfer functions determine the output from each neuron. Each neuron in a layer has the same transfer function. There are therefore three transfer functions to determine: one between layer A the input layer and layer B; one between layer B and layer C; and one between layer C and the output. It can be seen from Table 6-25 and Figure 6-34 that the most suitable arrangement of transfer function is the original arrangement of Tan-Log-Log which means that the model uses a Tansig function between the first two layers, a Logsig function between the second two layers and another Logsig function between the last two layers.

Table 6-25 The sum squared error of a neural network for varying arrangements of transfer functions

Transfer Function	Tan-Log-Log	Log-Log-Log	Tan-Tan-Tan	Tan-Log-Tan
Sum Squared Error (m^2)	10.714	13.729	13.7604	12.6

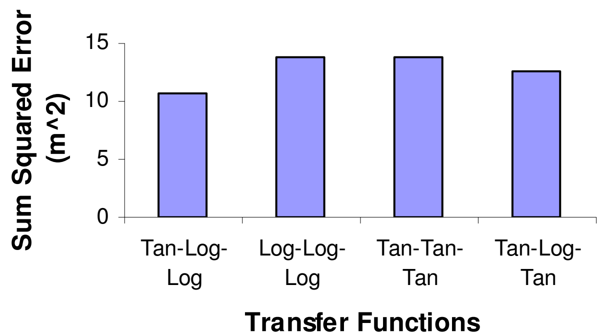

Figure 6-34 Sum squared error of a neural network for varying arrangements of transfer functions

6.5.1.4 Selection of training function.

The training function has a large role to play in the neural network model, as it determines how the model recognises patterns and learns trends. There are numerous possibilities of training functions, the most common and most relevant training functions were tested and the sum square error was calculated for each. The most relevant training functions were the following: trainlm (Levenberg-Marquardt back propagation), traingdx (gradient descent with momentum and adaptive learning rate back propagation) and traingdm (Gradient descent with momentum back propagation). It can be seen from Table 6-26 and Figure 6-35 that the most suitable training function is the default training function the Levenberg-Marquardt back propagation function.

Table 6-26 The sum squared error of a neural network for varying training functions

Training Function	TrainLm	Traingdx	Traingdm
Sum Squared Error (m^2)	10.714	165.744	227.137

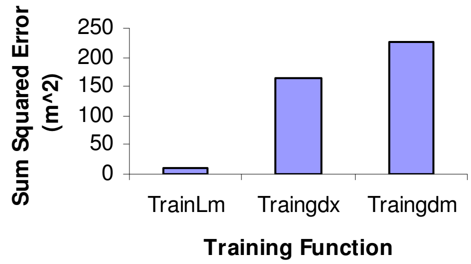

Figure 6-35 Sum squared error of a neural network for varying training functions

6.5.1.5 Selection of the number of inputs.

The selection of number of inputs is different to the selection of the other variables as there is a major limit on the number of inputs used in the model. Due to processing power as discussed in Section 4.5 there is a limit to the number of inputs which can be used. It can be seen from Table 6-27 and Figure 6-36 that when the number of inputs is increased the sum squared error decreases. Due to processing power limitations it is not possible to find the lowest sum squared error possible by increasing the number of inputs.

Table 6-27 The sum squared error of a neural network for varying number of inputs

Number of Inputs	6	18
Sum Squared Error (m^2)	10.714	3.5495

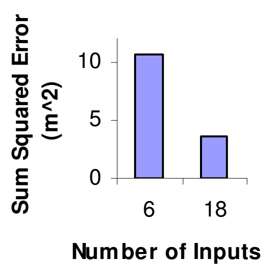

Figure 6-36 Sum squared error of a neural network for varying number of inputs

6.5.2 Prediction Time

The prediction time can be changed by changing the data the neural network is trained on. For example the model can be trained on data with an output (of river height) five or ten hours into the future. The accuracy of the system however will decrease with an increasing prediction time. This is so as river heights twenty four hours before a certain time have little or no impact on the river heights of the river at that time. As the basic flood warning system of river thresholds (Section 4.2) aimed at a warning time of five hours it was decided to design a neural network model with a ten hour prediction.

6.5.3 Accuracy

The artificial neural network was then designed with the following parameters (listed in Table 6-28). The final network had a sum squared error of 6.754 m^2.

Table 6-28 Parameters of Artificial Neural Network used in Neural Network Flood Warning System

Network Type	Feed-Forward backprop
Training Function	Trainlm
Number of Layers	3
Number of Neurons	(1) 7 (2) 6 (3) 1
Transfer Function	(1) Log (2) Tan (3) Tan
Number of Inputs	12
Prediction Time	10 hours

The data was trained on 17 years of data, 1982 to 1999 and tested on the years 2000, 2001 and 2002. Some results are presented in Figure 6-37, Figure 6-38, Figure 6-39 and Figure 6-40. Figure 6-40 shows the discrepancies that can occur using the neural network flood warning system.

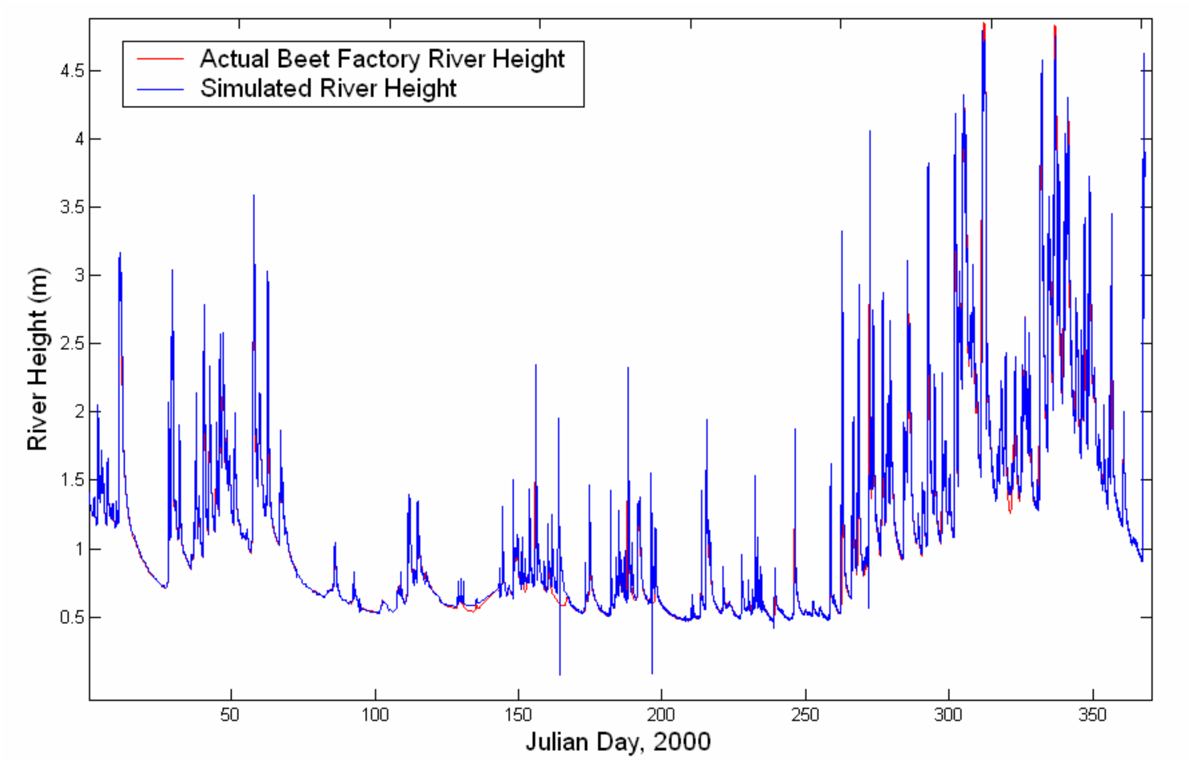

Figure 6-37 Simulated river height and actual river height, 2000

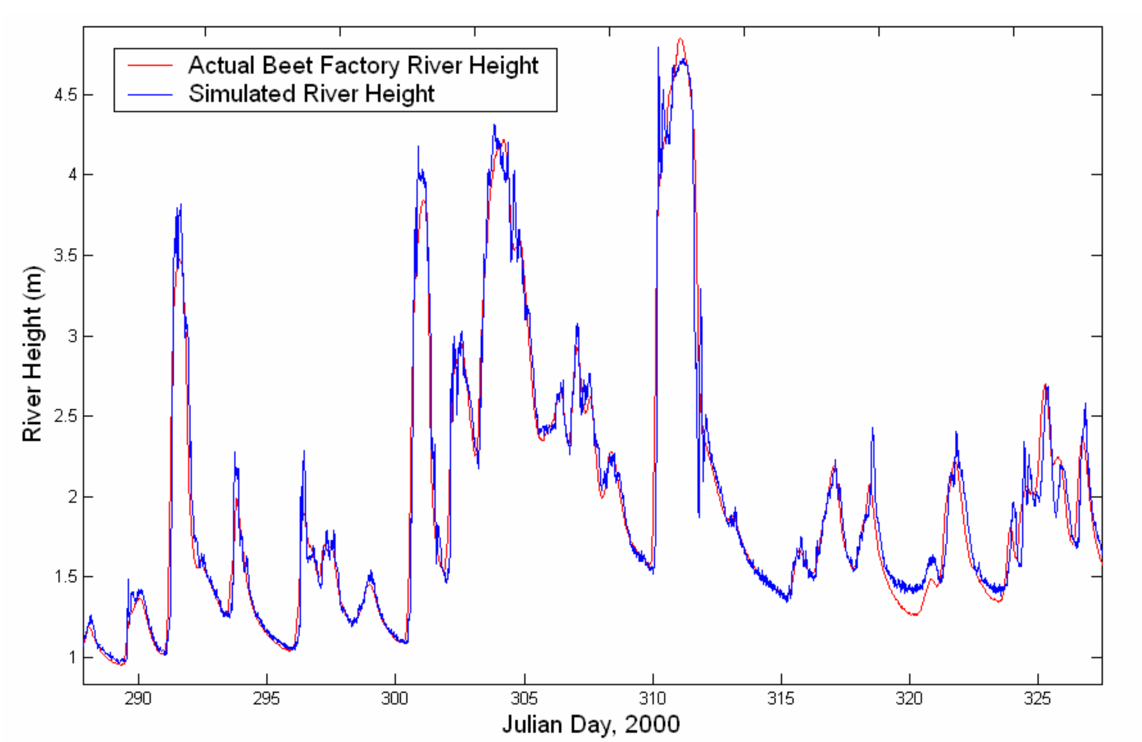

Figure 6-38 Simulated and actual river height for 17 Oct – 21 Nov, 2000

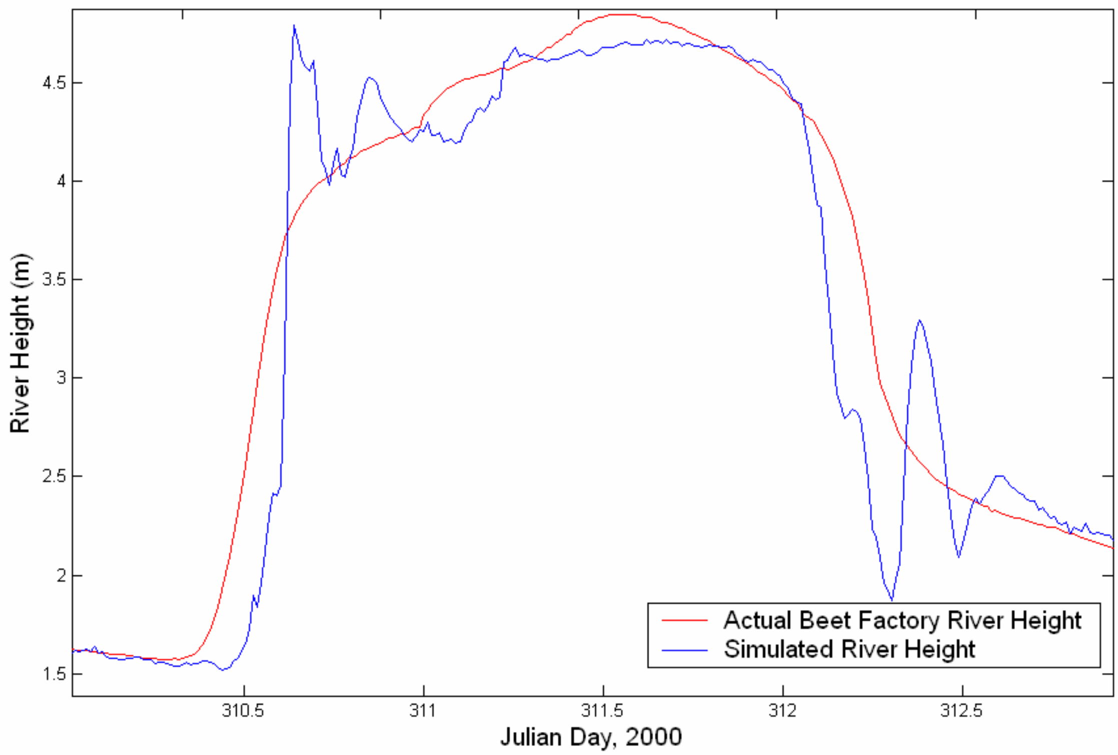

Figure 6-39 Simulated and actual river height for 6 Nov – 9 Nov, 2000

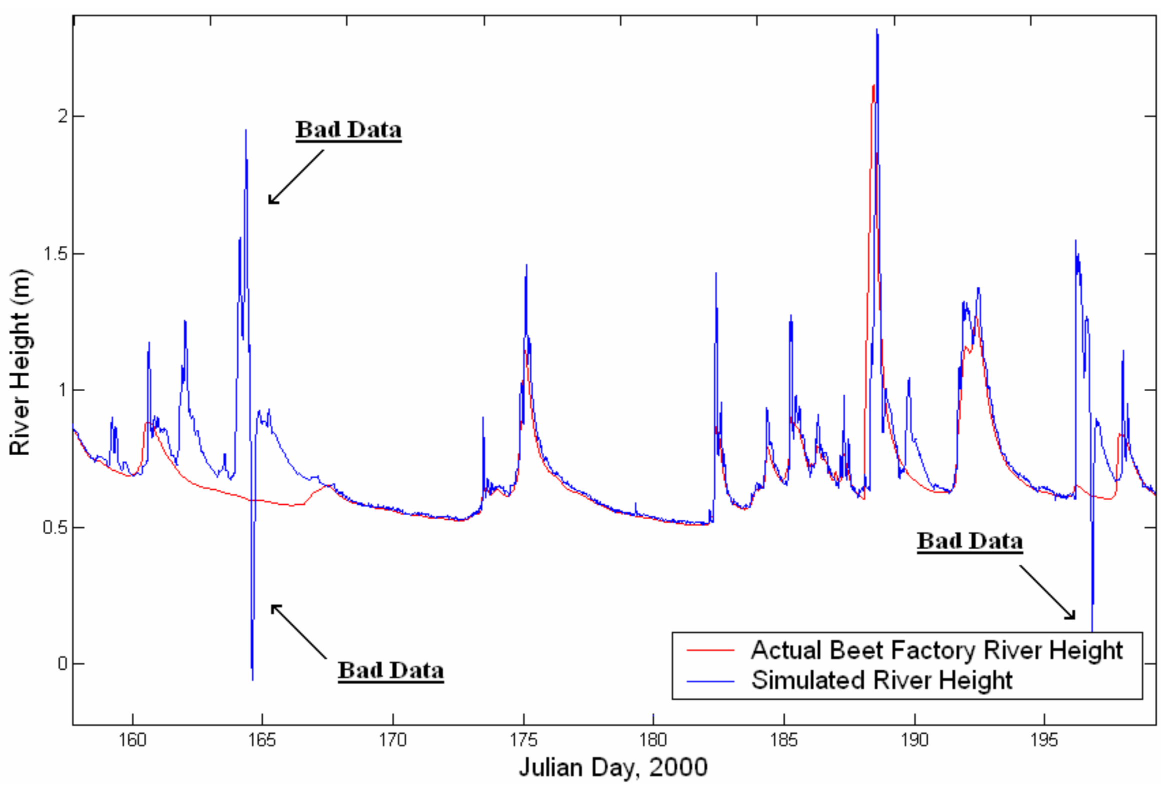

Figure 6-40 Simulated and actual river height for 9 Jun – 19 Jul, 2000

It can be seen from Figures 6-37 to Figures 6-40, that the neural network flood warning system an accurate modelling system. The system provides a 10 hour flood prediction with very little error. Upon inspection it was found that two flood peaks were simulated incorrectly. The river height prediction model simulated heights of 4 m and 3.7 m where in reality the heights were 3.4 m and 3.3 m respectively. Therefore the model predicted incorrectly two river heights at which flooding would occur. The missed flood accuracy of the system can be seen in Table 6-29. All actual flood peaks were represented correctly by the neural network flood warning system. Therefore the miss accuracy of the system is 100% as can be indicated in Table 6-29.

Table 6-29 Accuracies for the Neural Network Flood Warning System

	2000
Flood	7
Missed	0
False	2
Miss Accuracy (%)	100
False Accuracy (%)	73

Chapter 7

Discussion

7.1 Introduction

The flood warning systems analysed in chapter 6, are discussed to determine which may be the most suitable system for the Munster Blackwater Catchment. The possible integration of a number of warning systems is also discussed.

Table 7-1 Accuracies and Flood Warning Times (FWT) for Flood Warning Systems for stage 1 flooding.

	Miss Accuracy (%)	False Accuracy (%)	Average FWT (hours)	Range of FWT (hours)
TFWS	98	80	5	1.75 – 8
RRFWS	81	70	8	7 – 10
PFWS	72	52	18	10 – 25
NFWS	100	73	10	10

7.1.1 Threshold Flood Warning System (TFWS)

This flood warning system is currently in operation in the Munster Blackwater catchment and as seen in Section 6.2 is proving to be robust and efficient. A part of this research project was to improve the robustness of the system and this has been achieved. The results show that the average flood warning time of the system is approximately 5 hours with a range of 2 to 8 hours (See Table 7-1). This is the lowest flood warning time of all the flood warning systems analysed. The system has a miss accuracy of 98% for stage 1 flooding which is acceptable and the system has a false accuracy of 80% which means that 1 in every 5 floods predicted never occurs.

To set up the threshold flood warning system in another catchment considerable capital investment would be required which can be seen in Section 2.7 This would include a river height sensor, a data logger, a power supply and communications equipment. A base station system such as the one described in Section 2.9 would also be required. Some historical river height data for the site where the system is being installed as well as the flooding area is also required to determine, and continuously improve the river height threshold.

In summary, using the Dromcummer site (18 km upstream of Mallow), a typical warning time of five hours can be given and the warning is accurate approximately 86% of the time.

7.1.2 Rate of Rise Flood Warning System (RRFWS)

In Section 6.3 it is shown that this system adds an additional 3 hours flood warning time to the threshold flood warning system (See Table 7-1). However the accuracy of the combined system is compromised. The rate of rise flood warning system misses one in five floods. The system accuracy for false flood warnings is three out of ten.

The rate of rise flood warning system would be easy to incorporate into an existing threshold flood warning system as the required infrastructure is in place. It is planned to improve this concept and incorporate into the Muster Blackwater catchment in the next few months. To set up this flood warning system in another catchment the same infrastructure as the threshold flood warning system set up discussed in the previous section would be used. Similarly some historical river height data for the installation site as well as the area of flooding is also required to determine the correct rate of rise threshold and river height threshold.

In summary, the rate of rise warning concept has the potential to increase the warning time above that of the basic threshold system. However the accuracy of the prediction is less than that of the threshold system. Further work is required on this system.

7.1.3 Pressure Flood Warning System (PFWS)

As shown in Section 6.4 the pressure flood warning system is the least accurate of all flood warning systems. The missed flood accuracy of 72% means that the system misses approximately three out of the ten floods that occur. The false flood accuracy is 52% which means that for every two flood warnings provided, only one flood will occur (See Table 7-1).

The benefit of the pressure flood warning system is a large flood warning time compared to the threshold flood warning system. The flood warning time provided is approximately 18 hours. The range of warning times provided by the system is large, between 10 and 24 hours.

The pressure flood warning system requires an additional sensor – the barometer pressure sensor. Both live sites, Dromcummer and Duarrigle, currently do not contain an atmospheric pressure sensor. The installation of a pressure sensor would be quite simple and connection to the existing data logger would be straightforward.

To set up the pressure flood warning system in a new catchment it is similar to the set up of the rate of rise flood warning system and threshold flood warning system. A base recording station as well as site equipment such as an atmospheric pressure sensor, a data logger, a power supply and communications are required. Historical atmospheric pressure levels as well as historical river heights of flood events must also be obtained.

In summary the atmospheric flood warning system has the potential to increase the warning time up to as much as 24 hours. However the accuracy is low. It predicts floods on less than half the occasions. Further research is required to improve the system.

7.1.4 Neural Network Flood Warning System (NFWS)

This system proves to be the most accurate of all flood warning systems. It can be seen from Figures 6-37 and 6-39 that the simulation output of the neural network model is almost identical to the observations, giving a flood warning time of 10 hours.

The flood warning time as well as the number of inputs can also be increased if the processing power of the computer used to create the model is increased. By increasing the flood prediction time the accuracy of the system may decrease however to compensate for this the number of inputs to the neural network may be increased. This flood warning system should be incorporated as soon as possible into the Muster Blackwater Catchment.

This is an original concept and there are no live examples of this system in operation. The data recording program will have to automatically output the river height data to a file which may be read by a program running the neural network model. This program must then analyse the river height data and this data must be input sequentially into the neural network model. The program running this model must then output the results to a file which may be analysed graphically.

A current drawback is that since the neural network model uses an input from the Beet Factory site, it is required that data must be obtained from this site on a regular basis. This means that telecommunications system must be set up at the Beet Factory. This would require a GSM modem or landline. The installation of this system would be relatively easy, and the current drawback is cost.

To install in a new catchment however a threshold flood warning system must first be installed, that is two or more sites with river height recording equipment as well as a data logger, power supply and communications must be set up. A base station where the data can be recorded and analysed must all be set up. A great deal of historical river height data is also required in order to train the neural network.

In summary, the artificial neural network flood warning system is showing great promise. The system developed here gives a flood warning time of ten hours (this can easily be adjusted up or down) with almost perfect accuracy. The hydrograph outputs almost mimic the observations.

7.2 Comparisons of Flood Warning Systems

To determine which is the most suitable flood warning system it must first be decided what is the most important characteristic of a flood warning system; the number of floods missed by the system, the number of false flood warnings given by the system or the flood prediction time. In this project it was decided that the number of floods missed by the flood warning system and flood prediction time are the most important factors.

The flood warning systems were then compared to determine which is the most suitable flood warning system was for the Munster Blackwater. A simple weighting system was introduced to identify which was the optimum flood warning system. The miss accuracy was given a weighting of three, the false accuracy was given a weighting of two and the flood warning time (since it was such a low number) was given a weighting of five (See Table 7-2).

Table 7-2 Weighting and Ranking of Flood Warning System

	Miss Accuracy Weighting	False Accuracy Weighting	Warning Time Weighting	Total Weighting	Rank
TFWS	294	160	25	479	2
RRFWS	243	140	40	423	3
PFWS	216	104	90	410	4
NFWS	300	146	50	496	1

It can be seen from Table 7-2 that the neural network flood warning system is ranked number 1, which means that this is the best form of flood warning system analysed. The threshold flood warning system is second best due to its low warning time. While the rate of rise flood warning system proved to be third best due to its miss accuracy and the pressure flood warning system proved to be least favourable due to its low miss accuracy and low false accuracy.

7.3 Costs

This system of ranking in Section 7.2 did not take into account the costs involved in the set up of each flood warning system. If a flood warning system was set up in a new catchment the costs involved in set up of such a system would have to be considered. The approximate cost of set up of a single flood warning system are shown in Table 7-3.

Table 7-3 Costs of equipment

Equipment	Cost (€)
Mains Power	?
Site Infrastructure	5000
Sensors	3000
Data Logger	2000
Power Supply	500
GSM Modem	500
Base Station Console	2000
	13000

Mains power is essential and its cost is site dependant. In addition to the costs of infrastructure and sensors, estimated costs for computer scientist / engineer of about three months should be included at about €12,000. the site owners would also have to consider a maintenance cost.

7.4 Optimization of the Flood Warning Systems

The current system provides a warning time of approximately five hours, and is successful about 85% of the time. the single best way to improve on this is to add a modelling component. By incorporating the artificial neural network modelling scheme the warning time can be increased to ten hours and the accuracy significantly improved, from a perspective of less false warnings and less missed floods. Furthermore, the height of the flood can be predicted, i.e. whether the flood is likely to be a stage3, stage 2 or stage 1 flood event.

Chapter 8
Conclusion

8.1 Conclusions

The main conclusion of the analysis of flood warning concepts is that the flood warning system currently in place (the threshold flood warning system) in the Blackwater catchment, although providing a small flood warning time (approximately 5 hours), is reasonably accurate. The system over the period October 2003 to October 2004 has proved to be robust. Further measures, such as the integration of a GSM modem at both sites, are desirable to improve the systems reliability.

The integration of the website has enhanced the system and has been viewed over a thousand times since it was set up. It provides the people of Mallow with direct access to the flood warning system which speeds up communication of flood warnings. Feedback from users of the website has been positive and suggestions have been noted and changes to the website have been made.

The rate of rise (of river height) as a concept has potential to improve the warning time and accuracy of the river threshold system. A more rigorous examination of this concept is required. The inclusion of a barometric pressure sensor has the potential to improve the warning time significantly. The current analysis needs to be extended before judging this concept.

The neural network flood warning system has proved to be a very useful method of flood warning and should be set up as soon as possible in the Blackwater catchment. The neural network flood warning system's accuracy is excellent and the flood warning time provided is adequate for any flood protection plans made by the local authorities such as road blocks and diversions. With the development of more powerful computers the increased processing power would allow more accurate neural network models with more inputs (see Section 8.3). It is expected that the neural network model of flood warning will be used more extensively in the years to come.

8.2 Recommendations

1. Integrate the rate of rise flood warning system into the existing flood warning system.
   Reason: The flood warning time provided by the system is on average 60% greater than the flood warning time provided by the threshold flood warning system.

2. Integrate the atmospheric pressure flood warning system into the existing flood warning system.
   Reason: Apart from the large increase in flood warning time provided; the pressure flood warning system does not use river heights and the corresponding sensors. This would provide a back up system in the case of sensor failure

3. Integrate the neural network flood warning system into the existing flood warning system
   Reason: The accuracy of the neural network system is excellent. It also provides a significantly longer flood warning time than the basic river height threshold system.

4. Integrate the neural network flood warning system into the flood warning system website.
   Reason: This would give the people of Mallow access to a much more accurate flood warning system with a much greater warning time.

5. Publicise the flood warning system website.
   Reason: To ensure that the wider community of Mallow know of the website and can make use of it.

8.3 Suggestions for further research

- Increase the warning time of the neural network flood warning system. Using a more powerful computer, use more inputs to improve on accuracy.

- Connect other catchments to the website to create an all Ireland flood warning system.

- Incorporate rain gauges and a rainfall run off model into the flood warning system

- Incorporate rainfall or atmospheric pressure into the neural network, which would increase the flood warning time provided by the system.

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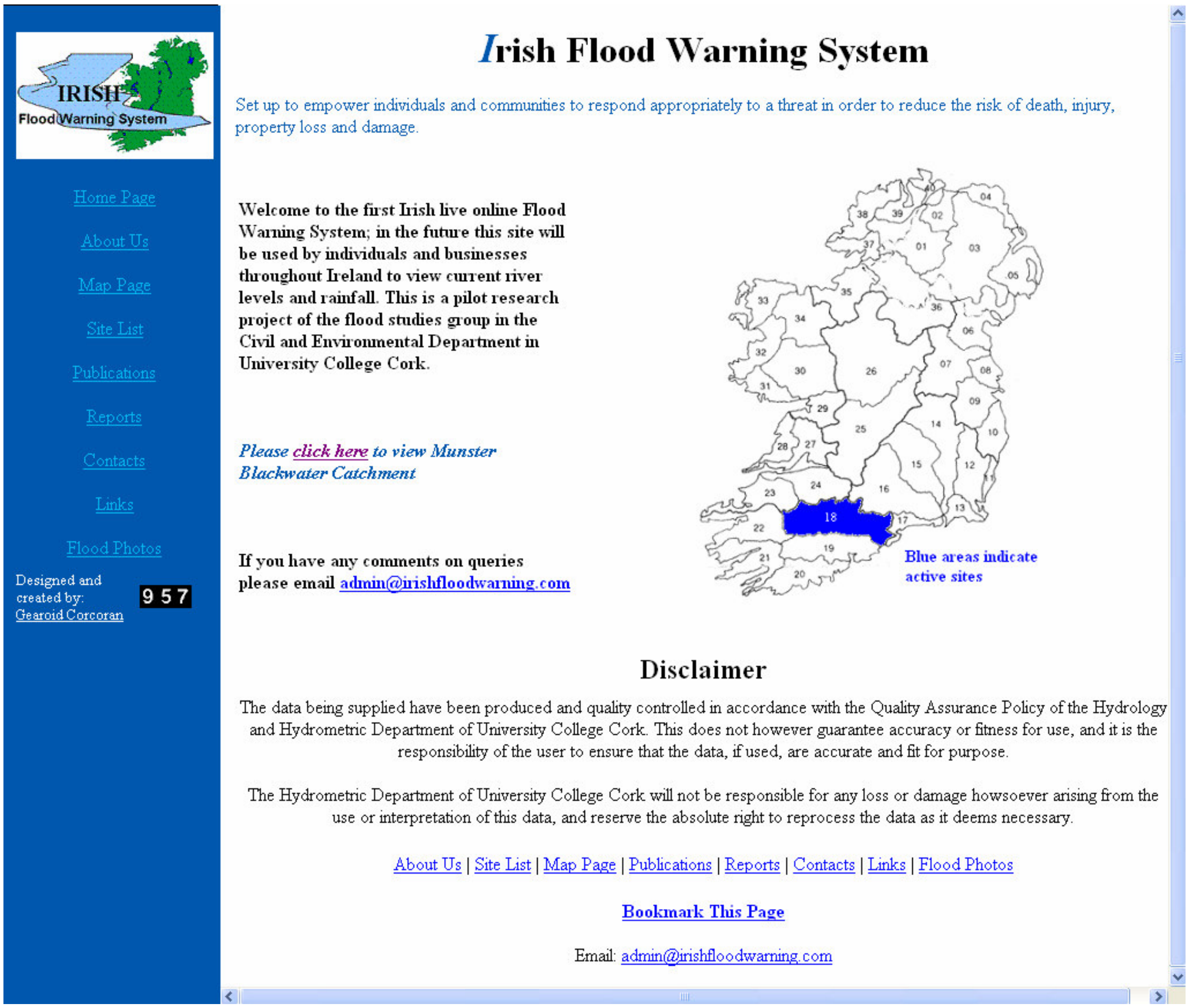
Appendices

Appendix A Screen Shot of Irish Flood Warning Website



Appendix B Sample of html code used in design of website

There are approximately 43 individual webpages, each webpage containing on average two to three pages of text. Rather than showing all the html code used in the project a sample is shown below.

index.html

```
<!DOCTYPE HTML PUBLIC "-//W3C//DTD HTML 4.01 Frameset//EN" "http://www.w3.org/TR/html4/frameset.dtd">
<html>
<head>
<title>Munster Blackwater Flood Warning Webpage</title>
<meta http-equiv="Content-Type" content="text/html; charset=iso-8859-1">
<meta name="Title" content="Irish Flood Warning Webpage">
<META NAME="Author" CONTENT="Gary Corcoran">
<META NAME="Subject" CONTENT="Flood Warning Webpage">
<META NAME="Description" CONTENT="~This is Irelands first live flood warning webpage">
<META NAME="Keywords" CONTENT="irish, flood, warning, river, level, munster, blackwater">
<META NAME="Language" CONTENT="English">
<META NAME="Distribution" CONTENT="Global">
<META NAME="Robots" CONTENT="All">


</head>

<frameset rows="*" cols="190,*" framespacing="0" frameborder="no" border="0">
  <frame src="linksbar.html" name="leftFrame" scrolling="NO" noresize>
                          <frame src="homepage.html" name="mainFrame">
  </frameset>

</frameset><noframes></noframes>
</html>
```

Homepage.html

```
<!DOCTYPE HTML PUBLIC "-//W3C//DTD HTML 4.01 Transitional//EN"
"http://www.w3.org/TR/html4/loose.dtd">
<html>
<head>
<!-- TemplateBeginEditable name="doctitle" -->
<title>Blackwater Flood Warning</title>
```

```
<!-- TemplateEndEditable -->
<meta http-equiv="Content-Type" content="text/html; charset=iso-8859-1">
<!-- TemplateBeginEditable name="head" -->
<!-- TemplateEndEditable -->
<style type="text/css">
<!--
.style1 {color: #0057AE}
.style3 {   color: #0057AE;
            font-weight: bold;
            font-style: italic;
            font-size: 36px;
}
.style8 {   color: #0057AE;
            font-weight: bold;
            font-style: italic;
}
-->
</style>
<script language="JavaScript" type="text/JavaScript">
<!--
function MM_preloadImages() { //v3.0
  var d=document; if(d.images){ if(!d.MM_p) d.MM_p=new Array();
    var i,j=d.MM_p.length,a=MM_preloadImages.arguments; for(i=0; i<a.length; i++)
    if (a[i].indexOf("#")!=0){ d.MM_p[j]=new Image; d.MM_p[j++].src=a[i];}}
}

function MM_findObj(n, d) { //v4.01
  var p,i,x;  if(!d) d=document; if((p=n.indexOf("?"))>0&&parent.frames.length) {
    d=parent.frames[n.substring(p+1)].document; n=n.substring(0,p);}
  if(!(x=d[n])&&d.all) x=d.all[n]; for (i=0;!x&&i<d.forms.length;i++) x=d.forms[i][n];
  for(i=0;!x&&d.layers&&i<d.layers.length;i++) x=MM_findObj(n,d.layers[i].document);
  if(!x && d.getElementById) x=d.getElementById(n); return x;
}

function MM_showHideLayers() { //v6.0
  var i,p,v,obj,args=MM_showHideLayers.arguments;
  for (i=0; i<(args.length-2); i+=3) if ((obj=MM_findObj(args[i]))!=null) { v=args[i+2];
    if (obj.style) { obj=obj.style; v=(v=='show')?'visible':(v=='hide')?'hidden':v; }
    obj.visibility=v; }
}

function MM_swapImgRestore() { //v3.0
  var i,x,a=document.MM_sr; for(i=0;a&&i<a.length&&(x=a[i])&&x.oSrc;i++) x.src=x.oSrc;
```

```
}

function MM_swapImage() { //v3.0
  var i,j=0,x,a=MM_swapImage.arguments; document.MM_sr=new Array; for(i=0;i<(a.length-2);i+=3)
   if ((x=MM_findObj(a[i]))!=null){document.MM_sr[j++]=x; if(!x.oSrc) x.oSrc=x.src; x.src=a[i+2];}
}
//-->
</script>
</head>

<SCRIPT LANGUAGE="JavaScript">

function addbookmark()
{
bookmarkurl="http://www.irishfloodwarning.com";
bookmarktitle="Flood Warning Webpage";
if (document.all)
window.external.AddFavorite(bookmarkurl,bookmarktitle);
}

</script>
<body onLoad="MM_preloadImages('irishmaphighlight.PNG','buttoninv.JPG')">
<TABLE WIDTH="100%" BORDER="0" CELLPADDING="0" CELLSPACING="0">
  <Tr>
    <Td><div style="text-align:CENTER; ">
      <table width="100%"  border="0">
        <tr>
          <td width="99%"><h1 align="center"><span class="style3">I</span><font color="#000000">rish Flood Warning System </font></h1>
            <p align="left" class="style1">Set up to empower individuals and communities to respond appropriately to a threat in order to reduce the risk of death, injury, property loss and damage.</p>
            <table width="100%">
              <tr>
                <td width="36%"><p align="left"><strong>Welcome to the first Irish live online Flood Warning System; in the future this site will be used by individuals and businesses throughout Ireland to view current river levels and rainfall. This is a pilot research project of the flood studies group in the Civil and Environmental Department  in University College Cork.</strong></p>
                  <p align="left"> </p>
                  <p align="left"><span class="style8">Please <a href="mappage.html">click here</a> to view Munster Blackwater Catchment</span></p>
                  <p align="left"> </p>
```

```
<p align="left"><strong>If you have any comments on queries please email <a href="mailto:%20admin@irishfloodstudies.com">admin@irishfloodwarning.com</a></strong></p>
</td>
<td width="64%" rowspan="3"><h2 align="center"><img src="irishmap.PNG" name="Image1" border="0" usemap="#campus" id="Image1" >
  <map name="campus">
   <area shape="poly" coords="91,298,75,301,74,320,87,326,101,325,107,322,113,323,119,321,156,326,164,334,172,323,174,319,177,303,149,303,148,292,139,293,136,286,128,292,122,290,112,293,100,295" href="blackhome.html" onMouseOver="MM_showHideLayers('Ballyd','','show');MM_swapImage('Image1','','irishmaphighlight.PNG',1)" onMouseOut="MM_showHideLayers('Ballyd','','hide');MM_swapImgRestore()" >
  </map>
</h2>
<p></p>
<div id="Ballyd" style="position:absolute; left:399px; top:326px; width:83px; height:21px; z-index:1; background-color: #FFFFFF; font-weight: bold; visibility: hidden;">
 <table width="100%"  border="2" bordercolor="#000000">
  <tr>
   <td><div align="center">
    <p><b>The Munster Blackwater Catchment.</b></p>
    <p><img src="http://rennes.ucc.ie/~gearoidc/warningvalue.png" name="Image3" id="Image3"></p>
   </div></td>
  </tr>
 </table>
</div>        </td>



 </tr>
</table>
<h2>Disclaimer</h2>
<p>The data being supplied have been produced and quality controlled in accordance with the Quality Assurance Policy of the Hydrology and Hydrometric Department of University College Cork. This does not however guarantee accuracy or fitness for use, and it is the responsibility of the user to ensure that the data, if used, are accurate and fit for purpose. </p>
<p>The Hydrometric Department of University College Cork will not be responsible for any loss or damage howsoever arising from the use or interpretation of this data, and reserve the absolute right to reprocess the data as it deems necessary.</p>
<table width="100%"  border="0">
 <tr>
  <td><div align="center"><a href="about.html" target="mainFrame">About Us</a> | <a href="site.html" target="mainFrame" >Site List</a> | <a href="homepage.html" target="mainFrame" >Map Page</a> | <a href="pubs.html"
```

```
target="mainFrame">Publications</a> | <a href="journals.html" target="mainFrame">Reports</a> | <a href="contacts.html" target="mainFrame">Contacts</a> | <a href="links.html" target="mainFrame">Links</a> | <a href="photos.html" target="mainFrame">Flood Photos</a> </div></td>
       </tr>
      </table>
      <div align="left">
       <p align="center"><font color="#000000"><A href="javascript:addbookmark()"><B>Bookmark This Page</B></A> <BR>
       </font></p>
      </div>
      <CENTER>
       <P><font color="#000000">Email: <A href="mailto:admin@irishfloodwarning.com">admin@irishfloodwarning.com</A></font></P>
      </CENTER>      </td>
    </tr>
   </table>
   <div align="left">
    <table width="100%"  border="0">

     </table>



    </div>
  </div></Td>
 </Tr>

</TABLE>
</body>
</html>
```

linksbar.html

```
<!DOCTYPE HTML PUBLIC "-//W3C//DTD HTML 4.01 Transitional//EN">
<html>
<head>
<title>Untitled Document</title>
<meta http-equiv="Content-Type" content="text/html; charset=iso-8859-1">
<style type="text/css">
<!--
body {
        background-color: #0057AE;
}
.style3 {color: #FFFFFF}
```

```
.style5 {color: #FFFFFF; font-size: x-small; }
.style6 {font-size: x-small}
-->
</style></head>
<body>
<table width="100%"  border="0">
<tr><td height="131" colspan="2"><img src="logo.GIF"> </td>
  <tr>
    <td height="339" colspan="2"><p align="center" class="style3"><A href="homepage.html" target=mainFrame><U><font color=##71b8ff>Home Page</font></U></A></p>      <p align="center" class="style3"><A
      href="about.html" target=mainFrame><U><font color=##71b8ff>About Us</font></U></A></p>
      <p align="center" class="style3"><A
      href="homepage.html" target=mainFrame><U><font color=##71b8ff>Map Page </font></U></A></p>
      <p align="center" class="style3"><A
      href="site.html" target=mainFrame><U><font color=##71b8ff>Site List</font></U></A></p>
      <p align="center" class="style3"><A
      href="pubs.html" target=mainFrame><U><font color=##71b8ff>Publications</font></U></A></p>
      <p align="center" class="style3"><A
      href="pubs.html" target=mainFrame><U><font color=##71b8ff>Reports</font></U></A></p>
      <p align="center" class="style3"><A
      href="contacts.html" target=mainFrame><U><font color=##71b8ff>Contacts</font></U></A></p>
      <p align="center" class="style3"><A
      href="links.html" target=mainFrame><U><font color=##71b8ff>Links</font></U></A></p>
    <p align="center" class="style3"><A
      href="photos.html" target=mainFrame><U><font color=##71b8ff>Flood Photos</font></U></A></p>    </td>
  </tr>
  <tr>
    <td><p class="style3 style6">Designed and created by: <span class="style6"><a href="mailto:garycocs@hotmail.com"><font color="#FFFFFF">Gearoid Corcoran</font></a></span> </p></td>
    <td><span class="style3"><IMG SRC="http://counter.digits.com/wc/-d/4/irishfloodwarning" ALIGN=middle WIDTH=60 HEIGHT=20 BORDER=0 HSPACE=4 VSPACE=2></span></td>
  </tr>
</table>

</body>
</html>
```

Appendix C Sample of Matlab code

dataplotthesis.m

```
load beet01.dat;
load beet02.dat;
load beet03.dat;
beetheight01 = beet01(:,7);
beetheight02 = beet02(:,7);
beetheight03 = beet03(:,7);
beetdate01 = beet01(:,6);
beetdate02 = beet02(:,6);
beetdate03 = beet03(:,6);
beetmax01 = max(beetheight01);
beetmax02 = max(beetheight02);
beetmax03 = max(beetheight03);
beetmin01 = min(beetheight01);
beetmin02 = min(beetheight02);
beetmin03 = min(beetheight03);

figure(1)
plot(beetdate02,beetheight02,'b');
xlabel('Time (Julian Day)','FontSize',14);
ylabel('River Height (m)','FontSize',14);
legend('Beet Factory Height');
load drom01.dat;
load drom02.dat;
load drom03.dat;
load drom87.dat;
dromheight01 = drom01(:,7);
dromheight02 = drom02(:,7);
dromheight03 = drom03(:,7);
dromheight87 = drom87(:,7);
dromdate01 = drom01(:,6);
dromdate02 = drom02(:,6);
dromdate03 = drom03(:,6);
dromdate87 = drom87(:,6);
drommax01 = max(dromheight01);
drommax02 = max(dromheight02);
drommax03 = max(dromheight03);
drommin01 = min(dromheight01);
drommin02 = min(dromheight02);
```

```
drommin03 = min(dromheight03);

figure(2)
plot(dromdate02,dromheight02,'b');
xlabel('Julian Days, 2002','FontSize',14);
ylabel('River Height (m)','FontSize',14);
legend('River Height at Dromcummer');


load duar01.dat;
load duar02.dat;
load duar03.dat;
duarheight01 = duar01(:,7);
duarheight02 = duar02(:,7);
duarheight03 = duar03(:,7);
duardate01 = duar01(:,6);
duardate02 = duar02(:,6);
duardate03 = duar03(:,6);
duarmax01 = max(duarheight01);
duarmax02 = max(duarheight02);
duarmax03 = max(duarheight03);
duarmin01 = min(duarheight01);
duarmin02 = min(duarheight02);
duarmin03 = min(duarheight03);
figure(3)
plot(duardate02,duarheight02,'b');
xlabel('Julian Days, 2002','FontSize',14);
ylabel('River Height (m)','FontSize',14);
legend('River Height at Duarrigle');
load mall01.dat;
load mall02.dat;
load mall03.dat;
mallheight01 = mall01(:,7);
mallheight02 = mall02(:,7);
mallheight03 = mall03(:,7);
malldate01 = mall01(:,6);
malldate02 = mall02(:,6);
malldate03 = mall03(:,6);
mallmax01 = max(mallheight01);
mallmax02 = max(mallheight02);
mallmax03 = max(mallheight03);
mallmin01 = min(mallheight01);
mallmin02 = min(mallheight02);
```

```
mallmin03 = min(mallheight03);
figure(4)
plot(malldate02,mallheight02,'b');
xlabel('Julian Days, 2002','FontSize',14);
ylabel('River Height (m)','FontSize',14);
legend('River Height at Mallow');
figure(5)
plot(malldate02,mallheight02,'b');
hold on;
plot(beetdate02,beetheight02,'r');
hold on;
plot(dromdate02,dromheight02,'g');
hold on;
plot(duardate02,duarheight02,'k');
xlabel('Julian Days, 2002','FontSize',14);
ylabel('River Height (m)','FontSize',14);
legend('River Height at Mallow Bridge','River Height at Beet Factory','River Height at Dromcummer','River Height at Duarrigle');

mallnewheight02=interp1(malldate02,mallheight02,beetdate02);

figure(6)
plot(mallnewheight02,beetheight02,'.');
hold on;
ylabel('River Height at the Beet Factory(m)','FontSize',14);
xlabel('River Height at Mallow Bridge (m)','FontSize',14);
legend('River Height at Mallow Bridge vs River Height at Beet Factory');

figure(7)
loglog(mallnewheight02,beetheight02,'.');
hold on;
ylabel('River Height (m)','FontSize',14);
xlabel('River Height (m)','FontSize',14);
legend('River Height at Mallow Bridge vs River Height at Beet Factory');

figure(8)
plot(dromheight02,beetheight02,'.');
hold on;
ylabel('River Height at the Beet Factory (m)','FontSize',14);
xlabel('River Height at Dromcummer (m)','FontSize',14);
legend('River Height at Dromcummer vs River Height at Beet Factory');

figure(9)
```

```
plot(duarheight02,beetheight02,'.');
hold on;
ylabel('River Height at the Beet Factory (m)','FontSize',14);
xlabel('River Height at Dromcummer (m)','FontSize',14);
legend('River Height at Duarrigle vs River Height at Beet Factory');

figure(10)
plot(dromheight02,duarheight02,'.');
hold on;
ylabel('River Height at Duarrigle (m)','FontSize',14);
xlabel('River Height at Dromcummer (m)','FontSize',14);
legend('River Height at Dromcummer vs River Height at Duarrigle');

figure(11)
plot(dromdate02,dromheight02,'b');
hold on;
plot(beetdate02,beetheight02,'r');
xlabel('Julian Days, 2002','FontSize',14);
ylabel('River Height (m)','FontSize',14);
legend('River Height at Dromcummer','River Height at Beet Factory');

figure(12)
plot(duardate02,duarheight02,'b');
hold on;
plot(beetdate02,beetheight02,'r');
xlabel('Julian Days, 2002','FontSize',14);
ylabel('River Height (m)','FontSize',14);
legend('River Height at Duarrigle','River Height at Beet Factory');

figure(13)
plot(duardate02,duarheight02,'b');
hold on;
plot(dromdate02,dromheight02,'r');
xlabel('Julian Days, 2002','FontSize',14);
ylabel('River Height (m)','FontSize',14);
legend('River Height at Duarrigle Height','River Height at Dromcummer');

load timedifferencepeaks.csv
load 15increment.csv
increment15=X15increment(:,1);
beetvdrom=timedifferencepeaks(:,1);
dromvduar=timedifferencepeaks(:,2);
beetvduar=timedifferencepeaks(:,3);
```

```
heighthist = HIST(timedifferencepeaks,increment15);
figure(14)
bar(increment15,heighthist,'k');
hold on;
xlabel('Time Difference between peaks (min)','FontSize',14);
ylabel('Frequency','FontSize',14);

figure(15)
plot(dromdate87,dromheight87,'b');
hold on;
xlabel('Julian Days, 1987','FontSize',14);
ylabel('River Height (m)','FontSize',14);
legend('River Height at Dromcummer');
```

rateofchange4hrs.m

```
load drom98.dat;
load drom99.dat;
load drom01.dat;
load drom02.dat;
load drom97.dat;
load drom00.dat;

dromheight98 = drom98(:,7);
dromheight99 = drom99(:,7);
dromheight01 = drom01(:,7);
dromheight02 = drom02(:,7);
dromheight97 = drom97(:,7);
dromheight00 = drom00(:,7);

dromdate98 = drom98(:,6);
dromdate99 = drom99(:,6);
dromdate01 = drom01(:,6);
dromdate02 = drom02(:,6);
dromdate97 = drom97(:,6);
dromdate00 = drom00(:,6);

size98=size(dromheight98,1);
size99=size(dromheight99,1);
size01=size(dromheight01,1);
size02=size(dromheight02,1);
```

```
size97=size(dromheight97,1);
size00=size(dromheight00,1);

road98=ones(size98,1)*2.136;
road99=ones(size99,1)*2.136;
road01=ones(size01,1)*2.136;
road02=ones(size02,1)*2.136;
road97=ones(size97,1)*2.136;
road00=ones(size00,1)*2.136;

field98=ones(size98,1)*2.2;
field99=ones(size99,1)*2.2;
field01=ones(size01,1)*2.2;
field02=ones(size02,1)*2.2;
field97=ones(size97,1)*2.2;
field00=ones(size00,1)*2.2;

rate98=ones(size98,1)*3.8;
rate99=ones(size99,1)*3.8;
rate01=ones(size01,1)*3.8;
rate02=ones(size02,1)*3.8;
rate97=ones(size97,1)*3.8;
rate00=ones(size00,1)*3.8;

clear drom98;
clear drom99;
clear drom01;
clear drom02;
clear drom97;
clear drom00;

dromtemp00=1;
dromindex00=1;

dromdatediff00(1) = dromdate00(2)-dromdate00(1);
dromheightdiff00(1) = dromheight00(2)-dromheight00(1);
dromslope00(1)=dromheightdiff00(1)/dromdatediff00(1);

while dromtemp00 < size00
   dromdatediff00(dromtemp00+1) = dromdate00(dromtemp00+1)-dromdate00(dromtemp00);
   dromheightdiff00(dromtemp00+1) = dromheight00(dromtemp00+1)-dromheight00(dromtemp00);
   dromslope00(dromtemp00+1)=dromheightdiff00(dromtemp00+1)/dromdatediff00(dromtemp00+1);
   dromtemp00=dromtemp00+1;
```

```
end;


dromindex00=1;
int=1;

while (dromindex00<size00)
    if (dromheight00(dromindex00)>=2.136&&dromindex00<size00)
      threshtime00(int)=dromdate00(dromindex00);
      threshlocat00(int)=dromindex00;
      int=int+1;
      while (dromheight00(dromindex00)>=2.136&&dromindex00<size00)
        dromindex00=dromindex00+1;
      end
    end
  dromindex00=dromindex00+1;
end

temp=int-1;

while (temp>0)
instantrate00(temp)=dromslope00(threshlocat00(temp)-20);
instantheight00(temp)=dromheight00(threshlocat00(temp)-20);
temp=temp-1;
end

combine=[threshtime00',instantrate00',instantheight00']
save instantrate00.dat combine -ascii;

figure(1);

hold on;

legend('Height','Slope','Flooding Height Threshold','Flooding Rate Threshold');

figure(1);
subplot(2,1,1)
plot(dromdate00,dromheight00,'k*');
ylabel('Height (m)');
title('Dromcummer Height Data');
legend('Height');
hold on;
plot(dromdate00,road00,'k:');
```

```
hold on;
plot(dromdate00,field00,'k:');
subplot(2,1,2)
bar(dromdate00,dromslope00,'k');
hold on;
plot(dromdate00,rate00,'k:');
hold on;
xlabel('Time');
ylabel('Rate (m/s)');
title('Duarrigle Height Data')

dromtemp01=1;
dromindex01=1;

dromdatediff01(1) = dromdate01(2)-dromdate01(1);
dromheightdiff01(1) = dromheight01(2)-dromheight01(1);
dromslope01(1)=dromheightdiff01(1)/dromdatediff01(1);

while dromtemp01 < size01
    dromdatediff01(dromtemp01+1) = dromdate01(dromtemp01+1)-dromdate01(dromtemp01);
    dromheightdiff01(dromtemp01+1) = dromheight01(dromtemp01+1)-dromheight01(dromtemp01);
    dromslope01(dromtemp01+1)=dromheightdiff01(dromtemp01+1)/dromdatediff01(dromtemp01+1);
    dromtemp01=dromtemp01+1;
end;


dromindex01=1;
int=1;

while (dromindex01<size01)
        if (dromheight01(dromindex01)>=2.136&&dromindex01<size01)
            threshtime01(int)=dromdate01(dromindex01);
            threshlocat01(int)=dromindex01;
            int=int+1;
            while (dromheight01(dromindex01)>=2.136&&dromindex01<size01)
                dromindex01=dromindex01+1;
            end
        end
    dromindex01=dromindex01+1;
end

temp=int-1;
```

```
while (temp>0)
instantrate01(temp)=dromslope01(threshlocat01(temp)-20);
instantheight01(temp)=dromheight01(threshlocat01(temp)-20);
temp=temp-1;
end

combine=[threshtime01',instantrate01',instantheight01']
save instantrate01.dat combine -ascii;

% % figure(1);
% %
% % hold on;
% %
% % legend('Height','Slope','Flooding Height Threshold','Flooding Rate Threshold');
% %
% % figure(1);
% % subplot(2,1,1)
% % plot(dromdate01,dromheight01,'k*');
% % ylabel('Height (m)');
% % title('Dromcummer Height Data');
% % legend('Height');
% % hold on;
% % plot(dromdate01,road01,'k:');
% % hold on;
% % plot(dromdate01,field01,'k:');
% % subplot(2,1,2)
% % bar(dromdate01,dromslope01,'k');
% % hold on;
% % plot(dromdate01,rate01,'k:');
% % hold on;
% % xlabel('Time');
% % ylabel('Rate (m/s)');
% % title('Duarrigle Height Data')

dromtemp02=1;
dromindex02=1;

dromdatediff02(1) = dromdate02(2)-dromdate02(1);
dromheightdiff02(1) = dromheight02(2)-dromheight02(1);
dromslope02(1)=dromheightdiff02(1)/dromdatediff02(1);

while dromtemp02 < size02
   dromdatediff02(dromtemp02+1) = dromdate02(dromtemp02+1)-dromdate02(dromtemp02);
```

```
    dromheightdiff02(dromtemp02+1) = dromheight02(dromtemp02+1)-dromheight02(dromtemp02);
    dromslope02(dromtemp02+1)=dromheightdiff02(dromtemp02+1)/dromdatediff02(dromtemp02+1);
    dromtemp02=dromtemp02+1;
end;


dromindex02=1;
int=1;

while (dromindex02<size02)
        if (dromheight02(dromindex02)>=2.136&&dromindex02<size02)
            threshtime02(int)=dromdate02(dromindex02);
            threshlocat02(int)=dromindex02;
            int=int+1;
            while (dromheight02(dromindex02)>=2.136&&dromindex02<size02)
                dromindex02=dromindex02+1;
            end
        end
    dromindex02=dromindex02+1;
end

temp=int-1;

while (temp>0)
instantrate02(temp)=dromslope02(threshlocat02(temp)-20);
instantheight02(temp)=dromheight02(threshlocat02(temp)-20);
temp=temp-1;
end

combine=[threshtime02',instantrate02',instantheight02']
save instantrate02.dat combine -ascii;

% % figure(1);
% %
% % hold on;
% %
% % legend('Height','Slope','Flooding Height Threshold','Flooding Rate Threshold');
% %
% % figure(1);
% % subplot(2,1,1)
% % plot(dromdate02,dromheight02,'k*');
% % ylabel('Height (m)');
% % title('Dromcummer Height Data');
```

```
% % legend('Height');
% % hold on;
% % plot(dromdate02,road02,'k:');
% % hold on;
% % plot(dromdate02,field02,'k:');
% % subplot(2,1,2)
% % bar(dromdate02,dromslope02,'k');
% % hold on;
% % plot(dromdate02,rate02,'k:');
% % hold on;
% % xlabel('Time');
% % ylabel('Rate (m/s)');
% % title('Duarrigle Height Data')

dromtemp99=1;
dromindex99=1;

dromdatediff99(1) = dromdate99(2)-dromdate99(1);
dromheightdiff99(1) = dromheight99(2)-dromheight99(1);
dromslope99(1)=dromheightdiff99(1)/dromdatediff99(1);

while dromtemp99 < size99
  dromdatediff99(dromtemp99+1) = dromdate99(dromtemp99+1)-dromdate99(dromtemp99);
  dromheightdiff99(dromtemp99+1) = dromheight99(dromtemp99+1)-dromheight99(dromtemp99);
  dromslope99(dromtemp99+1)=dromheightdiff99(dromtemp99+1)/dromdatediff99(dromtemp99+1);
  dromtemp99=dromtemp99+1;
end;


dromindex99=1;
int=1;

while (dromindex99<size99)
    if (dromheight99(dromindex99)>=2.136&&dromindex99<size99)
      threshtime99(int)=dromdate99(dromindex99);
      threshlocat99(int)=dromindex99;
      int=int+1;
      while (dromheight99(dromindex99)>=2.136&&dromindex99<size99)
        dromindex99=dromindex99+1;
      end
    end
  dromindex99=dromindex99+1;
end
```

```
temp=int-1;

while (temp>0)
instantrate99(temp)=dromslope99(threshlocat99(temp)-20);
instantheight99(temp)=dromheight99(threshlocat99(temp)-20);
temp=temp-1;
end

combine=[threshtime99',instantrate99',instantheight99']
save instantrate99.dat combine -ascii;

% % figure(1);
% %
% % hold on;
% %
% % legend('Height','Slope','Flooding Height Threshold','Flooding Rate Threshold');
% %
% % figure(1);
% % subplot(2,1,1)
% % plot(dromdate99,dromheight99,'k*');
% % ylabel('Height (m)');
% % title('Dromcummer Height Data');
% % legend('Height');
% % hold on;
% % plot(dromdate99,road99,'k:');
% % hold on;
% % plot(dromdate99,field99,'k:');
% % subplot(2,1,2)
% % bar(dromdate99,dromslope99,'k');
% % hold on;
% % plot(dromdate99,rate99,'k:');
% % hold on;
% % xlabel('Time');
% % ylabel('Rate (m/s)');
% % title('Duarrigle Height Data')

dromtemp97=1;
dromindex97=1;

dromdatediff97(1) = dromdate97(2)-dromdate97(1);
dromheightdiff97(1) = dromheight97(2)-dromheight97(1);
dromslope97(1)=dromheightdiff97(1)/dromdatediff97(1);
```

```
while dromtemp97 < size97
   dromdatediff97(dromtemp97+1) = dromdate97(dromtemp97+1)-dromdate97(dromtemp97);
   dromheightdiff97(dromtemp97+1) = dromheight97(dromtemp97+1)-dromheight97(dromtemp97);
   dromslope97(dromtemp97+1)=dromheightdiff97(dromtemp97+1)/dromdatediff97(dromtemp97+1);
   dromtemp97=dromtemp97+1;
end;


dromindex97=1;
int=1;

while (dromindex97<size97)
      if (dromheight97(dromindex97)>=2.136&&dromindex97<size97)
         threshtime97(int)=dromdate97(dromindex97);
         threshlocat97(int)=dromindex97;
         int=int+1;
         while (dromheight97(dromindex97)>=2.136&&dromindex97<size97)
            dromindex97=dromindex97+1;
         end
      end
   dromindex97=dromindex97+1;
end

temp=int-1;

while (temp>0)
instantrate97(temp)=dromslope97(threshlocat97(temp)-20);
instantheight97(temp)=dromheight97(threshlocat97(temp)-20);
temp=temp-1;
end

combine=[threshtime97',instantrate97',instantheight97']
save instantrate97.dat combine -ascii;

% % figure(1);
% %
% % hold on;
% %
% % legend('Height','Slope','Flooding Height Threshold','Flooding Rate Threshold');
% %
% % figure(1);
% % subplot(2,1,1)
```

```
% % plot(dromdate97,dromheight97,'k*');
% % ylabel('Height (m)');
% % title('Dromcummer Height Data');
% % legend('Height');
% % hold on;
% % plot(dromdate97,road97,'k:');
% % hold on;
% % plot(dromdate97,field97,'k:');
% % subplot(2,1,2)
% % bar(dromdate97,dromslope97,'k');
% % hold on;
% % plot(dromdate97,rate97,'k:');
% % hold on;
% % xlabel('Time');
% % ylabel('Rate (m/s)');
% % title('Duarrigle Height Data')

dromtemp98=1;
dromindex98=1;

dromdatediff98(1) = dromdate98(2)-dromdate98(1);
dromheightdiff98(1) = dromheight98(2)-dromheight98(1);
dromslope98(1)=dromheightdiff98(1)/dromdatediff98(1);

while dromtemp98 < size98
   dromdatediff98(dromtemp98+1) = dromdate98(dromtemp98+1)-dromdate98(dromtemp98);
   dromheightdiff98(dromtemp98+1) = dromheight98(dromtemp98+1)-dromheight98(dromtemp98);
   dromslope98(dromtemp98+1)=dromheightdiff98(dromtemp98+1)/dromdatediff98(dromtemp98+1);
   dromtemp98=dromtemp98+1;
end;


dromindex98=1;
int=1;

while (dromindex98<size98)
      if (dromheight98(dromindex98)>=2.136&&dromindex98<size98)
         threshtime98(int)=dromdate98(dromindex98);
         threshlocat98(int)=dromindex98;
         int=int+1;
         while (dromheight98(dromindex98)>=2.136&&dromindex98<size98)
            dromindex98=dromindex98+1;
         end
```

```
        end
    dromindex98=dromindex98+1;
end

temp=int-1;

while (temp>0)
instantrate98(temp)=dromslope98(threshlocat98(temp)-20);
instantheight98(temp)=dromheight98(threshlocat98(temp)-20);
temp=temp-1;
end

combine=[threshtime98',instantrate98',instantheight98']
save instantrate98.dat combine -ascii;

% % figure(1);
% %
% % hold on;
% %
% % legend('Height','Slope','Flooding Height Threshold','Flooding Rate Threshold');
% %
% % figure(1);
% % subplot(2,1,1)
% % plot(dromdate98,dromheight98,'k*');
% % ylabel('Height (m)');
% % title('Dromcummer Height Data');
% % legend('Height');
% % hold on;
% % plot(dromdate98,road98,'k:');
% % hold on;
% % plot(dromdate98,field98,'k:');
% % subplot(2,1,2)
% % bar(dromdate98,dromslope98,'k');
% % hold on;
% % plot(dromdate98,rate98,'k:');
% % hold on;
% % xlabel('Time');
% % ylabel('Rate (m/s)');
% % title('Duarrigle Height Data')
```

Appendix D Sample of River Level Heights at the four stations during specific flood events