QUEEN'S UNIVERSITY BELFAST

FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

School of Planning, Architecture and Civil Engineering

Thesis for the Degree of Master of Science in Water Resources Management

Title: An Assessment of the Water Balance of the Strangford Lough Catchment

Fiona Smith

SEPTEMBER 2010

“An Assessment of the Water Balance of the Strangford Lough Catchment”

By

Fiona Smith

A Thesis submitted to the Faculty of Engineering and Physical Sciences

School of Planning, Architecture and Civil Engineering

In Partial Fulfilment of the Requirements for the Degree of

MSc. in Water Resources Management

THE QUEEN’S UNIVERSITY BELFAST

2010

Declaration

I confirm the following:

(i) the dissertation is not one for which a degree has been or will be conferred by any other university or institution;

(ii) the dissertation is not one for which a degree has already been conferred by this university;

(iii) that this work submitted for assessment is my own and expressed in my own words. Any use made within it of works of other authors in any form (e.g. ideas, figures, text, tables) are properly acknowledged at their point of use. A list of the references employed is included;

(iv) the composition of the dissertation is my own work.

Signed ………………………………………………………………....

Date ………………………………………………………………….

Abstract

With the introduction of the Water Framework Directive (Directive 2000/60/EC), the goal to achieve ‘good status’ for all surface and ground waters in Europe by 2015 is increasing pressure to assess the status of all water bodies. Assessing any water body comprises of assessing its entire contributing catchment in order to identify problem sources and put in place management plans to resolve any water quality/quantity issues.

The aim of this project is to model freshwater runoff from the entire Strangford Lough catchment and use information derived from calibration and catchment delineation to regionalise the model parameters. The entire catchment is delineated using a 10m*10m resolution DEM and Arc Hydro tools in ArcGIS 9.3. Four gauged subcatchments are then used to calibrate the NAM rainfall runoff model and parameters representing the ungauged subcatchments are consequently derived on the basis of their physical characteristics. Once regionalised, the model then simulates overland flow, interflow and baseflow from each contributing subcatchment, thus providing a detailed description of runoff into Strangford Lough. This simulation of runoff, from ungauged catchments in particular, and separation of runoff into its components offers to increase our understanding of pollution sources throughout the entire Strangford Lough catchment.

Recommendations are made to improve model simulations through the collection of additional data, by establishing relationships between the catchment’s physical characteristics and the model’s parameters and by carrying out further modelling of urban areas within the catchment and mudflats around the Lough.

Acknowledgements

The author would like to thank Dr. Björn Elsäßer for his supervision and guidance throughout the project. The author would also like to thank staff from the NIEA and Rivers Agency for their co-operation, time and assistance. The author’s gratitude also goes out to Lorraine Barry who provided initial guidance using ArcGIS. Finally, the author would like to acknowledge the continuous support of her friends and family.

Table of Contents

List of Figures

List of Tables

Glossary

ArcGIS: Software used to derive catchment boundary

BGS: British Geological Survey

DEM: Digital Elevation Model

FEH: Flood Estimation Handbook

GIS: Geographical Information System

HOST: Hydrology of Soil Type

NAM: Danish translation of Precipitation-Runoff Model

NIEA: Northern Ireland Environment Agency

OSNI: Ordnance Survey Northern Ireland

SAAR: Average Annual Rainfall (mm)

Umax: Maximum surface storage

Lmax: Maximum root zone storage

CQOF: Amount of flow contributing to overland flow

CKIF: Time constant for routing interflow

CK12: Time constant for routing overland and interflow

TOF: Threshold for overland flow

TIF: Threshold for interflow

Tg: Threshold for groundwater flow

CKBF: Time constant for routing baseflow

R^2: Coefficient of determination

WBL: Water balance error

1. Introduction

1.1 Context of the project

With the introduction of the Water Framework Directive (Directive 2000/60/EC) and its goal to achieve 'good status' for all surface and ground waters in Europe by 2015, there is increasing pressure to assess the status of all water bodies, identify problem sources and put in place management plans to resolve any water quality/quantity issues. These assessments are carried out on a catchment-wide scale, which the Water Framework Directive also introduced as the standard operating procedure across the EU. A number of similar policies have been introduced across the globe, e.g. the Unified Federal Policy for a Watershed Approach to Federal Land and Resource Management (United States), and these policies have driven the need for advancements both in mapping software and hydrologic simulation models in order to speedily delineate catchment boundaries, more accurately represent their physical characteristics and provide solutions for the management of water resources.

For the Strangford Lough catchment, however, the sources of adverse impacts are unknown in a number of its contributing river catchments (Comber River, Dibney River) and therefore further investigations are required.

1.2 Aims and Objectives

The aim of this project is to assess the water balance of the Strangford Lough catchment. The first objective is to successfully delineate the Strangford Lough catchment boundary and each of its subcatchments using ArcGIS. The second objective is to model freshwater runoff from the entire Strangford Lough catchment using the NAM rainfall-runoff model and to assess its suitability in examining the catchment's nutrient budget.

The necessity for carrying out the first objective is twofold. Firstly, the areas of gauged and ungauged catchments are required as inputs to the rainfall-runoff model and secondly, physical characteristics of all subcatchments need to be speedily derived so that the calibrated model can be regionalised. The report will therefore deal with the first objective entirely before moving onto the second objective. Meeting the first objective will then provide the necessary information to run the NAM rainfall-runoff model, thus improving our understanding of the relationship between surface, root zone and groundwater storages in the Strangford Lough catchment.

2. Site Description

2.1 Location

The Strangford Lough catchment is located on the east coast of Northern Ireland and experiences a temperate maritime climate, with a mean annual temperature of 9ºC and mean annual precipitation of 800-1000mm. The majority of weather fronts come from a south-west direction as a result of the south west prevailing winds which carry most of the rainfall experienced by the UK and Ireland. The entire Strangford Lough catchment area totals to 647.38km^2 with a maximum elevation reaching to 290m. Appendix A1 shows the sub-catchments within the Strangford Lough catchment as designated by the NIEA. The largest contributing catchment is the Quoile, which accounts for 37% of the drainage into Strangford Lough, with the next two largest rivers (Comber and Blackwater) draining just 17%. The Lough itself is not greatly influenced by these freshwater sources and is therefore mostly saline throughout.

2.2 Land Use

A land cover map of Northern Ireland was established through the setting up of CORINE (Co-ordination of Information on the Environment) in 1985 (Cruickshank, 1997). The programme was initiated by the European Commission and was to be carried out for all Member States (European Environment Agency & Environment Protection Agency, 2006). The results of the CORINE land survey for the Strangford Lough catchment is illustrated in Appendix A2. From this, we can see that the majority of land is used for heterogeneous agricultural purposes and is cultivated in complex patterns having high and low productivity. Complex cultivation patterns consist of small areas of land (must be less than 25 hectares) (Commission of the European Communities, 1994) comprising of pasture and a range of different crops (oats, wheat, barley, corn, potatoes). Land is also made available for livestock, predominantly in the Quoile and Dibney (South-East Down Stream) catchments, and pig and poultry in the R.Dibney and R.Comber catchments respectively (Queen's University Belfast School of Biology and Biochemistry, 2004). There are also some specifically designated regions of arable land, particularly to the north of the Lough, where soils are freely draining and have optimum pH thus lending themselves to the production of cereal (mainly barley) and potato crops. There is some urbanisation to the north and south of the Lough where greater runoff would be expected due to the impermeable nature of paved surfaces. A small amount of quarries were set up throughout the catchment, most likely to use the underlying greywacke as a building material.

2.3 Solid and Drift Geology

The solid geology of the Strangford Lough catchment is shown in Appendix A3. Solid geology is the underlying rock which originally formed the landmass and may be overlain by drift geology (superficial deposits) or may be exposed as rock outcrops at the surface (BGS, 2010). The dominant underlying bedrock of the Strangford Lough catchment is a Silurian shale (Cruickshank, 1997) belonging to the Gala Group (previously known as the Strangford Group) (see Appendix A3) and dates back to the Lower Palaeozoic period. The shale comprises of greywacke sandstones and mudstones but is intruded a number of times by igneous rocks, mostly dolerite. To the north of the catchment there is a change in geology as Sherwood Sandstone extends from Belfast down towards Newtownards. Within this stretch of sandstone lie sills and dykes of dolerite as well as some sedimentary evaporitic and argillaceous rocks. A lithological description of the two dominant bedrocks is outlined in Table 2.1.

BGS Lexicon Units	Lithological Description
Gala Group	Graded beds that may include wacke sandstone, siltstone and mudstone in variable proportions, interpreted as turbidites. Rare interbedded graptolite-bearing beds.
Sherwood Sandstone Group	Sandstone, red, yellow and brown, part pebbly; subordinate red mudstone and siltstone.

Table 2.1: Dominant underlying bedrock geology of the Strangford Lough catchment (BGS, 2009)

Overlying the solid geology are the superficial deposits which were formed in the Quaternary, the latest geological period of time (BGS, 2010). As can be seen in Appendix A4, the dominant superficial deposit in the Strangford Lough Catchment is diamicton till, a type of poorly sorted sediment resulting from glacial activity (BGS, 2010). It is thought that this mixed material deposited in mounds known as drumlins was the work of a glacier originating at Lough Neagh (Cruickshank, 1997). These drumlins are interrupted by rock outcrops to the west but to the north, the deposits seem to resemble glacial outwash, composing mainly of alluvium, sand, silt and gravels.

With regard to permeability and hydraulic conductivity, the dominant Silurian shale bedrock underlying most of Co. Down is often classified as an ‘impermeable basement’ but may still serve as an aquifer storing and transmitting groundwater through its fractures and cracks. The Triassic sandstone however is a younger (approximately 230 million years old), softer and more permeable bedrock and can often have up to 20% specific yield (Downing, 1998).

2.4 Soils

The formation of soils in Northern Ireland has been impacted by a range of factors; climate, relief and most significantly parent material. For the Strangford Lough catchment, soils have been primarily derived from shale and sandstone. Soils derived from the shale are usually of a clay loam or sandy silt loam texture whereas soils derived from Sherwood sandstone in the north of the catchment tend to be of a loamy sand texture (Cruickshank, 1997).

Between 1987 and 1997, the Department of Agriculture Northern Ireland (DANI) carried out soil surveys from which the Ordnance Survey Northern Ireland (OSNI) published 1:50,000 scale maps and a 1:250,000 scale map covering all of Northern Ireland. In order to identify the soil types of the Strangford Lough catchment, a combination of the 1:250,000 and the 1:50,000 soil maps were examined. Because the 1:50,000 map was not yet digitised, a generalized map of the 1:50,000 soil map was used (Cruickshank, 1997). These maps coupled with the BGS drift geology map (Appendix A4) were used to derive an estimate of the type of soil in the Strangford Lough catchment (Table 2.2).

From the maps, it was derived that the majority of soils were brown earths, brown rankers (shallow soils less than 40cm deep) and surface water/groundwater gleyed soils. From the 1:50,000 soil map, brown earths and rankers were classified as free draining soils whereas gleyed soils indicated impeded drainage.

2.5 Hydrology of Soil Types (HOST)

With the completion of the soil survey, a new classification system was initiated to enable a more accurate representation of soils in Northern Ireland (Cruickshank, 1997). The project was to tie in with the update of the Flood Studies Report (1975), i.e. the Flood Estimation Handbook, as the old soil classification system (WRAP- Winter Rainfall Acceptance Potential) was replaced. The HOST classification system was built on 3 factors (Boorman, et al., 1995);

- Catchment scale hydrological parameters (baseflow index, standard percentage runoff)
- Soil properties (depth to impermeable or gleyed (waterlogged) layer, integrated air capacity as a measure of storativity and the presence of peat)
- Hydrogeology of the substrate (permeable, slowly permeable or impermeable)

With the use of conceptual models, 29 HOST classes were created (Appendix A5), of which 23 are found in Northern Ireland. Table 2.2 shows the HOST classification of the most common soils in the Strangford Lough catchment which were derived using Appendix C, Volume 4 of the Flood Estimation Handbook (Houghton-Carr, 1999).

Soil Type Abbreviation	Soil Type Description	Underlying Geology	HOST Classification
SWG1	Surface Water Gley & Groundwater Gley	Shale	22
SWG1	Surface Water Gley & Groundwater Gley	Shale Till	24
SWG1/M	Surface Water Gley & Groundwater Gley	Marl	24
BE	Brown Earths	Sands & Gravels	5
BE/M	Brown Earths	Marl	18
ALL	Alluvium	Slightly permeable substrate	8 or 9
P	Peat	Shale	27
SH	Shallow Soils	N/A	N/A
URB	Urban Areas	N/A	N/A

Table 2.2: Soil type and HOST classification of the most common soils in the Strangford Lough catchment

2.6 Slope

For the majority of the catchment the slope generally doesn't exceed 10 degrees. There are a number of areas along the catchment boundary (particularly to the north, south and west) where the underlying shale is left exposed at slopes ≥ 40°. In the north of the catchment, rock (undifferentiated) is exposed near the urban area of Newtownards where slopes vary between 10-20º.

2.7 Water Quality

As can be seen from Appendix A6, the current status of all rivers in the Strangford Lough catchment according to the Water Framework Directive is that of less than good. It is hoped however that good status will be achieved by 2021 by reducing nutrient loadings (nitrate and phosphorous) and mitigating the effects of this nutrient enrichment on invertebrate communities (NIEA, 2008). Aims have also been set to achieve good water status by 2027 in Lake Clea which has been subjected to eutrophication.

Heavily modified water bodies, i.e. those bodies that have been subjected to morphological changes are also illustrated in Appendix A6 (PEP_WQ and MEP_WQ). It is intended that both of these river stretches will be of good ecological potential by 2021, as an earlier deadline is practically technically infeasible.

With regard to groundwater bodies, one of the two in the Strangford Lough catchment area are of good status with the Belfast groundwater body stretching into north of the catchment being classed as poor with respect to qualitative and quantitative counts (NIEA, 2008) (Figure 2.1).

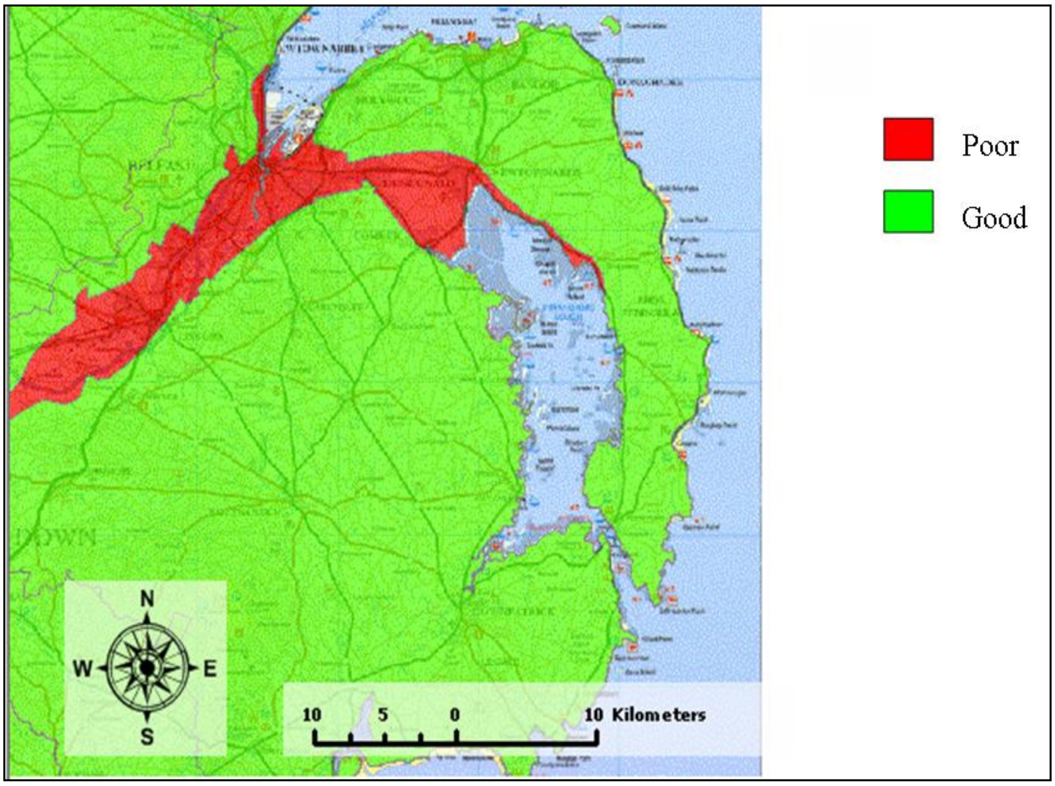


Figure 2.1: Overall status of groundwater bodies (NIEA, 2008)

There is however some cause for concern as shown by the groundwater vulnerability map in Appendix A7. Vulnerability classes are derived from vulnerability codes which take into account depth and permeability of superficial deposits, type of bedrock aquifer, the depth of clay within the superficial deposits and depth to water table. Vulnerability ranges from low to high (1-5) and characteristics of each class are explained in Appendix A8. As a result of these input factors, the majority of the Strangford Lough catchment is classified as having high groundwater vulnerability (Figure 2.2).

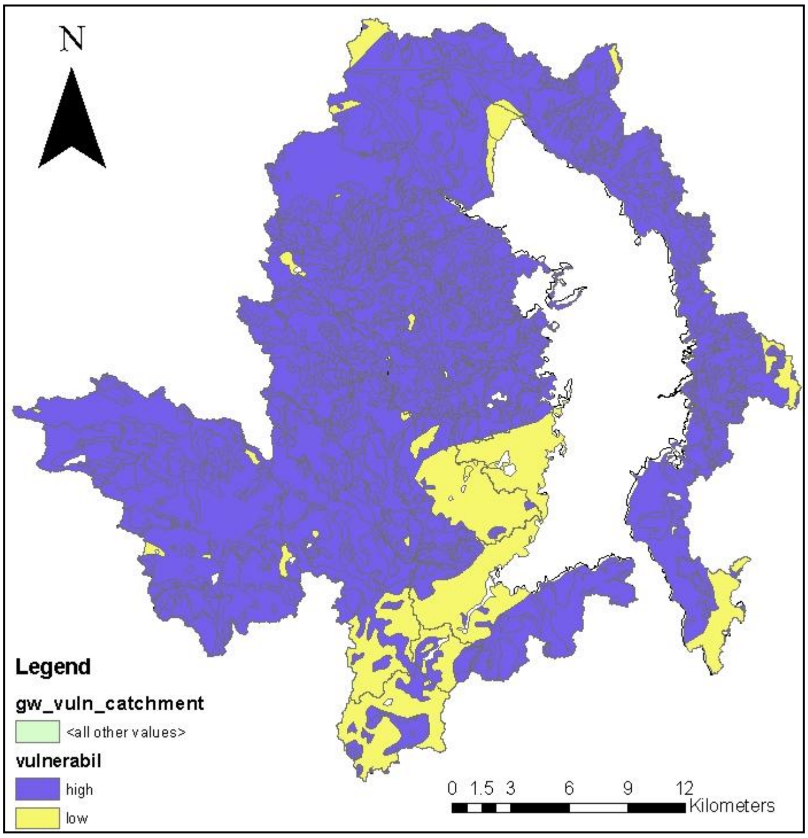


Figure 2.2: Groundwater vulnerability in the Strangford Lough catchment (GSNI, 2010)

With regard to coastal waters, elevated nutrient levels in the north end of Strangford Lough causes the entire body to be classified as being of moderate quality, with coastal waters to the east of the Ards Peninsula of good status (Figure 2.3)

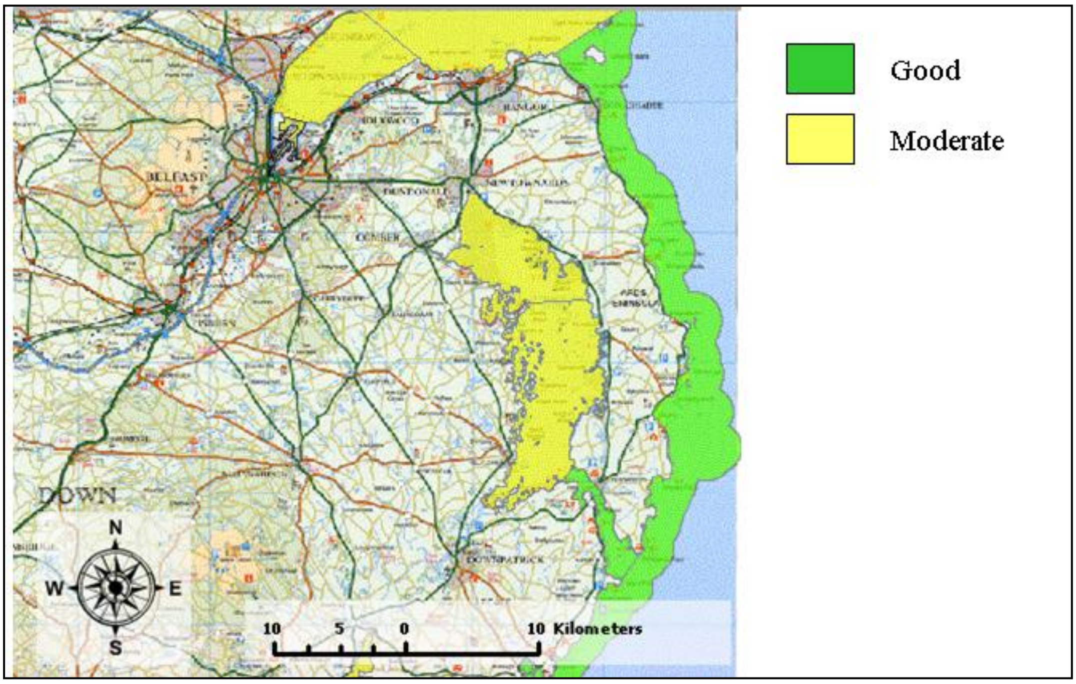


Figure 2.3: Coastal water quality (NIEA, 2008)

3. Literature Review

This literature review will address the theory and practice behind assessing a water balance for a catchment in the UK. Firstly, instruments used to measure rainfall, evapotranspiration and streamflow will be described as well as possible errors associated with these measurements. The use of geographical information systems (GIS) and hydrological modelling in assessing a catchment-wide water balance will then be discussed.

3.1 Hydrological Cycle

The concept of the hydrological cycle is one which has been around since the 17th century (Shaw, 1994). The driving force behind the cycle is the sun's solar radiation which causes temporarily stored water to evaporate, rise into the atmosphere and condense thus forming clouds. If the clouds become cooled then precipitation takes place and the moisture may either re-vaporize back to the atmosphere, become temporarily stored in lakes/vegetation or reach the ground surface (Wilson, 1990). In reaching the ground surface, water may return to its temporary storage via overland flow, interflow (lateral flow in the top soil horizon) or baseflow (flow via underlying aquifers).

It is anticipated, however, that the rate at which the processes within the hydrologic cycle occur may be subjected to change over the next few decades. If temperatures rise due to the global warming effect, the air will be capable of holding more moisture thus more evapotranspiration will take place. If there is more moisture in the air then precipitation will be more intense thus causing more intense runoff. Equally, drought will be prolonged if the increased air temperature demands more evaporation. However, taking account of the warming alongside the cooling effect of some gases e.g. sulphur dioxide, it is difficult to predict, especially at the correct scale, what the impacts of climate change are going to be on the hydrologic cycle, as is illustrated in Table 3.1 (Frederick, 2002).

Water Resources Region	Canadian Climate Model	Hadley Climate Model
New England	-8	9
Mid-Atlantic	-13	10
South Atlantic-Gulf	-61	0
Great Lakes	-12	20
Ohio	-21	6
Tennessee	-33	4
Upper Mississippi	-23	20
California	26	27

Table 3.1: Projected Changes in Average Annual Runoff, 1995-2030 under two climate models by water resource region (in percentages) (Frederick, 2002)

3.2 The Water Balance

The first recorded evidence of a water balance assessment was in the 17th century when Perrault and Mariotte showed that rainfall minus evaporation equalled river flow for the River Seine (Shaw, 1994). The most common way to assess the water balance is by using the following equation:

$$P - E = O - I \pm U \pm S \qquad \text{(Equation 3.1)}$$

Where P is precipitation, E is evapotranspiration, O is surface outflow, I is surface inflow, U is underground outflow and S is change in storage (surface and subsurface).

3.3 Meteorological Data

In order to gain an accurate understanding of a catchment's hydrology, one must consider its climate, topography and geology (Wilson, 1990). Dealing firstly with climate, the primary parameters of interest to this study are precipitation and evapotranspiration, the latter of which is affected by humidity, temperature and wind. Gaining an accurate measurement of these meteorological factors across a catchment can prove difficult as will be discussed below.

3.3.1 Rainfall

The type of rainfall a catchment may experience depends on its geographic location (with regard to general circulation system, latitude and distance from sea) and its topography (elevation, slope, orientation) (Linsley, et al., 1975). There are three types of rainfall which temperate humid climates are subjected to, namely frontal, convective and orographic rainfall (Newson, 1994). Frontal rainfall occurs when warm and cool air masses meet (Raudkivi, 1979) and convective rainfall occurs as a result of differential heating, with warm air rising into cooler air space (Linsley, et al., 1975). The former of these is usually enhanced by orographic rainfall, as moisture laden air is forced to rise above a mountainous barrier, thus cooling and precipitating. Although snow is a significant form of precipitation for many parts of the world, the area of interest in this study is subjected to only minor precipitation as snow.

3.3.2 Measuring Rainfall

The design of a rain gauge network within a river catchment must be carefully planned in order to consider the type of rainfall and the varying nature of rainfall, in both time and space (Shaw, 1994). Rodda (1969) illustrated the importance of considering the rainfall type by reporting that convective rainfall had almost double the areal error of frontal rainfall.

It has been shown that mean rainfall measurements will not change above a certain number of gauges (Raudkivi, 1979), yet confidence limits continuously decrease with fewer gauges (Neff, 1965). In between these extremes lie an optimum number of rain gauges which can enable a hydrometric system to be cost effective and efficient. Bleasdale (1965) provided the minimum number of gauges recommended by the UKMO (UK Meteorological Office) for estimating monthly areal rainfalls for river catchments (see Table 3.2). Gauge spacing meeting UK data requirements for a water balance assessment is set at 7.5-9km (Newson, 1994) given the uniform nature of frontal rainfall. Positioning of rain gauges must also be carefully considered as a uniform distribution of gauges will not necessarily achieve the most representative sample. It is therefore advised that with increasing climatic variation (i.e. steep slopes), spacing between gauges be reduced (Raudkivi, 1979).

Square Kilometres (Approx.)	Number of Rain Gauges
26	2
260	6
1300	12
2600	15
5200	20
7600	24

Table 3.2: Minimum Number of Rain Gauges for Monthly Percentage of Average Rainfall Estimates (Bleasdale, 1965)

From studies carried out on Muskingham Basin, Ohio, it was shown that the standard error for rainfall averages varied with network density and area (US Weather Bureau, 1947). Linsley (1975) stated that the depth of sampling error usually increased with increasing areal mean precipitation and decreased with increasing network density, duration of precipitation and area. Johanson (1971) showed that the number of gauges was more important than the network density in determining streamflow from precipitation measurements.

3.3.3 Collection Instruments

The collection of rainfall in the UK dates as far back as 1729 (Newson, 1994). The primary tools used to measure rainfall are storage gauges and recording gauges, with the later addition of the radar. Where measurements are required for flood warning systems, the recording gauge (e.g. tipping bucket) or radar would be the most suitable option to take but for the purposes of a water balance assessment, measurements using a storage gauge are adequate (Newson, 1994). The standard British storage gauge is made from copper, installed 30cm above the ground and has a circular catchment area of 150cm^2 (Wilson, 1990). Storage gauges are useful for placement in remote regions as they require little maintenance and can be unmanned for up to a season (Linsley, et al., 1975). Errors in measurement can be introduced if the gauge becomes damaged (thus changing the catchment area), if the reading is taken inaccurately or if the gauge is exposed to strong winds (Linsley, et al., 1975). Exposure to strong winds can be reduced by surrounding the gauge with vegetation but the UK Meteorological Office caution that the distance between the object and their standard gauge should be four times the height of the gauge to avoid sheltering effects on the rainfall data. In an investigation into the effects of exposure on rain gauges, Green (1969) reported that the best way to achieve the most accurate measurement was to set the rain gauge at ground level and surround it with an anti-splash grid. The US has adopted the Alter shield as standard for protecting against overexposure (Figure 3.1).

Figure 3.1: Alter-type wind shield (NovaLynx Corporation, 2010)

There are a number of methods that have been derived in order to calculate actual precipitation based on the relationship between a shielded and an unshielded gauge. One such relationship is shown in Equation 3.2;

$$ln\frac{P_{UG}}{P_A} = b\ ln\frac{P_{UG}}{P_{SG}} \qquad \text{(Equation 3.2)}$$

where P_{UG} is the unshielded gauge catch, P_A is the actual precipitation, b is a calibration coefficient depending on the type of gauge and P_{SG} is the shielded gauge catch (Linsley, et al., 1975).

3.3.4 Rainfall analysis

Once the data is collected, it first must be checked. The data can be checked by plotting a double mass curve, i.e. the accumulated annual precipitation for the gauge in question versus the mean accumulated annual precipitation for all gauges (Linsley, et al., 1975). A change in slope may indicate that the gauge location has been changed, an obstruction is causing a change in wind pattern around the gauge, the measurements are been recorded by a different person or the type of gauge recording changed (Raudkivi, 1979; Wilson, 1990).

The data must then be converted from point data to catchment values. The three most common methods used to average precipitation depth over area are the arithmetic mean, Thiessen polygons and isohyetal contours. The first method involves averaging all the point values and works well when variation between gauges is low and the catchment area is uniform (Wilson, 1990). Thiessen polygons create a zone of influence for each gauge, by connecting adjacent stations and bisecting the connecting line perpendicularly to meet other bisectors (Fetter, 2001). An alternative method is to draw the bisecting line at mean altitude rather than mid-length but it has been shown that this only slightly alters the result (Wilson, 1990). Thiessen polygons are inflexible in that the polygons are quite laboursome to construct and the addition of a new gauge calls for new polygons to be created (Linsley, et al., 1975). The best way to note the orographic influences on rainfall distribution is to draw isohyetal contours, i.e. lines of equal rainfall depth.

Publishing the Flood Studies Report (1975) allowed the rainfall depth at any point in the UK and Ireland to be estimated for a given duration and return period. This point data can then be converted into an areal value by applying an areal reduction factor.

3.3.5 Evapotranspiration

Evapotranspiration is the combined term used to describe evaporation and transpiration and accounts for that part of the hydrological cycle in which water from the land, soil and vegetation vaporises under latent heat and returns to the atmosphere (Wilson, 1990). The two main governing climatic processes controlling the rate of evaporation are the energy supply and the aerodynamic removal of saturated air (measured by temperature, humidity and wind) (Linsley, et al., 1975). However, transpiration rates are also affected by vegetation type (Wilson, 1990), generally increasing with increasing root depth. However, evapotranspiration can only occur if there is an available water supply in the soil. As a result, the concept of potential evapotranspiration, i.e. the amount of evapotranspiration that could occur provided adequate soil moisture conditions were maintained, was introduced. The concept consequently became an indicator of optimum water requirements for crops (Ponce, 1989) and indicated the amount of irrigation required in periods of reduced precipitation.

3.3.6 Direct Measurement

Evaporation measurements date back as far as 1772 in the UK (Newson, 1994). The earliest measurements were designed to measure open water evaporation using an evaporation pan. The standard British square evaporation pan is sunken into the ground so that 534mm lies below ground level and 76mm projects above the ground. This differs from the standard Class A pan in the US which is raised 150mm off the ground (Wilson, 1990).

However, measuring open pan evaporation is not representative of a typical UK catchment where much of the catchment is covered with vegetation and thus the rate of evapotranspiration differs due to varying reflectivity and albedo (Newson, 1994). In order to take these factors into account, the lysimeter has become the most common type of instrument to directly measure evapotranspiration.

The lysimeter essentially assesses the water balance within its containment of soil and plants, and knowing values of precipitation, moisture storage and any outputs, it can calculate evapotranspiration losses by the change in weight (Erie, et al., 1982). Large lysimeters provide information on soil moisture uptake (Yang, et al., 2000) and have a distinct advantage over smaller lysimeters in that there is less error associated with them (ASCE, 1996). Regardless of the accuracy, however, the soil within the container must be representative of the surrounding soil type, moisture content, temperature, etc. in order to achieve an accurate measurement of actual evapotranspiration (ASCE, 1996).

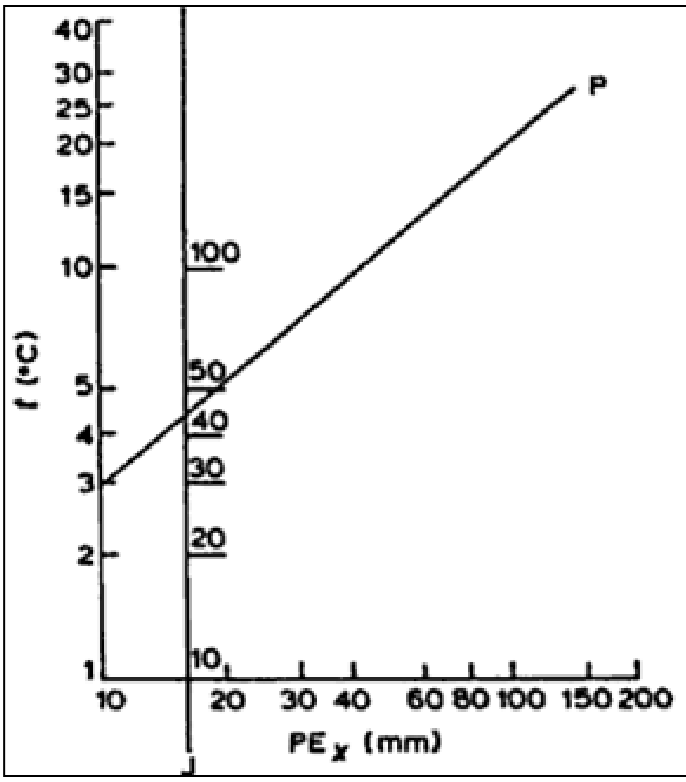
3.3.7 Indirect Measurement

Because of the difficulty in accurately representing surrounding conditions in the lysimeter and the difficulty involved in handling large lysimeters, a number of efforts have been made to find a way to calculate potential and actual evapotranspiration indirectly. A summary of these methods is described below.

Blaney and Criddle (1962) derived a temperature dependant method by which the crop's consumptive use of water was calculated taking into account day length, temperature and an empirical consumptive use crop coefficient. This method was elaborated on by Doorenbos and Pruitt (1977) who also took sunshine hours, humidity and wind speed into account. Thornwaite also carried out investigations into deriving a temperature based formula to calculate evapotranspiration. He produced a method by which once the heat index (J) was found (dependant on monthly temperature) the potential evapotranspiration could be found by using Figure 3.2 and Equation 3.3 (Wilson, 1990). The equation adjusts the standard potential evapotranspiration monthly value by specifying the number of days in a month and the number of hours of sunlight. However, Stephens and Stewart (1963) reported that after comparing measured values and values obtained from a number of calculating methods, the correlation coefficient for the Thornwaite method was the lowest for both evaporation and evapotranspiration.

$$PE = PE \times \frac{DT}{360} mm \qquad \text{(Equation 3.3)}$$

where $PE = potential\ evapotranspiration$
$D = number\ of\ days\ in\ the\ month$
$T = average\ number\ of\ hours\ between\ sunrise\ and\ sunset$



t(°C)	PE$_x$
26·5	135·0
27·0	139·5
27·5	143·7
28·0	147·8
28·5	151·7
29·0	155·4
29·5	158·9
30·0	162·1
30·5	165·2
31·0	168·0
31·5	170·7
32·0	173·1
32·5	175·3
33·0	177·2
33·5	179·0
34·0	180·5
34·5	181·8
35·0	182·9
35·5	183·7
36·0	184·3
36·5	184·7
37·0	184·9
37·5	185·0
38·0	185·0

Figure 3.2: Finding potential evapotranspiration (unadjusted) using Thornwaite's method (Wilson, 1990)

In 1948, Penman created a combined model using the energy balance and the aerodynamic equations to derive an equation which calculated potential evaporation based on normal climatic measurements, i.e. mean air temperature, relative humidity, wind velocity and hours of sunshine (Wilson, 1990; Linsley, et al., 1975). The processes involved in evapotranspiration, however, made the calculation more complex and in order to overcome these additional factors (Figure 3.3), Penman published coefficients to help determine the evapotranspiration of a certain soil or grassed area.

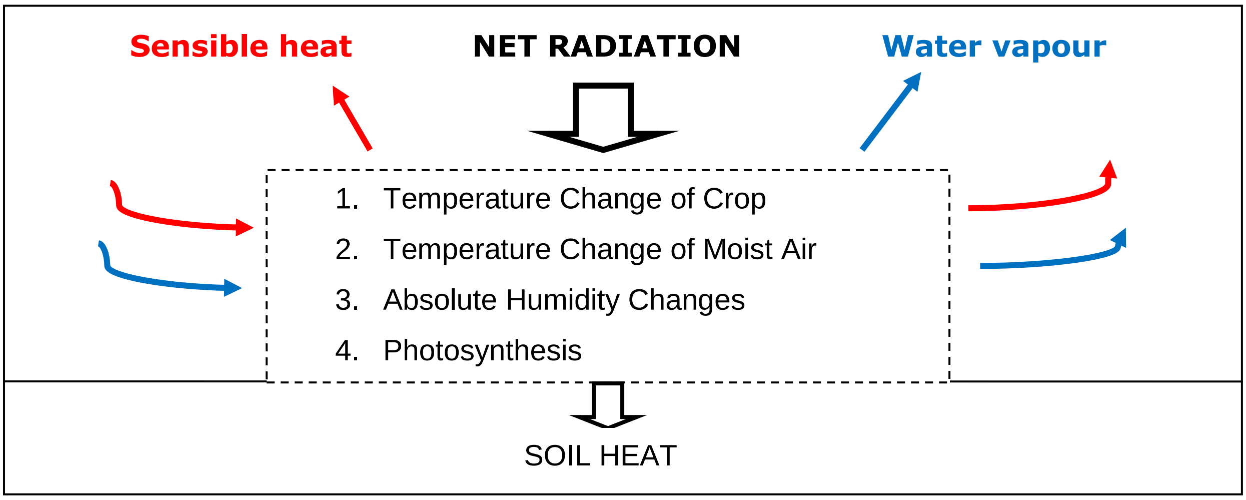


Figure 3.3: Governing processes in potential evapotranspiration (Newson, 1994)

A modified version of the Penman equation (the Penman-Monteith equation) is currently used to calculate potential evapotranspiration in the MORECS system (the Meteorological Office Rainfall and Evaporation Calculation System). Potential evapotranspiration may then adjusted to calculate the actual evapotranspiration by taking into account the canopy resistance at no water stress, the maximum amount of water available to the crop, the soil moisture deficit and the soil-crop combinations (Hough & Jones, 1997).

3.3.8 Network Design

Substantially less measurement stations are required to get an estimate of evaporation or evapotranspiration than that which is required for precipitation. Usually one is adequate for estimation but since evaporation varies with altitude, a catchment may need more than one station if there is a substantial change in altitude within its boundary (Shaw, 1994).

3.4 Stream Flow Data

3.4.1 Measuring stage-discharge

Using a current meter to measure velocity is the most common method in the US (Linsley, et al., 1975). The stream is typically divided into a number of vertical slots and the average velocity of each section is measured at 0.6*depth from the surface. Each average velocity is multiplied by its respective cross sectional area to get the discharge and the sum of all vertical sections is taken as the total discharge for the stream (Shaw, 1994). Large channels can be accessed by using a pulley system to lower the current meter into the channel (Wilson, 1990). Incremental discharges at the shoreline are often taken as zero (Linsley, et al., 1975).

There are a number of simpler methods by which the velocity of a channel can be calculated. In times of low flows, volumetric gauging can be used whereby a container of known volume is filled and timed. In dangerous conditions, the travel time of a floating object over a known distance can be used to calculate velocity, taking into account that surface velocity is 20% faster than average velocity (Newson, 1994). Volume and velocity can be calculated effectively in a turbulent river (e.g. mountainous river) by introducing a chemical or fluorescent dye into it (Shaw, 1994). The chemical is then measured downstream whereby the speed of travel indicates velocity and the end concentration indicates volume through dilution.

River level can be measured either manually using a staff gauge or continuously by attaching a pen to a floating gauge installed in a stilling house (Linsley, et al., 1975). Water levels can also be measured by a pressure transducer which senses water levels through change in pressure and is placed in the stream and connected to the recorder by cable (Shaw, 1994).

Relating stage and discharge however relies on a section or channel control. A section control can be either natural or in the form of a weir where the gravity head over the weir can be related to velocity and the structure is of known cross section, thus discharge is easily computed (Linsley, et al., 1975). A channel control is more likely to change with time (e.g. erosion/deposition of sediment) and may therefore need more maintenance and more measurements to maintain an accurate stage discharge relationship (Wilson, 1990). Plotting simultaneous stage and discharge measurements for a particular location can produce a reliable rating curve for that location (Wilson, 1990). Its level of reliability can be determined by investigation the scatter of the plot about the mean line.

3.4.2 Error

Choosing a location to gauge stream flow must be carefully planned. The gauge must be located so that it will not be bypassed in a flood event and it must be sited so that it avoids being located at an outfall or intake (Newson, 1994). The flow rate of a channel may be affected by a number of factors such as flow distortion around bends, turbulence and sediment transport (Newson, 1994). Manning's equation (Equation 3.4) also describes how the channel geometry can affect the flow rate, particularly the cross-sectional area (*A*), the slope (*S*) and the Manning's resistance factor (n) (Wilson, 1990).

$$Q = \frac{AR^{\frac{2}{3}}S^{\frac{1}{2}}}{n} \qquad \text{(Equation 3.4)}$$

In the above equation, *Q* represents discharge and *R* represents hydraulic radius (cross sectional area/wetted perimeter). The Manning's resistance factor increases with increasing vegetation and obstructions (Chow, 1959).

3.4.3 Network

River gauging stations tend to be the most expensive measurement equipment used within any hydrological section. Choosing which streams to gauge may be based on future planned use or future possibility of flooding. The development of estimating flows for ungauged sites however reduces the need for an increased gauging network. The ability to derive synthetic records also reduces pressure on maintaining stations which may be subjected to flood damage, vandalism and abrasion as a result of sediment transport (Newson, 1994; Linsley, et al., 1975).

3.5 Runoff Processes

Having investigated the inputs and outputs of the water balance, the processes by which available water (precipitation-evapotranspiration) travels via the land must now be examined. Once precipitation (in this case rainfall) wets the ground, infiltration and consequential percolation may occur if the surface layer is permeable. If the surface is impermeable, or the rainfall intensity is greater than the infiltration rate, rainfall will directly runoff the surface (Wilson, 1990). The runoff components of a temperate humid climate can be illustrated as in Figure 3.4 below (Newson, 1994).

However, once precipitation stops, moisture in the soil undergoes losses through evaporation, transpiration and percolation to the water table. Once water stops draining freely, it is said that field capacity is reached and at this stage the soil becomes more vulnerable to the effects of evapotranspiration, until wilting point is reached and the soil can no longer support its vegetation (Linsley, et al., 1975).

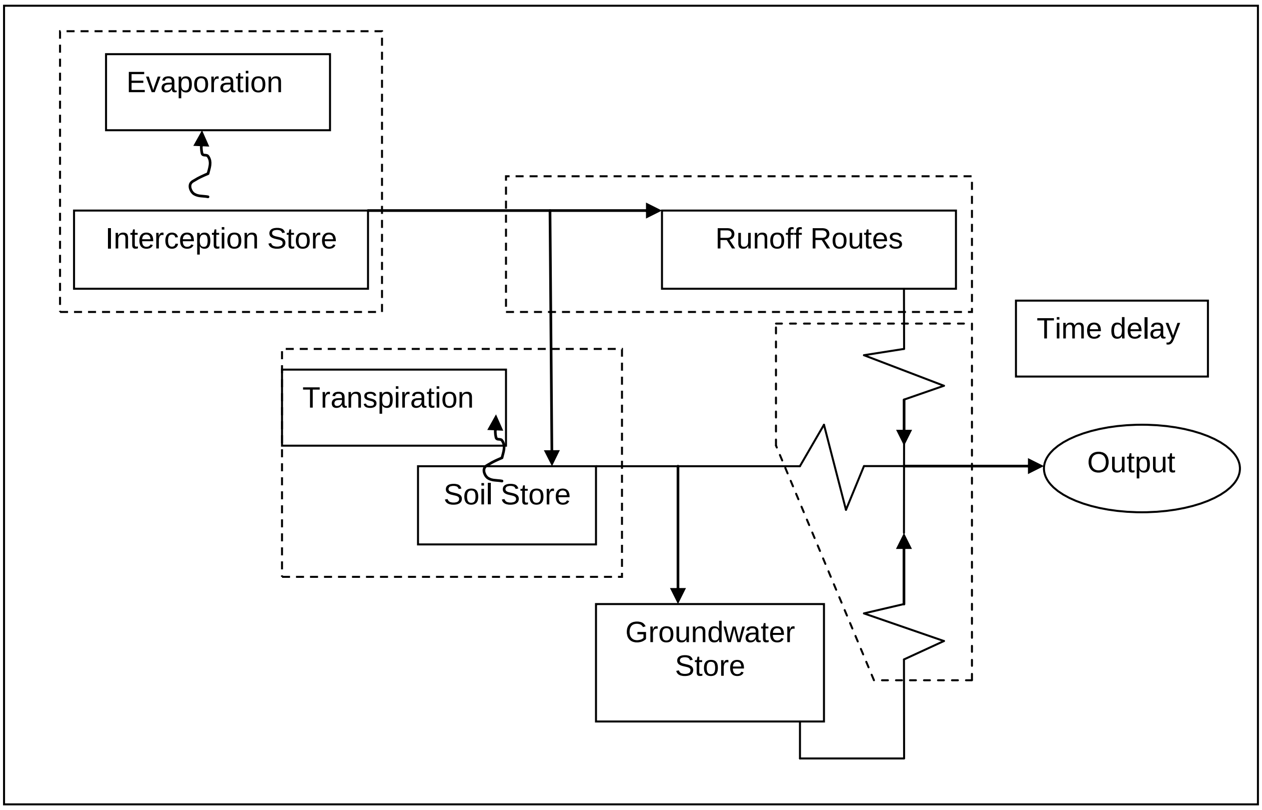


Figure 3.4: Runoff processes interpreted using storage areas (Newson, 1994)

As can be seen in Figure 3.4, the amount of runoff theoretically depends on the capacity of each storage area but in a given catchment, the runoff is affected by the physical and climatic characteristics of that catchment, as discussed below.

- Area of catchment: The size of the catchment ultimately determines the volume of runoff and runoff volume generally increases with increasing catchment area. However, the larger the catchment, the lower the peak runoff tends to be (Wilson, 1990). Rain falling on the boundary of a large catchment will take longer to reach the control section than it would if it were a smaller catchment, i.e. the time of concentration for a larger catchment tends to be greater. The impact of large storms is also reduced as the intensity of the storm is lowered over the larger area (Thompson, 1999). The additional benefit of more storage in larger underground aquifers and in watercourses and lakes also helps the catchment to react in a more sluggish manner (Raudkivi, 1979).
- Shape of catchment: The shape of a catchment directly impacts the time of concentration (Wilson, 1990), e.g. a rectangular catchment of $10km^2$ will have a longer time of concentration than fan-shaped catchment of the same area. The shape of the catchment therefore controls the impacts of various rainfall patterns.

- Slope: Surface runoff rates increase with increasing steepness of slope (higher water velocities) and decreasing infiltration rates as vegetation is often scarcer on steeper slopes (Thompson, 1999).
- Catchment orientation affects the type of climate the catchment will be susceptible to. For example, a catchment facing southwest in the UK or Ireland will probably be more susceptible to frontal rain as a result of the southwest prevailing winds carrying moisture from the Atlantic Ocean.
- Soil type: The type of soil in the catchment directly impacts whether precipitation infiltrates or runs off the surface. Appendix A classifies soils and slopes according to how much winter precipitation the soil is likely to hold, therefore inversely giving a relationship between soil type and probable runoff.
- Drainage network/ Water storage capacity: The greater the stream frequency, the faster a catchment is to respond, i.e. a marshy catchment will sluggishly respond with large times of concentration whereas a well-drained catchment will transfer precipitation speedily, potentially causing a higher flood peak at the control section.
- Vegetation cover/Land use: Land use affects the amount of runoff by affecting the infiltration rate and also by reducing the amount of available water (e.g. forested areas show much greater amounts of evapotranspiration than grassland areas, (Wilson, 1990)). Vegetated areas also reduce the rate of runoff as leaf letter creates a sort of porous media through which the water can flow. Resistance however is reduced with increased flow (Newson, 1994). Urban areas create large amounts of overland runoff as a result of the amount of paved surfaces.
- Amount, type, duration and distribution of precipitation: Although not common in the UK or Ireland, a change in precipitation from rainfall to snowfall would obviously put water available for runoff into storage. The distribution of precipitation also affects the amount of runoff, minimising or maximising the time of concentration depending on its areal distribution (as per shape of catchment), e.g. an elongated catchment is most prone to a sharp rise to flood peak if the storm is moving downstream. Duration and intensity of precipitation affect the occurrence and rates of infiltration (see Section 3.5.2).
- Evapotranspiration and interception: As discussed previously, an increase in evapotranspiration or interception creates a deficit within the water balance and the amount of runoff is thus reduced.

3.5.1 Overland Flow

Although most textbooks deal with overland flow as a single entity, Newson (1994) and Thompson (1999) distinguish between *Hortonian overland flow* and *saturation-excess overland flow*. Hortonian overland flow dates back to Horton's observations in the US where he noted that small areas of temporary storage fill up before the rate and depth of overland runoff increase. This series of events resulted from rainfall intensity exceeding the infiltration rate (Wilson, 1990). Saturation-excess overland flow however results from the soil reaching its infiltration capacity thus forcing excess rainfall to flow overland (Newson, 1994).

3.5.2 Infiltration

Although the lateral movement of moisture in the unsaturated zone plays a part in the hydrological cycle, the vertical movement of water, i.e. infiltration, has a much more significant effect on runoff processes. Infiltration is where water enters the soil, is stored and is then passed through to the phreatic surface by percolation (Thompson, 1999). Horton describes the process in the following formula:

$$f = f_c + \mu e^{-Kt} \qquad \text{(Equation 3.5)}$$

Where f is the infiltration rate at any time t, f_c is the infiltration capacity after time t, μ is the change in infiltration capacity and K is a constant for a particular soil and surface. Further research has shown that infiltration capacity depends on a number of things; type of soil (porosity and permeability), cover, slope, initial moisture content, duration of rainfall but in particular rainfall intensity (Wilson, 1990).

It has been found that f_c increases with increasing rainfall intensity but it is believed that it does not increase to the same extent in natural conditions. Highly intense rainfall can cause finer silts to be washed into surface pores causing the infiltration capacity for exposed soils to decrease sharply. The compacting action of the man and animals may also have a similar effect. Conversely, grass and vegetation encourages infiltration capacity as the soil becomes a network of pathways for the water to infiltrate (roots, insects) and saturation is rarely reached given that the vegetation is transpiring (Wilson, 1990).

In a bid to describe the hydrology of various soil types, soils were classified according their soil type, depth, permeability and slope initially in the FSR (IOH, 1975) and most recently in the FEH (1999) (Appendix A5).

3.5.3 Groundwater Flow

Although groundwater recharge may result from times of high river flows, the constant renewal of storage primarily comes from precipitated water percolating down to the water table (Shaw, 1994). The time taken to percolate can be anywhere between 4 and 45 years (Newson, 1994), depending on the geology of the catchment. Connected pores allow rock formations to act as deep underground storage tanks and the more permeable the rock (or the more fissured the rock), the faster the groundwater flow rate (still years in large catchments) (Newson, 1994). The governing equation for groundwater flow is Darcy's Law (Equation 3.6), where Q is groundwater flow, k is the hydraulic conductivity of the rock (a measure of how easily water flows through the medium), i is the hydraulic gradient and A is the cross section of the rock.

$$Q = kiA \qquad \text{(Equation 3.6)}$$

Baseflow plays a vital role in the hydrological cycle, sustaining rivers when it is not precipitating. In order to know how long we can rely on the baseflow to contribute to the river, a baseflow index (BFI) was developed (Institute of Hydrology, 1980).

3.6 The use of GIS in water resources management

With the establishment of the catchment as one of the most significant units in environmental management, manual methods of their delineation have ceased to be practical and the automatic generation of topographical parameters has now become the necessity. Using GIS to derive hydrological features from DEMs and the increasing availability of datasets such as land use and underlying soils have allowed hydrological model data requirements to become easily accessible and user friendly.

The use of GIS in water resources management however has surpassed catchment delineation and is now aiming to become the hydrological model rather than supply information to the hydrological model. This has become easier with the availability of interpolated climate data but development is still ongoing to create a GIS based hydrological model (Maidment, 1996).

GIS is applied in a number of ways to help manage the quality and quantity of water resources more efficiently and effectively, e.g. the mapping of areas prone to flood risk, the determination of inputs for hydrological models, the determination of mean annual runoff using a precipitation grid, the determination of nutrient losses using livestock data and a leaching coefficient (Jordan and Smith, 2005). Although it is most commonly used in the management of rural catchments, GIS can be used to more accurately model flow from source to sink in global climate models (Famiglietti, et al., 2010).

3.7 Factors affecting accuracy of the extraction of hydrological features from DEMs

A number of studies have been carried out examining those factors contributing to inaccurate derivation of hydrological features from DEMs and their consequent impact on hydrological simulations when used in spatially distributed models. Literature shows that the main affecting factors stem from the accuracy and resolution of the DEM as illustrated by the following studies.

Kenward, et al. (2000) carried out a study to assess the impact of DEM vertical accuracy on hydrologic predictions. They reported that varying vertical resolution had an effect on size of drainage area and accuracy in determining elevation and topographic features such as drainage channels and ridges. Bertolo (2000) agreed but stated that a DEM is acceptable once the ratio of average drop per pixel to vertical resolution is greater than one, thus highlighting the possible need for greater vertical resolution in low lying areas. Liu, et al. (2005) illustrated the effects of both DEM accuracy and resolution by demonstrating the increasing quality of derived features when a 20m resolution DEM derived using LiDAR was employed.

With regard to the use of DEMs in further hydrological modelling, Zhang and Montgomery (1994) noted that peak discharges increased with decreasing grid size as slope calculations increased with decreasing accuracy in horizontal resolution. DEMs with lower vertical resolution proved to simulate increased runoff volumes, decreased peak flows and variation in time to peak (Kenward, et al., 2000). A study carried out by Wolock and Price (1994) also proved that DEM accuracy and resolution impacted hydrological values.

Methods in deriving and interpolating DEMs have also been shown to impact further topographical and hydrological analysis. Older DEMs which have been manually profiled usually contain systematic errors or ‘striping’ which makes subsequent DEM analysis inaccurate, particularly in low-lying regions (Kumler, et al., 1995). The striping is usually in the east-west direction causing a biased influence on drainage paths and often creating additional ‘sinks’ as a result of creating blockages to the north and south (Garbrecht & Martz, 1999). These sinks are also known to be a product of rounding elevation values in order to save memory, thus turning gentle slopes into abrupt step-like features (O’Callaghan and

Mark, 1984). The number of sinks was shown to increase with decreasing resolution and decreasing variation in elevation (Garbrecht & Martz, 1999).

Garbrecht & Martz (1999) and Bertolo (2000) draw attention to the range of different algorithms available for extracting hydrological features from DEMs and their impact on catchment delineation. In general however, the literature suggests that those algorithms used in ArcGIS seem to be the most appropriate among other algorithms and are described in more detail in the Section 4.

In a study carried out by Garbrecht and Martz (1994), the accuracy of drainage features derived from DEMs was quantified. It was concluded that in order for drainage features to be derived within 10% accuracy, the DEM used should have a grid area less than 5% of the network reference area, i.e. grid area (10*10) divided by network reference area (mean subcatchment area) multiplied by 100 should be < 5%.

3.8 Classification of Hydrological Models

The most common type of model used in engineering hydrology is that of a mathematical model (Ponce, 1989). In 1996, Refsgaard illustrated the different classifications of hydrological models applicable to both catchments and individual components of the hydrological cycle, e.g. groundwater modelling, as can be seen in Figure 3.5.

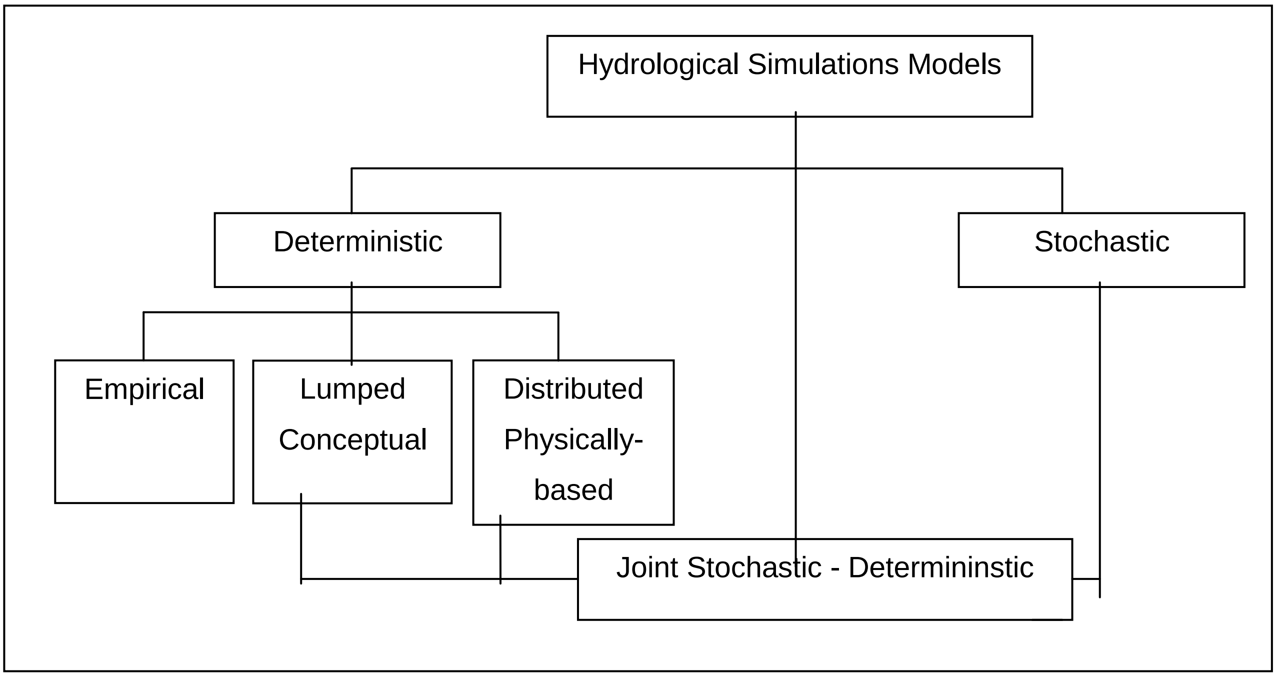


Figure 3.5: Classification of hydrological models according to process description (Abbott & Refsgaard, 1996)

The two main types according to Refsgaard's classification are deterministic and stochastic. A deterministic model is based on the laws of physical/chemical processes and will therefore yield the same output given a particular input every time. Stochastic on the other hand models random components which could present themselves based on a given time series.

There are three distinct types of deterministic model, the empirical black box type, the lumped conceptual model and the distributed physically based model. Black box models can be empirically derived hydrological methods (e.g. the unit hydrograph), statistically based methods (e.g. antecedent precipitation index) or hydro informatics based methods (neural networks and evolutionary algorithms) (Abbott & Refsgaard, 1996).

Lumped conceptual models can describe temporal variations of physical processes but simplify them spatially by averaging all parameters over the entire catchment area (Ponce, 1989). They then take account of net rainfall in different storage areas and simulate catchment response using hypothetical linear reservoirs. Because the simulation equations are semi-empirical with a physical basis, calibration of the model is vital (Abbott & Refsgaard, 1996).

In contrast, distributed physically based models can model both temporal and spatial variations. Their ability to model spatially has led to their use in modelling flow in saturated and unsaturated zones within a catchment (Ponce, 1989), to predicting the effects of urbanization and modelling soil erosion (Abbott and Refsgaard, 1996).

However, despite the accurate representation that a distributed model may offer, its data requirements are much greater than that of a conceptual model and therefore a conceptual lumped model is preferable for prediction in ungauged basins (Kling & Gupta, 2009). Also, the Strangford Lough catchment is considered a mid-size catchment and it is considered adequate to assume only temporal variation (Ponce, 1989).

3.9 Factors Affecting Performance of NAM Rainfall-Runoff Model

Refsgaard and Storm (1996) listed the four sources of error in hydrological modelling as the following:

- errors in meteorological input data
- errors in observed data
- errors and simplifications made in the model structure (e.g. the lumped nature of the model)

- errors as a result of using non-optimal parameters (sometimes affected by parameter interaction)

Early studies showed that input data, and in particular precipitation, are the most substantial contributors to error in modelling runoff (Singh and Woolhiser, 1976, Xu and Vandewiele, 1994; Paturel, et al., 1995). Xu, et al. (2006) elaborated in a separate study and reported that the type of error (random or systematic), the magnitude of error, the season of the year and the catchment's physical characteristics all contributed to the response and performance of the model. Liden and Harlin (2000) found that the magnitude of actual water balance components affected the model performance by testing the same model in different climates. Dry catchments were examined by Gan, et al (1997) who found that their performance was affected by model structure, data quality and the auto calibration objective function.

Errors in observed flow are another major factor causing modelled runoff to be inaccurate and are more prevalent when rating curves have not been well developed. The calibration period has also been found to be of importance to certain catchments, e.g., Yapo, et al. (1996) showed that the minimum length of data required for model calibration was 8 years but Gan, et al (1997) showed that calibration length was not as important for dry catchments. In the same study, dry catchments were shown to not be affected significantly by model complexity, a result which Engleland, et al. (2005) also found for catchments in general. However, the latter study only focused on examining one conceptual rainfall runoff model and parameter uncertainty tends to vary with model used. Conversely, Yapo, et al. (1996) found that, in their study, parameter uncertainty was at its least in periods of wet weather.

Perrin, et al. (2001) studied parameter uncertainty and showed that complex models outperformed simpler models during calibration but simpler models proved more robust during validation. This suggests that more parameters lead to greater parameter uncertainty and model over-parameterisation. However, Kuczera (1997) found that the greater the number of parameters used in the shuffled complex evolution (SCE) algorithm, the more likely it was to find the global optimum. This theory suits the NAM model as it uses the SCE algorithm (Duan, et al., 1992) and has nine parameters for optimisation.

The objectives used in calibration were also found to affect model performance. Although using multiple objective auto calibration is more representative of the fit required between observed and simulated flow, its use results in tradeoffs between objectives and no one optimal set of parameters can be achieved. For the NAM model, a number of combinations of different parameter values (known as a Pareto set) all lead to the same goodness of fit between simulated and observed hydrographs (Madsen, 2000). Therefore choosing an optimal set of parameters requires weighting each objective equally and drawing a balanced aggregate solution (Madsen, 2000).

3.10 Regionalisation Methods

Regionalisation is the application of parameters to ungauged catchments using information based on catchment climatic and physical characteristics. Research into prediction in ungauged catchments has recently been re-initiated by the International Association for Hydrologic Sciences (IAHS). The initiative known as PUB (Prediction in Ungauged Basins) aims to drive research away from relying on the use of historical data to calibrate models and project research into creating hydrological models with reduced predictive uncertainty which are based on understanding elements of the hydrological cycle (IAHS, 2010).

There are a number of existing methods that can be used to predict parameter values in ungauged catchments. The first and most commonly used is that of linear regression. In this method, single or multiple catchment characteristics can be employed to establish a relationship in order to predict the parameters of the ungauged catchment. The method performs well when catchment characteristics are similar and when a linear relationship exists (Yokoo, et al., 2001).

The nearest neighbour method can also be used to regionalize model parameters. Parameters can be found by mean weighting parameters from surrounding catchments or an interpolation method (usually Kriging) can be employed to find unknown parameter values based on nearby catchments (Vandewiele & Elias, 1995). This geographical approach works well if the catchments' parameters are similar but, in various case studies (Vandewiele & Elias, 1995; Li, et al., 2010), this method has proved the least preferable.

Hydrological similarity is another method that can be employed to regionalize parameters and has already been used for flood estimation in ungauged catchments (IOH, 1999). Unlike nearest neighbour, the geographical location of the catchment plays no role but its hydrological characteristics (determined by area, average annual rainfall for a given period and baseflow index) are used to group similar catchments (Robson and Reed, 1999).

Li, et al. (2010) introduced the index model as the best regionalization model for their study on 227 catchments in south-east Australia. Results from the index model proved most accurate when compared to those produced using linear regression, nearest neighbour and hydrological similarity models. Although the linear regression model was a close second, the index model proved to provide a better estimate for poor-fairly gauged catchments. Their study seems to be in line with the PUB initiative by suggesting the use of index models in conceptual rainfall-runoff models and reducing predictive uncertainty.

In summary, the existing literature suggests that substantial research is underway for the purposes of prediction in ungauged catchments and although the index method looks promising, the method requires further testing.

4 GIS Methodology

In order to meet the first objective, two digital elevation models (DEMs) covering Co. Down were accessed, an initial DEM of 25m horizontal and vertical resolution and a subsequently obtained DEM of 10m horizontal and vertical resolution. The delineations would be carried out using the Arc Hydro extension available through ArcGIS 9.3.

The 25m DTM was obtained from the LANDMAP project which produced the first IfSAR DEM for the British Isles. The DEM was produced using two SAR (Synthetic Aperture Radar) images which were obtained by flying an antennae multiple times over land (Belliss, et al., 2000) and which were shown to have a vertical accuracy of 8-14m based on a kinematic GPS study. The 10m dataset was gathered by the Ordnance Survey Northern Ireland (OSNI) using aerial photography and a GPS flown device to add control points to the photography from which 95% of the data was confirmed as being within +/- 1m accuracy (OSNI, 2007).

Although the 25m DEM was already interpolated when it was obtained, the 10m dataset required the elevation points to be merged and interpolated. Inverse Distance Weighting (IDW) was the method used to interpolate these data points and is based on the formula below (Equation 4.1). The method employs a number of neighbouring points (in this case twelve) to determine an appropriate weighting that can be applied to the predicted location which depends on its distance from each measured location.

$$Z(s)_0 = \sum_{i=1}^{N} \lambda_i \, Z(s_i) \qquad \text{(Equation 4.1)}$$

Where: $Z(s_{i)}$ = the measured value at the i^{th} location
λ_i = an unknown weight for the measured value at the i^{th} location
s_0 = the prediction location
N = the number of measured values

Once the interpolation was complete the DEM was ready for the catchment delineation process. The steps undertaken in this process are identical for both DEMs and are outlined in Figure 4.1 below. All subsequent figures illustrating the implementation of the method use the output of the 10m dataset for reasons discussed in Section 6.

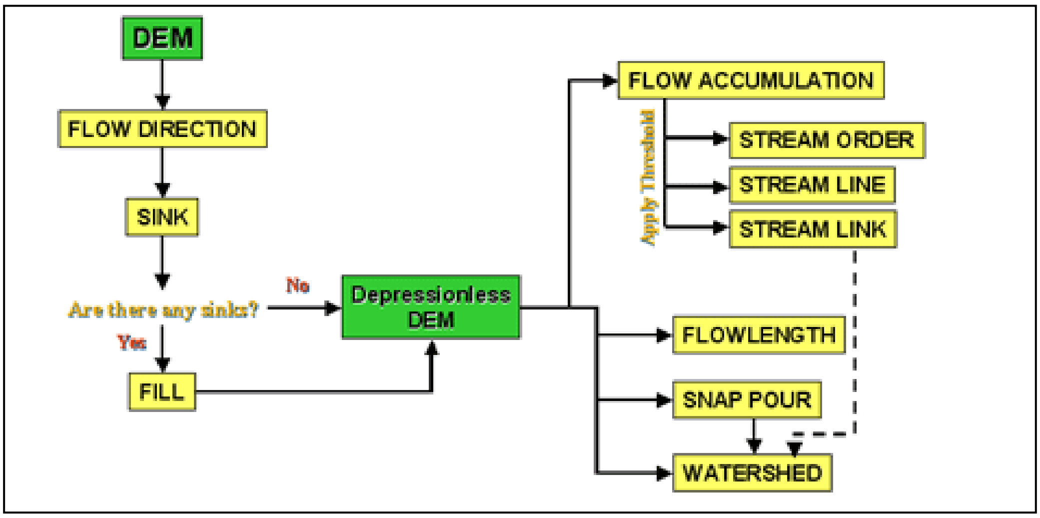


Figure 4.1: Steps taken to delineate catchment boundary from DEM

The first step taken to delineate the Strangford Lough catchment boundary was the reconditioning of the DEM. DEM reconditioning is the implementation of the AGREE method developed at the University of Texas at Austin in 1997. The system adjusts the surface elevation of the DEM to be consistent with vector coverage, which in this case was a water line vector accessed from the OSNI (2007). For the reconditioning to take place, three values were required, the number of cells for stream buffer, the smooth drop/raise and the sharp drop/raise. Essentially the number of cells selected as stream buffer controls the extent of reconditioning and may be estimated using the distance between a derived drainage line and the OSNI drainage line. The smooth and sharp drop/raise values determine the amount by which the cells underlying the vector line should be dropped or raised. Because no values had yet been determined, all three values were left at default.

The Agree DEM was then used to determine flow direction, i.e. to determine which cells flow into other cells. However, because of the topography of the area and errors in the DEM, some cells lay below all their surrounding cells in what is known as a sink. The hydrologic functions within Arc Hydro allow these sinks to be filled and therefore a depressionless DEM can be used to determine flow direction. The flow direction is illustrated through directional coding in the output raster (Figure 4.2).

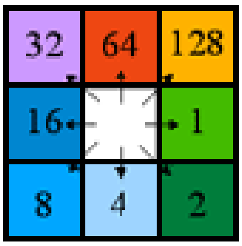


Figure 4.2: Coding of flow direction raster

So as illustrated by Figure 4.2, a cell value of 1 represents an easterly flow direction, whereas a cell value of 128 represents a north easterly flow direction, etc.

Once the flow direction was determined, the flow accumulation tool was used to determine the stream network. Because no weight raster (e.g. rainfall amount) was provided, a weight of one was applied to each cell, with the output raster having values relating to the number of cells that contribute to each cell, i.e. cells nearby Strangford Lough have higher flow accumulation values than those close to the watershed boundary (see Figure 4.3). Flow direction and flow accumulation were then used as inputs to delineate the watershed.

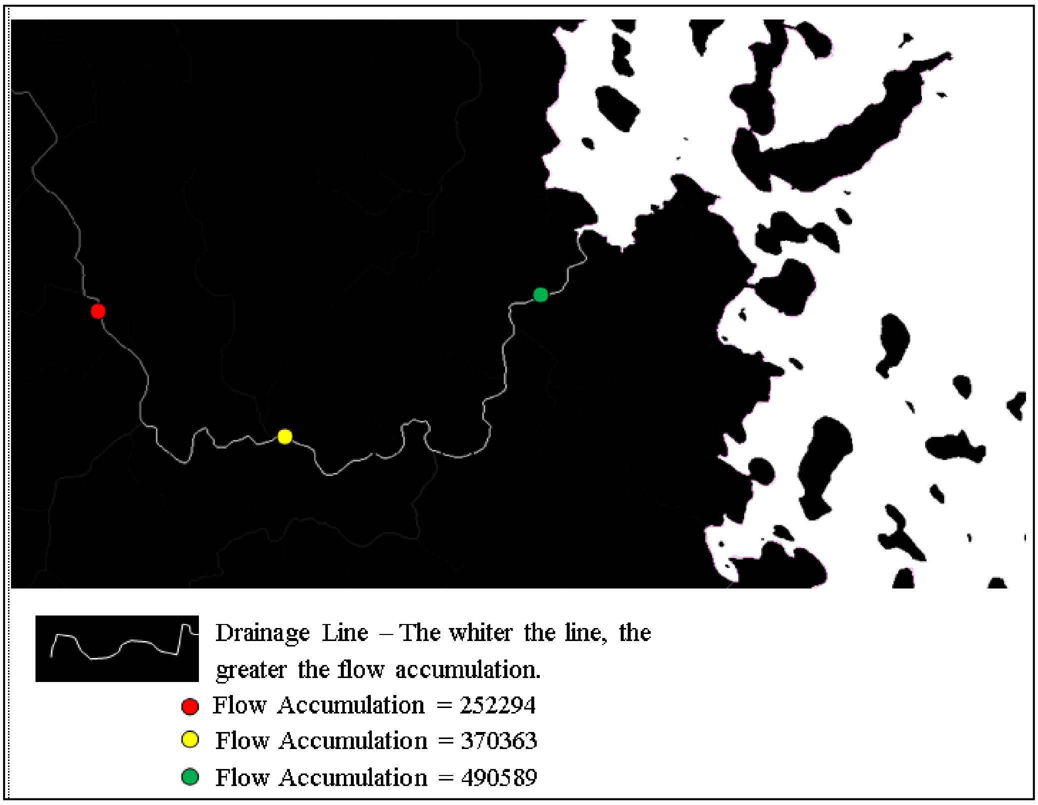


Figure 4.3: Flow accumulation values along a drainage line

The next step in the process was to define streams and in order to do so, a threshold value was required, i.e. the minimum number of cells that constitute a stream. Although threshold values vary with climate, the general rule of thumb is to set the threshold value at 1% of the maximum flow accumulation (Tarboton, 2003), which in this case was 291582 cells. The threshold value was later reduced to 20000 in order to give a greater stream definition (Appendix C2).This threshold was not changed further based on visual comparison of results.

Once the streams were defined, a grid of stream segments was created using the stream segmentation tool and the resulting values were then used to create a catchment grid. Catchment polygons were then processed using the catchment grid values and drainage lines were generated for each catchment polygon based on stream definition (Appendix B1). The adjoint catchment processing tool was used to speed up point delineation through the aggregation of upstream catchments. Point delineation was then carried out at every drainage point contributing to Strangford Lough (Appendix B2).

5 Results of Catchment Delineation using ArcGIS

This chapter describes the results of catchment delineation using the 10m and 25m resolution DEM.

5.1 DEM Reconditioning

Appendix C1 shows the difference in the 10m resolution DEM before and after it was reconditioned. The most significant differences lie in the streams in the upland part of the catchment.

5.2 Flow Direction

The attribute tables of the two flow direction rasters (*fdr* produced from the 10m DEM and *Fdr25M* produced using the 25m DEM) are presented in Table 5.1 below. It can be seen that the number of cells used to derive flow direction from the 10m DEM is approximately 50 times that of the 25m DEM. The percentage column also shows a 2%-6% increase/decrease in each flow direction as a result of increasing DEM resolution.

Directional Coding	Direction	Count		Percentage	
		25m Flow Direction Raster	10m Flow Direction Raster	25m Flow Direction Raster	10m Flow Direction Raster
1	East	406827	25152808	15.01	18.257
2	South-East	244565	8166355	9.02	5.93
4	South	463185	31500502	17.09	22.86
8	South-West	252926	6233373	9.33	4.52
16	West	450252	26266889	16.61	19.06
32	North-West	228058	5355658	8.42	3.89
64	North	419070	29652133	15.46	21.52
128	North-East	245019	5443288	9.04	3.95
	Total	2709902	137771006		

Table 5.1: Comparing the number of cells used in determining flow direction

5.3 Stream Definition

Stream definition using a stream threshold of 291582 cells and 20000 cells are compared in Appendix C2. As illustrated, the threshold value provided by the general 1% rule did not adequately describe the drainage pattern within the catchment but a reduction to 20000 cells provided a more accurate representation.

5.4 Drainage Lines

Figures 5.1 and 5.2 below use the official OSNI drainage line (2007) to compare the accuracy of the drainage lines derived using the 25m and 10m resolution DEMs in an area of high relief. Two things are particularly noticeable. Firstly, the accuracy of the 10m derived drainage line follows the OSNI drainage line much more closely than that derived using the 25m DEM. Secondly, the number of drainage lines defined by the 10m DEM is greater than that using the 25m DEM.

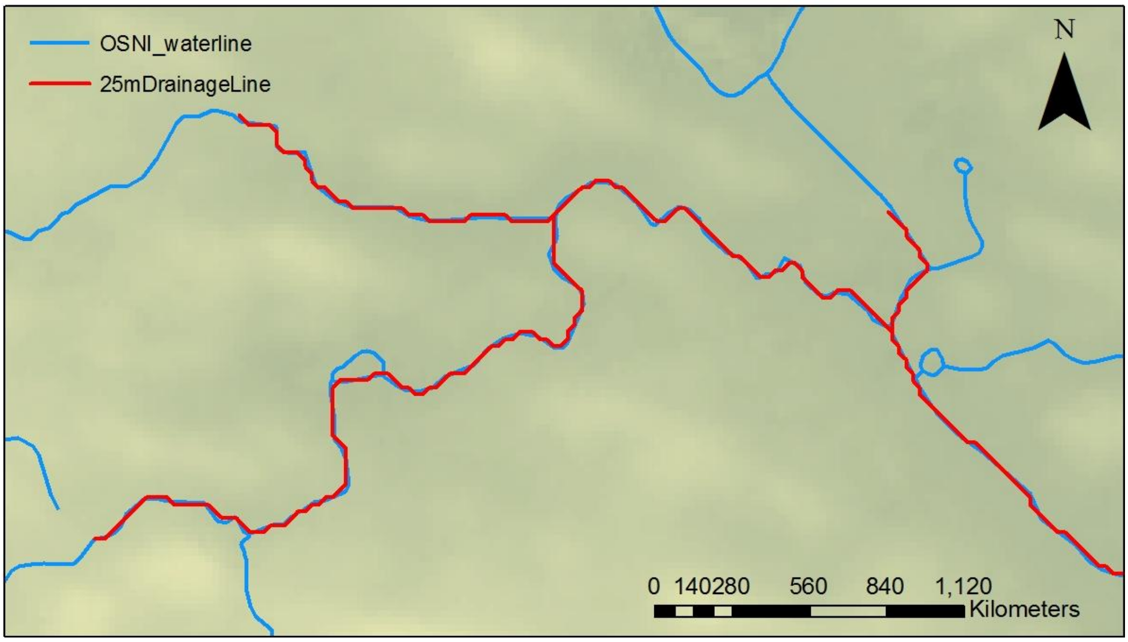


Figure 5.1: Comparison of 25m drainage line against official drainage line (OSNI, 2007) in mountainous region

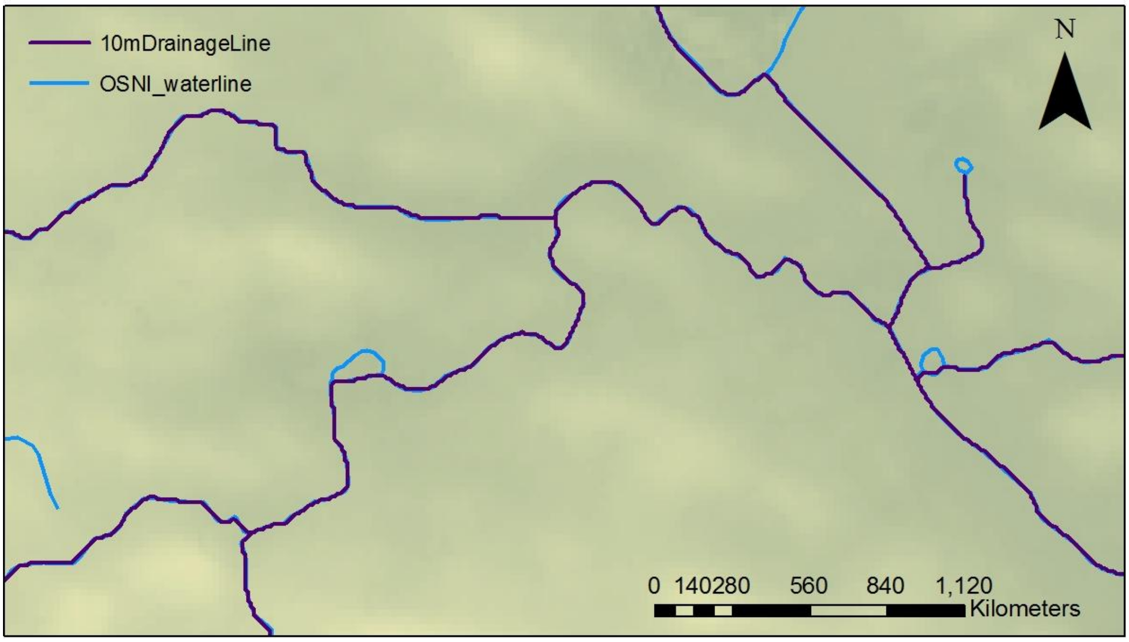


Figure 5.2: Comparison of 10m drainage line against official drainage line (OSNI, 2007) in mountainous region

Figures 5.3 and 5.4 below simultaneously compare all three drainage lines in a lowland and urban region respectively. Although the 10m drainage line follows the OSNI waterline more closely than the 25m drainage line does, there is still a noticeable difference between the 10m and the OSNI waterline. Figure 5.4 draws more attention to this difference by using the town of Comber as the background image. Clearly if either the 10m or 25m DEM were used in further hydrologic modelling, e.g. for flood risk assessment, the consequences would be significant.

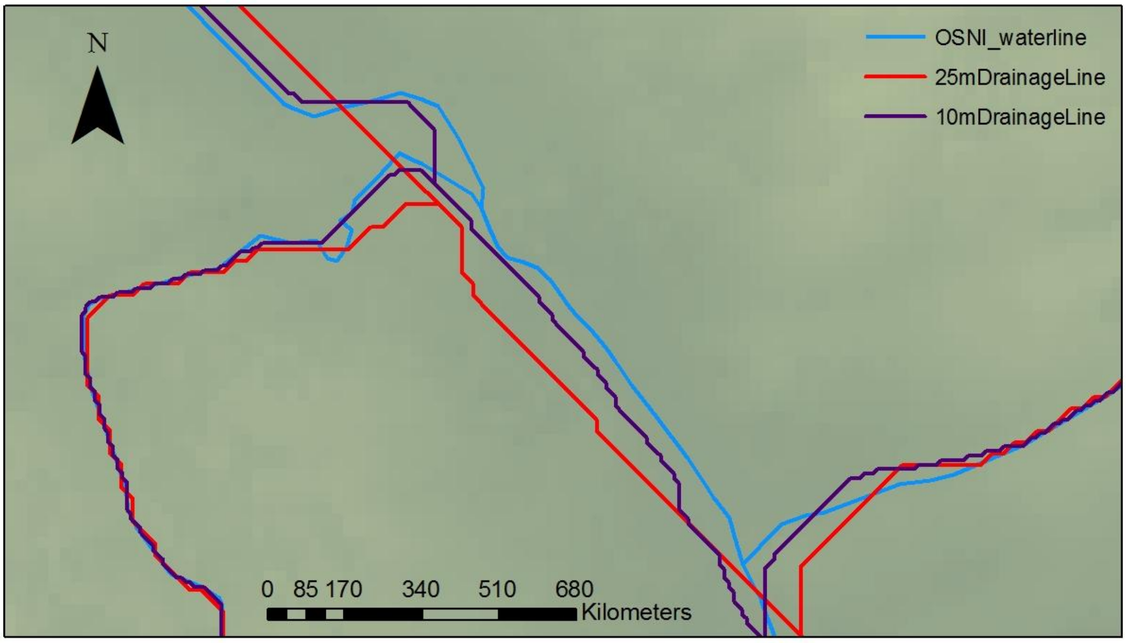


Figure 5.3: Comparison of 10m, 25m and OSNI drainage line in lowland region (outside Comber)

Figure 5.4: Comparison of 25m, 10m and official drainage line in an urban area (Comber)

5.5 Catchment Boundary

The final catchment boundaries using the 25m and 10m DEMs are compared in Appendix C3.

As can be seen from Table 5.2, the area delineated using the 25m DEM (697.21km^2) substantially exceeds the area derived by the 10m DEM (648.39km^2). The two delineations particularly differ on the north-eastern arm of the peninsula and the south-west corner of the Quoile catchment. It is likely that increasing resolution rectified this north-easterly/south-westerly stretch as illustrated by Table 5.1.

It can also be noted that there are a greater number of sub-catchments delineated using the 10m. Where 12 sub-catchments have been delineated in the 25m derived catchment, 199 have been delineated using the 10m dataset, thus indicating a more accurate delineation.

	25m DEM	**10m DEM**	**Official (OSNI/NIEA)**
Total Catchment Area (km^2)	697.21	648.39	647.37
Length of Drainage Line (km)	270.31	350.468	525.26

Table 5.2: Comparing characteristics of the 25m DEM, 10m DEM and NIEA/OSNI data

6 Discussion of Catchment Delineation using ArcGIS

The results of the 10m and 25m DEM delineations are compared against each other as well as the official NIEA catchment boundary in order to discuss the influence of DEM resolution on the quality of hydrological features extracted.

6.1 Comparing delineated catchments using 10m and 25m resolution DEMs

As described in the methodology section, any depressions in the DEM were filled in order for the flow direction to be determined, despite whether the depressions were natural or indeed already existing errors in the DEM. The relationship between DEM error and resolution is illustrated by comparing the number of sinks in the 10m resolution and 25m resolution DEMs. As can be seen in Figure 6.1 below, there are substantially fewer sinks in the greater resolution DEM.

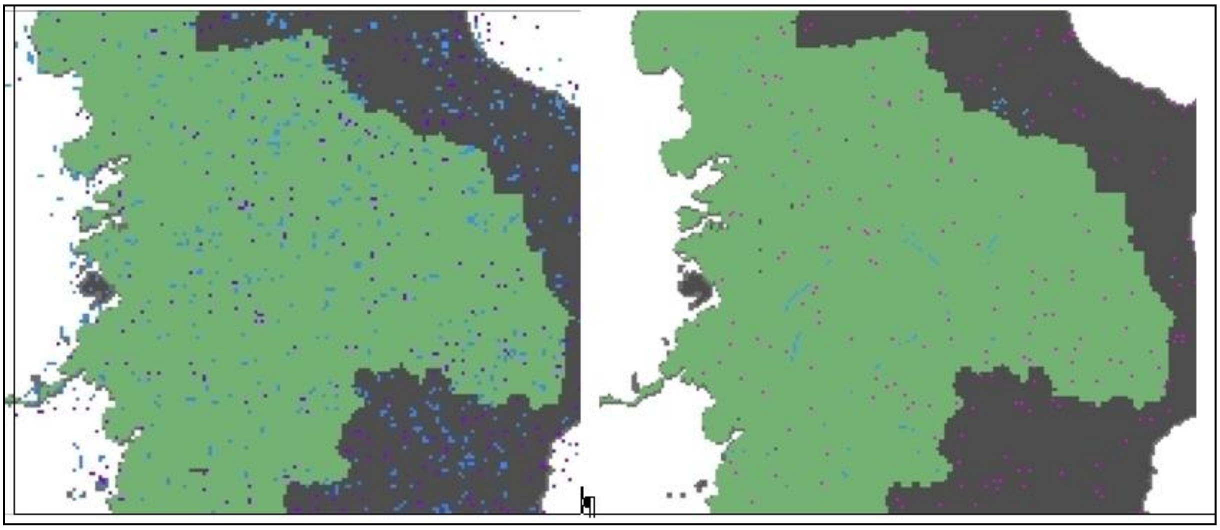


Figure 6.1: Comparison of Number of Sinks in 10m (right) and 25m (left) resolution DEMs

A greater resolution DEM however proves essential throughout the entire delineation process. Table 5.1 shows the number of cells used to calculate the flow direction for both the 10m and 25m DEMs. It is clear that increasing the DEM resolution increases the number of cells from which flow direction can be determined. The impact of using a greater number of cells is illustrated particularly well in Figures 5.1 - 5.4 where the extent and accuracy of drainage lines derived from the 10m and 25m DEM resolutions are compared. Figures 5.1 and 5.2 illustrate how a longer drainage line can be achieved by increasing the stream threshold value, whereas Figures 5.3 - 5.4 highlight the limitations of using a 10m*10m DEM for urban hydrological studies. Should hydrological modelling be necessary for urban areas in the Strangford Lough catchment, it may be useful to acquire LiDAR(Light Detection and Ranging) data which would speedily provide a DEM of higher accuracy and resolution, therefore improving any further hydrological analysis (Liu, et al.,2005). Differential GPS could also be carried out as a validation procedure.

DEM resolution also affects the length of drainage line derived as shown on Figure 5.1. However, the stream threshold value chosen in the methodology is the key to defining a good stream network, i.e. the smaller the threshold value the greater the stream network.

It must be noted however that the first step, i.e. DEM reconditioning (Appendix C1), was expected to reduce the inaccuracies of misplaced drainage lines in low-lying areas (Garbrecht & Martz, 1999). In this step, cells containing the OSNI waterline were dropped/raised in relation to the cells surrounding them, thus creating a biased flow direction. As is evident in Appendix C1, however, the reconditioning was ineffective in low-lying areas. It is possible that the reason for this is that an insufficient number of cells were chosen as the stream buffer, i.e. the default number of cells was 5, whereas in when the delineated drainage line was compared with the OSNI drainage line, 15 cells were required for accuracy in low-lying areas.

As suggested in the literature review, the DEM grid area divided by the mean subcatchment area be less than 5% should drainage features be derived within 10% accuracy. Table 6.1 below shows how both DEM resolutions fulfil this criterion but the results illustrate the extent of error when the 25m DEM was derived.

DEM Resolution	Mean Subcatchment Area (km^2)	%
25m*25m	6.58	0.095
10m*10m	3.26	0.031

Table 6.1: Calculation showing both DEMs should derive drainage features within 10% accuracy

6.2 Comparing NIEA catchment boundary with that delineated using 10m resolution DEM

The Strangford Lough catchment boundary used by the NIEA was obtained in order to compare it against the outline of the 10m delineation. The two compared well (see Appendix D1), with the most significant discrepancy in the River Blackstaff catchment in the middle of the Ards Peninsula (see Fig 6.2). Interestingly, this was also noted during the Flood Estimation Handbook (FEH) project, in which catchments were delineated using a DTM so that physical characteristics (e.g. altitude, aspect, slope) could be easily derived for the purposes of flood estimation. The handbook reports that the Blackstaff catchment did not pass the validation test whereby the ratio between delineated and official boundary was not to exceed 1.1.

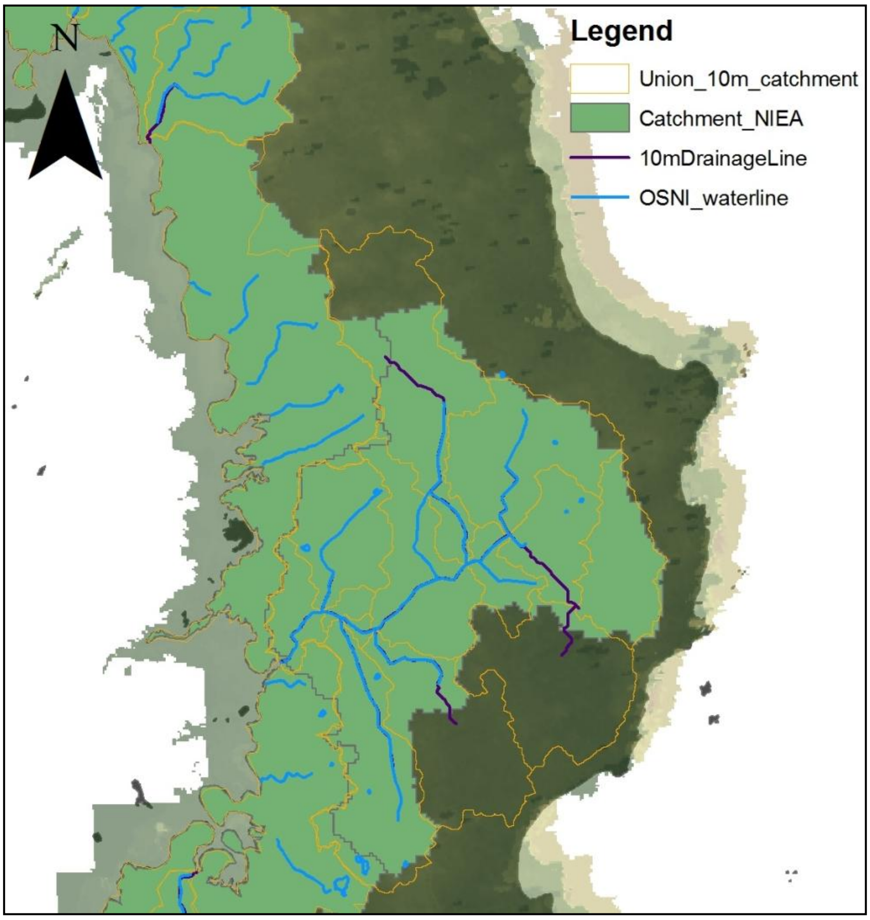


Figure 6.2: Most significant area of difference

The reason for a larger sub-catchment area as shown in the above figure is because of the longer drainage line derived from the 10m DEM. The possible insensitivity of the OSNI drainage line was also noticed when the Delamont gauging station was plotted and there was no indication of a drainage line at the station. However, this is not a fair representation of the entire catchment as the extent of the OSNI waterline generally exceeds the waterline derived by the 10m DEM (see Table 5.2).

There was some confusion with one particular area of direct drainage however, as neither DEM drainage lines clearly showed the source of the Ballymoran Burn (Figure 6.3). On first inspection it was thought that *location 1* was the source of the river, meaning that the NIEA catchment divide was placed incorrectly. The Rivers Agency was consequently consulted regarding this matter and for the purposes of clarification, they presented their derived

Ballymoran Burn catchment (Figure 6.4). The two delineated catchments differ by 9.905km^2, a difference which is explained by a more accurate Rivers Agency dataset from which they could extract hydrological features.

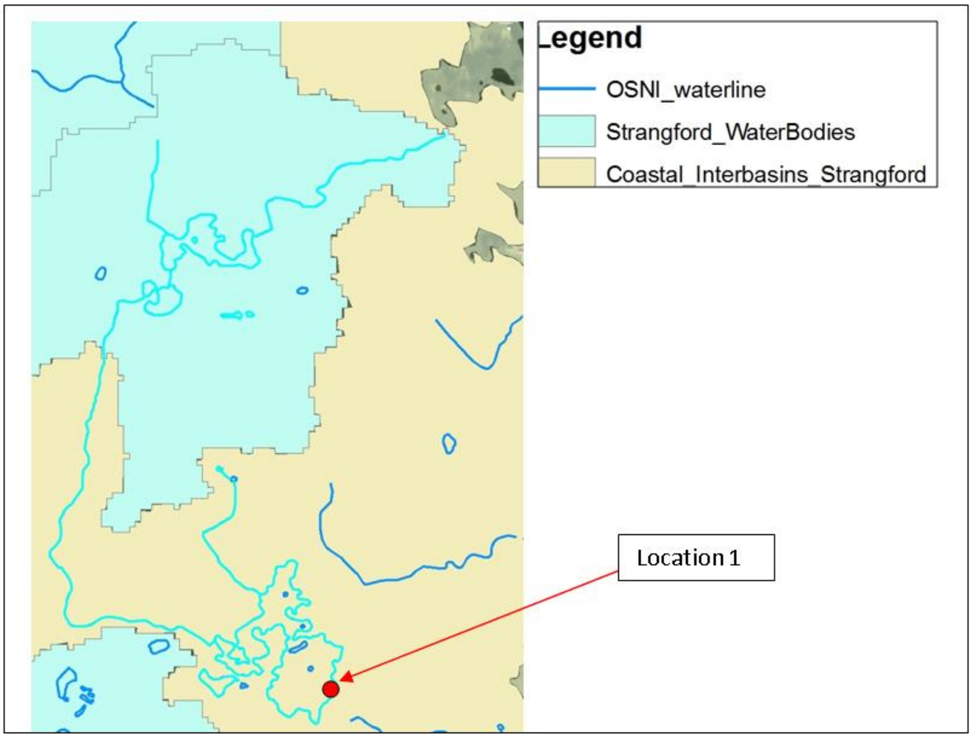


Figure 6.3: Ballymoran Burn and NIEA catchment divide

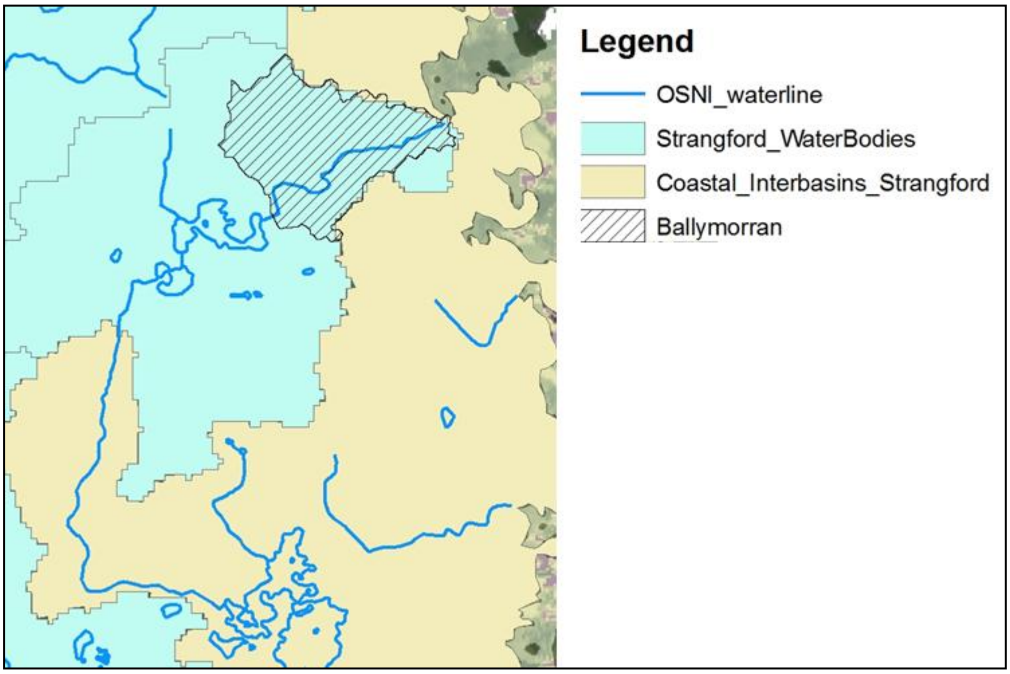


Figure 6.4: Ballymoran Burn catchment, courtesy of Rivers Agency

The remainder of differences between the two derived catchments is a matter of merging sub-catchments to form larger sub-catchments and re-classifying the smaller drainage systems as direct runoff.

It is not surprising that the 10m resolution DEM produced a very similar catchment boundary to that of the NIEA boundary, as the DEM used to produce the NIEA boundary was of 50m horizontal by 10m vertical. Thus, it may be concluded that the vertical resolution of a DEM is substantially more important than the horizontal resolution when delineating a large catchment boundary. This is confirmed by Garbrecht & Martz (1999) who explain the importance of vertical resolution and the ratio of horizontal to vertical resolution in the process of defining streams in low-lying areas.

7 NAM Rainfall Runoff Model: Methodology

In order to simulate runoff for the entire Strangford Lough catchment, MIKE 11's NAM rainfall-runoff model was used. NAM was originally developed by the Department of Hydrodynamics and Water Resources at the Technical University of Denmark as a conceptual lumped deterministic model with the objective of being able to identify model parameters purely from rainfall and streamflow records (Nielsen and Hansen, 1973). Essentially, the model simulates runoff into its overland, interflow and base-flow components and provides a thorough understanding of the catchment in question by inter-relating these three storage areas.

The first step taken to set up the model involved meeting the necessary data requirements i.e. rainfall, potential evapotranspiration and observed discharge. The model was then automatically and manually calibrated using four gauged sub-catchments in order to find the best fitting parameters to describe their contribution to runoff into Strangford Lough. The final step taken was the regionalisation of ungauged subcatchments so that the entire runoff into Strangford Lough could be accounted for.

7.1 Meeting Data Requirements

7.1.1 Raw Rainfall Data

Daily and hourly rainfall data was sourced from the MIDAS dataset with the permission of the British Atmospheric Data Centre. Both manual and automatic rain gauges were chosen based on their location, their period of record, their quality of record and their measurement type (i.e. daily/hourly). The data was presented in columns (Figure 7.1) which represented various attributes of the rain gauge station and the data it collected. These attributes are defined in Table 7.1 below.

Column in Daily Rainfall Data	**Description**
id	Rain gauge number
id_type	Identifier type
ob_date	Observation date
version_num	Represents which data had been quality checked by the Met Office
met_domain_name	Describes measurement type (rain, wind, etc) and interval of measurement (daily, hourly, etc)
ob_end _ctime	Clock time at end of observation
ob_day_cnt	Observation day count
src_id	Station identifier (unique)

rec_st_ind	Describes the status of a particular record, i.e. if it is exactly as the original record or if additional values have been added
prcp_amt	Displays the amount of precipitation recorded, measured to the nearest 0.1 millimetre
ob_day_cnt_q	Quality code on day count
prcp_amt_q	Describes the quality of data by comparing it to surrounding data points. The quality code is made up of 5 digits describing accumulation, estimation/correction, accuracy, original value and level of quality control reached

Table 7.1: Explanation of column headings in daily rainfall data

Once the data was separated using the unique station identifier number, Microsoft Excel was then used to eliminate duplicate records, poor quality data and identify sections of missing data. Poor quality data was eliminated based on its version number and quality code.

	A	B	C	D	E	F	G	H	I	J	K	L
1	id	id type	ob date	version num	met domain name	ob end ctime	ob day cnt	src id	rec st ind	prcp amt	ob day cnt q	prcp amt q
3112	973017	RAIN	1976-02-13 00:00	1	DLY3208	900	1	1503	1001	2.1	0	1209
3113	973017	RAIN	1976-02-14 00:00	0	DLY3208	900	5	1503	1012	18.5		20000
3114	973017	RAIN	1976-02-14 00:00	1	DLY3208	900	1	1503	1001	0	0	9
3115	973017	RAIN	1976-02-15 00:00	1	DLY3208	900	1	1503	1001	1.5	0	9
3116	973017	RAIN	1976-02-16 00:00	1	DLY3208	900	1	1503	1001	0	0	9
3117	973017	RAIN	1976-02-17 00:00	1	DLY3208	900	1	1503	1001	0	0	9
3118	973017	RAIN	1976-02-18 00:00	1	DLY3208	900	1	1503	1001	0.5	0	9
3119	973017	RAIN	1976-02-19 00:00	1	DLY3208	900	1	1503	1001	0.9	0	9
3120	973017	RAIN	1976-02-20 00:00	1	DLY3208	900	1	1503	1001	0	0	9

Figure 7.1: Elimination of Unchecked Data

As shown in the figure above, good quality data was indicated by version number equal to 1 whereas poor quality data was indicated by version number equal to 0. As shown by Figure 7.2, some data lines represented the accumulated total of more than one day's rainfall, which in some cases were also indicated by the version number = 0. These data lines would prove unsuitable as input data for the NAM rainfall runoff model as each time step (i.e. 1 day or 1 hour) must be the same in a given time series file.

	A	B	C	D	E	F	G	H	I	J	K	L
1	id	id type	ob date	version num	met domain name	ob end ctime	ob day cnt	src id	rec st ind	prcp amt	ob day cnt q	prcp amt q
3111	973017	RAIN	1976-02-12 00:00	1	DLY3208	900	1	1503	1001	10.8	0	1209
3112	973017	RAIN	1976-02-13 00:00	1	DLY3208	900	1	1503	1001	2.1	0	1209
3113	973017	RAIN	1976-02-14 00:00	0	DLY3208	900	5	1503	1012	18.5		20000
3114	973017	RAIN	1976-02-14 00:00	1	DLY3208	900	1	1503	1001	0	0	9
3115	973017	RAIN	1976-02-15 00:00	1	DLY3208	900	1	1503	1001	1.5	0	9
3116	973017	RAIN	1976-02-16 00:00	1	DLY3208	900	1	1503	1001	0	0	9
3117	973017	RAIN	1976-02-17 00:00	1	DLY3208	900	1	1503	1001	0	0	9
3118	973017	RAIN	1976-02-18 00:00	1	DLY3208	900	1	1503	1001	0.5	0	9
3119	973017	RAIN	1976-02-19 00:00	1	DLY3208	900	1	1503	1001	0.9	0	9

Figure 7.2: Eliminating Accumulated Totals and Daily Duplicate Values

The above figure also shows some of the codes used to describe varying data quality. When duplicate values existed for certain days, data with 'prcp_amt_q' closer to 9 indicated that a higher level of quality control was reached, thus that data was saved.

7.1.2 Finding Spatial Distribution of Rainfall

Once the rainfall data was analysed, rainfall stations having no missing data were used to derive Thiessen polygons for their respective river catchments using ArcGIS. However, early results showed large discrepancies in the water balance and it was therefore decided that additional stations were necessary and that those stations having short periods of missing data (e.g. a month per year) would be included in a bid to satisfy the water balance.

The final set of rain gauges used to calibrate the model are illustrated on Appendix E1. A program called Grid Inquest was used to convert the rain gauges' latitude and longitude co-ordinates to easting and northing co-ordinates and the gauges were then plotted using Excel and ArcGIS.

For each of the rainfall stations, the recorded data was stored in time series files (.dfs0) in MIKE Zero. Within the file properties, a certain amount of information had to be specified:

- the title (e.g. station name)
- the type of axis (equidistant, non-equidistant, calendar, relative)
- the starting date and time of the data
- the time step between each record (day, hour, etc.)
- the number of time steps (364 for a year of data)
- the type of record (rainfall, evapotranspiration, discharge, etc.)

- the unit of measurement (mm, cm, etc.)
- the time series type, i.e. how the parameter was measured (instantaneous, accumulated, step accumulated, reverse/normal)

Figure 7.3 shows a rainfall file's typical properties.

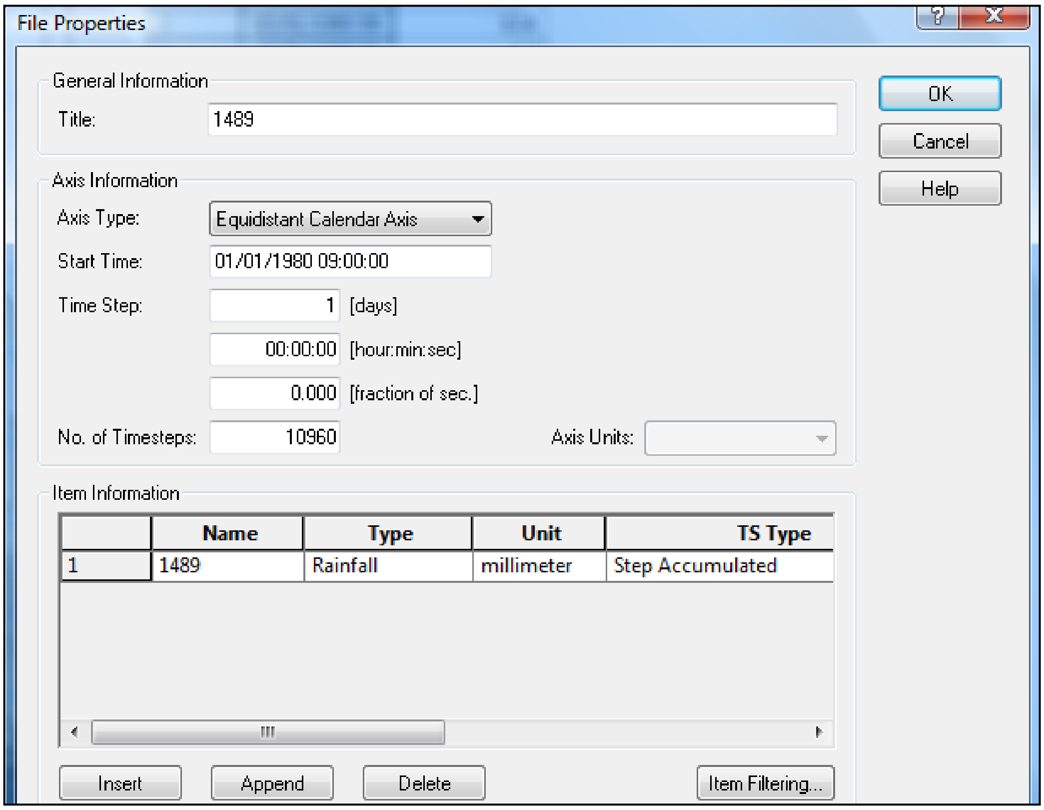


Figure 7.3: Typical rainfall time series file properties

Once the time series file was created, the rainfall stations contributing to each respective catchment were added under the time series 'weighted average' tab. A Thiessen weight was applied to each contributing station, and those stations not contributing for a certain period of time were denoted '-1' (see Tables 7.2-7.5). The following tables describe the rainfall contributing to each of the four catchments.

Data Span	**Rainfall Station Number**							**Total**
	16399	**16408**	**16440**	**16439**	**1508**	**16435**	**30875**	
83-90	0.002	0.0002	0.668	0.329	-1	-1	-1	1
91-95	0.002	-1	-1	0.406	0.102	0.489	-1	1
96-03	0.066	-1	-1	-1	0.414	0.512	-1	1
2004-2007	-1	-1	-1	-1	0.374	0.521	0.105	1

Table 7.2: Initial Thiessen weights for Comber catchment

Data Span	Rainfall Station Number			Total
	1489	16448	16377	
2001-2009	0.203	0.605	0.192	1

Table 7.3: Initial Thiessen weights for Ballynahinch catchment

Data Span	Rainfall Stations			Total
	16444	16447	55642	
83-04	0.024	0.975	-1	1
2004-current	-1	-1	1	1

Table 7.4: Initial Thiessen weights for Delamont catchment

Data Span	Rainfall Stations						Total
	16451	16377	16447	16399	1489	16448	
80-00	0.403	0.179	0.144	0.198	0.075	-1	1
00-09	0.193	0.059	-1	0.121	0.057	0.569	1

Table 7.5: Initial Thiessen weights for Kilmore catchment

In order to achieve the best fitting model, hourly rainfall data was added to the 'distribution in time' tab. The software used these hourly stations to distribute the daily rainfall proportionately in smaller time steps (i.e. a measurement every hour). Weightings were applied in a similar manner to those for the daily data.

7.1.3 Evapotranspiration Data

Potential evapotranspiration data spanning a year was sourced from the Met Office. Data from the Clones weather station was used due to limited data availability and its relative proximity to the catchment. The total annual evapotranspiration from this dataset estimated a value of 415mm at the Clones station which compares favourably to that suggested by Cruickshank (1997) who estimated a value of 350mm for evapotranspiration in the east lowlands of Northern Ireland. A time series file for potential evapotranspiration was also created in MIKE Zero and is similar to Figure 7.3 above. The location of this file was specified under the time series tab.

7.1.4 Hydrometric Data

Hydrometric data for four river stations in the catchment, namely Kilmore Bridge, Comber, Ballynahinch and Delamont, was obtained from the Rivers Agency. The location of these stations (Appendix E2) was also obtained from the Rivers Agency. Areas of the gauged catchments were listed in performance reports by Jacobs and these areas compared favourably with those areas derived using the 10m resolution DEM (see Table 7.6).

Catchment Name	Area Using 10m Delineation (km^2)	Area Provided by Rivers Agency (km^2)
Kilmore	186.16	186.6
Comber	59.49	61.8
Ballynahinch	51.7	48.7
Delamont	2.25	2

Table 7.6: Comparison of Delineated Catchment Areas with Official Catchment Areas

As with the evapotranspiration data, a time series file was created for the observed discharge at each of the hydrometric stations and then its location was specified under the time series tab.

7.1.5 Initial Conditions

The degree of catchment wetness was required before any calibration was initiated. Actual surface and root zone storage at the start of each simulation run (January) were taken to be 0.9 of their maximum storage. Overland flow, interflow and baseflow were also required for each gauged catchment. Baseflow was determined by examining observed discharge records after a long period of drought. Overland flow was estimated using storm event records and interflow was then estimated as the remaining portion of flow. Although these conditions are only estimates, once the first six months of simulation have been carried out, the effects of initial conditions should be neglible (DHI, 2009).

7.2 Model Calibration

Once the four gauged catchments were set up with their rainfall, evapotranspiration, observed discharge data and initial conditions, the model was ready to be calibrated. Model calibration is essential for the adjustment of simulated flow to observed measurements of flow. Calibration can be manual, automatic or a combination of both. During calibration, DHI (2009) suggest that the following objectives are taken into account, prioritising certain objectives if so relevant to the study:

1. A good agreement between the average simulated and observed catchment runoff (i.e. a good water balance)
2. A good overall agreement of the shape of the hydrograph

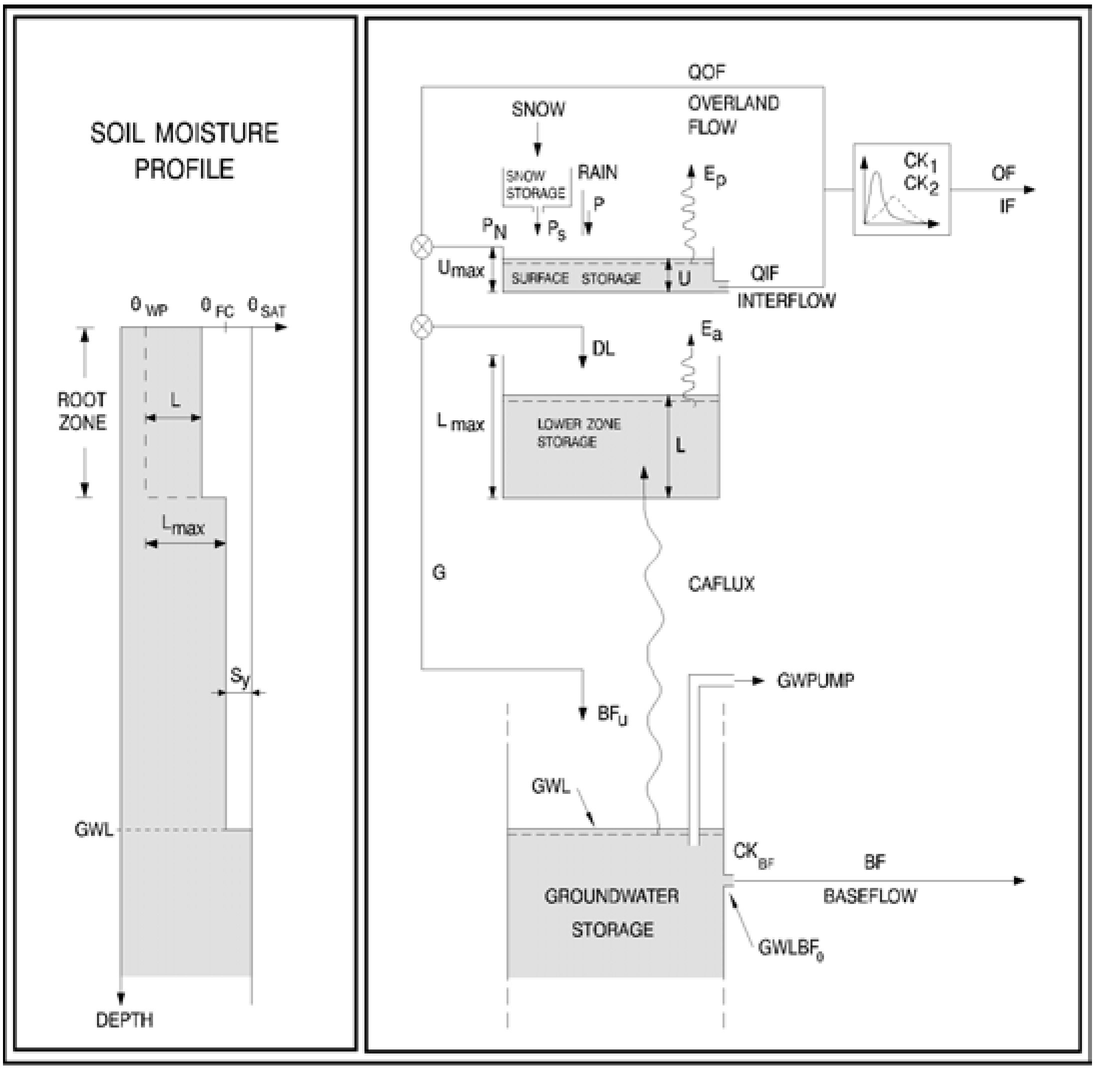
3. A good agreement of the peak flows with respect to timing, rate and volume
4. A good agreement for low flows

For this study, a combination of auto calibration and manual calibration was used. For the first auto calibration run, the minimisation of water balance error and root mean square error were prioritised and the maximum number of iterations was set to 2000. A new simulation file was then created in which an unsteady rainfall-runoff model was selected. The input files containing rainfall, evapotranspiration and observed discharge data were located and an appropriate simulation period was selected. Based on literature, (Yapo, et al., 1996; Xu and Vandewiele, 1992, 1994), it was decided that ten years of rainfall, evapotranspiration and streamflow data were to be used to produce a reliable calibration, with a similar data length preferable for validation. The initial simulation time step was set to 12 hours but this was later reduced to 1 hour to allow for a more accurate model simulation. Once the results were directed to an appropriate storage location, the simulation was initiated. Using each catchment's rainfall and evapotranspiration, the model generated its own simulated discharge; auto calibrated 9 key parameters and calculated both the water balance error and the root mean square error (Equation 7.1).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}[Q_{obs,i} - Q_{sim,i}]^2}{\sum_{i=1}^{N}[Q_{obs,i} - \overline{Q_{obs}}]^2} \qquad \text{(Equation 7.1)}$$

Where $Q_{sim,i}$is the simulated discharge at time i, $Q_{obs,i}$ is the observed dischrage at time i and Q_{obs} is the average observed discharge.

The 9 key model parameters essentially split the catchments runoff into three storage areas; surface, root zone and groundwater storage, as shown in Figure 7.4 (snow storage is not applicable to the Strangford Lough catchment). After auto calibration, the model was manually calibrated in order to achieve optimal values for the 9 key parameters.



1997-fmd\Nam-1.cdr\alj

Figure 7.4: Structure of NAM model

7.2.1 Estimation of Model Parameters

Because of the lack of experience on the user's behalf, the user felt that values for some of the parameters should be estimated in a bid to guide the manual calibration process. Each of the parameters are described below, including the method used to estimate their value.

- Umax represents the maximum amount of water that could be stored in surface depressions, vegetation and also the first few centimetres of soil. Umax tends to increase with heavily vegetated areas e.g. forests and tends to decrease in impermeable areas (e.g. rocky outcrops) and increasing slope as shown by Viessman, et al. (1977). Once Umax is reached, excess water can either infiltrate to lower root zone storage, groundwater storage or flow towards the sea via interflow or overland flow. Although the DHI manual suggested that Umax be estimated as 0.1Lmax, this formula was not strictly abided and a more general approach was taken, i.e. Umax increased with increasing Lmax.

- Lmax is the maximum amount of moisture available in the root zone for vegetation to use in transpiration. The amount available depends on the soil and vegetation type and the DHI manual suggested that an estimate may be obtained using the following formula:

(Field Capacity –Wilting Point)(Effective Root Depth)*

Unfortunately no information on root depths could be sourced and values sourced for field capacity and wilting point represented a general sandy clay loam. It was therefore decided to use an alternative estimation method provided by Cruikshank (1997).In his 'Soils and the Environment: Northern Ireland' book, soil moisture properties for the most common soils across Northern Ireland are detailed, of which two are found in the Strangford Lough catchment (see Table 7.7 below).

Series	Horizon	Avt (%)
Brown Earth Shale Till	Ap	24.08
	Bw	22.75
SWG1 Shale Till	Ap	21.83
	Bg	15.05
	C	12.76

Table 7.7: Percentage of water available for plant use at different soil horizons

Avt is the percentage of water available for plant use and is given for brown earths and gleyed soils overlying shale till here. In order to estimate Lmax however, a soil depth was required over which the percentages could be applied. The following working (Table 7.8) uses the Kilmore catchment as an example, where approximately half of the soils are shallow (i.e. less than 40cm soil depth) and half are described as the SWG1 soils overlying shale till (of which the user estimates an average soil depth of 100cm). Diminishing water availability with increasing depth has not been taken into account as the depths are very rough estimates.

	Available Water for Plant Use (%)	Estimated Average Depth(cms)	Available Water for Plant Use (mm)	Catchment Average (mm)
Surface water and groundwater gleyed soils	21.83	100	218.3	157.31
Shallow soils (using brown earths)	24.08	40	96.32	

Table 7.8: Estimate of Lmax for the Kilmore catchment

- CQOF is an estimate of the proportion of moisture that returns to the sea as overland flow. It is largely influenced by the type of soils underlying the catchment and the type of land cover (i.e. agricultural/urban). It was decided however to focus the estimation of CQOF on the soil type alone because (as agriculture was the dominant land use type) the type of agriculture (i.e. intensive/low productivity) was usually reflected in the soil and drift geology.

  As explained in Section 2.5, all soils in Northern Ireland were classified according to their hydrologic properties. One of the classifications by which the soils were grouped was catchment characteristics and consequently, the baseflow index (BFI) and standard percentage runoff (SPR) had been calculated for all soil types (see Table 7.9 for HOST classes in Strangford Lough).

Abbreviation	HOST Classification	BFI	SPR
SWG1	22	0.315	60
SWG1	24	0.312	39.7
SWG1/M	24	0.312	39.7
BE	5	0.9	14.5
BE/M	18	0.518	47.2
ALL	8	0.56	44.3
P	27	0.259	60

Table 7.9: The main HOST classes in the Strangford Lough catchment and their respective BFI and SPR values

Therefore by combining SPR with the areal distribution of various soils, an estimate of CQOF was achieved. The calculation for the Comber catchment is shown in Table 7.10

.

Abbreviation	Soil Description	Underlying Geology	HOST Classification	SPR (%)	Catchment Fraction	Catchment Runoff
SWG1	Surface Water Gley and Groundwater Gley	Shale till	24	39.7	0.7	0.278
BE	Brown Earths	Sand/Gravel	5	14.5	0.1	0.014
SWG1	Surface Water Gley and Groundwater Gley	Shale	22	60	0.2	0.12
						0.412

Table 7.10: Calculation of CQOF for the Comber Catchment

- CKIF is the time constant for interflow. Since interflow is not usually the main flow component, this time constant is usually small and not very important. Interflow is considered proportional to surface storage (U) and to vary linearly with relative moisture content in the lower zone storage (L/L_{max}). Generally when CK12 increased, CK1F was assumed to also increase.

- CK_{12} is the time constant for routing interflow and overland flow. The value of CK_{12} depends on a number of factors:
    1. the size of the catchment, i.e. the smaller the catchment the lower the time constant CK_{12}
    2. the underlying drift and solid geology of the catchment thus influencing the rate at which the catchment responds to rainfall
    3. the slope of the river determines how quickly water will runoff the land.

  The value of CK12 can be estimated by finding the time of concentration of a catchment. Kirpich's formula (see Equation 7.2) was used initially to calculate the time of concentration for each catchment. However, it was later discovered that the formula was only valid for catchments less than 200 acres and the values were recalculated using Hathaway's formula (Equation 7.3) (Ponce, 1989).

$$T_c = 0.06628\left(L^{0.77}/S^{0.385}\right) \qquad \text{(Equation 7.2)}$$

$$T_c = 0.606 \frac{ln^{.467}}{s^{.234}}$$ (Equation 7.3)

The following values were calculated as the time of concentrations for the four gauged catchments using the above formulae.

Gauged Catchment	T_c (hours)	
	Kirpich	Hathaway
Comber	3.05	3.53
Kilmore	8.05	7.28
Ballynahinch	3.14	2.97
Delamont	0.074	0.43

Table 7.11: Calculated time of concentrations for the gauged catchments

The above concentration times for Comber and Kilmore compared favourably with the Flood Estimation Handbook (FEH) method for calculating time to peak from catchment descriptors (Table 7.12) using Equations 7.4 and 7.5.

Station No.	Catchment	DPSBAR	PROPWET	DPLBAR	URB EXTENT OLD	URB EXPANSION	URB EXTENT NEW	Tp
205011	Kilmore	67.55	0.53	15.27	0.02	1.07	0.03	6.14
205020	Comber	65.93	0.52	7.81	0.04	1.07	0.04	3.95

Table 7.12: Catchment descriptor values for Comber and Kilmore catchments (Bayliss, 1999)

$$Tp(0) = 4.270 DPSBAR^{-0.35} PROPWET^{-0.8} DPLBAR^{0.54} (1 + URBEXT)^{-5.77}$$ (Equation 7.4)

Where;

- $DPSBAR$ is the mean of all internodal slopes for the catchment (m/km) and characterises overall steepness
- $PROPWET$ is the proportion of time when soil moisture deficit was less than 6mm
- $DPLBAR$ is the mean of distances between each node (on a regular 50m grid) and the catchment outlet, thus characterising catchment size and configuration.
- $URBEXT$ is the extent of urban and suburban land cover, which must be updated by applying an urban expansion factor which is calculated using the following equation:

$$URBAN\ EXPANSION = 0.8165 + 0.2254 \tan^{-1} \frac{2010 - 1967.5}{21.25}$$ (Equation 7.5)

All of the above characteristics were calculated in the FEH in a bid to estimate flood peaks for ungauged catchments. The calculations were derived from a 50m*50m DTM with digitised river information taken from 1:50,000 OS maps. The calculated characteristics are available in Appendix A of Volume 5 of the Flood Estimation Handbook (Institute of Hydrology, 1999).

- TOF represents the root zone threshold value for overland flow, i.e. when L/Lmax exceeds this threshold value (between 0 and 1), then overland flow occurs. Smaller catchments tend to have larger threshold values than those of large catchments. Absorbent catchments containing sands and gravels and a low water table tend to have a high threshold value whereas those catchments with many areas of rock outcrop would tend to have lower thresholds (from 0.3 – 0.5)

- TIF is the root zone threshold value for interflow, i.e. L/Lmax must exceed TIF in order for interflow to happen. This threshold usually tends to be smallest out of all the thresholds, with interflow usually occurring before any recharge or overland flow.

- Tg is the root zone threshold value for ground water recharge. Recharge does not happen unless L/Lmax exceeds Tg. This value is particularly important for describing the beginning of a wet season. In areas of rock outcrop, the threshold value was estimated at a lower value because of the low availability of root storage.

- CKBF is the time constant for routing baseflow. For catchments experiencing long periods of drought, an estimation of CKBF can be made using regression analysis (see Equation 7.6).

$$Q(t) = Q_0 e^{-\alpha t} \qquad \text{(Equation 7.6)}$$

The above equation describes the receding limb of a hydrograph in dry periods and the inverse of α gives an indication of the time constant for routing baseflow in the catchment. Because of the temperate maritime climate experienced by Northern Ireland, a reasonable estimate of CKBF could not be calculated, as the maximum dry spell lasted only a couple of weeks.

7.3 Manual Calibration

Although the estimated parameters indicated a range from which optimal parameters could be estimated, their values often further removed the simulated flow from the observed flow. As a result, the auto calibrated parameters were adjusted by examining both numerical and graphical performance of the model. Numerical performance was evaluated through the coefficient of determination and water balance error values whereas graphical performance was evaluated by examining the shape of simulated versus observed hydrographs.

7.4 Regionalisation

Parameters from the four calibrated sub-catchments were used as a guide to describe the hydrologic characteristics of the remaining ungauged subcatchments, thus allowing freshwater runoff to be modelled for the entire Strangford Lough catchment. Firstly however it was necessary to define the subcatchments. In order to do so, a combination of the official NIEA catchment and the delineated catchment using 10m DEM were used. The basis for grouping sub-catchments revolved around the river network they belonged to, their time of concentration and their soil type, drift and solid geology. Appendix E3 illustrates which subcatchments were grouped together.

Contributing rainfall was calculated for each of the grouped subcatchments in the same manner as it was calculated for the gauged catchments. The rainfall stations used for these subcatchments are illustrated on Appendix E4 below. Hourly stations used to distribute the data into smaller time steps are marked in green in the same figure.

Despite the seemingly extensive network of rain gauges, the simulation period was limited to run from 1983 to 1995 as a result of an inadequate rainfall station network after 1995. Within this simulation period, there still remained a number of catchments with missing periods of data due to a heavy reliance on one or two rain gauges (see Table 7.13)

Catchment	Periods of Missing Data
Direct 4	October 1990 - March 1991, May 1991 - September 1991
Direct 5	July 1986, September 1986 - December 1986,October 1990 - March 1991, May 1991 - September 1991
Direct 6	April 1986 - June 1987
Ballymoran	April 1986 - June 1987
Rathcunningham	April 1986 - June 1987

Table 7.13: Periods of missing rainfall data within simulation period

In order to regionalise the calibrated catchment parameters, a combination of regression analysis, user's judgement and calculation methods (Section 7.2.1) was used. This process was undertaken with a great degree of care as the quality of parameters chosen for the ungauged catchments could not be calibrated.

A number of parameters for the ungauged catchments were designated by examining the link between physical characteristics and calibrated parameters of the gauged catchments, i.e. U_{max}, CQOF, CKIF, TOF, TIF and CKBF. However, the remaining parameter values namely L_{max}, CK12 and Tg were calculated using one-predictor-variable regression. These model parameters were chosen for regionalisation through regression analysis as a result of having suitable predictor parameters and reliable observed values from which to derive regression parameters (α and β)

Calibrated Catchment	Umax (x)	Lmax (y)	n	$\beta = \frac{\sum xy - \frac{\sum x \sum y}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}}$	$\alpha = \frac{\sum y - \beta \sum x}{n}$
Comber	16.1	298	4	27.81	-195.6
Kilmore	18.7	295			
Ballynahinch	11.6	109			
Delamont	13.2	173			

Table 7.14: Calculating regression parameters

As can be seen from the table above, Umax was used to predict the value of Lmax for each of the ungauged subcatchments based on the strong relationship developed during calibration between these two parameters. Once the regression parameters α and β were calculated (Table 7.14), a value for Lmax was calculated for each subcatchment using the following equation:

$$y' = \alpha + \beta x \qquad \text{(Equation 7.7)}$$

Where y' = the estimated Lmax value for the subcatchment in question and x is its Umax value.

In order to regionalise the CK12 values of the calibrated catchments, time of concentration values calculated using Hathaway's formula were used. Because the values didn't match those derived by the model, regression analysis was used to predict CK12 values based on the calculated times of concentration and calibrated CK12 values from the Comber and

Kilmore catchments. Reasons why the Delamont and Ballynahinch gauged catchments were not used are described in Section 9. Regression parameters were calculated using the same formula as shown in Table 7.14.

Tg was the final model parameter to be derived using regression analysis. The Lmax values for the four gauged catchments were used to derive Tg values for the ungauged subcatchments in the same manner as Umax was used to initially derive Lmax. One adjustment was made however for the Quoile catchment for which regression analysis derived a Tg value of over 1. In the context of the model, a value exceeding 1 would not be logical and thus the value was reduced to 0.85.

A new RR Parameter file was set up with all the contributing subcatchments, their individual rainfall and evapotranspiration data, their respective hydrologic descriptors (Appendix F3) and a resulting combined catchment called Strangford Lough was thus created. The simulation was set to run for the period 01/01/1983 to 31/12/1995 due to rainfall data restrictions and total freshwater runoff for the entire Strangford Lough catchment was simulated.

8 NAM Rainfall-Runoff Model Results

This chapter presents the results of auto and manual calibration of each of the gauged catchments and subsequent regionalisation of the model. During the first auto calibration runs, the weightings of certain contributing rainfall stations were adjusted in order to satisfy the catchments' water balances. Model parameters were then optimised once the water balances proved satisfactory.

8.1 Comber Catchment

8.1.1 Water Balance

Initial water balance results showed that catchment inputs greatly exceeded catchment outputs. In order to improve the water balance, it was decided to re-examine the choice of rain gauges contributing to the Comber catchment runoff. The initial choice of rain gauges was based on the completeness of data at the rainfall stations, i.e. stations having periods of missing data were not preferable. It was decided to re-prioritise and use those stations closest to the catchment. The model was rerun using the new set of gauges but results showed simulated flow to be 32% greater than observed flow and this was still considered a substantial water balance gap (see Figure 8.1 below).

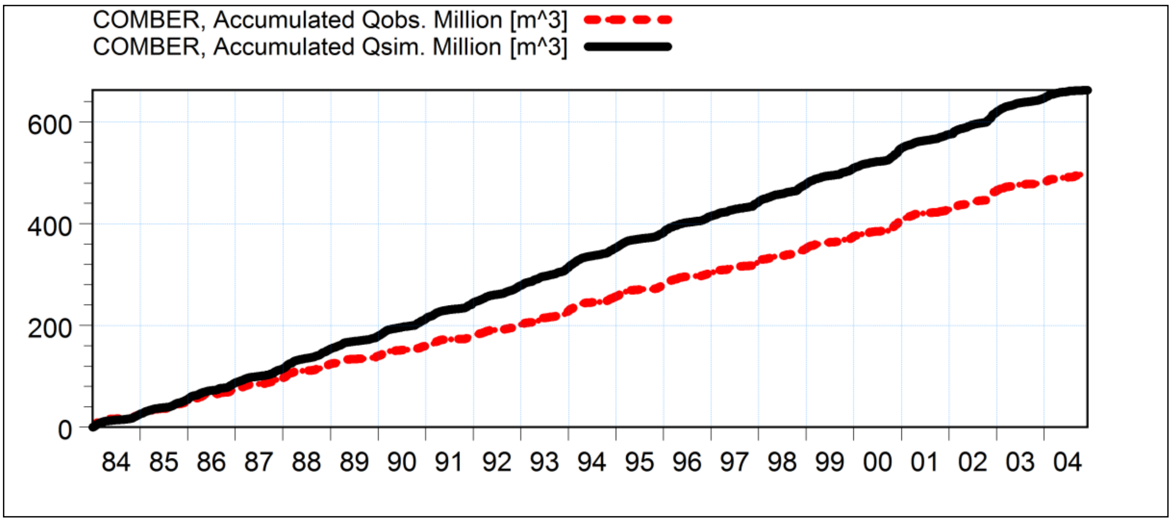


Figure 8.1: Accumulated observed versus simulated for the Comber catchment after change in rainfall stations

It was decided to manually adjust the rainfall distribution which was previously achieved using Thiessen polygons. As can be seen from Appendix F1, the majority of rainfall stations are located to the south-west of the Comber catchment, an area which experiences a greater amount of rainfall due to its elevation (see graph in Figure 8.2). In order to counteract the effect of elevation on rainfall, the weightings on stations 16440 and 16435 were increased while the weightings on stations 16439, 1508 and 30875 were decreased.

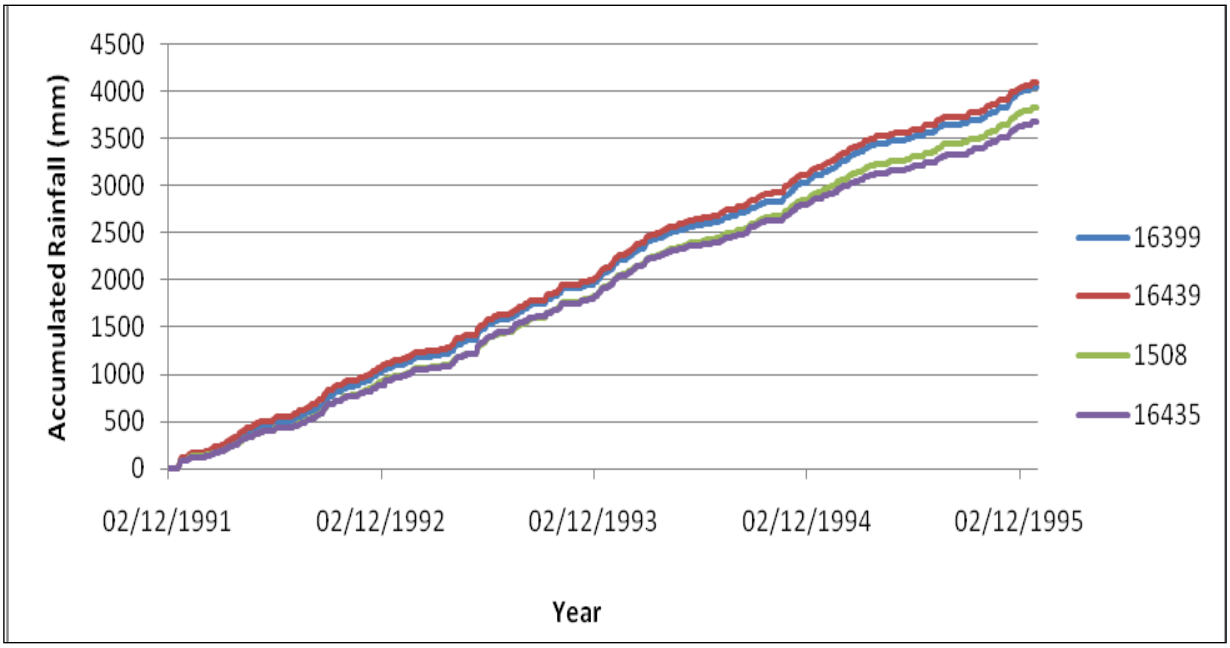


Figure 8.2: Comparison between rainfall stations of accumulated annual rainfall

As can be seen from Table 8.1 below, the total amount of available rainfall data was not used, as 85-95% of the data was found to prove adequate to satisfy the water balance equation. The need to restrict the amount of input rainfall may be a result of not taking into account the number of water abstractions within the catchment (see Chapter 9 for further discussion). However, it is also noted in the river gauge station reviews (provided by Jacobs and the Rivers Agency) that between 1993-1996 and 2000-2003, observed discharge may have been overestimated as a result of debris and weed growth. This in turn would cause the model to require additional rainfall (perhaps 100-120% of the measured rainfall) to match that of observed discharge.

	Rainfall Station Number							**Total**
	16399	**16408**	**16440**	**16439**	**1508**	**16435**	**30875**	
Combination 1	0.0021	0.0001	0.618	0.23	0	0	0	0.851
Combination 2	0.002	0	0	0.206	0.102	0.639	0	0.949
Combination 3	0.066	0	0	0	0.214	0.57	0	0.85
Combination 4	0	0	0	0	0.224	0.571	0.1	0.85

Table 8.1: Weightings and combinations of rainfall stations used for the Comber catchment

Figure 8.3 below illustrates the accuracy of the water balance achieved (observed exceeding simulated by 2.5%) using the combination of rainfall distribution as in Table 8.1 above.

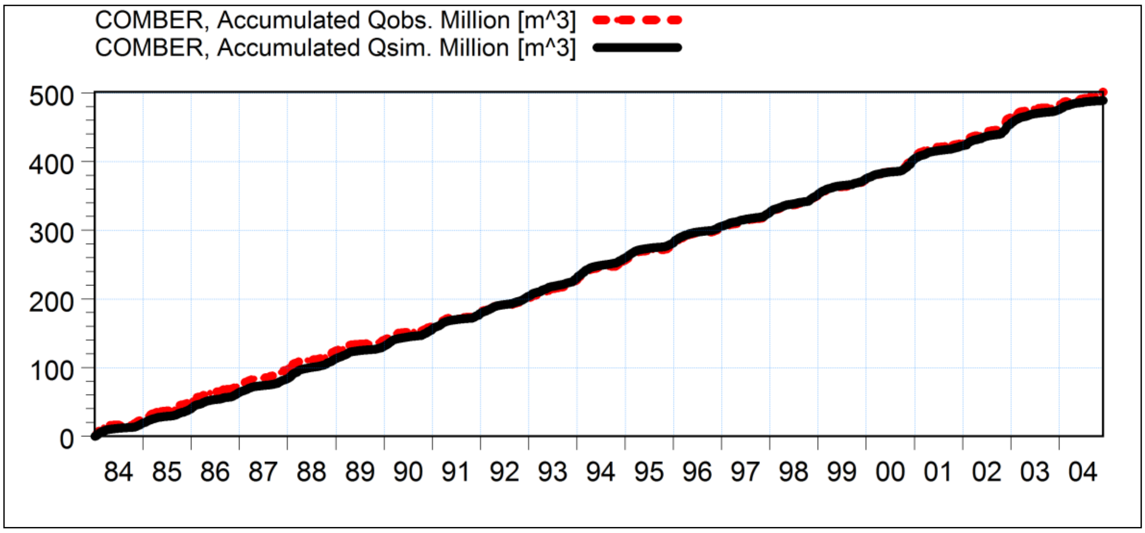


Figure 8.3: Plot of accumulated observed versus simulated flow after change in Thiessen weights

8.1.2 Calibration of Model Parameters

Initial results of auto calibration for the Comber catchment are shown below.

Umax	*Lmax*	*CQOF*	*CKIF*	*CK1.2*	*TOF*	*TIF*	*TG*	*CKBF*
19.7	296	0.503	856.1	10.1	0.774	0.678	0.721	3859

Table 8.2: Initial auto calibration results

In order to optimise the 9 key parameters, auto calibration results were examined both graphically and numerically. The initial coefficient of determination yielded through auto calibration was 0.571, indicating that the simulated and observed flows did not match particularly well. In a bid to improve the fit between observed and simulated, the parameters were manually adjusted until an optimal set were found (see Table 8.3 below).

Umax	Lmax	CQOF	CKIF	CK12	TOF	TIF	TG	CKBF	R^2	WBL
16.4	238	0.664	455.8	9.15	0.556	0.232	0.746	2788	0.625	0%

Table 8.3: Parameters after manual calibration

Although the effect of optimising these parameters was numerically noticeable, it was felt that the modelled flow was responding slower than the observed. In order to rectify this, the simulation time step was reduced from 12 hours to 1 hour, thus allowing the model to more accurately describe the catchment's response. Two hourly rainfall stations were also added as input data, from which the MIKE software distributed the daily data accordingly. With these changes made, auto calibration was rerun and the parameters in Table 8.4 below were produced.

Umax	Lmax	CQOF	CKIF	CK12	TOF	TIF	TG	CKBF
16.1	298	0.502	628.7	8.09	0.715	0.89	0.972	3708

Table 8.4: Auto calibrated parameters after addition of hourly data and time step

The results minorly improved, yielding an R^2 value of 0.649 and a water balance error of -1.4%. On graphical examination, the overall shape of the simulated hydrographs compared well against the observed hydrograph, although the volume of simulated peak flows was usually less than that observed and so CQOF was increased from 0.502 to 0.56. As can be seen from Figure 8.4 below, this change did not affect the difference in volume and it was decided to leave the CQOF value as it was originally.

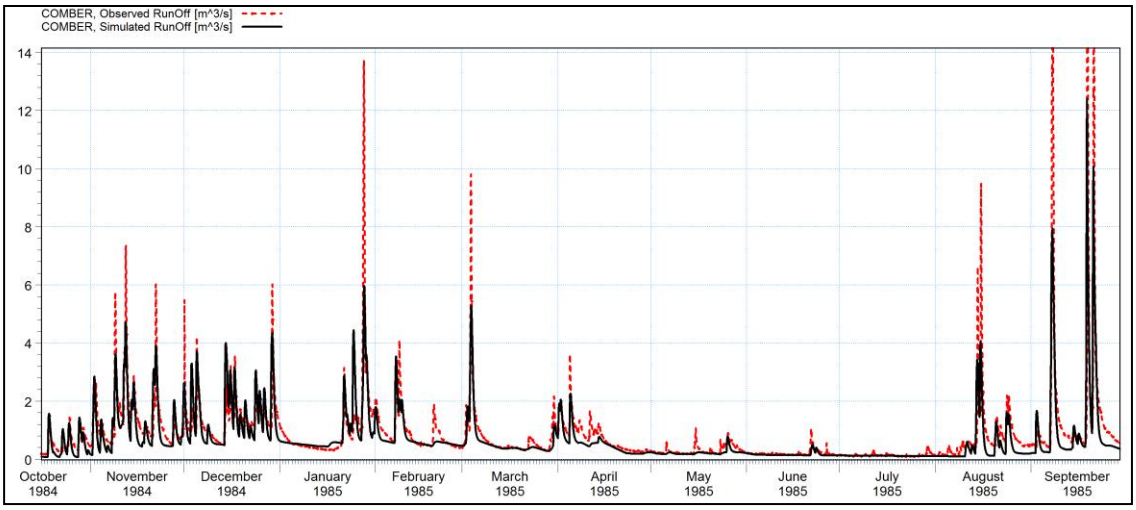


Figure 8.4: Comparison of simulated flow versus observed flow for one hydrological year

Any further manual calibration failed to produce a greater numerical fit. Parameters in Table 8.4 were used to validate the model. A final value of $R^2 = 0.617$ and water balance error of -5.1% was obtained

8.2 Delamont Catchment

8.2.1 Water Balance

Simulation runs for the Delamont catchment were split into two periods, the first spanning from 1989 to 1994 and the second spanning from 2004 to 2009. These runs were carried out separately as a result of missing observed discharge data for the period 1995-2004.

Initial calibration for the period 89-94 used rainfall data from stations 16444 and 16447 which both lie outside the catchment (see Figure 8.5). However initial water balance results showed that these stations provided 42% extra rainfall than the catchments outputs required. Due to the small area of the catchment it was decided to reduce the amount of rainfall being contributed by 16447, so that the final weightings chosen were as shown in Table 8.5 below. These weightings produced a water balance with simulated exceeding observed flow by 2.6% (Figure 8.6).

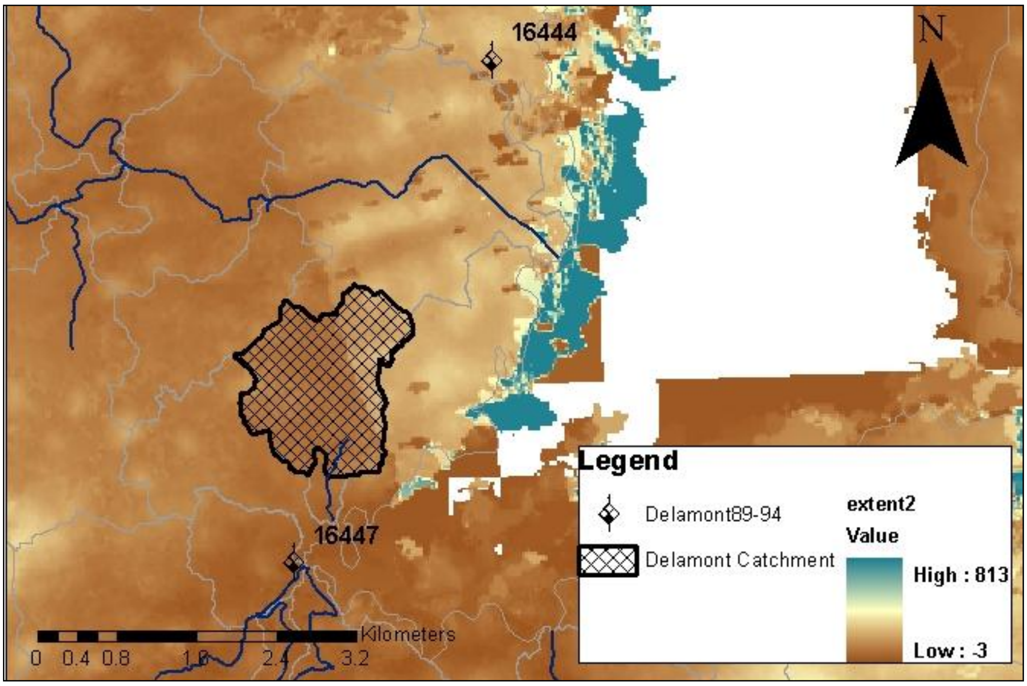


Figure 8.5: Location of rainfall stations

	Rainfall Stations		Total
	16444	16447	
Areal Distribution	0.024	0.776	0.8

Table 8.5: Final Thiessen weights for Delamont catchment

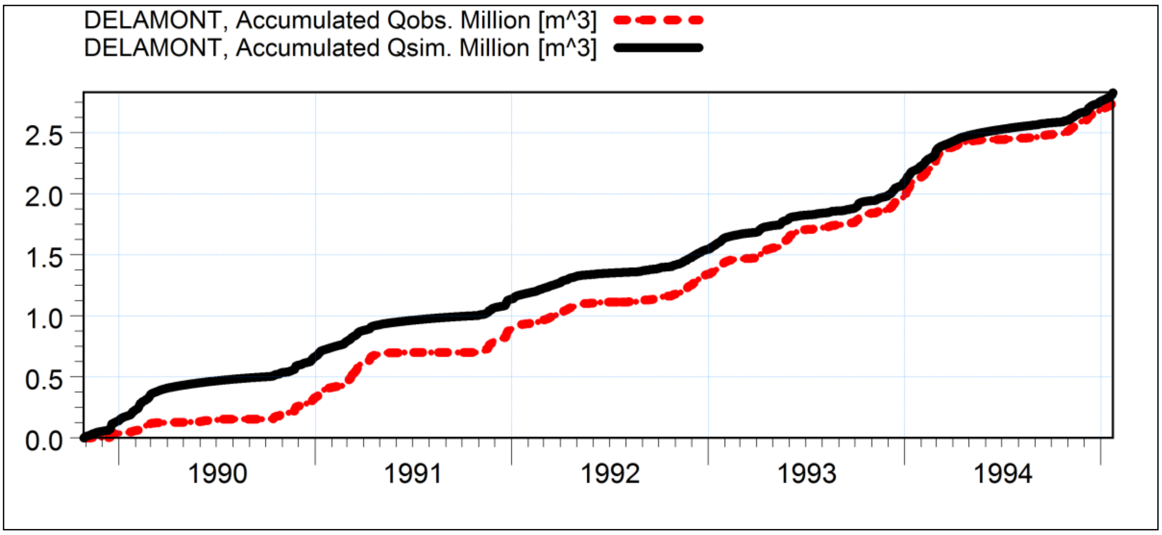


Figure 8.6: Accumulated observed versus simulated plot for Delamont (part 1)

The second simulation period used one rainfall station namely 55642 (Appendix E4). Once again due to the size of the catchment, the rainfall measured at 55642 was reduced to by 20%, proving to be an excellent water balance match (-0.1%) (Figure 8.7).

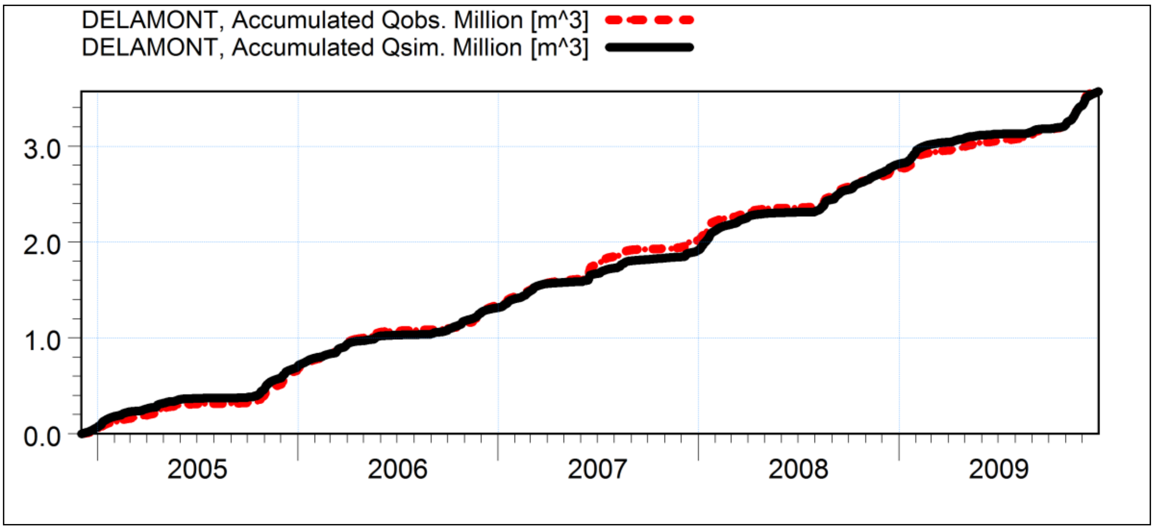


Figure 8.7: Accumulated observed versus simulated plot for Delamont (part 2)

8.2.2 Calibration of Model Parameters

Parameter	Value (89-94)	Value (05-09)	Lower Bound	Upper Bound
Umax	18.4	15.6	10	20
Lmax	299	103	100	300
CQOF	0.463	0.626	0.1	1
CKIF	900.8	344.4	200	1000
CK1.2	17	18	10	50
TOF	0.646	0.0202	0	0.99
TIF	0.841	0.39	0	0.99
TG	0.972	0.323	0	0.99
CKBF	3939	1130	1000	4000
CK2	17	18	10	50
CQLOW	0	0	0	100
CKLOW	1.00E+04	1.00E+04	1.00E+03	3.00E+04

Table 8.6: Auto calibrated parameters for Delamont catchment (period 1 & 2)

The table above compares auto calibration results from both auto calibration runs on the Delamont catchment. The values appear to describe two different catchments with the first simulation describing a large absorbent catchment and the second describing a smaller catchment with low root zone storage and extremely low threshold values.

Judging by the size of the Delamont catchment, its underlying geology, soil type and land use, it was decided that the parameters representing the 89-94 period were more reliable than those of the 05-09 period. The initial Nash coefficient from auto calibration was 0.732, a good starting point before manual calibration. From the graphical presentation of results it was felt that the first year of flow was hindering a good match for the latter years and was therefore removed. As a result, R^2 increased from 0.732 to 0.86. An auto calibration run was selected once again yielding the parameters below.

Umax	Lmax	CQOF	CKIF	CK12	TOF	TIF	TG	CKBF	R^2	WBL
14.3	170	0.604	281.6	15.7	0.472	0.563	0.789	1764	0.86	-0.10%

Table 8.7: Auto calibrated parameters for Delamont after first year of data removal

Although the parameters yielded a good fit numerically, the CK12 value is far from its estimated value (see Table 7.11). As a result the simulation time step was reduced from 12 hours to 1 hour and hourly rainfall data from station 1525 at Killough was added to distribute the daily rainfall data in smaller time intervals. Auto calibration was selected again and the results are presented in Table 8.8 below.

Umax	Lmax	CQOF	CKIF	CK12	TOF	TIF	TG	CKBF	R^2	WBL
13.4	171	0.53	201	12.7	0.497	0.669	0.836	1983	0.84	0.00%

Table 8.8: Auto calibrated parameters after addition of hourly data

The simulation time step was reduced to 15minutes in a bid to rectify the lengthy CK12 value again. As can be seen from the auto calibration results below, this did not impact the routing constant for overland flow and interflow and in fact reduced the coefficient of determination.

Umax	Lmax	CQOF	CKIF	CK12	TOF	TIF	TG	CKBF	R2	WBL
13.2	173	0.527	229.2	12.2	0.463	0.618	0.797	1554	0.838	0

Table 8.9: Auto calibration results after further reduction in time step

Graphical examination confirmed that the CK12 value was far too high, with Figure 8.8 below showing a typical example of the effect of a large CK12 value. Using the graph as an estimate, the CK12 value was reduced to 2 hours and the remaining parameters were adjusted based on the user's judgement. These parameters are shown in Table 8.10, and although they resulted in a lower coefficient of determination (0.717), the timing of the flood peaks was accurate.

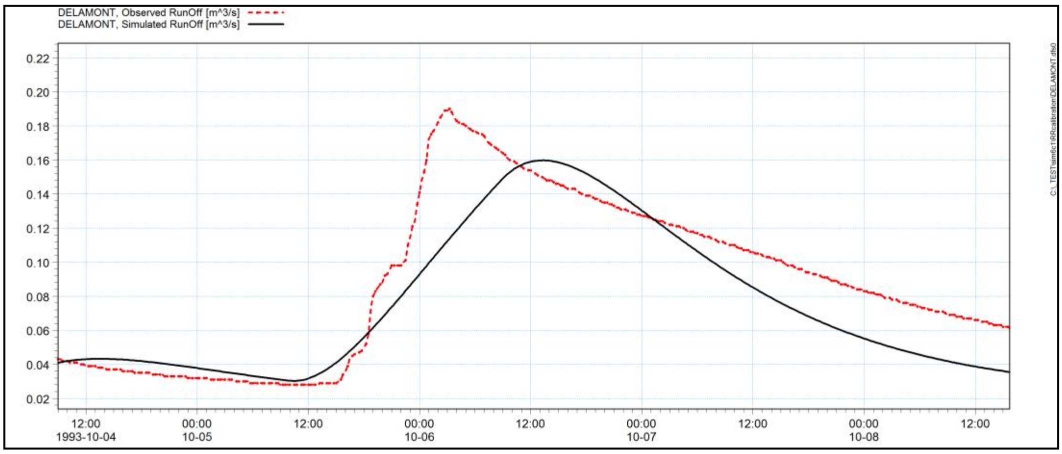


Figure 8.8: Effect of large CK12 value

Umax	Lmax	CQOF	CKIF	CK12	TOF	TIF	TG	CKBF
18	300	0.5	200	2.2	0.75	0.6	0.76	3900

Table 8.10: Manually adjusted parameters for Delamont 1

The parameters in Table 8.10 were then used as validation for the 05-09 period. The resulting coefficient of determination was a poor 0.564, and manual adjustment bearing the first simulation parameters in mind did not increase the goodness of fit between simulated and observed flow.

8.3 Ballynahinch Catchment

8.3.1 Water Balance

Initial results showed observed runoff exceeding simulated by 24.8%. This result differed from the Comber and Delamont catchments in that simulated usually exceeded observed flow. The initial selection of rain gauges was re-examined and a number of additional stations were chosen in order to get a more accurate representation of rainfall contributing in the catchment.

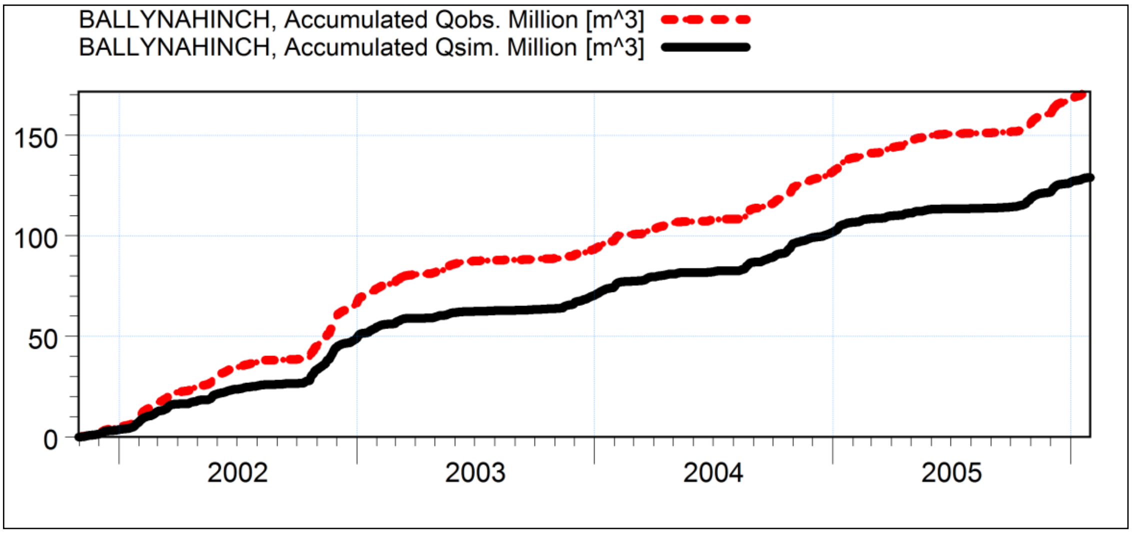


Figure 8.9: Initial auto calibration results for Ballynahinch catchment

In re-examining the catchment and contributing rainfall stations, it was noted that the Ballynahinch catchment lies to the north-east of a mountainous area (Appendix F2) and therefore probably experiences orographic rainfall. As a result, weighting at Dromara station (16377) was increased from 0.292 (as designated by the Thiessen polygons) to 0.792 as it was more representative of elevation affected rainfall (see Figure 8.10). Weighting at Hillsborough and Ballynahinch (Kinedale) rainfall stations were reduced (by 0.1 and 0.2 respectively).

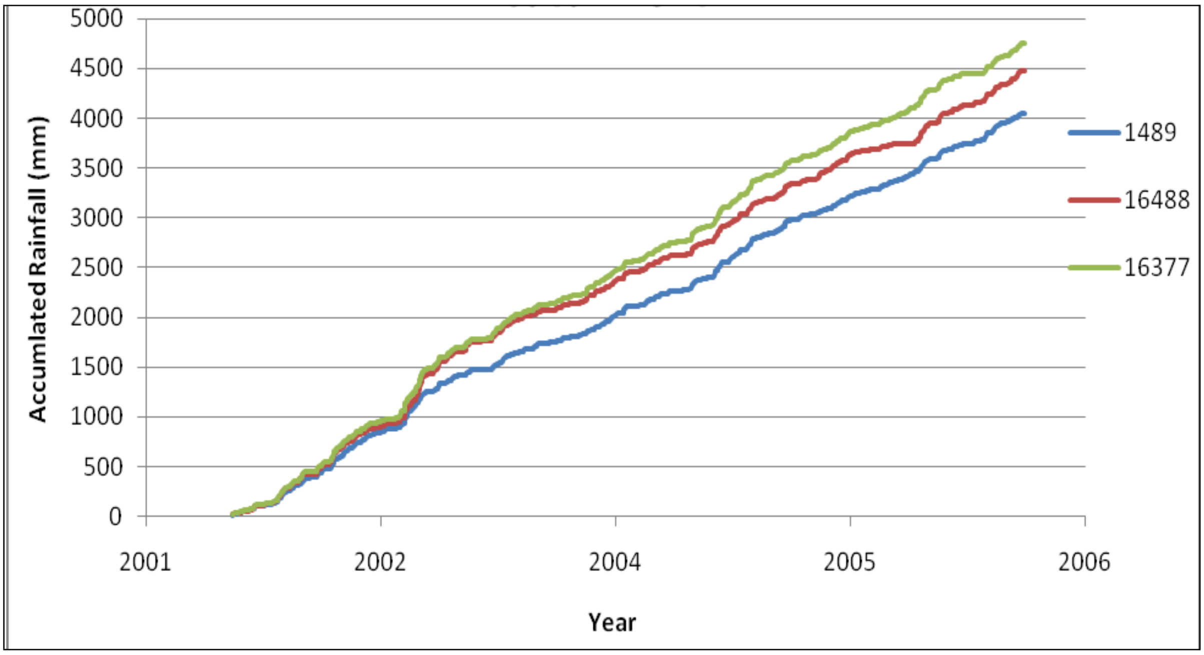


Figure 8.10: Comparison of rainfall totals from different contributing stations for the Ballynahinch catchment

This resulted in a perfect water balance being achieved for the period 2001-2006 (see Figure 8.11).

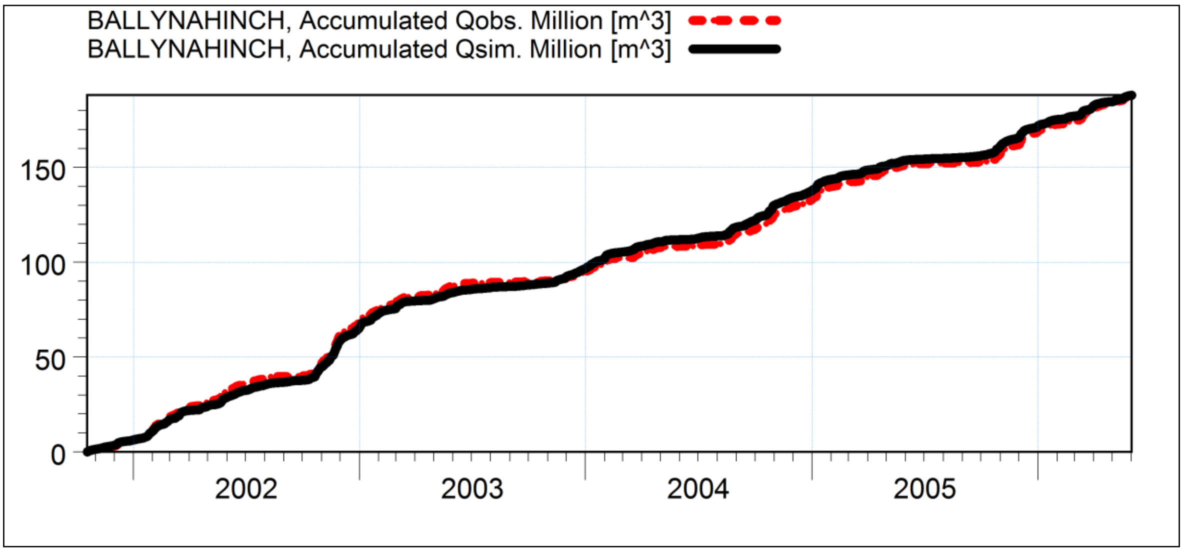


Figure 8.11: Accumulated observed versus simulated flow for the Ballynahinch catchment

8.3.2 Calibration of Model Parameter

Umax	Lmax	CQOF	CKIF	CK1,2	TOF	TIF	TG	CKBF
11.3	*105*	*0.874*	*259.9*	*22.9*	*0.726*	*0.153*	*0.431*	*1223*

Table 8.11: Initial auto calibration results for Ballynahinch catchment

Initial auto calibration results showed a very good correlation between observed and simulated with the coefficient of determination arriving at 0.889. Further manual calibration on these parameters did not result in any improvement. Because the CK12 value was of particular concern (taking into account the size of the catchment) the simulation time step was reduced from 12 hours to one hour and hourly data from Katesbridge was added as a guide for distributing the daily rainfall data into smaller time steps. The results of these changes are presented in the table below.

Umax	*Lmax*	*CQOF*	*CKIF*	*CK1.2*	*TOF*	*TIF*	*TG*	*CKBF*	*R2*	*WBL*
11.6	109	.805	257.7	20	.704	.371	.316	1039	.901	-0.1%

Table 8.12: Auto calibration results after change in time step

Although the additional data improved the fit, it did not have the desired effect on CK12.

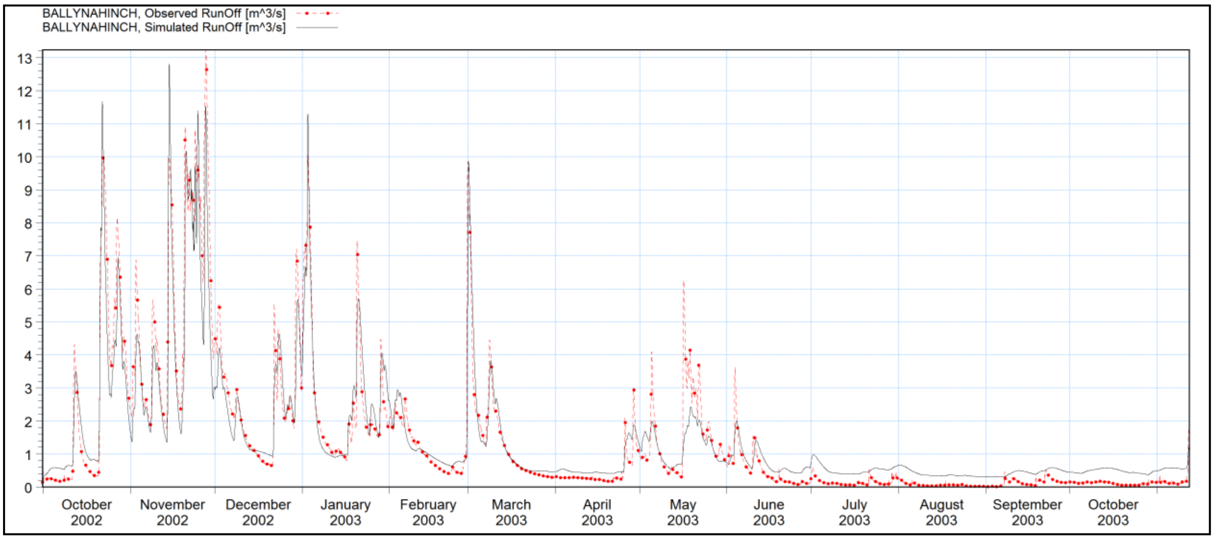


Figure 8.12: Graphical examination of observed versus simulated hydrographs

The observed versus simulated hydrographs were examined and it was felt that despite the excellent numerical fit, the simulated baseflow was a little too high in places, the simulated peaks were arriving a little late, the amount of observed overland flow was greater than simulated and the recession limb of observed hydrographs generally exceeded that of the simulated. In order to take account of these, Tg was increased by 0.1, CK12 was reduced by 5 hours and CKIF was increased to 300 hours. However the manual calibration resulted in a reduction in goodness of fit (r^2 = 0.816) and an unsatisfactory graphical representation. Therefore the auto calibrated parameters (Table 8.12) were used.

Validation was not carried out on the Ballynahinch catchment due to the length of data on record.

8.4 Kilmore Catchment

8.4.1 Water Balance

As with the previous gauged catchments, initial calibration results showed an inconsistency between simulated and observed flow. In a bid to get a more accurate account of rainfall in the Kilmore catchment, available rainfall stations were re-examined. A number of additional rainfall stations (Figure 8.13) were chosen as a result of de-prioritising the quality of data. These stations coupled with already existing stations were used to derive the catchment’s rainfall distribution and re-simulate runoff.

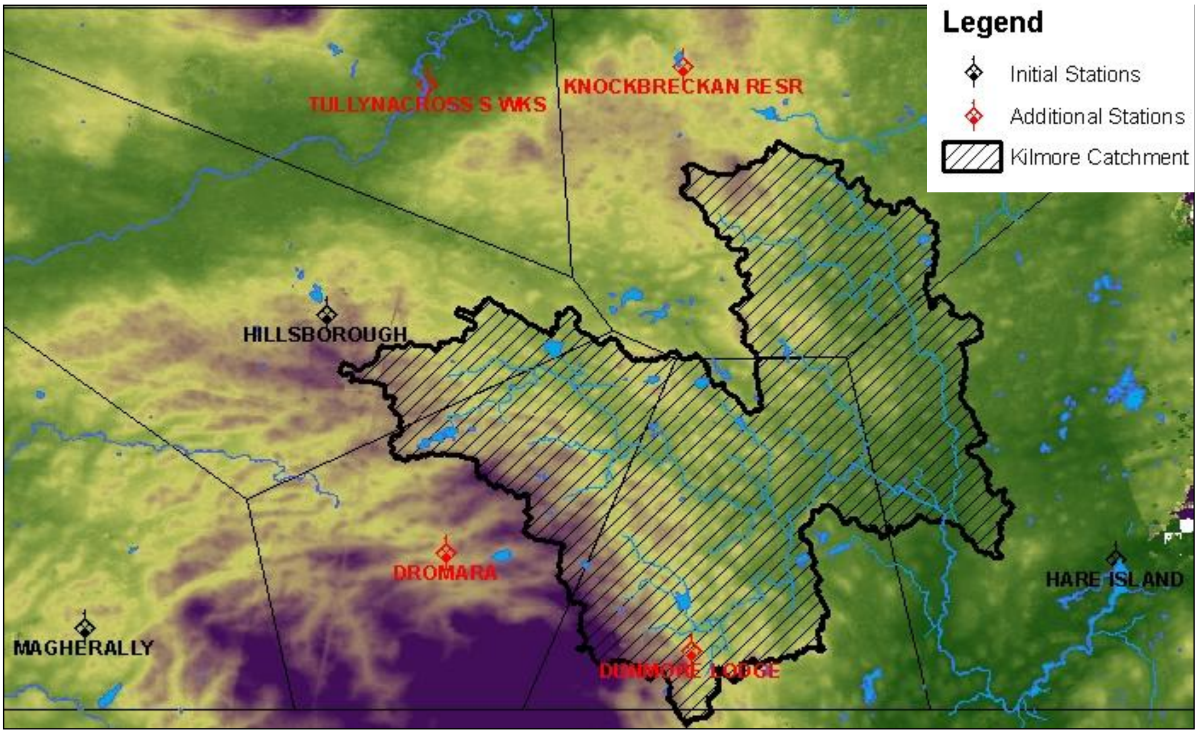


Figure 8.13: Initial and additional rainfall stations for the Kilmore catchment

Figure 8.14 below plots accumulated observed discharge against accumulated simulated discharge, where we can see that the difference in the observed and simulated water balance is 5.3%, i.e. simulated runoff exceeds observed discharge by 32mm/year over a span of 30 years.

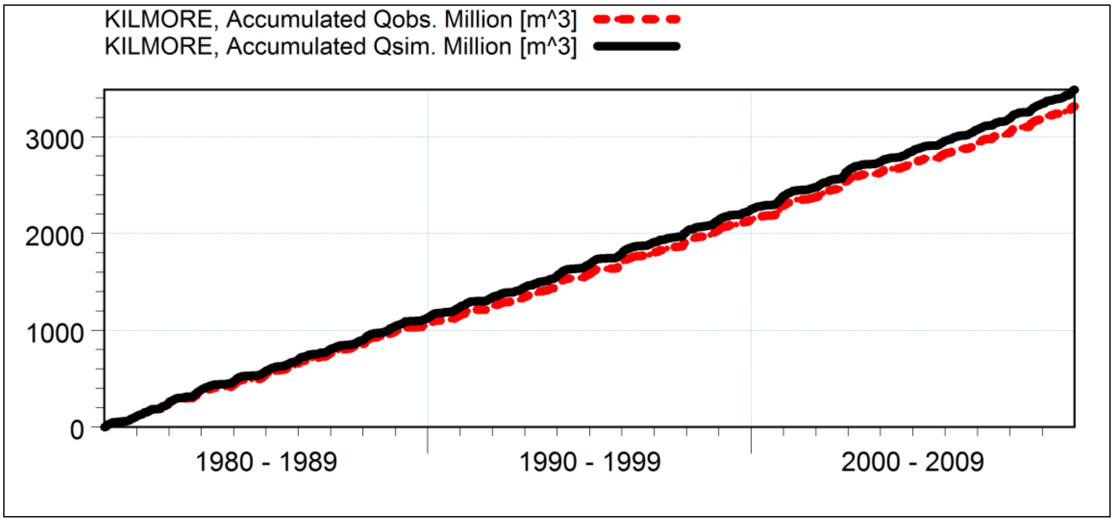


Figure 8.14: Accumulated simulated and observed flow plot for the Kilmore catchment

8.4.2 Calibration of Model Parameters

Table 8.13 below shows the values derived from auto-calibration.

Umax	Lmax	CQOF	CKIF	CK12	TOF	TIF	TG	CKBF	R^2	WBL
19.6	300	0.77	786.4	21.1	0.782	0.591	0.908	2730	0.773	-5

Table 8.13: Initial auto calibration results for Kilmore catchment

Four additional stations containing hourly rainfall data were used to distribute the daily rainfall data in time and the simulation time step was reduced to 1 hour. The improvement is shown in the results below (Table 8.14).

Umax	Lmax	CQOF	CKIF	CK12	TOF	TIF	TG	CKBF	R^2	WBL
18.7	295	0.82	682.1	18.6	0.764	0.537	0.813	2202	0.885	-7.90%

Table 8.14: Auto calibration results after addition of hourly data and reduction in time step

Manual adjustment of the parameters did not result in any improvement in correlation coefficient. A validation period from 1990 to 2009 was available from the lengthy data record and using the above parameters the model showed an overall goodness of fit of $R^2 = 0.728$. However, this correlation rose to 0.863 for the period 1990-2000 thus suggesting a change in observed discharge for the period 2000-2009.

8.5 Regionalisation Results

Between calibrated parameters, calculated parameters, linear regression and user's judgement, the model parameters for regionalisation were derived and are shown in Appendix F3.

8.6 Assessing the water balance

The Strangford Lough catchment average values for each of the water balance components were calculated for the period 1983 – 1995 and the results are presented in Table 8.15 below.

Water Balance Components (%)					
Rainfall	Actual Evapotranspiration	Recharge	Overland Flow	Interflow	Baseflow
100	46.73	17.43	22.25	13.33	16.79

Table 8.15: Components of water balance expressed as percentages of precipitation for 1983-1995

Appendix F4 shows the calculated water balances for the year 1995 for each of the individual subcatchments. The entire Strangford Lough runoff is shown in Table 8.16 and the separation of runoff into its three separate components is illustrated for the Quoile catchment in Appendix F5.

Year	Q-simulated (mm)
1983	246.7
1984	504
1985	500.1
1986	475.9
1987	432.3
1988	623.2
1989	395.8
1990	492.6
1991	440.9
1992	472
1993	535.5
1994	574.1
1995	440.3
1983-1995	6133.5

Table 8.16: Entire Strangford Lough runoff

Figure 8.15 illustrates the variation in precipitation in each of the river catchments contributing to Strangford Lough. The river catchments of Ballymoran and Rathcunningham are excluded as they contain periods of missing data.

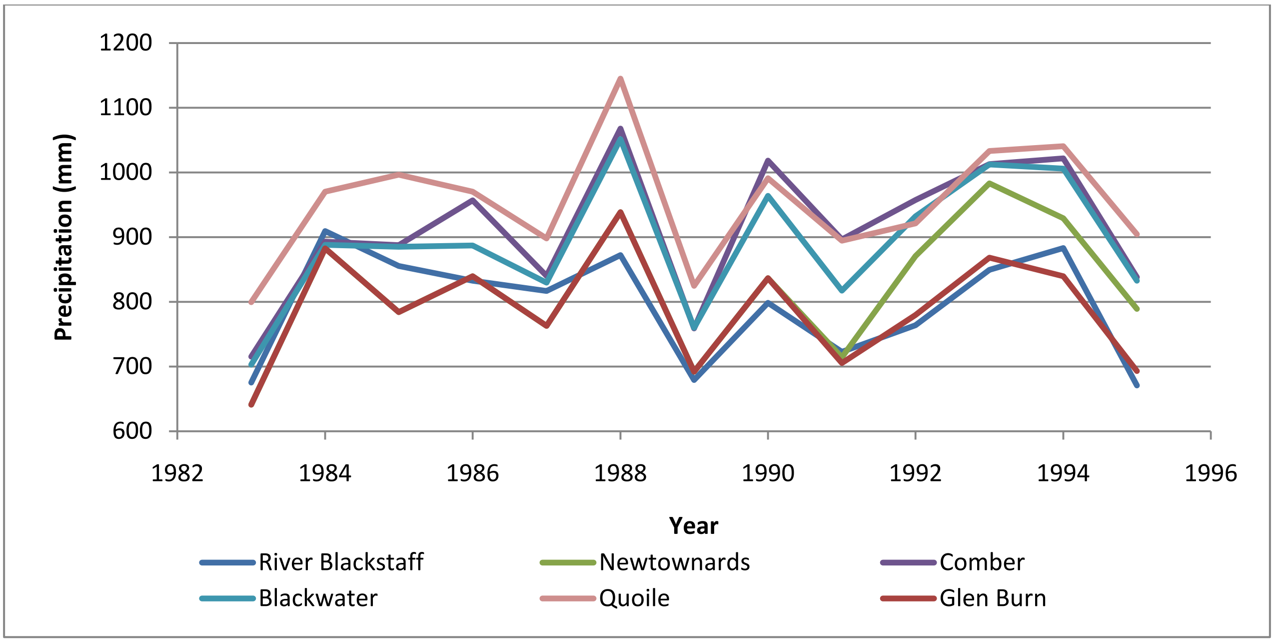


Figure 8.15: Annual precipitation through the catchment

Figure 8.16 compares actual evapotranspiration in each of the river catchments (again excluding Rathcunningham and Ballymoran) against the potential evapotranspiration data used.

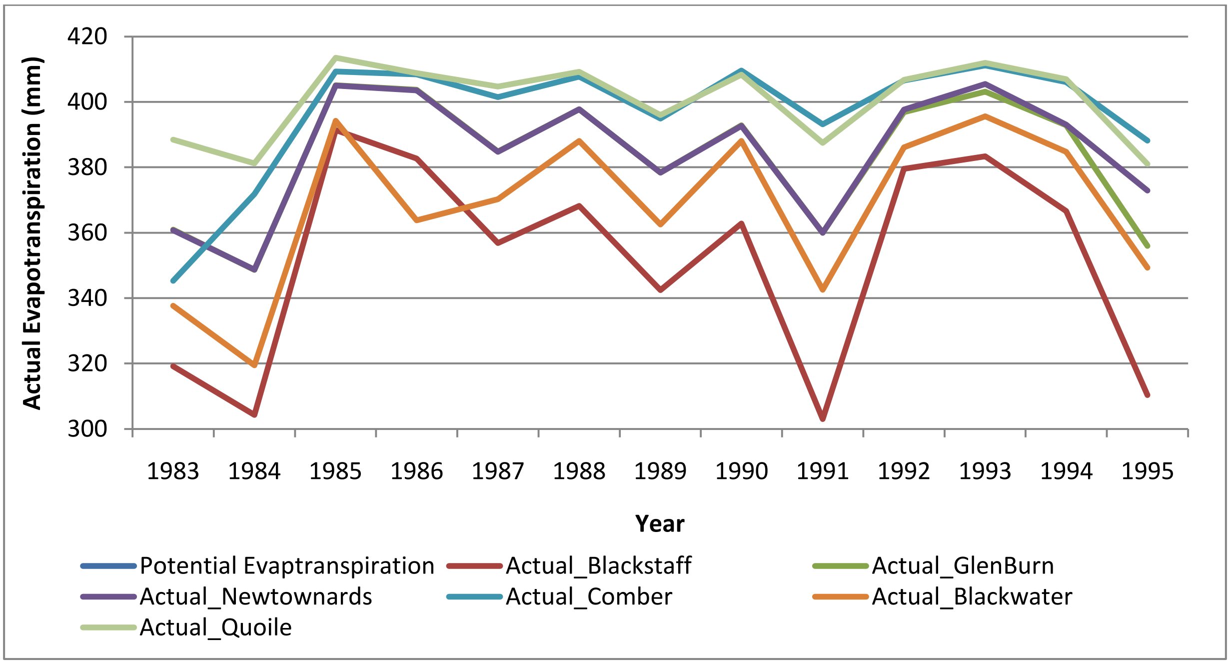


Figure 8.16: Annual potential and actual evapotranspiration throughout the catchment

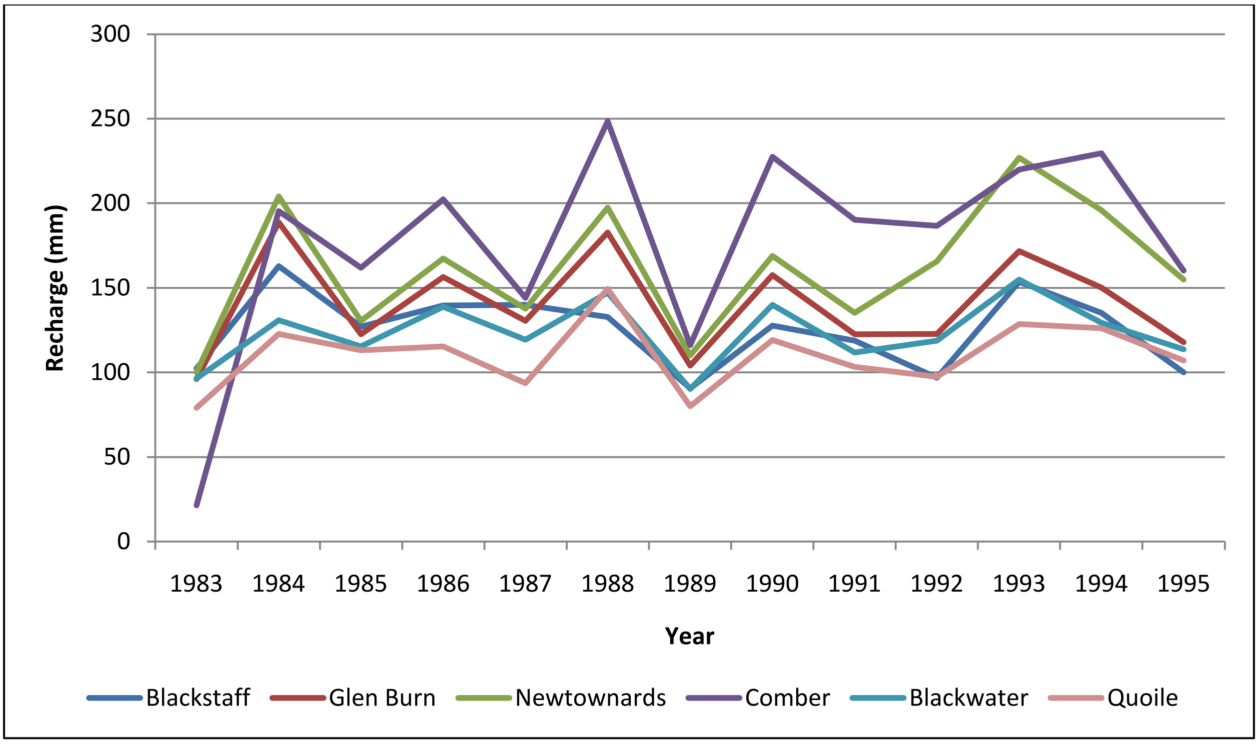


Figure 8.17: Plot of recharge in river catchments against time (year)

Figure 8.17 compares the variation in recharge throughout every catchment over the simulation period (again excluding Rathcunningham and Ballymoran)

9 Discussion

9.1 Assessing Rainfall Input

As discussed in the literature review, errors in input precipitation have the greatest impact on simulated model output. In order to verify the Thiessen derived precipitation amount, the average annual precipitation for Comber and Kilmore was calculated and compared against the listed SAAR values provided in the FEH. The initial estimates compared well with the SAAR values particularly taking into account the fact that a different period of rainfall was used to calculate the two values. However, from Table 9.1 it can be seen that the adjustment made to Comber rainfall resulted in a gap of 14% in SAAR value and rainfall data used in the model. As discussed later, this 14% probably represents the amount of water abstraction for the purposes of irrigation and human consumption.

	Comber (1980-2003)	Kilmore (1980-2009)
Initial Average Annual Rainfall (mm)	943.23	1030.50
Annual Average Rainfall After Thiessen Weight Adjustments (mm)	797.54	No Change
SAAR 1961-1990 (mm)	934	968
Percentage Difference (%)	14.61	-6.48

Table 9.1: Comparing SAAR values with Thiessen distributed and subsequently amended rainfall data used as model input

9.2 Calibration

9.2.1 Comber

The calibration results for the Comber catchment seem to represent the catchment well in terms of its time of concentration, surface and soil storage capacity, runoff coefficient, threshold values and time constant for routing baseflow. Graphically, the simulated peak flows did not reach the volumes of those in observed flows but it was decided that calibrating until the peaks matched was inappropriate due to two findings in the rating review. Firstly, flow recordings were shown to be elevated relative to rainfall particularly between 1993-1996 and 2000-2003 and secondly, it was noted that further spot gaugings were required to develop an out of bank relationship between flow and water level (Jacobs and Rivers

Agency, 2009). The best fit for the Comber catchment therefore yielded a Nash's coefficient of 0.649. However, this relatively low match may be accounted for by the lack of consideration for water abstraction within the catchment. The Comber catchment overlies an aquifer of high productivity, i.e. Sherwood Sandstone, and this aquifer is of local importance to the towns of Comber, Newtownards and Dundonald as well as to their agricultural hinterland. The Comber catchment is predominately made up of Class 2 agricultural land, indicating high productivity and an ideal soil profile for the growth of cereal crops and horticulture. Although the CORINE land database specifies areas of non-irrigated arable land to the north of the Lough, local knowledge indicates that there are areas of irrigated land around Newtownards and Comber. It is likely that these losses through water abstractions are also why the amount of contributing rainfall was reduced.

The coefficient of determination during validation fell by 4.9% compared with that achieved during calibration. This indicates some instability in the model as a result of parameter uncertainty or model complexity.

9.2.2 Delamont

The initial two sets of auto calibration parameters for the separate Delamont simulation periods were strikingly different. The first set appeared to describe a very absorbent catchment with high storage, low overland runoff and high threshold values. The second set described a much smaller flashier catchment with low root zone storage and extremely low threshold values. This however is not reflected in the plot of flow duration curve (Figure 9.1) from which two things are noticed:

- the plots using the two periods of observed discharge data are very similar
- the first catchment marginally demonstrates a more rapid response

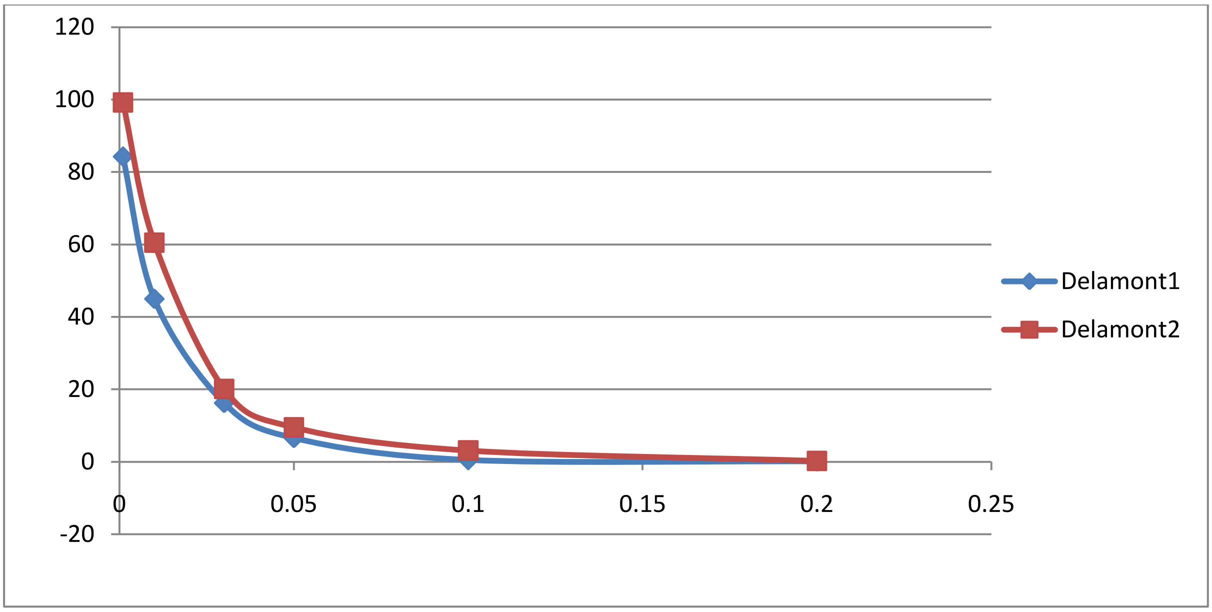


Figure 9.1: Flow duration curves representing the observed discharge during the two simulation periods

The fact that the two periods are similar in streamflow and are not so described through their model parameters indicates a weakness in input data and suggests that station 55642 was unsuitable to provide rainfall data for the Delamont catchment.

There was one common parameter between the two simulation periods however and that was the time constant for routing overland flow and interflow (CK12), which was auto calibrated at six times its estimated value. When this was reduced, the results showed that the first simulation period adapted well after manual calibration but the second period did not. The primary reason for this is that no hourly or sub-hourly rainfall stations were available nearby for the model to more accurately distribute rainfall from station 55642 in smaller time steps.

It is also likely that the difficulty in modelling the Delamont catchment stems also from a short record of streamflow data.

9.2.3 Ballynahinch

The parameters derived from auto calibration for the Ballynahinch catchment seem to represent its physical characteristics well. The catchment is located at a relatively high altitude and as a result has poor vegetation, shallow soils, steep slopes and many exposed rock outcrops. Therefore a low Umax and Lmax were expected and a high proportion of runoff was expected to occur via overland flow. The threshold values are also representative of the catchment, with interflow occurring before overland flow and recharge to groundwater happening with relative ease (direct contact with groundwater storage due to rock outcrops).

The main aim of the manual calibration process, however, was to reduce the time of concentration from 20 hours to approximately 13-14 hours. However, this task proved unsuccessful for the user, both numerically and graphically. This proved frustrating when the later described Kilmore catchment (of which Ballynahinch is a sub-catchment) turned out to have a lesser CK12 value of 18.6 hours. It is likely that the main source of data error in this catchment is that of the flow record used to calibrate the model, as the record is relatively short (8 years) and additional spot gaugings are required to improve the rating curve.

9.2.4 Kilmore

The auto calibrated parameters for the Kilmore catchment describe the catchment very well, particularly the storage capacity, the threshold values and the CK12 value. The value for CKBF was thought to be low, with a value of 3900 hours more indicative of the catchment's underlying 'impermeable basement'. Generally however, a very good overall fit was achieved with the Kilmore catchment which was as a result of the following factors;

1. An extensive range of daily rain gauges were in place very close to if not within the catchment.
2. These storage gauges were evenly distributed throughout the catchment giving a description of rainfall from the Slieve Croob summits (south-east) to the Ballygowan drumlins (north) to the eastern lowlands.
3. Four automatic recording gauges at Katesbridge, Hillsborough Met Office, Saintfield and Hare Island were available, again lying very close to the catchment and covering a span of 20 years hourly rainfall data.
4. The calibration was also successful as a result of streamflow records extending 30 years and thus a well established rating curve at Kilmore Bridge on the River Annacloy. It was noted in the rating review report that all flows were reprocessed in 2002 thus making the rating more accurate and this is reflected in a gauging station data quality score of 0.614 (fair).

The fact that the numerical goodness of fit indicator rose to 0.863 when the last 9 years were excluded from validation suggests that there may have been a change in trends relating rainfall to runoff. Figure 9.2 shows decreasing flows relative to rainfall, suggesting perhaps an increase in evapotranspiration for the period 2001-2009 as a result of changing climatic conditions or perhaps there is some local abstraction of surface water/groundwater.

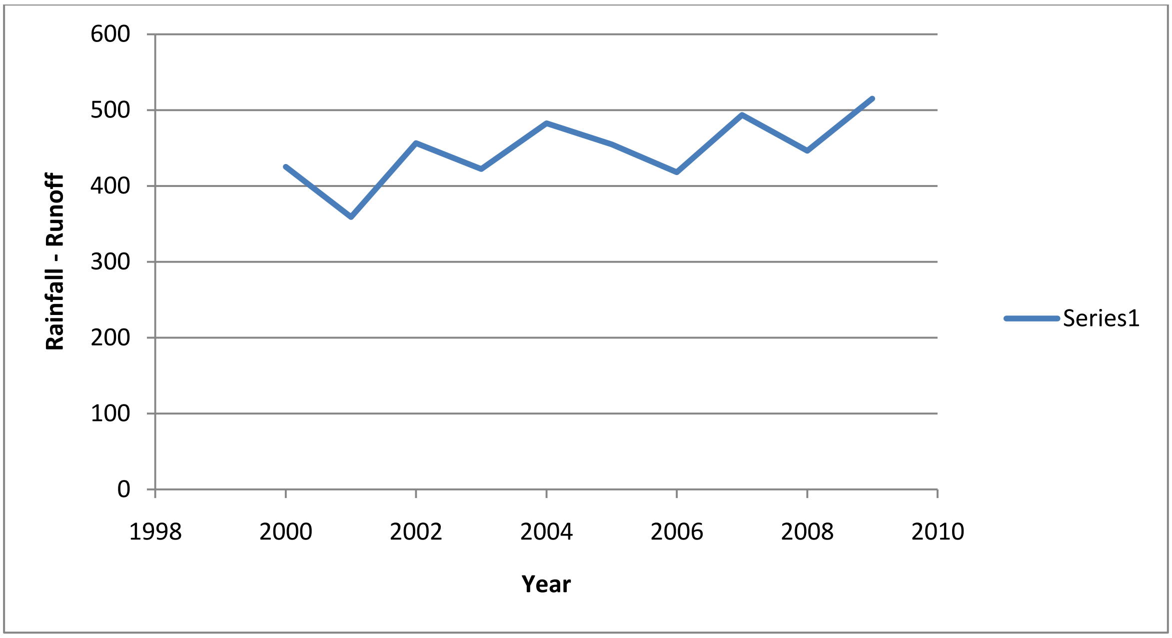


Figure 9.2: Decreasing flows relative to rainfall in the Kilmore catchment

The coefficient of determination during Kilmore validation fell by 17.74% compared with that achieved during calibration. This indicates a greater degree of instability for this catchment than that for Comber, perhaps resulting from greater parameter uncertainty.

9.2.5 Evapotranspiration Data

It is likely also that the lack of variation in evapotranspiration data affected the calibration process of each of the catchments. The data available provided only one year of monthly averaged values thus simulating the exact amount of evapotranspiration every year. This is unlikely especially when trends in climatic variation are examined (Figure 8.15-8.17). In order to achieve better evapotranspiration values, weekly potential evapotranspiration data from the MORECS soil moisture model could be obtained and thus model calibration and validation could be improved.

9.3 Regionalisation

9.3.1 Grouping subcatchments

In the first step of regionalisation, subcatchments were grouped according to the river network they belonged to. This process was undertaken bearing in mind that the NIEA catchment differed slightly from the catchment derived by the 10m DEM and initial information gathered on the NIEA delineation methods indicated that catchments boundaries were manually edited based on local knowledge regarding drainage patterns after the initial delineation. Consequently altering the NIEA catchment divisions was only undertaken for areas of direct drainage which differed substantially in physical characteristics.

In the late stages of the project (22/09/2010) contradictory information was supplied, stating that (to his recollection) no adjustments to the Strangford Lough catchment delineation had been made and that the boundary was not definitive. This information therefore suggests that the 10m delineated boundary may have been more accurate (as a result of a more accurate horizontal resolution) and that from it, river catchments could have been defined with more confidence.

Initially the ideal method of regionalising model parameters for NAM was to group subcatchments based on their physical characteristics and not their river catchments. However, the most reliable parameters were those derived during calibration of the Comber and Kilmore gauged catchments. These catchments both have a wide range of elevation values (6m -140m), slopes ranging from greater than 40º to completely flat land, land cover varying from exposed rock to shallow soils to unknown depths of shale till and land use varying from high to low productivity agriculture. Therefore it was decided to take a river catchment approach rather than a physical characteristic approach.

9.3.2 Regionalisation of Model Parameters

Regionalisation was based on clearly developed relationships developed during calibration of the four gauged catchments. There were a number of parameters which often proved unreliable and therefore they could not be used with confidence. CKBF, for example, was often determined from auto calibration to be at about 1000 hours which for a region dominated by shale is unreasonable.

Lmax, CK12 and Tg were determined for the ungauged parameters using linear regression. However, the parameters which were used as ‘observed values’ were actually just estimated parameters (using calculation methods) and already calibrated parameters (which cannot be entirely relied on) and so it is important to highlight that error was introduced even by using an established regionalisation method.

The remaining parameters, CQOF, CKIF, TOF and TIF, which were determined by users judgement could also have been determined using multiple linear regression had values been established for qualitative catchment characteristics e.g. soil type, land use and drift geology. Quantifying these characteristics would have led to a better understanding of the catchments’ hydrological processes. Values calculated for time of concentration could also have been used to help determine CKIF had they proved to yield a better fit when entered in calibration.

9.4 Assessment of water balance

Runoff from the entire Strangford Lough catchment was simulated using the parameters in Table 8.15, thus runoff for each of the subcatchments was divided into overland flow, interflow and baseflow. Appendix F5 illustrates this for the River Quoile from October 1991 to January 1992. It is clear that the majority of runoff occurs via overland flow and that interflow is marginally greater than baseflow.

The plots in Figures 8.15 and 8.16 show some trends in climatic conditions over the simulation period 1983-1995. Precipitation peaked in every catchment in 1988 and subsequently plummeted in 1989 and 1991. Although this decrease in rainfall is reflected with a decrease in actual evapotranspiration for 1989, its impact is not as obvious as that of 1991, where both precipitation and evapotranspiration markedly decrease. It is reasonable to assume that moisture stored from the increased rainfall in 1988 provided adequate moisture so that actual evapotranspiration only decreased marginally. The plot of recharge versus time (Figure 8.17) better reflects the decrease in precipitation for both years despite the increased amount of recharge in 1988.

9.5 Suitability of Model for Further Use

The advantage of using this conceptual lumped hydrological model for further studies is its limited data requirements. In terms of input requirements, rainfall data (preferably daily or hourly) and potential evapotranspiration (preferably monthly for every year) are the only two measurements needed to run the model. In calibrating the model, a streamflow record of approximately 20 years is preferable and once these requirements are met, the NAM model can simulate, relatively well, the response of the catchment in question. There are, however, a number of sources of error in this model as described in the section below.

9.5.1 Errors in data input

As reported in the literature review, the largest source of error stems from precipitation data input. The BADC report 5% accuracy from rain gauges in current use although this is not guaranteed at sites which are more exposed. Errors may be derived in taking the observation or recording the actual time of observation. Rain gauges may not be ideally located to accurately represent the amount of rainfall (e.g. over exposure to wind). As shown in Section 9.2.2, some rain gauges also may not have been suitable for the application to their catchment in question.

Because of the limited network of instruments measuring evapotranspiration in Ireland, a year of data from the Clones station was used. Although it provides a close approximation, an evapotranspiration measurement taken within the catchment in monthly intervals for the entire simulation period would be preferable for model calibration and validation. This data would also increase our understanding of soil moisture deficit and allow for drought management, particularly in the west of the catchment where shallow soils are vulnerable.

9.5.2 Errors in observed data

It is likely that the river flow data used in calibration introduced a degree of error, judging by the gauging station data quality described in Table 9.2 below. Whereas the Kilmore station on the R. Annacloy has a streamflow record of greater than 30 years, the remaining stations, particularly Delamont, have a more limited data record (5 years maximum for Delamont). A lengthy record of data is essential for an optimal calibration as it takes into account variations in climate and it allows a reliable rating curve to be developed. Consequently, the set of 'optimal' parameters describing the Delamont catchment are unlikely to be optimal and therefore its runoff and the runoff of subcatchments similar to it may not be accurately represented in the entire Strangford Lough catchment model.

Station Name	Station Number	Catchment Area (km^2)	Measurement Instrument	Gauging Station Data Quality (GSDQ)
Kilmore Bridge (R. Annacloy)	205011	186.6	Velocity-Area Station	High Flows - Good Low Flows - Caution General – Fair
Comber (R. Enler)	205020	61.8	Flat V weir	High Flows - Caution Low Flows - Caution General – Fair
Delamont (R. Delamont)	205025	2	Fibreglass flume	High Flows – Caution Low Flows - Caution General - Caution
Dromore Street (R. Ballynahinch)	205036	48.7	Velocity-Area Station	High Flows - Caution Low Flows - Caution General - Caution

Table 9.2: Summarised description of river gauging stations (Jacobs Consultancy & Rivers Agency, 2008)

9.5.3 Other areas of error

As described in the literature review, errors also arise from the structure of the model, i.e. the number of parameters used and the effect of lumping rainfall input to produce runoff. Although there is a lack of literature available on the latter, studies have shown that parameter uncertainty introduces further error to the model. Using a non-optimal set of parameters is also obviously a factor affecting model performance and although manual calibration attempted to obtain optimal parameters, the lack of inexperience and limited time restricted the user somewhat in achieving a set of parameters which may possibly be more suited to the gauged catchments. This inexperience may also have hindered the user in regionalising model parameters.

9.6 Possible Future Use for Model

Should the calibrated model and consequently the regionalised model improve (Section 11), then the model would be suitable to use in further hydrological studies and engineering applications, e.g. water quality modelling, climate change assessment, flood estimation and the impacts of further water abstractions. However, in the Strangford Lough catchment, and throughout Northern Ireland, it is well known that diffuse sources of pollution (e.g. nitrates, phosphorous and pesticides) are the main causes for many of the rivers having less than good status according to the Water Framework Directive. Although many of the water quality issues in rivers have been resolved and good status is expected in 2015, there are still some catchments contributing to Strangford Lough whose sources of pollution have not been identified, e.g. the Rivers Dibney and Comber. In order to address this, the NAM rainfall runoff model could be used to provide flow information for further water quality modelling, particularly in the ungauged catchments.

Obtaining an accurate estimate of river flow is essential for calculating total pollutant loads and modelling catchment water quality. The advantage of using a model like NAM to generate flows for water quality modelling is twofold. Firstly the need for additional river gauging stations is eliminated and secondly, overland flow can be determined immediately. The value for overland flow is of particular importance because in times of high flows a large amount of sediments are transported, do not undergo natural denitrification and, as a result, threaten the ecological status of rivers and streams. Identifying the sources of diffuse pollution and using flows generated from this model would allow for best management practices to be put in place and the consequential reduction in nutrient loadings in rivers.

The model could also be used to assess the impact of management practices on groundwater quantitative status, particularly in the Comber and Newtownards subcatchments. It has already been noted that groundwater is being abstracted from the underlying Sherwood Sandstone in order to meet the needs of human consumption and agricultural irrigation and that currently this groundwater body is classified as being of poor status under the Water Framework Directive. The model could also be used to assess if the irrigation supply is adequate/inadequate to maintain optimum soil conditions in this intensive region of agriculture.

As mentioned previously, the impact of climate change on the Strangford Lough catchment could be assessed using this model. However, relying on the output of one hydrological model for reporting changes in hydrological processes is not advisable as studies using different models on the same catchment have reported very different impacts of climate change (Jiang, et al., 2007). Similar studies assessing the sensitivity of the model to changing various parameters could also be assessed in a bid to improve understanding of the catchment e.g. test how sensitive recharge is to change in land cover/soil type (characteristics which most parameters reflect). Again however, Madsen, et al. (2002) cautions the interpretation of the results of these analyses as the interdependence between parameters is often not accounted for.

10 Conclusions

As a result of the Water Framework Directive, further examination is required to find the pollution sources in some river catchments contributing to Strangford Lough. The consequences of not complying with the Directive would result in a substantial fine and more importantly, would put the sensitive ecological status of Strangford Lough at further risk. This project set out to examine the suitability of combining current data with the NAM rainfall runoff model to assess the nutrient budget of Strangford Lough and thus allow for best management practices to be put in place. In order to do so, the project set out to achieve two objectives, firstly to successfully delineate the Strangford Lough catchment boundary and secondly to use information from this delineation to model freshwater runoff into Strangford Lough.

The first objective was achieved using the Arc Hydro extension tools in ArcGIS 9.3. Increased vertical and horizontal DEM resolution proved to very successfully delineate the subcatchments and overall drainage area contributing to Strangford Lough. From the delineation, it was noted that increasing DEM resolution and accuracy would be required for hydrological studies of urban areas within the catchment. Revelations late in the project indicated that the boundary derived in this study probably exceeded the accuracy of that used by the NIEA. This information allows future users to utilise this delineated catchment with confidence and even possibly derive characteristics from it to use in a spatially distributed model. Looking further ahead, should GIS become developed enough, this derived catchment could provide the basis of modelling runoff using GIS software alone.

The second objective was performed using the NAM rainfall-runoff model, a conceptual lumped model describing the movement of moisture by continuously accounting for it in three interrelated storage areas (surface, root zone and groundwater). The model was calibrated using four gauged catchments and then regionalised to account for all the subcatchments. Calibration proved successful for the most part, but a longer period of hourly rainfall data and streamflow records would have been preferable for the Delamont catchment. Regionalisation was based primarily on user’s judgement and relationships established between parameters and estimated values during calibration. However, the process would have been more thorough had the calibration of the Delamont catchment been more reliable and had a quantitative relationship between the physical characteristics (soil, land use) of the catchment and the model parameters been easier to establish.

The model created in this study has already been used to simulate freshwater runoff into Strangford Lough and make a preliminary assessment of trends in climatic variation and the impact of these on components of the water balance. However, with the ability of this software to define the amount of runoff at any point that is overland flow, the software proves very suitable for assessing nutrient budgets of gauged and ungauged catchments which threaten the sensitive ecological status of Strangford Lough. The model could be put to further use and could assess the impacts of implementing nutrient management plans, predict the effects of climate change on hydrological processes within the catchment or assess the impact of further water abstraction from the north of the catchment.

However, as a result of the findings in this thesis, it would be advisable to obtain additional data (irrigation/abstraction quantities, hourly rainfall data, more detailed evapotranspiration data and longer streamflow records), assess the confidence of model simulations, take into account hydrologically different areas (urban, mudflats) and develop more reliable relationships between physical catchment characteristics and model parameters.

11 Recommendations

In order for the model to be used in further hydrological studies and engineering applications, the author would suggest the following additional work to be undertaken.

1. Quantities of water abstraction in Comber catchment would be required should a correct water balance assessment of this region be carried out. Taking into account irrigation and abstraction in a model rerun would undoubtedly alter the water balance and may also impact the model parameters.
2. Additional rainfall data should be collected in the Delamont catchment, preferably by automatic recording gauges due to the size of the catchment. This would not only be more beneficial to the calibration process but also to the regionalisation process as practically all areas of direct drainage are physically very similar to the Delamont catchment.
3. The potential evapotranspiration data used in this model was a year of monthly averaged data from Clones. One year does not take account of any trends in climatic variation and if the soil moisture balance of any of the subcatchments in the Strangford Lough catchment were to be examined further; more accurate data would be required in terms of a smaller recording time step, closer gauge location and a much longer record length.
4. For a more detailed assessment of the entire catchment, urban areas within the catchment and the mudflats surrounding Strangford Lough could be modelled. The hydrological properties of these areas differ substantially from the already modelled rural Strangford Lough catchment and using the model in detailed water quality studies would require these areas to be included.
5. Should the model be used in further studies, the confidence of its simulations may need to be assessed. Madsen (2000) suggests that for a proper assessment, parameter uncertainty should be assessed by statistical interpretation (equifinality – Beven and Binley, 1992) as well as examining the equivalence of parameter sets as a result of multi-objective simulations.
6. On a Northern Ireland scale, work should be carried out to establish a link between physical characteristics (soil, underlying drift and land use) and possible model parameters. This would include the use of the 1:50000 soil maps of which only a generalised version was used for this project. Although parameters will vary between models, a database should be made available which takes into account the catchment's characteristics and quantifies their ability to store water both above and

below the ground surface. This would make estimating Umax, Lmax, Tof, Tif and Tg a great deal easier.

7. A more accurate assessment should also be undertaken regarding the type of agricultural activities and the amount of runoff expected from this activity. For the Strangford Lough catchment, the majority of land was agricultural, for which literature suggested a range of runoff coefficients between 0.08 and 0.41. Should a more detailed breakdown have been available, the runoff coefficient CQOF could have been more confidently established (in a similar way to how CK12 was established using a time of concentration formula).
8. Should points seven and eight be achieved, it would be less challenging to assess the impact of implementing management plans (e.g. change of land use).

References

Abbott, M.B. & Refsgaard, J.C., 1996. Distributed hydrological modelling. Kluwer Academic Publishers.

American Society of Civil Engineers (ASCE), 1996. Hydrology Handbook, 2nd ed. ASCE Manuals and Reports on Engineering Practice No. 28.

Bayliss, A.C., 1999. Catchment Descriptors. Volume 5 of the Flood Estimation Handbook. Centre for Ecology and Hydrology.

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

Belliss, S. McNeill, S. Barringer, J. Pairman, D. & North, H. 2000. Digital terrain modelling for exploration and mining. New Zealand Minerals & Mining Conference Proceedings.

Bertolo, F., 2000. Catchment delineation and characterisation, a review. Catchment Characterisation and Modelling EuroLandscape Project. Available at: http://agrienv.jrc.ec.europa.eu/publications/pdfs/CatchRev.pdf [Accessed 01 July 2010].

Blaney, H.F. & Criddle, W.D., 1962. Determining consumptive use of irrigation water requirements. USDA Technical Bulletin No. 1275, Washington, D.C.

Bleasdale, A., 1965. Rain gauge networks development and design with special reference to the United Kingdom. International Association of Scientific Hydrology Symposium on Design Hydrological Networks, Quebec.

Boorman, D.B. Hollis, J.M. & Lilley, A., 1995. Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom. Institute of Hydrology. Report No. 126.

British Geological Survey (BGS), 2009. GeoIndex [Online]. Available at http://194.66.252.141/?mainserv=gsni&Title=GeoIndex [Accessed19 May 2010]

British Geological Survey (BGS), 2010. Geological Map Data. Available at: http://www.bgs.ac.uk/products/digitalmaps/digmapgb_drift.html [Accessed 31 May 2010].

Chow, V.T., 1959. Open Channel Hydraulics. McGraw-Hill, New York/London.

Commission of the European Communities, 1994. CORINE Land Cover – Part 2 Nomenclature. Commission of the European Communities.

Cruickshank, J.G., 1997. Soil and environment: Northern Ireland. Agricultural and Environmental Science Division, DANI and The Agricultural and Environmental Science Department, The Queen's University of Belfast.

DHI, 2009. MIKE 11, A modelling system for rivers and channels, reference manual. DHI.

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:327:0001:0072:EN:PDF [Accessed 02 June 2010].

Doorenbos, J. & Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper No. 24, FAO, Rome.

Downing, D. (on behalf of the UK Groundwater Forum), 1998. Groundwater – our hidden asset, British Geological Survey.

Duan, Q. Sorooshian, S. & Gupta, V., 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resources Research, Vol. 28, No. 4 1015-1031.

Engeland, K. Xu, C. & Gottschalk, L., 2005. Assessing uncertainties in a conceptual water balance model using Bayesian methodology. Hydrological Sciences Journal 50 (1).

European Environment Agency and Environment Protection Agency, 2006. CORINE land cover update for 2006. Available at: http://www.epa.ie/downloads/data/corinedata/ [Accessed 20 August 2010].

Erie, L.J. French, O.F. Bucks, D.A. & Harris, K., 1982. Consumptive use of water by major crops in the south-western United States. US Department of Agriculture, Conservation Research Report No. 29, Washington, DC, 40 pp.

Fetter, C.W., 2001. Applied hydrogeology. 4th ed., International Edition. Prentice Hall, New Jersey.

Famiglietti, J. Graham, S. Prietzsch, C. Mohr, K. Maidment, D. Olivera, F. Asante, K. & Lear, M., 2010. GIS applications in regional and global hydrology. Available at: http://www.ce.utexas.edu/prof/maidment/visual/dallas/jay/sld001.htm [Accessed 16 August 2010].

Frederick, K.D., 2002. Water resources and climate change. Edward Elgar Publishing Ltd.

Garbrecht, J., & Martz, L.W., 1994. Grid size dependency of parameters extracted from digital elevation models. Computers and Geosciences, 20(1):85-87.

Garbrecht, J., & Martz, L. W., 1999. Digital elevation model issues in water resources modelling. Available at: http://proceedings.esri.com/library/userconf/proc99/proceed/papers/pap866/p866.htm [Accessed 29 August 2010].

Gan, T.Y. Dlamini, E.M. & Biftu, G.F., 1997 Effects of model complexity and structure, data quality, and objective functions on hydrologic modelling. Journal of Hydrology 192, 81-103.

Geological Survey Northern Ireland (GSNI), 2010. Map of groundwater vulnerability Northern Ireland. GSNI.

Green, M.J., 1969. Effects of exposure on the catch of rain gauges. Technical Publication 67, Water Research Association.

Hough, M.N. & Jones, R.J.A., 1997. The United Kingdom Meteorological Office Rainfall and Evaporation Calculation System (MORECS), Hydrology and Earth System Sciences, Volume 1, Issue 2, 227-239.

Houghton-Carr, H. (1999). Restatement and application of the Flood Studies Report rainfall-runoff method, Flood Estimation Handbook, Volume 4. Institute of Hydrology.

Institute of Hydrology, 1975. Flood Studies Report. Natural Environment Research Council (NERC), London.

Institute of Hydrology (IOH), 1980. Low Flow Studies. Research Report No. 3. Centre for Ecology & Hydrology.

Institute of Hydrology (IOH), 1999. Flood Estimation Handbook (five volumes). Centre for Ecology & Hydrology.

International Association of Hydrological Sciences (IAHS), 2010. Predictions in Ungauged Basins. Available at: www.iahs-pub.org [Accessed 18 August 2010].

Jacobs and Rivers Agency, 2009. Northern Ireland Hydrometric Review.

Jiang, T. Chen, Y.D. Xu, C-Y. Chen, X. Chen, X. & Singh, V.P., 2007. Comparison of hydrological impacts of climate change simulated by six hydrological models in the Dongjiang Basin, South China. Journal of Hydrology 336, 316-333.

Jordan, C. & Smith, R.V., 2005. Methods to predict the agricultural contribution to catchment nitrate loads: designation of nitrate vulnerable zones in Northern Ireland. Journal of Hydrology 304, 316-329.

Johanson, R.C., 1971. Precipitation network requirements for streamflow estimation, Stanford University Department of Civil Engineering Technical Report 147.

Kenward, T. Lettenmaier, D. P. Wood, E. F. & Fielding, E., 2000. Effects of digital elevation model accuracy on hydrologic predictions, Remote Sensing of Environment, 74(3): 432-444.

Kling, H. & Gupta, H., 2009. On the development of regionalization relationships for lumped watershed models: The impact of ignoring sub-basin scale variability. Journal of Hydrology 373, 337-351.

Kuczera, G., 1997. Efficient subspace probabilistic parameter optimization for catchment models. Water Resources Research. 33 (1), 177–185.

Kumler, M. Russell, E. & Ochis, H., 1995. Identifying and removing systematic errors in USGS digital elevation models (DEMs), Poster presented at the annual GIS in the Rockies Conference, Denver, CO.

Li, M. Shao, Q. Zhang, L. & Chiew, F.H.S., 2010. A new regionalization approach and its application to predict flow duration curve in ungauged basin. Journal of Hydrology 389, 137-145.

Liden, R. & Harlin, J., 2000. Analysis of conceptual rainfall-runoff modelling performance in different climates. Journal of Hydrology 238, 231-247.

Linsley, R.K. Kohler, M.A. & Paulhus, J.L.H., 1975. Hydrology for engineers, 2nd Edition, McGraw-Hill, New York; London.

Liu, X. Peterson, J. & Zhang, Z., 2005. High-resolution DEM generated from LiDAR data for water resource management. In: MODSIM05 International congress on modelling and simulation: Advances and applications for management and decision making, Melbourne, Australia.

Madsen, H., 2000. Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. Journal of Hydrology 235, 276-288.

Madsen, H. Wilson, G. & Ammentorp, H.C., 2002. Comparison of different automated strategies for calibration of rainfall-runoff models. Journal of Hydrology 261: 48-59.

Maidment, D., 1996. GIS and hydrologic modelling – an assessment of progress. Presented at The Third International Conference on GIS and Environmental Modelling, Sante Fe, New Mexico. Available at: http://www.ce.utexas.edu/prof/maidment/gishydro/meetings/santafe/santafe.htm [Accessed 08 August 2010].

Muller, J.P., 2007. Global DEM inter-operability: GEOSS. Available at: http://wgiss.ceos.org/meetings/wgiss24/Projs-and-Apps/GDTT/Muller-GEOSS-status-071014...pdf [Accessed 07 July 2010].

Neff, E.L., 1965. Principles of precipitation network design for intensive hydrologic investigations, WMO-IASH Symposium on Design of Hydro meteorological Networks, Quebec.

Nielsen, S.A. & Hansen, E., 1973. Numerical simulation of the rainfall-runoff process on a daily basis. Nordic Hydrology 4, 171-190. Munksgaards, Copenhagen.

Newson, M., 1994. Hydrology and the river environment. Clarendon Press, Oxford.

Northern Ireland Environment Agency (NIEA), 2008. Strategic Environmental Assessment for the Water Framework Directive River Basin Management Plans and Programmes of Measures – North Eastern RBD, Updated Environmental Report and Appendices. NIEA.

Nova-Lynx Corporation, 2010. The model 260-952 rain gauge wind screen. Available at: http://www.novalynx.com/images/260-952.jpg [Accessed 10 May 2010].

O'Callaghan, J. F. & Mark, D.M., 1984. The extraction of drainage networks from digital elevation data. Computer Vision, Graphics, and Image Processing, 28:323-344.

Ordnance Survey of Northern Ireland (OSNI), 2007. Digital terrain model product guide. Department of Culture Arts and Leisure.

Paturel, J.E. Servat, E. & Vassiliadis, A., 1995. Sensitivity of conceptual rainfall-runoff algorithms to errors in input data — case of the GR2M model. Journal of Hydrology 168, 111–125.

Perrin, C. Michel, C. & Andreassian, V., 2001. Does a large number of parameters enhance model performance? Comparative assessment of common catchment model structures on 429 catchments. Journal of Hydrology 242, 275-301.

Ponce, V.M., 1989. Engineering hydrology. principles and practices, Prentice Hall.

Queen's University Belfast (School of Biology and Biochemistry), 1994. Strangford Lough ecological change investigation, work package 6: Anthropogenic contamination in Strangford Lough

Raudkivi, A.J., 1979. Hydrology, an advanced introduction to hydrological processes and modelling. Pergamon Press.

Refsgaard, J.C. & Knudsen, J., 1996. Operational validation and intercomparison of different types of hydrological models. Water Resources Research, Vo. 32, No. 7, 2189-2202.

Refsgaard, J.C. & Storm, B., 1996. Construction, calibration and validation of hydrological models. In: Abbott, M.B., Refsgaard, J.C. (Eds.). Distributed Hydrological Modelling, Kluwer Academic Press, The Netherlands, pp. 41–54.

Robson, A. & Reed, D., 1999. Statistical procedures for flood frequency estimation, Volume 3 of the Flood Estimation Handbook. Centre for Ecology and Hydrology.

Rodda, J.C., 1969. Hydrological network design – needs, problems and approaches. WMO/IHD Report No. 12

Shaw, E.M., 1994. Hydrology in practice, 3rd ed. Chapman & Hall.

Singh, V.P. & Woolhiser, D.A., 1976. Sensitivity of linear and nonlinear surface runoff models to input errors. Journal of Hydrology 29, 243–249.

Stephens, J. C. & Stewart, E. H., 1963. A comparison of procedures for computing evaporation and evapotranspiration. Publication 62, International Association of Scientific Hydrology, 123-133.

Tarboton, D.G., 2003. Watershed delineation from Digital Elevation Models, GIS in water resources. Available at: http://www.crwr.utexas.edu/gis/gishydro04/Introduction/Exercises/Ex4.htm [Accessed 26 June 2010].

Thompson, S.A., 1999. Hydrology for water management, A.A.Balkema, Rotterdam.

US Weather Bureau in cooperation with Corps Engineers, 1947. Thunderstorm rainfall, Hydrometeorology Report 5, 234-259.

Vandewiele, G.L. & Elias, A., 1995. Monthly water balance of ungauged catchments obtained by geographical regionalization. Journal of Hydrology 170, 277-291.

Viessman, W. Knapp, J.W. Lewis, G.L. & Harbaugh, T.E., 1977. Introduction to hydrology, 2nd ed. New York: Harper and Row.

Wolock, D., & Price, C., 1994. Effects of digital elevation model map scale and data resolution on a topography-based watershed model. Water Resources Research, 30(11), 3041-3052.

Wilson, E.M., 1990. Engineering hydrology, 4th ed. Palgrave MacMillan.

Xu, C-Y. & Vandewiele, G.L., 1992. Reliability of calibration of a conceptual water balance model: the humid case. In: T.F. Russell, R.E. Ewing, CA. Brebbia, W.G. Gray and G.F. Pinder (Editors), Mathematical Modelling in Water Resources. Denver, CO.

Xu, C-Y. & Vandewiele, G.L., 1994. Sensitivity of monthly rainfall runoff models to input errors and data length. Journal of Hydrological Sciences 39 (2), 157–176.

Xu, C-Y. Tunemar, L. Chen Y-D. & Singh, V.P., 2006. Evaluation of seasonal and spatial variations of lumped water balance model sensitivity to precipitation data errors. Journal of Hydrology 324, 80-93.

Yang, J. Li, B. & Liu, S., 2000. A large weighing lysimeter for evapotranspiration and soil water–groundwater exchange studies, Hydrological Processes 14, 1887-1897.

Yapo, P. O. Gupta, H. V. & Sorooshian, S., 1996. Automatic calibration of conceptual rainfall–runoff models: sensitivity to calibration data. Journal of Hydrology 181(1/4), 23–48.

Yokoo, Y. Kazama, S. Sawamoto, M. & Nishimura, H., 2001. Regionalization of lumped water balance model parameters based on multiple regression. Journal of Hydrology 246, 209-222

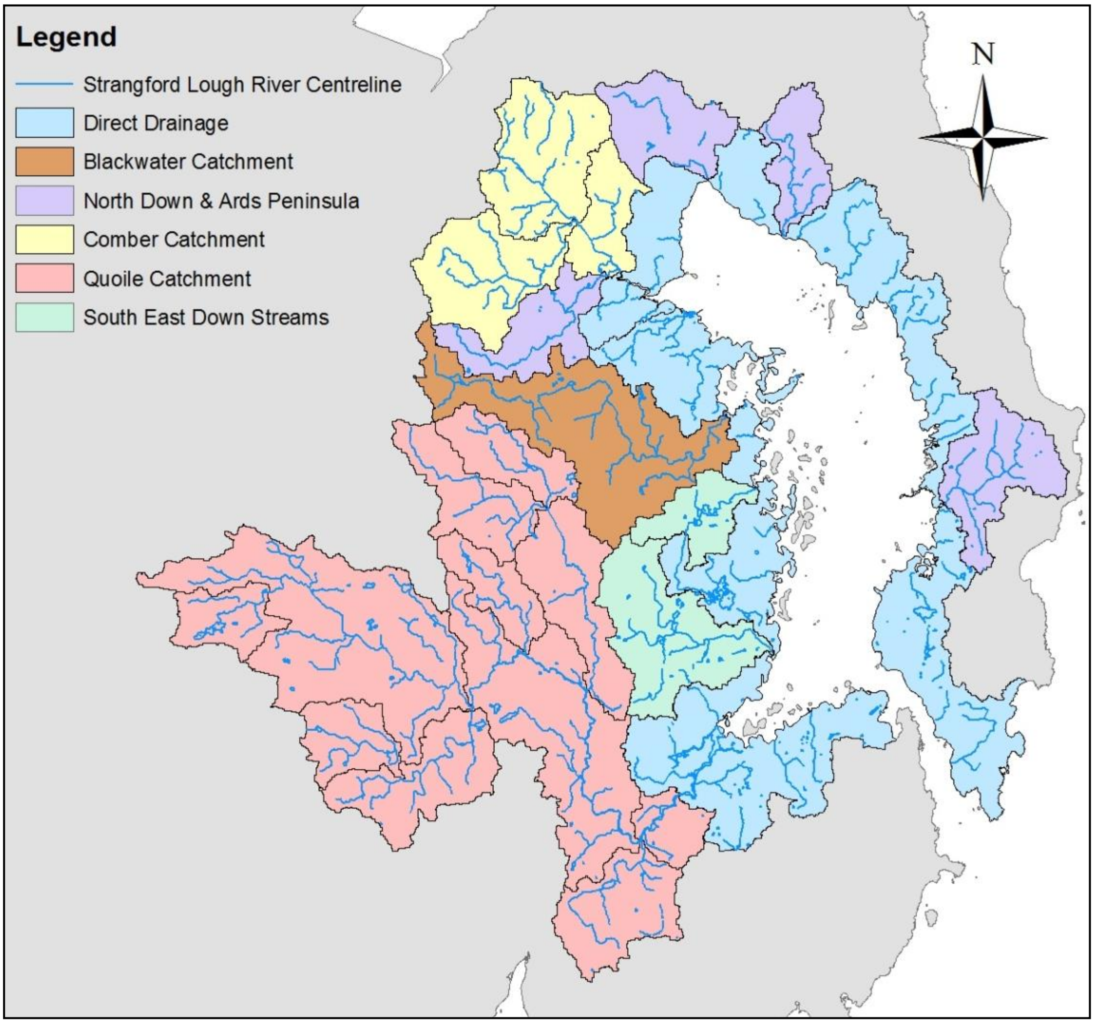
Zhang, W. & Montgomery, D.R., 1994. Digital elevation model grid size, landscape, representation and hydrologic simulations. Water Resource Research 30 (4), 1019-1028.

.

APPENDIX A:

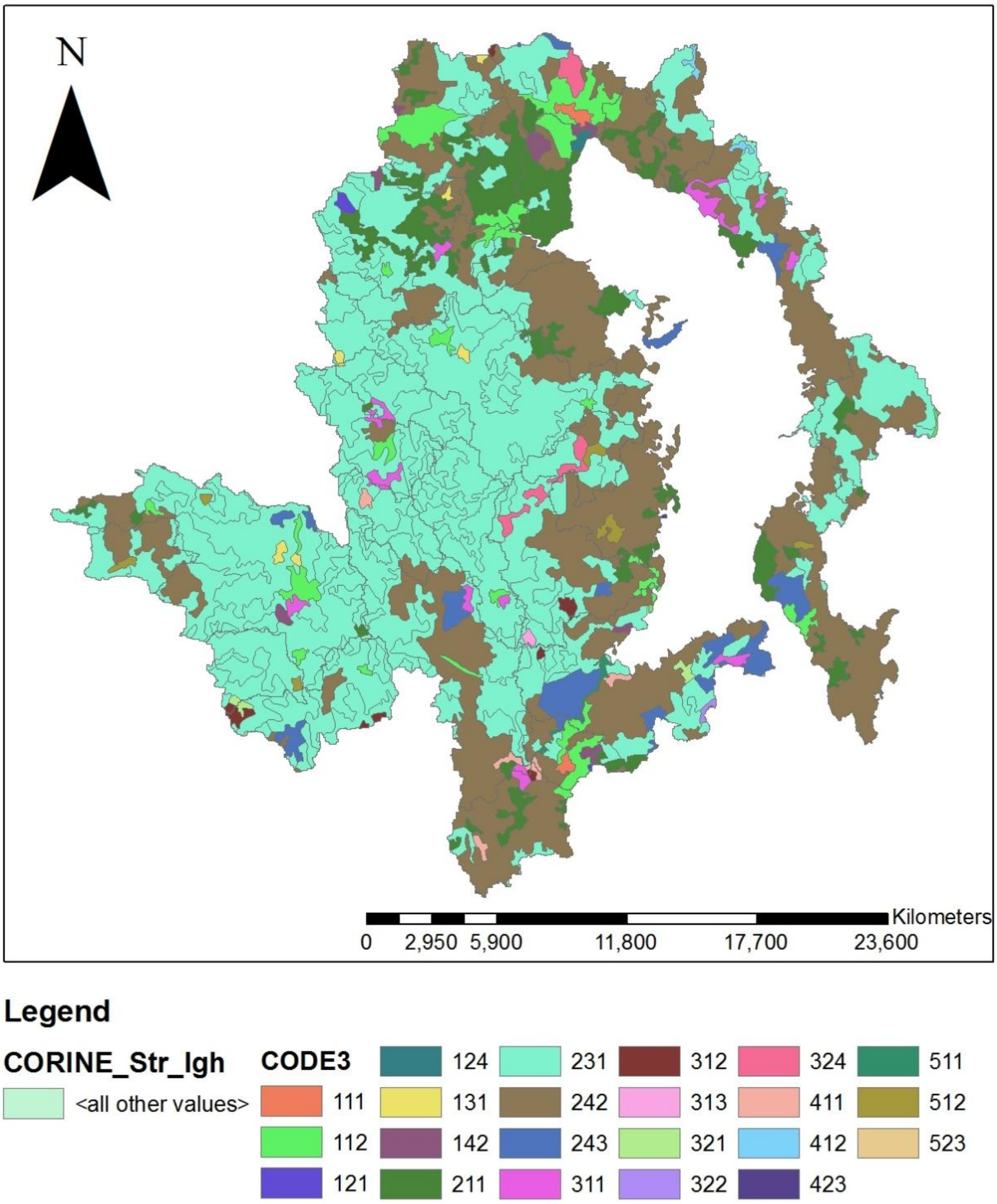
ILLUSTRATIONS RELATING TO SITE DESCRIPTION

APPENDIX A1: NIEA subcatchments of Strangford Lough & their areal contributions



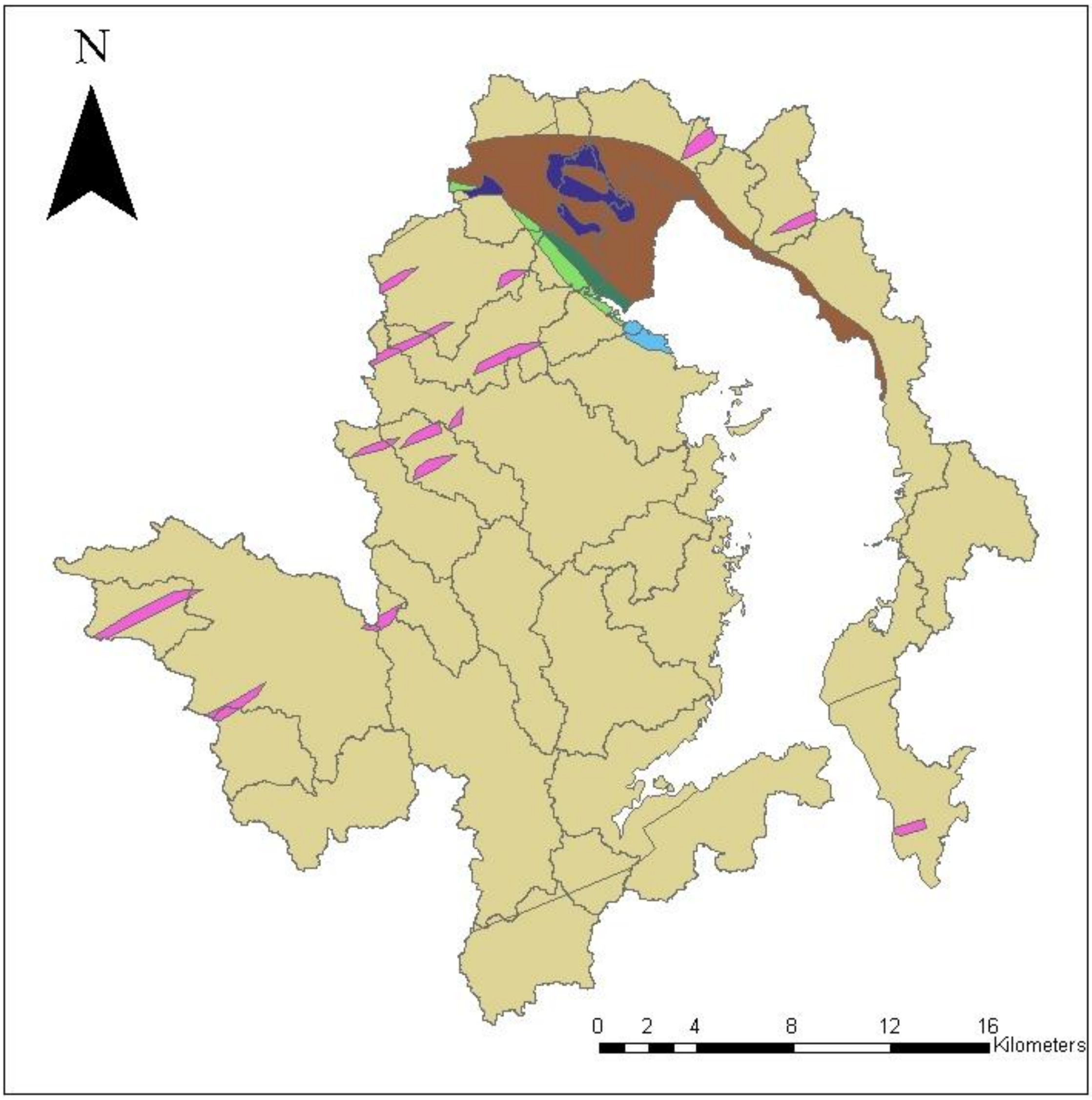
Sub-Catchments	Area (km^2)	% Total Area
Blackwater	50.08	7.74
North Down & Ards	67.71	10.46
Comber	62.66	9.68
Quoile	244.27	37.73
South-East Down	40.86	6.31
Direct Drainage	181.79	28.08
Total Area	**647.37**	**100**

APPENDIX A2: CORINE land use in the Strangford Lough catchment



Code	Description
231	High and low productivity land
242	Complex cultivation patterns
211	Non-irrigated arable land
112	Discontinuous urban fabric
243	Land principally occupied by agriculture

APPENDIX A3: Solid geology of the Strangford Lough catchment (BGS, 2010)



Legend

catchment bedrock

<all other values>

RCS_D

LIMESTONE, ARGILLACEOUS ROCKS AND SUBORDINATE SANDSTONE, INTERBEDDED

MAFIC IGNEOUS-ROCK

MUDSTONE, CHERT AND SMECTITE-CLAYSTONE

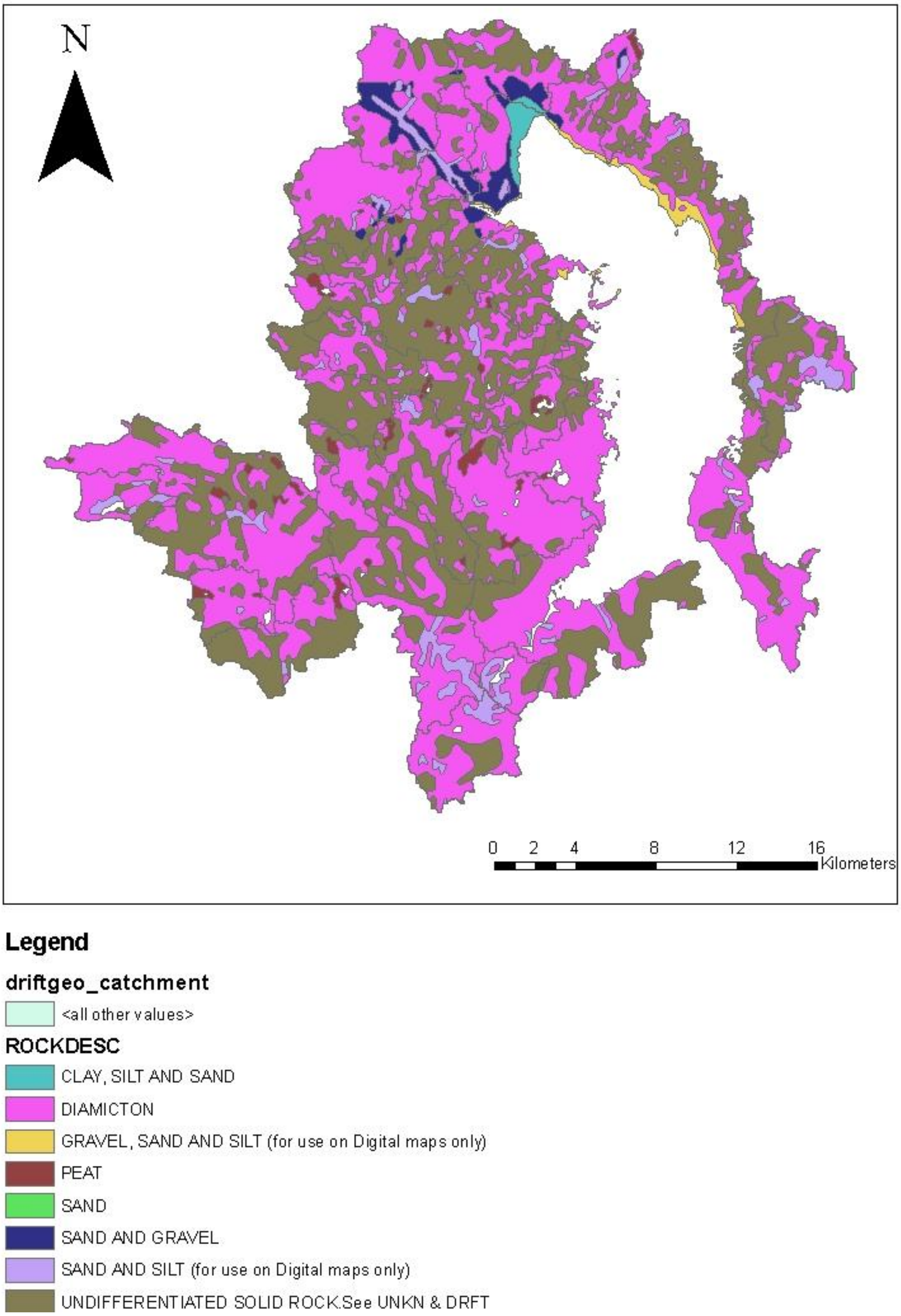
SANDSTONE AND SUBORDINATE BRECCIA

SANDSTONE AND [SUBEQUAL/SUBORDINATE] LIMESTONE, INTERBEDDED

SANDSTONE, SILTSTONE AND MUDSTONE

WACKE

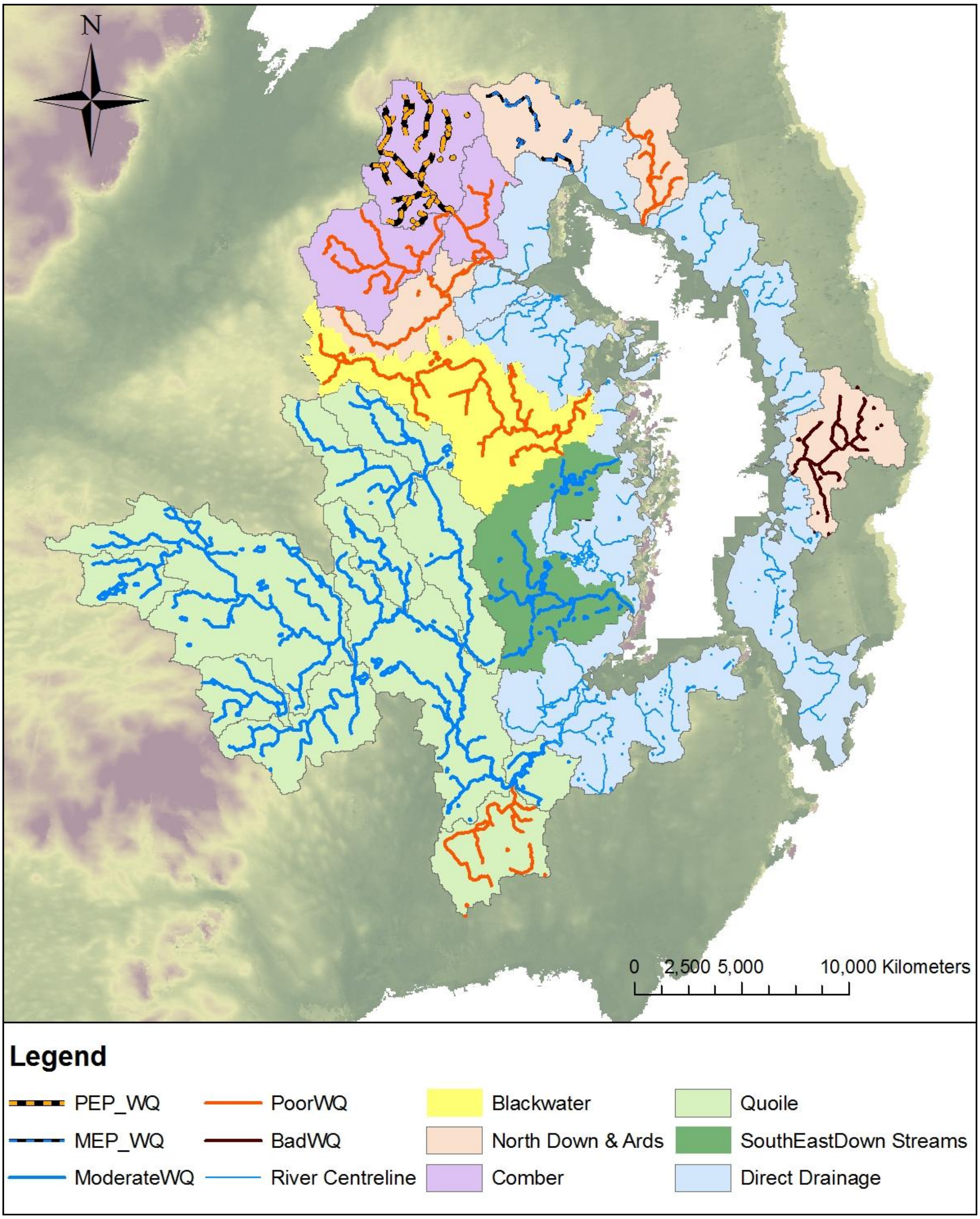
APPENDIX A4: Drift Geology of the Strangford Lough catchment (BGS, 2010)



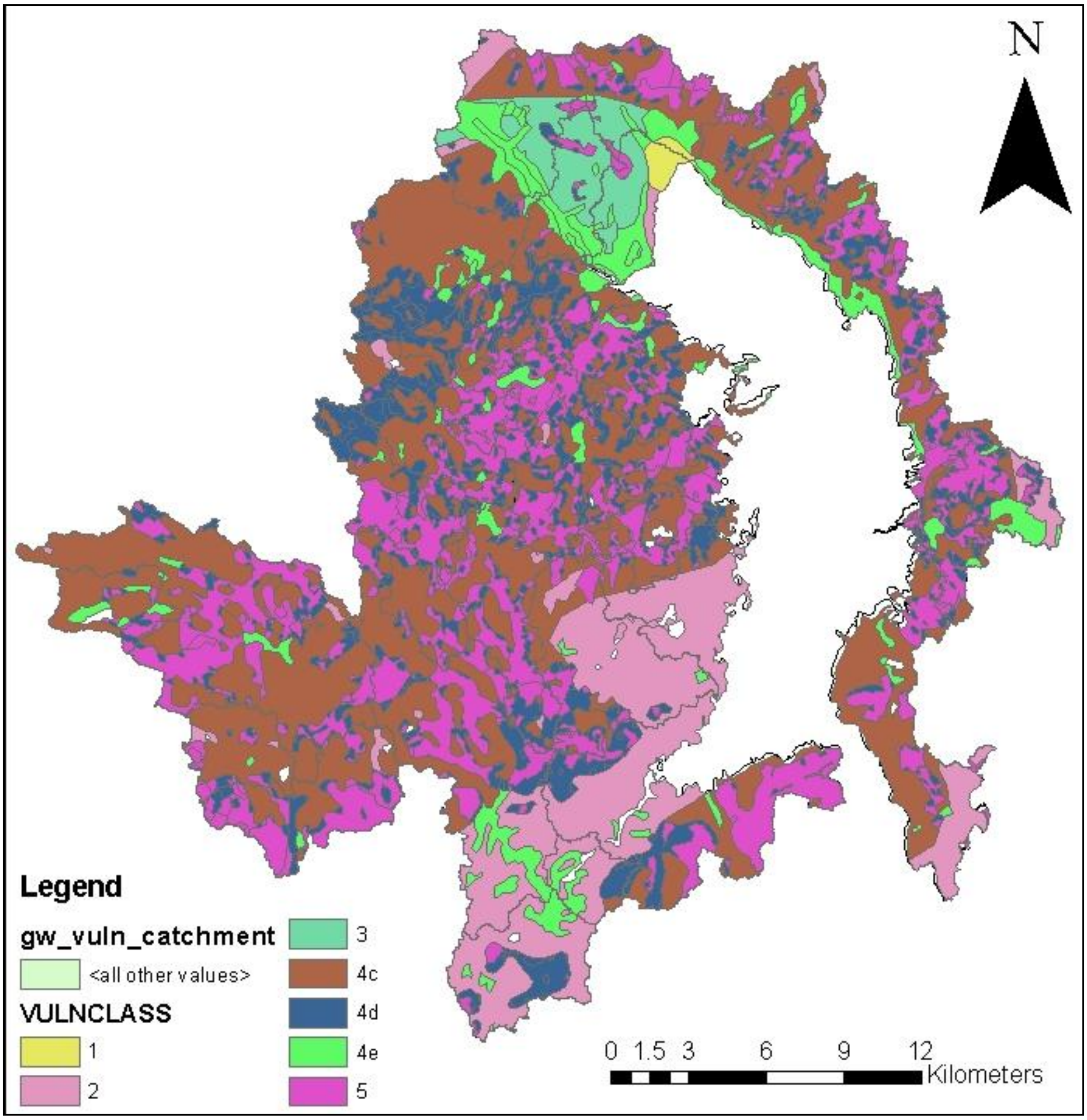
APPENDIX A5: 29 HOST classifications (Cruickshank, 1997)

<table>
<tr><th rowspan="2">Substrate Hydrogeology</th><th colspan="8">Mineral Soils</th><th rowspan="2" colspan="2">Peat Soils</th></tr>
<tr><th>Groundwater or aquifer</th><th>No impermeable or gleyed layer with 100cm</th><th colspan="4">Impermeable layer within 100cm or gleyed layer at 40-100cm</th><th colspan="2">Gleyed layer within 40cm</th></tr>
<tr><td>Weakly consolidated, microporous, by-pass flow uncommon (Chalk)</td><td rowspan="6">Normally present and at > 2m</td><td>1</td><td rowspan="6" colspan="4">13</td><td rowspan="6" colspan="2">14</td><td rowspan="6" colspan="2">15</td></tr>
<tr><td>Weakly consolidated, microporous, by-pass flow uncommon (Limestone)</td><td>2</td></tr>
<tr><td>Weakly consolidated, macroporous, by-pass flow uncommon</td><td>3</td></tr>
<tr><td>Strongly consolidated, non or slightly porous, by-pass flow common</td><td>4</td></tr>
<tr><td>Unconsolidated, macroporous, by-pass flow very uncommon</td><td>5</td></tr>
<tr><td>Unconsolidated, microporous, by-pass flow very uncommon</td><td>6</td></tr>
<tr><td>Unconsolidated, macroporous, by-pass flow very uncommon</td><td rowspan="2">Normally present and at < 2m</td><td colspan="4">7</td><td>IAC < 12.5</td><td>IAC >=12.5</td><td>Drained</td><td>Undrained</td></tr>
<tr><td>Unconsolidated, microporous, by-pass flow common</td><td colspan="4">8</td><td>9</td><td>10</td><td>11</td><td>12</td></tr>
<tr><td rowspan="2">Slowly permeable</td><td rowspan="6">No significant groundwater or aquifer</td><td rowspan="2" colspan="2">16</td><td>IAC >7.5</td><td>IAC<=7.5</td><td rowspan="2" colspan="2">24</td><td rowspan="2" colspan="2">26</td></tr>
<tr><td>18</td><td>21</td></tr>
<tr><td>Impermeable (Hard)</td><td colspan="2">17</td><td>19</td><td>22</td><td colspan="2"></td><td colspan="2">27</td></tr>
<tr><td>Impermeable (Soft)</td><td colspan="2" rowspan="3"></td><td>20</td><td>23</td><td colspan="2">25</td><td colspan="2"></td></tr>
<tr><td>Eroded peat</td><td colspan="4" rowspan="2"></td><td colspan="2" rowspan="2">28, 29</td></tr>
<tr><td>Raw peat</td></tr>
<tr><td>Unclassified</td><td colspan="3">Urban, Lakes</td><td colspan="7"></td></tr>
</table>

APPENDIX A6: Water quality in the Strangford Lough catchment (NIEA, 2008)



APPENDIX A7: Groundwater vulnerability classes for the Strangford Lough catchment (GSNI, 2010)



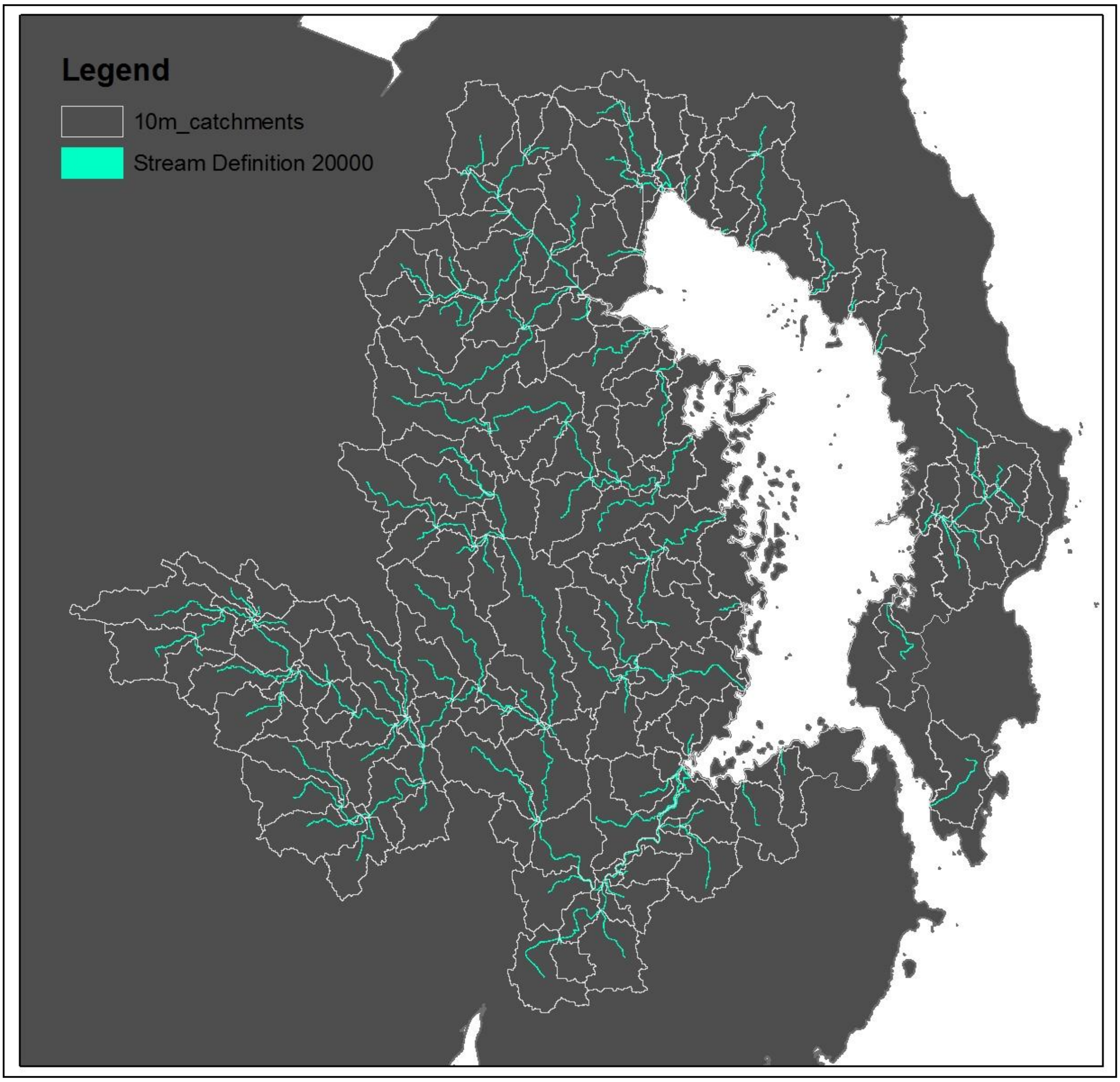
APPENDIX A8: Explanation of vulnerability classes (GSNI, 2010)

Vulnerability class	Superficial deposits thickness	Superficial deposits permeability	Depth of clay within superficial deposits sequence	Depth to water table in drift deposits (where aquifer)	Vulnerability
1	10 – 30 m drift	Low	Clay < 5 m	0	Low
2	3 – 10m drift	Low	Clay < 5 m	0	Low
3	3 – 10m drift	Moderate	Clay < 5 m	0	High
4c	1 – 3m drift	Low	Clay < 5 m	0	High
4d	No drift	None	Clay < 5 m	0	High
4e	1 – 10m drift	High	Clay < 5 m	1-10m to water	High
5	No drift	None	Clay < 5 m	0	High

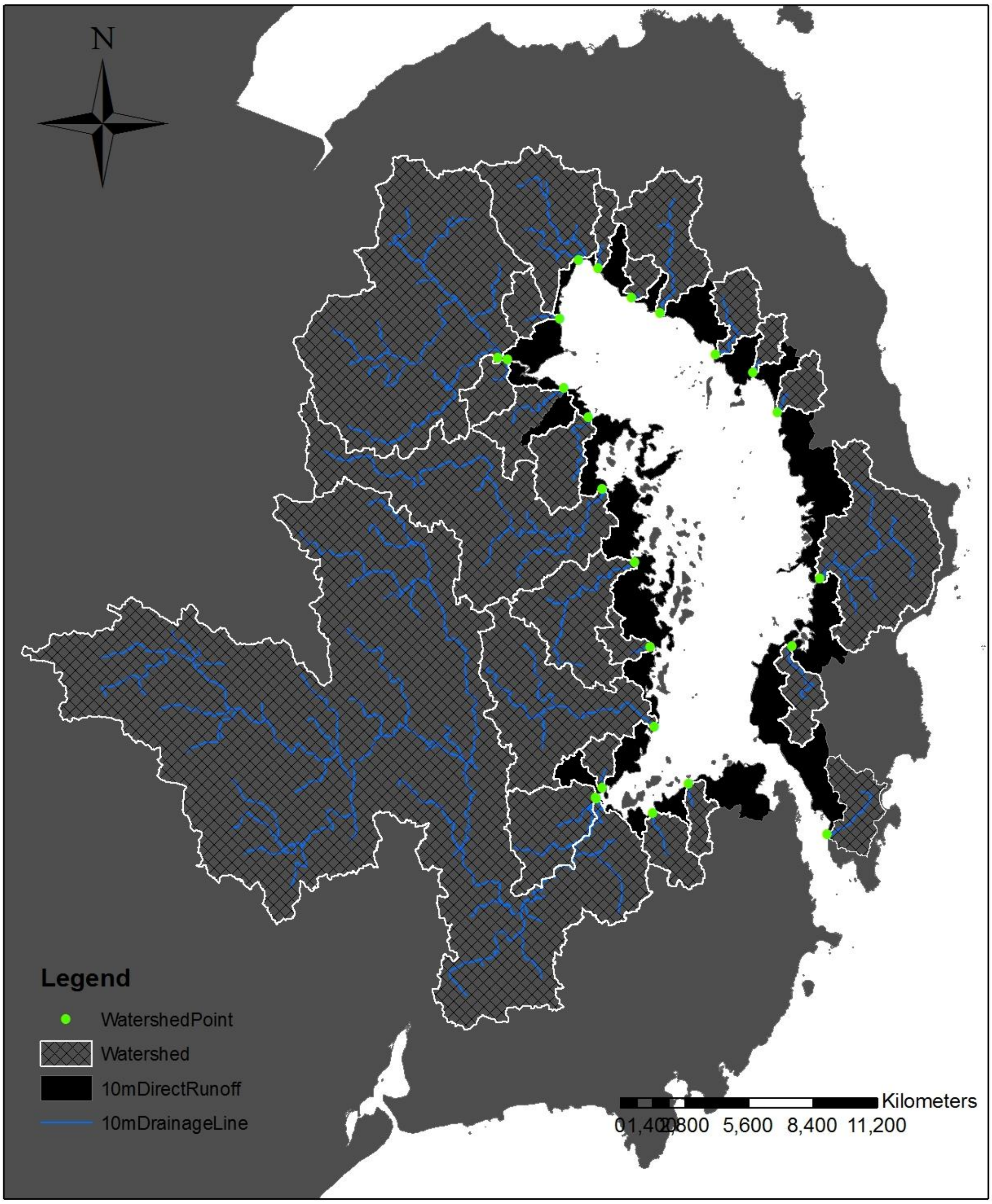
APPENDIX B:

ILLUSTRATIONS RELATING TO GIS METHODOLOGY

APPENDIX B1: Subcatchments and drainage line derived using 10m DEM



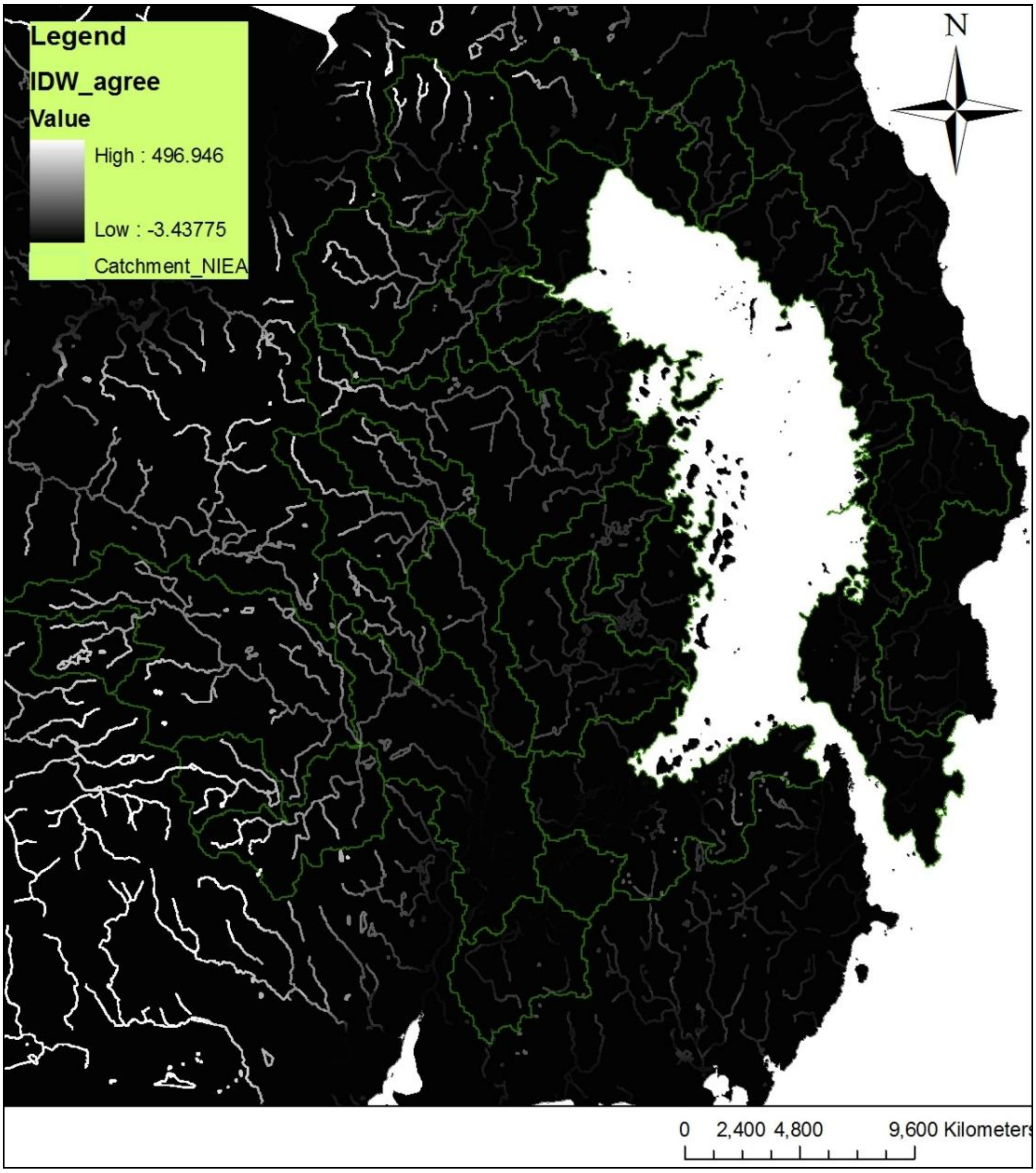
APPENDIX B2: Drainage points, their watersheds and direct runoff contributing to Strangford Lough



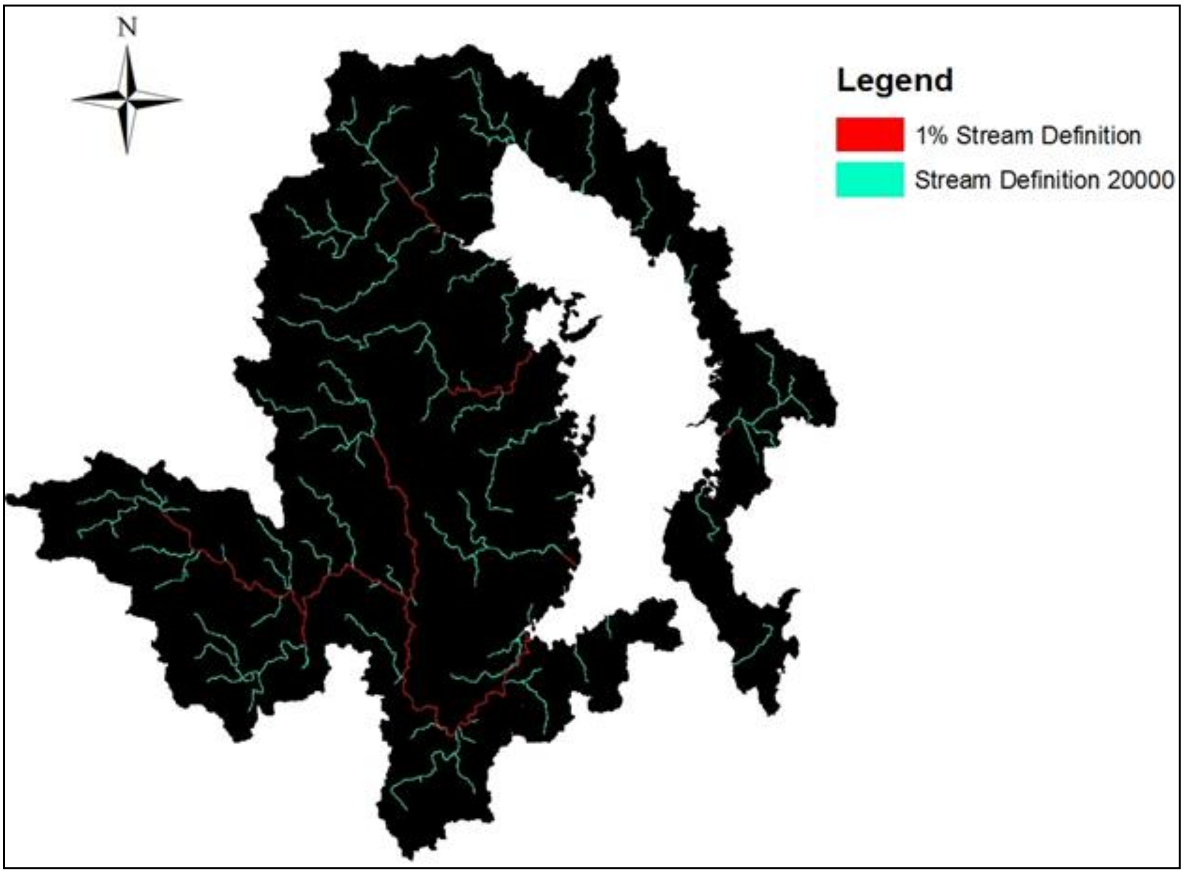
APPENDIX C:

ILLUSTRATIONS RELATING TO GIS RESULTS

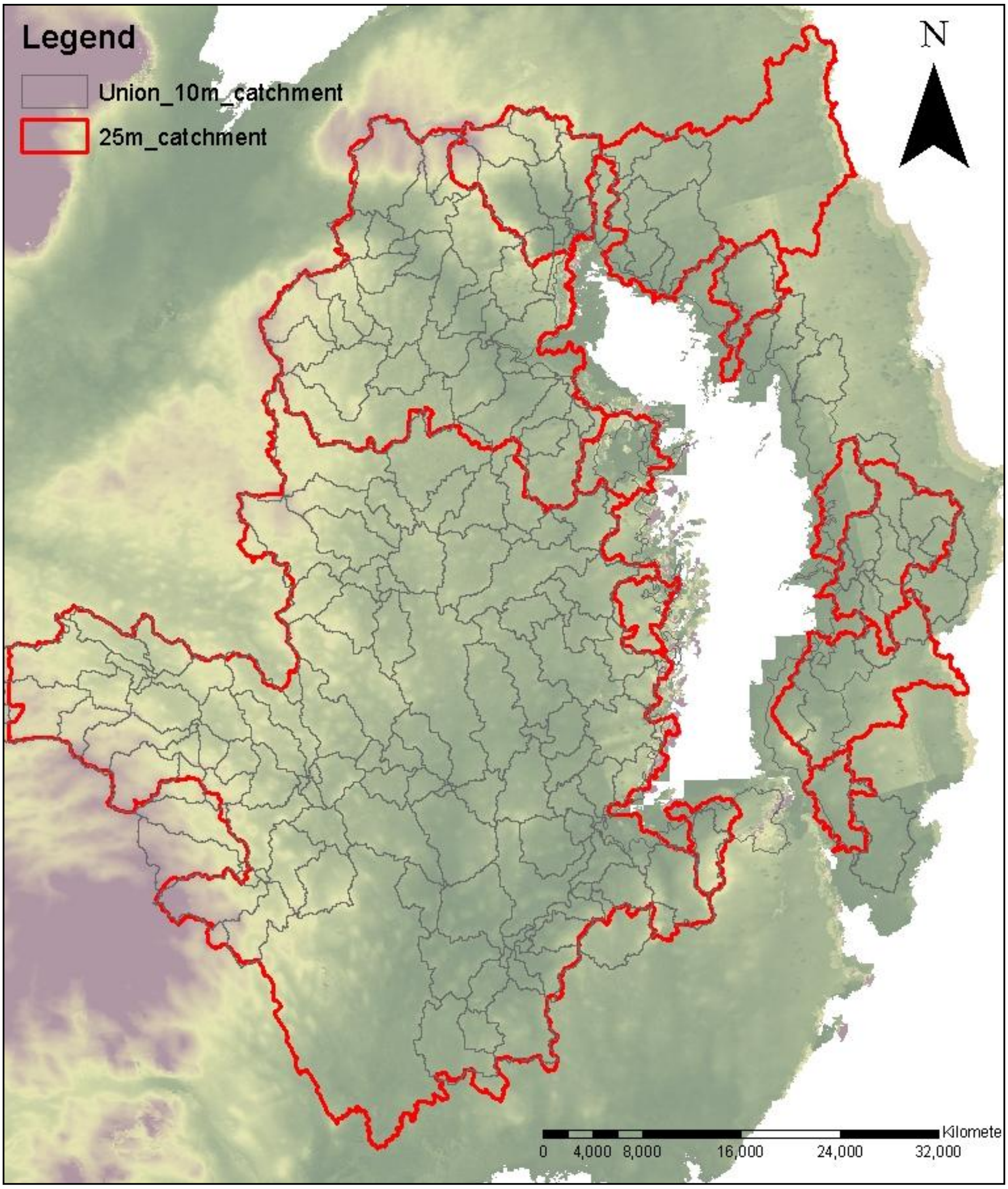
APPENDIX C1: Difference between original DEM and AGREE DEM



APPENDIX C2: Illustrating the increase in stream definition with a decrease in stream threshold



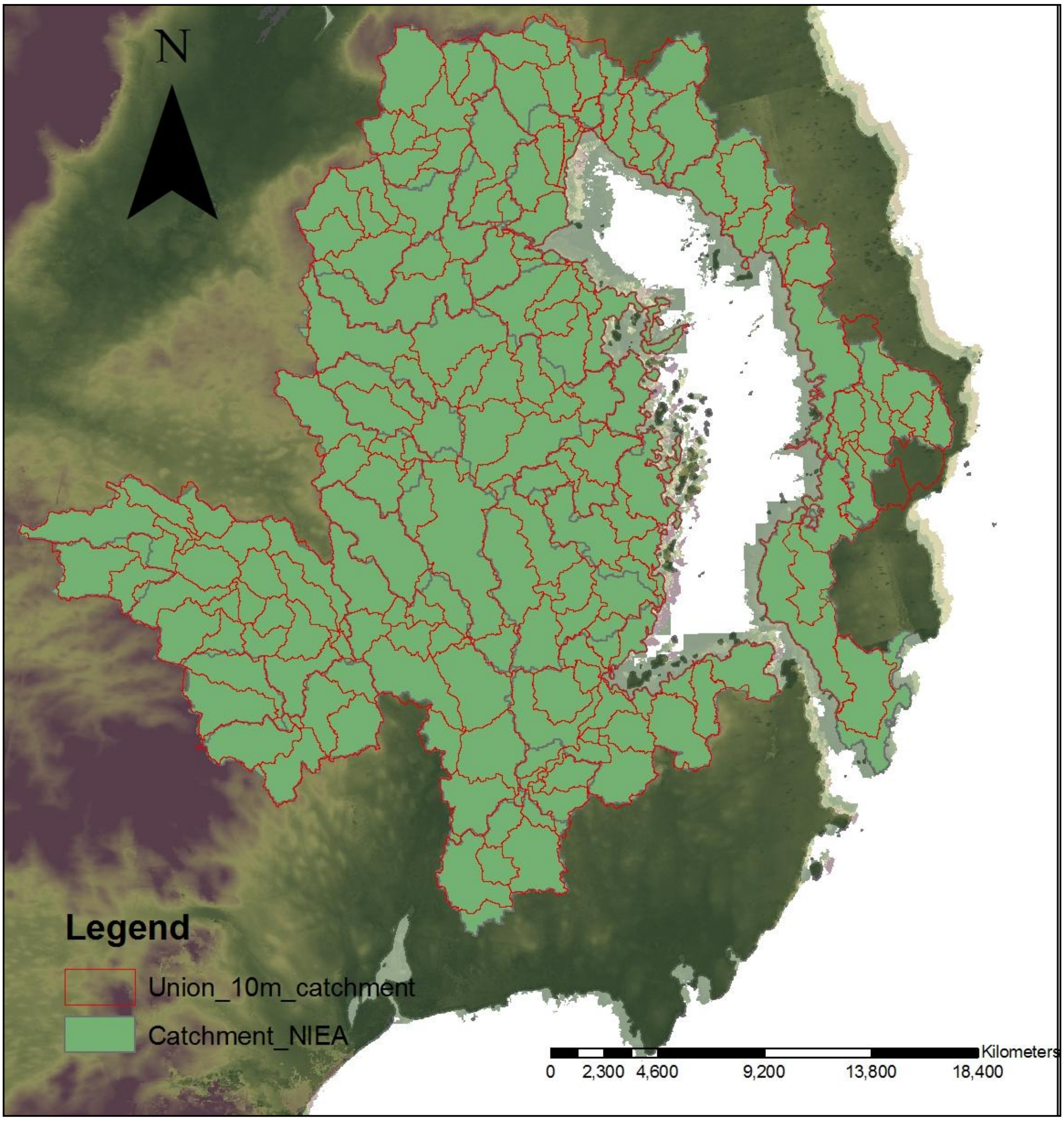
APPENDIX C3: Delineated catchments using the 25m and 10m DEMs



APPENDIX D:

ILLUSTRATIONS RELATING TO GIS DISCUSSION

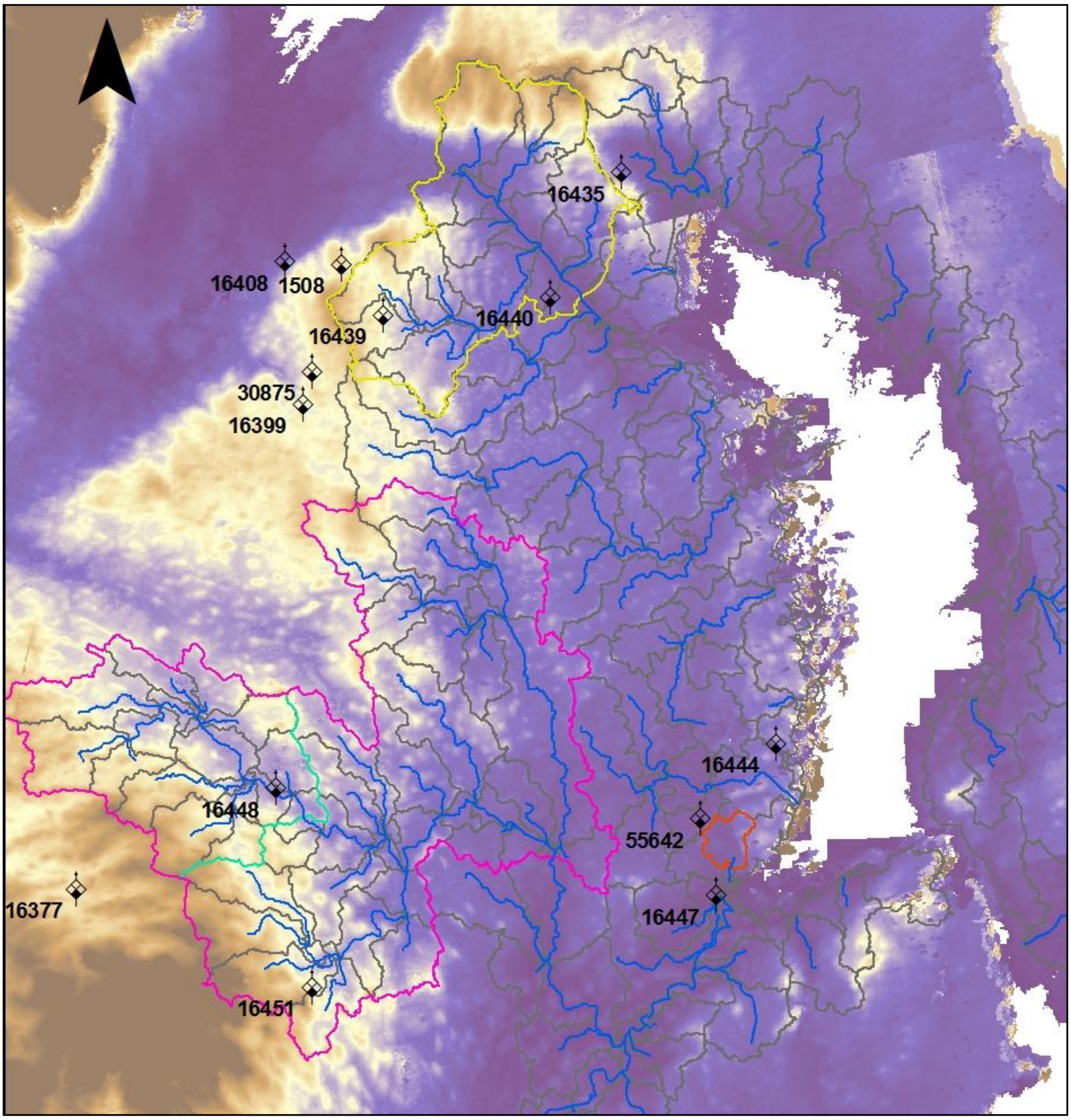
APPENDIX D1: Comparing the 10m delineated catchment against the NIEA catchment



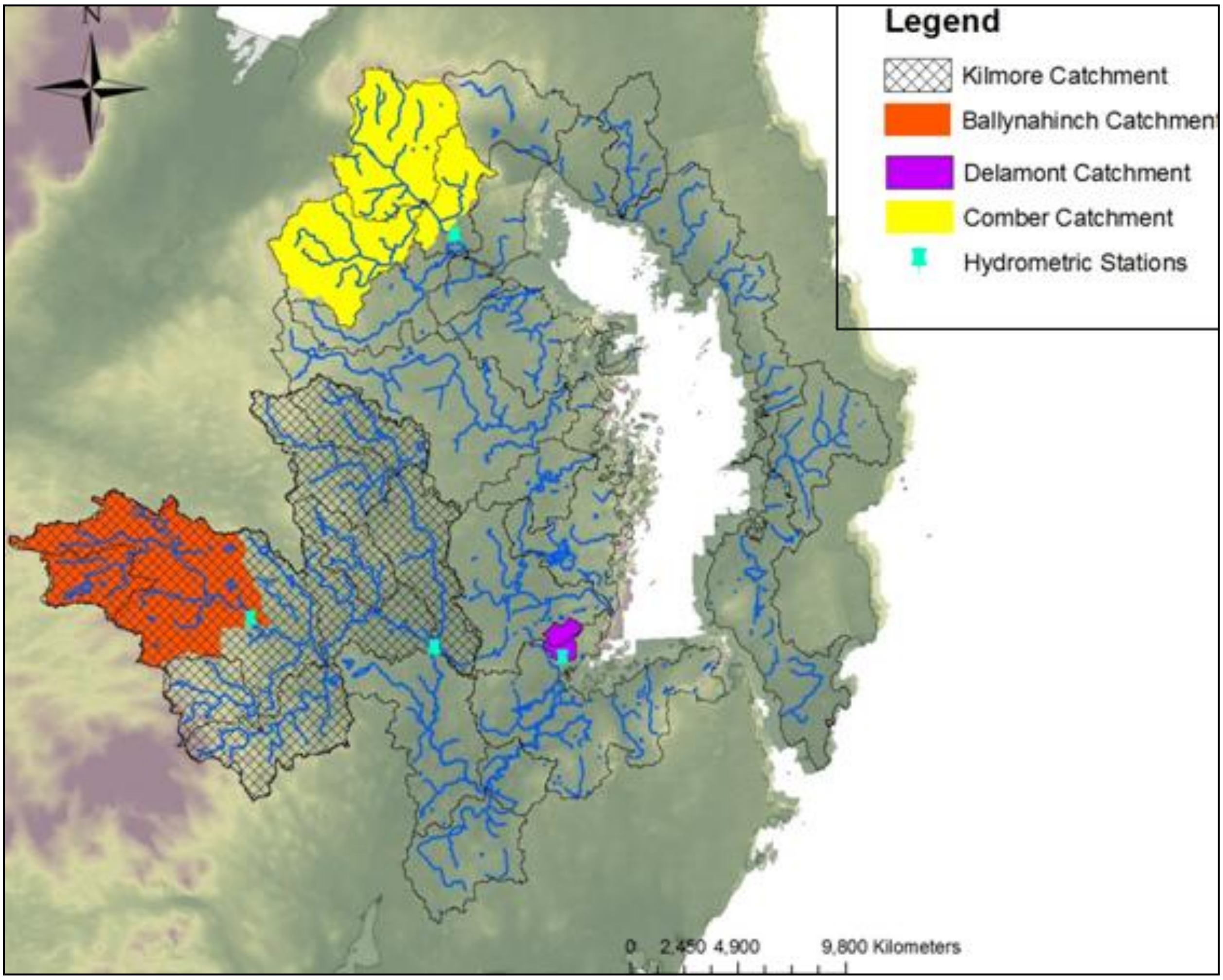
APPENDIX E:

ILLUSTRATIONS RELATING TO NAM METHODOLOGY

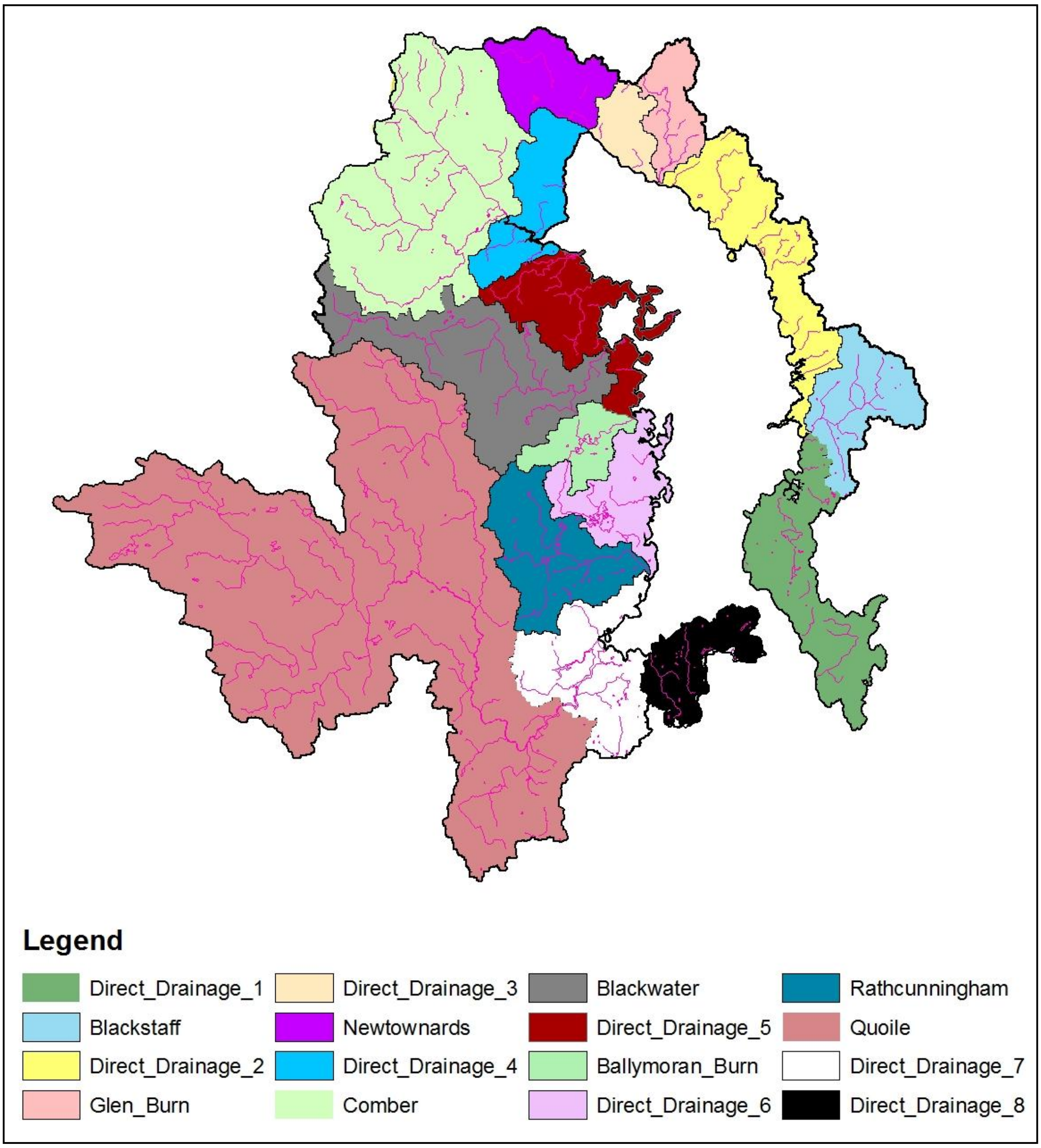
APPENDIX E1: Rainfall stations used for model calibration



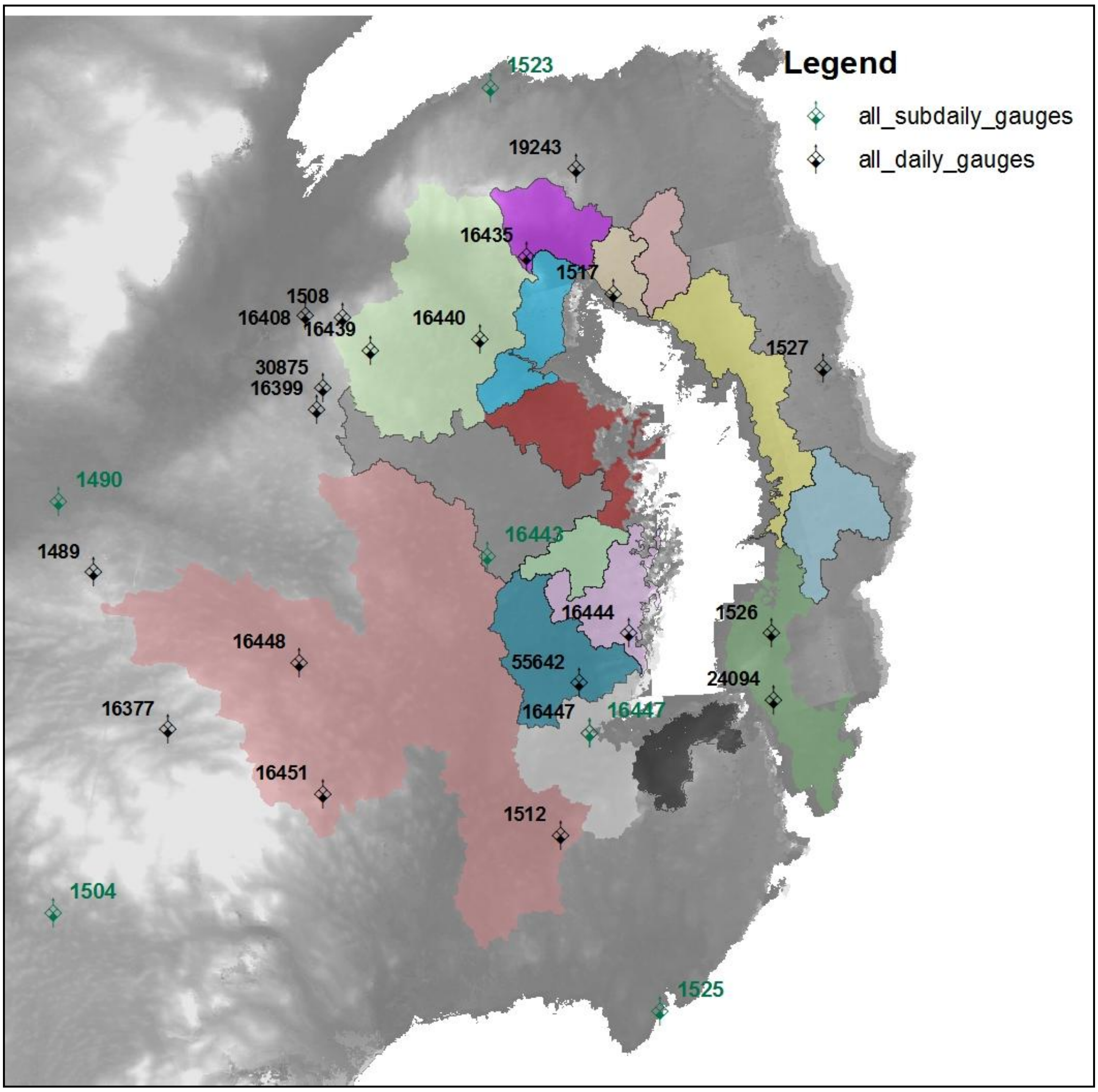
APPENDIX E2: Hydrometric stations and their respective catchments



APPENDIX E3: Subcatchments grouped according to their characteristics



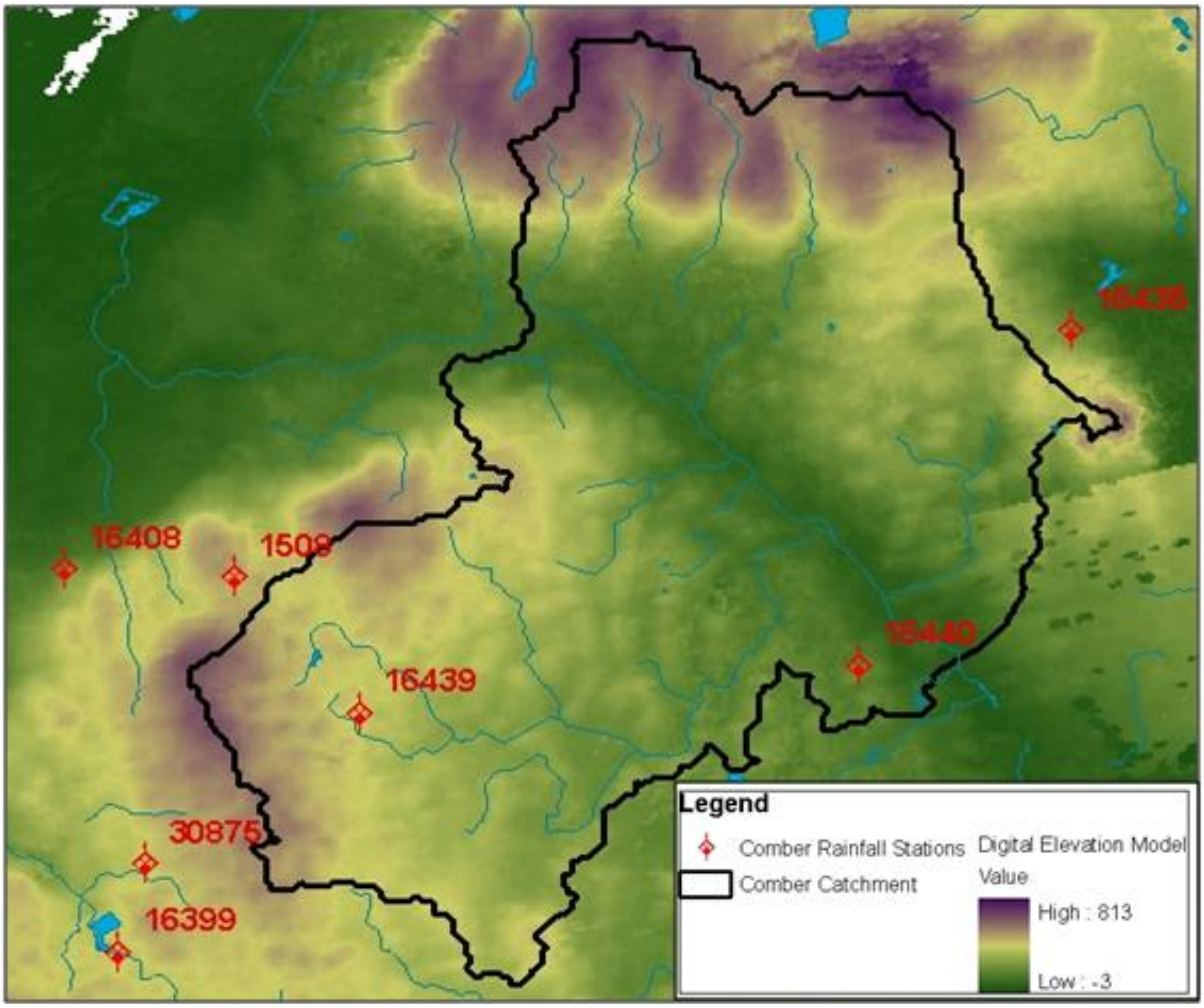
APPENDIX E4: Rainfall stations (hourly and daily) used in model regionalisation



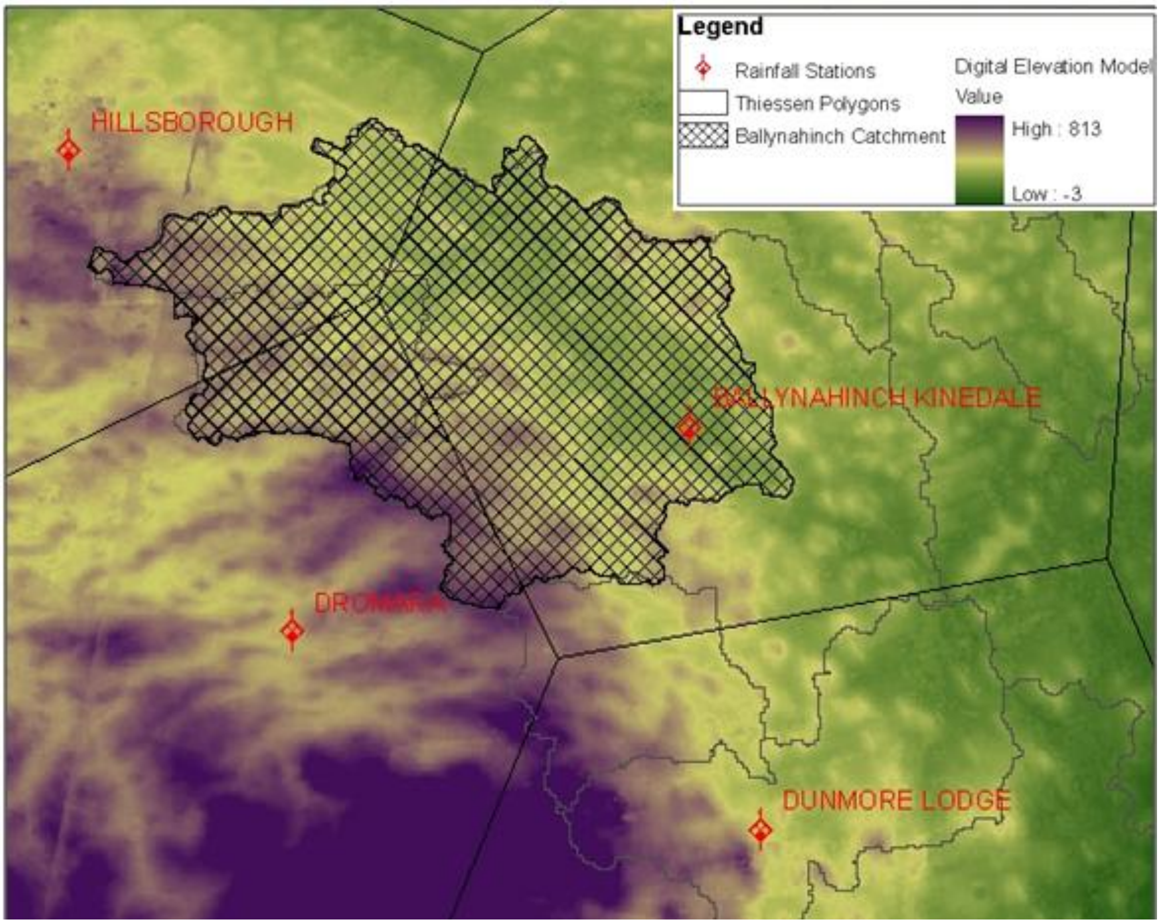
APPENDIX F:

ILLUSTRATIONS & TABLES RELATING TO NAM RESULTS

APPENDIX F1: Location of rainfall stations contributing to Comber catchment



APPENDIX F2: Location of the Ballynahinch catchment



APPENDIX F3: Parameters derived through regionalisation

Catchment	Umax	Lmax	CQOF	CKIF	CK12	TOF	TIF	TG	CKBF
Direct Drainage_1	14.5	207.63	0.66	610	7.81	0.73	0.6	0.70	3900
Blackstaff	10	82.49	0.8	300	6.17	0.6	0.45	0.37	3900
Direct Drainage_2	12.5	152.01	0.75	300	5.13	0.7	0.55	0.55	3900
Glen Burn	14	193.72	0.66	600	8.39	0.73	0.55	0.66	3900
Direct Drainage_3	14	193.72	0.57	500	2.56	0.73	0.6	0.66	3000
Newtownards	14	193.72	0.6	550	5.81	0.73	0.55	0.66	3000
Comber	17	277.15	0.5	620	8.21	0.75	0.65	0.88	3000
Direct Drainage_4	15	221.53	0.55	400	3.10	0.75	0.65	0.73	3000
Direct Drainage_5	11	110.30	0.7	400	17.75	0.7	0.6	0.44	3900
Blackwater	11	110.30	0.9	400	14.39	0.6	0.45	0.44	3900
Ballymoran Burn	11.5	124.20	0.8	400	14.74	0.65	0.5	0.48	3900
Direct Drainage_6	14.5	207.63	0.52	550	5.04	0.7	0.6	0.70	3900
Rathcunningham	14	193.72	0.53	700	30.12	0.7	0.6	0.66	3900
Direct Drainage_7	13.5	179.82	0.52	660	14.19	0.7	0.6	0.62	3900
Direct Drainage_8	12.5	152.01	0.8	300	6.79	0.7	0.55	0.55	3900
Quoile	19	300.00	0.78	800	38.52	0.76	0.56	0.85	3900

APPENDIX F4: Water balances for each of the sub-catchments for the calendar year 1995

Sub-Catchment	Rainfall (mm)	Potential Evapotranspiration (mm)	Actual Evapotranspiration (mm)	Recharge (mm)	Overland Flow (mm)	Interflow (mm)	Baseflow (mm)
DIRECT1	659.3	414.9	356.2	102.1	132.3	75.2	123.3
BLACKSTAFF	670.7	414.9	310.3	100.1	163	101.3	108.7
DIRECT2	703.9	414.9	344.9	104.4	130.7	127.6	109.5
GLEN BURN	692.8	414.9	355.9	117.9	140.3	81	125.5
DIRECT3	692.8	414.9	356.2	128.6	117.7	92.7	134
NEWTWONARDS	788.7	414.9	372.9	154.9	162.2	100.2	161.8
COMBER	837.3	414.9	388	159.8	173.8	117.7	180.9
DIRECT4	810.3	414.9	378.5	147.5	147.4	140.2	162.9
DIRECT5	810.3	414.9	352.1	163.6	201.3	95.4	175.3
BLACKWATER	832.7	414.9	349.3	113.6	271.1	101.6	118
BALLYMORAN	462.6	414.9	237.8	76.4	76.6	49.9	54.2
DIRECT6	462.6	414.9	283.5	62.8	46.4	45.1	48.8
RATHCUNNINGHAN	462.6	414.9	279.6	72.5	50.9	35.2	55.7
DIRECT7	746	414.9	348.8	179.3	149.8	70.8	180.4
DIRECT8	737.2	414.9	334.9	112.7	167.8	125	110.8
QUOILE	904.3	414.9	381	107.1	322	100.8	111

APPENDIX F5: Total runoff, overland flow, interflow and baseflow for the Quoile catchment