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Phosphorus loss from soil to water in the Lee catchment – A spatial analysis

By

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Abstract

In most fresh water systems, phosphorus is considered to be the key limiting nutrient and excessive introduction of phosphorus into surface waters is likely to lead to eutrophication. In Ireland, where eutrophication is the main threat in terms of water quality, it is believed that over 70% of phosphorus reaching inland waters emanates from agricultural sources. With the improved control of farmyard losses, most of the phosphorus is now considered to originate from diffuse field sources. The River Lee catchment, 1135 km² in area, was monitored through a network of 56 stream water quality sites that were sampled 8 times over 2 years, during base and storm flow conditions. The 56 subcatchments draining to the sampling sites are representative of different land uses, different soil types and different climate conditions occurring in the catchment. In this mostly rural study area, land is almost entirely dedicated to agriculture and natural areas. This ensured that most of the phosphorus was coming from diffuse sources and not from point sources.

A large part of the work consisted in collecting and processing the data describing the study area: land use, agricultural management practices, soil type and precipitation. Intense use of GIS tools was made at this stage to extract and manage the information. Great attention was given to explain the sources and the transformations applied to these data. A lack of available data is actually often reported when dealing with phosphorus loss studies at such a large scale. To investigate the relationships between the different variables and the SRP concentrations in the rivers, simple and multiple regression analyses were carried out. The proportion of land dedicated to agriculture was identified to be the best predictor of the log-transformed Soluble Reactive Phosphorus (SRP) concentrations during storm flow (R^2=0.89). Phosphorus losses also appear to increase with stocking density, fertiliser P and Soil P levels. In terms of land use, cultivated land is the main contributor to the P transfers followed by grassland. In contrast, phosphorus levels appeared to decrease with the increasing proportion of forestry and peat land. *Réalta*, the Irish phosphorus model, was also used and evaluated for the Lee catchment.

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Chapter 1

Introduction

1.1 Definition of Problem

Water quality remains good in Ireland compared to the rest of the European countries, although it has deteriorated in the last few decades. Some improvements in term of water quality have even been observed for some years, stopping the continuous decline experienced since surveys first commenced in the 1970's (Cork County, 2004).

However, eutrophication, which is affecting a considerable proportion of the surface waters in Ireland is now seen as the main threat to these systems (Toner, 2005). Eutrophication is the over-enrichment of a water body with nutrients, resulting in excessive growth of organisms and depletion of oxygen concentration. The nutrient enrichment is typically caused by compounds containing Nitrogen (N) or Phosphorus (P). While, in a European context, much of the effort seems to be done to reduce pollution caused by nitrates (with the EU Nitrate Directive for example), it is now well-established that phosphorus is usually the key limiting nutrient in fresh waters (EEA, 2004). It means that, in the natural environment, phosphorus concentration is generally insufficient to support continued growth and expansion of algae. But if P is introduced to surface waters artificially, growth is then promoted until that or another nutrient is exhausted again. If no limiting factor occurs, algal bloom and eutrophication will then generally result.

Control of eutrophication is important to protect sensitive aquatic species, especially salmon and trout, in the case of Irish rivers. But it is also a way to keep water quality compatible with economic, leisure and potable water supply activities. The water drawn from a eutrophic lake will actually need much more treatment to make it suitable for distribution. In this regard, water quality in the Lee catchment is particularly important since the water abstraction point for most of the drinking water for Cork City and its region is immediately upstream of the Inniscarra Dam on the River Lee.

Much work has already been done in Ireland on the control of point discharges to water, such as the effluents from waste water treatment plants or from industrial activities. Now the big challenge is to address the problem of diffuse phosphorus loss from agriculture. Almost half the eutrophication of Irish rivers is due to agricultural sources (McGarrigle, 2002). It is also considered that over 70 % of phosphorus reaching inland waters and coming from human activities emanates from agricultural sources (EPA, 1999). The situation could be worse in term of eutrophication if much of the phosphorus losses were not occurring during winter months, which are generally associated with important rain events.

Phosphorus loss from agriculture can either come from fields or from farmyards, i.e. directly from manure storage facilities to water, for example. While losses from farmyards can be controlled quite easily (but costly) with improvements in the facilities, it is different for field losses. They actually have different sources which can contribute at the same time (Tunney, 2000):

- Heavy rain shortly after spreading fertiliser or manure
- Heavy rain on fields where animals are intensively grazed
- Soils where phosphorus has accumulated over many years of fertilization

Field reservoirs of P seem to have a large influence on P losses, and this is worrying when considering the fact that reducing the build-up of phosphorus in soils can take decades (Culleton, 2000). Up to the 1950's Irish soils were naturally deficient in phosphorus. Over the past 50 years and with the widespread use of chemical fertiliser, testing for soil phosphorus have shown a tenfold increase in the P concentration in Irish soils (Tunney, 2002). Fertiliser usage has now been reduced in Ireland but large phosphorus surplus are still calculated for agriculture leading to unnecessary costs and accumulation in soils.

The study of phosphorus loss to water has received increased attention in the past decades but still remains a relatively new area of study. Progress is still needed for a better understanding of the physical process involved in the transfers of P to water. But beyond understanding the mechanisms comprehension, it is also a pressing necessity to develop models that can predict the diffuse loss of P. Many of them have already been created, based either on a deterministic or on an empirical approach. While the deterministic ones try to model the complex physical process, the empirical ones try to relate the site characteristics and management practices with the losses of phosphorus. The interest of this last approach is then to develop tools for the management and the minimization of P loss from agricultural sources.

1.2 Background: phosphorus basics

The chemical element phosphorus (P) normally occurs in nature as part of a phosphate ion, consisting of a phosphorus atom and some number of oxygen atoms; the most abundant form is called orthophosphate and has four oxygen atoms (PO_4^{3-}). Phosphorus is essential for plant and animal life: many of the chemical reactions in living cells involve phosphate ions. They mediate energy transformations in living cells and also play a critical role in cell development and DNA formation. Insufficient soil P can therefore result in delayed crop maturity, reduced flower development, low seed quality, and decreased crop yield (Hyland, 2005). When P fertilisers were first developed in the 19th century, and increasingly used world-wide in the 20th century, they resulted in a dramatic increase in plant and animal production.

1.2.1 The Phosphorus Cycle

The phosphorus cycle is the biogeochemical cycle that describes the movement of phosphorus through the lithosphere, hydrosphere, and biosphere. It is mainly cycling through water, soil and sediments. Unlike many other biogeochemicals (e.g. Nitrogen), the atmosphere does not play a significant role in the movements of phosphorus, because phosphorus and phosphorus-based compounds are usually solids at the typical ranges of temperature and pressure found on Earth.

Phosphorus is most commonly found in rock formations and ocean sediments as phosphate salts. Phosphate salts that are released from rocks through weathering usually dissolve in soil water and will be absorbed by plants. Phosphorus usually controls primary productivity in most natural ecosystems, both terrestrial and aquatic. Often, humans will also extract phosphate and apply it as a fertilizer. The plants may then be consumed by herbivores that in turn may be consumed by carnivores. After death, the animal or plant decays, and the phosphates are returned to the soil. Runoff may carry them back to the ocean or they may be reincorporated into rock, remaining there for millions of years. Eventually, phosphorus is released again through weathering and the cycle starts over.

Phosphorus moves through plants and animals much faster than it does through rocks and sediments, making the phosphorus cycle overall one of the slowest biogeochemical cycles.

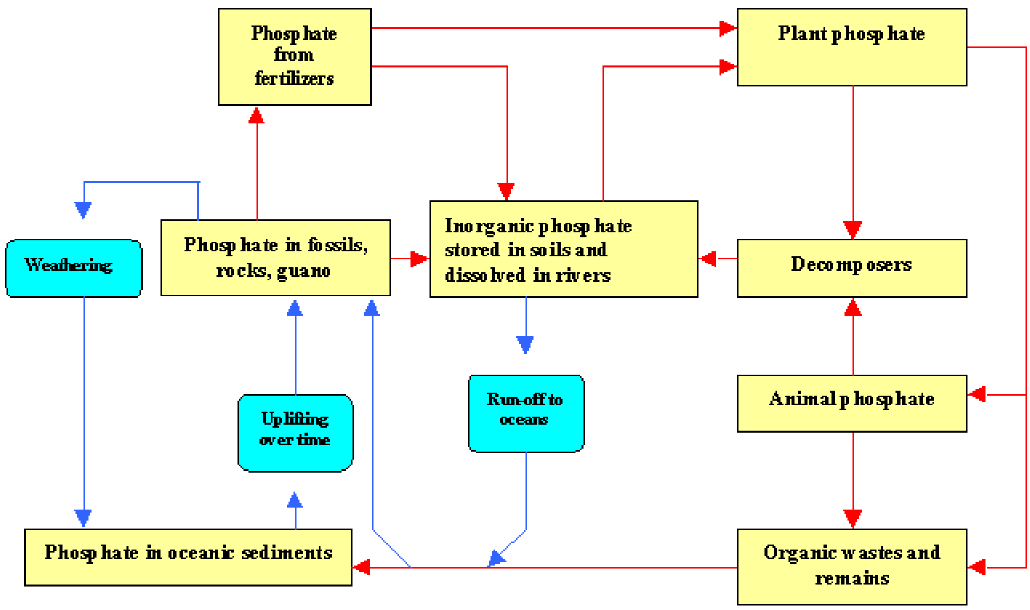

Figure 1.1: Schematic representation of the general Phosphorus cycle (Lenntech, 2006).

1.2.2 Phosphorus in soil

Phosphorus exists in many different forms in soil. Soil P can be in organic and inorganic forms, but these are not discrete entities with indistinct forms occurring (Sharpley, 2003). Organic P consists of undecomposed residues, microbes, and organic matter in the soil. Inorganic P is usually associated with Aluminum, Iron and Calcium compounds of varying solubility and availability to plants. The different forms of P and general P transformation are shown on Figure 1.2:

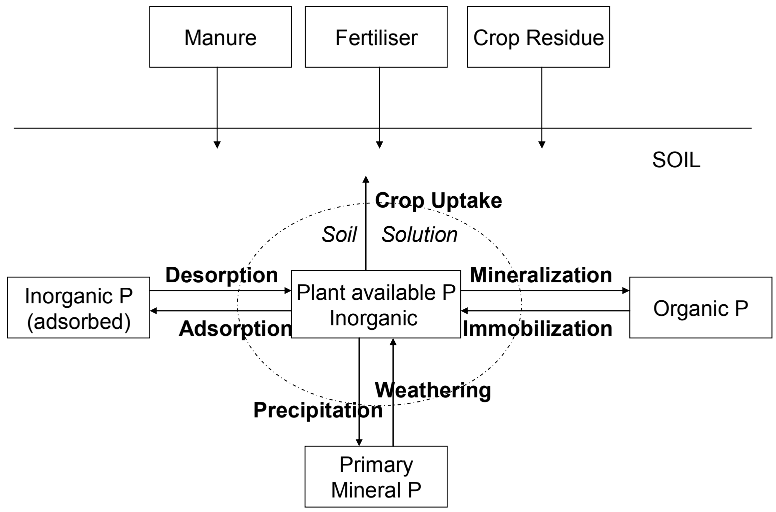

Figure 1.2: Sources, forms and transformation of soil Phosphorus.

Different transformation processes increase or decrease plant available P:

- Weathering and precipitation: P-rich minerals are weathered and made available to plants over a long period of time, whereas phosphorus can become, at the opposite, unavailable through precipitation when plant available P (orthophosphate) reacts with dissolved iron and aluminum in acid soils or calcium in calcareous soils to form phosphate minerals.
- Mineralization and Immobilization: Mineralization is the microbial conversion of organic P to orthophosphate while immobilization is the consumption of the plant available P by microbes.
- Adsorption and Desorption: Adsorption is the chemical binding of P to soil particles while desorption is the release of adsorbed P into the soil solution. Adsorption differs from precipitation by the greater reversibility of the binding to soil particle.

In fact, only a fraction of the total P is available to plants. The soil P system can then be described according to phosphorus availability with 3 different "pools of P" (Wortman, 2005):

- A small proportion of soil P is dissolved in the soil solution in the orthophosphate form, the form that is taken up by plants. As the plant depletes orthophosphate in the soil solution, dissolved P is replenished from the second major soil P pool called labile P.
- Labile P is phosphorus that is held by relatively weak bonds to soil particles (adsorbed P) and organic matter (Organic P).
- The third soil P pool, non-labile or stable P, is held strongly to soil particles (mineral P) and in highly recalcitrant form bonds to organic matter in all soils. Stable P is considered unavailable to plants and is released at a very slow rate to the labile and soluble P pools.

Table 1.1: The Primary soil P pools.

P pools	**Soluble soil P**	**Labile soil P**	**Stable P**
fraction	< 1%	< 5%	> 95%
availibility	readily available to plants	weakly bonded to soil particles	tightly bonded to soil particles

Most P fertilizers are composed of water soluble P compounds and some manure P is water soluble (Wortman, 2005). The application of fertilizer or manure P causes an initial dramatic increase in soluble P in the soil at the point of contact. Chemical equilibrium is then rapidly re-established as much of the added P enters the labile P pool. Over time some of the P in the labile pool is converted into more stable organic and mineral forms. The immediate effect of P fertilization and manure P applications is to increase the capacity of the labile P pool to replenish solution P and total soil P. The net long-term effect depends on soil properties, P removal by crops, and P loss by other mechanisms.

The main source of phosphorus lost to water is as dissolved orthophosphate and P associated with suspended particles.

1.2.3 Phosphorus in water

Phosphorus exists in water in either a particulate phase or a dissolved phase. Particulate matter includes living and dead plankton, precipitates of phosphorus, phosphorus adsorbed to particulates, and amorphous phosphorus. The dissolved phase includes inorganic phosphorus and organic phosphorus.

Organic phosphate is phosphate that is bound to plant or animal tissue. It is formed primarily by biological processes. It can be found in sewage due to the contribution of body waste and food residues

Inorganic phosphate is phosphate that is not associated with organic material. Types of inorganic phosphate include orthophosphate and polyphosphates. Orthophosphate is the most stable kind of phosphate and, again, is the form that is used by plants. It is therefore the form which should be considered first when dealing with eutrophication. It is produced by natural processes and is found in sewage. Polyphosphates, which are found in detergents, are unstable in water and will eventually convert to orthophosphate.

1.3 Literature Review: P loss to water

Eutrophication due to phosphorus losses from agriculture is nowadays the most critical impact of agriculture on the water quality of Irish rivers and lakes (McGarrigle, 2002; Toner, 2005). For a long time, farmyards were the main contributor of agricultural P losses to surface waters. However, with the improved control of phosphorus loss, diffuse sources are now of more concern. Different studies (Jordan, 2005; Morgan, 2000) show evidence that around 70 to 80 % of the phosphorus lost could be accounted for by losses from fields.

The transfer of phosphorus from the terrestrial environment to the water environment can occur in soluble and particulate forms. This latter form includes P associated with soil particles and organic material eroded during flow events. It constitutes between 75 and 90% of P transported in surface runoff from cultivated land (Sharpley, 1996a). On the other hand, surface runoff from grass, forest, or non-cultivated soils carries little sediment and is consequently dominated by dissolved P (about 80%). In this regard it is noted that over 90% of agricultural land in Ireland is devoted to grassland (Tunney, 2000).

The release of P in dissolved form occurs when rainfall interacts with a thin layer of surface soil, typically less than 5 cm, (Sharpley, 1985) to desorb soil P before leaving the field as surface runoff. The remaining rainfall percolates through the soil profile where sorption of P by subsoil generally results in low concentrations of plant available P in subsurface flow. Leaching and groundwater transport of P usually contribute less than 10% of the total P transport (Tiessen 1996).

In Ireland, the rainfall regime which is generally characterized by long duration events of low intensity is not likely to cause important overland flow. Hydrological studies at a site in Dripsey (County Cork) showed that sub-surface flow accounted for 80 percent and surface overland flow accounted for 20 percent of the total annual streamflow (Kiely, 2000). There is now evidence that, in Irish conditions, much of the total annual phosphorus export may come from a relatively small number of heavy rainfall events during the year, typically between 10 and 20 (Tunney, 2000). It is also established that a relatively small proportion of a catchment, close to the stream network and hydrologically active, will greatly contribute to the P losses to water.

There are a number of parameters having an influence on P exports which can be found in the literature. Two types of factors are usually used to explain the P loss from agricultural land to surface waters: the source and the transport factors. Erosion, surface runoff and subsurface flow are mainly cited in the literature as transport factors. These parameters are linked in fact with characteristics of the catchment such as the topography, the vegetation cover, the land use, the precipitation, the geology, etc. The source parameters are more related to the management practices: the quantity of chemical fertilize applied, the quantity and the type of manure applied, the application methods, the application rate, etc.

One source parameter that the scientific community has now widely accepted as influencing the amount of P lost to water, is the soil P level. The soil P level is generally accessed through soil test P values. Work in Ireland (Tunney, 2000, 1997) and in different countries in the world (Brookes, 1997; Sibbeson, 1997) has now shown that higher levels of phosphorus in soils increase the risk of losses of phosphorus to water. Attempts were also made (Sharpley, 1996b) to find the factors influencing the relationship between dissolved P in surface runoff and soil P. But a single or average relationship could not be found as several soil and land management factors also influence the relationship.

Numerous mathematical models have been developed to simulate the transport of agricultural chemicals to surface waters. We can name for example HSPF (Hydrologic Simulation Program - Fortran, Johanson *et al.*, 1984), ARM (Agricultural Runoff Model, Donigan *et al.*, 1977) or EPIC (Erosion-Productivity Impact Calculator, Sharpley and Williams, 1990). However, a major limitation to the use of these models is often the lack of detailed parameterisation data on soil physical, chemical, and biological properties as well as climate, crop, and tillage information. This is especially the case for large catchments like the Lee catchment.

This is why indexing procedures to identify agricultural soils and management practices that can have an impact on receiving water bodies have been developed. Indexing systems only give relative and qualitative indications but make information more easily and rapidly interpretable for field personnel or farm advisors.

The first P indexing system was developed by Lemunyon and Gilbert (1993) in the United States as a field tool to identify soils vulnerable to P runoff. It was designed as a multi-criteria analysis approach to rank fields according to the relative risk for contributing P to surface waters, accounting for source (soil P and rate, method, and timing of applied P) and transport (surface runoff, erosion, leaching, and landscape position) factors. This site assessement approach, modified according to the regional factors, has now been adopted by the majority of the US states as part of their nutrient management planning strategies (Hughes, 2005).

Phosphorus Ranking scheme have now also been developed in Europe and in Ireland (Magette, 2002) based on the Lemunyon and Gilbert approach. The Magette P index was developed at both catchment and farm scale. The objective is to produce simple decision support tools in nutrient loss management. In a policy context and with the implementation of the Water Framework Directive, such tools are actually more and more necessary.

1.4 Phosphorus: Policy context

At the European level, different legislative measures have been taken to tackle the problem of water pollution. There is no directive focusing only on phosphorus but a number of them are in relation with phosphorus in rivers:

- The **Urban Waste Water Treatment Directive** (91/71/EEC) requires waste water to be treated to the secondary level for all agglomerations of more than 2000 population equivalents (p.e.) discharging to freshwaters and estuaries and for all agglomerations of more than 10000 p.e. discharging to coastal waters. Collecting systems must be provided for all agglomerations larger than 2000 p.e. Sensitive water bodies must be identified according to the criteria in the Directive and in these areas and the catchment of sensitive areas, more advanced treatment with nutrient removal must be provided. This Directive has already leaded to a reduction in nutrient discharges from point sources.

- The **IPPC Directive** (96/61/EC Integrated Pollution Prevention and Control) aims to control and prevent pollution to water by reducing or eliminating industrial emissions which can typically result in high phosphorus loads in water bodies.

- More recently, the **Water Framework Directive** (WFD) was adopted by the European Union in 2000 and transposed into Irish law in 2003. The WFD aims at maintaining "high status" of waters where it exists, preventing any deterioration in the existing status of waters and achieving at least "good status" in relation to all waters by 2015. It includes all sizes and types of river (and other water types). The definition of good status in the case of surface waters is based on both ecological status and chemical status. The Directive, considered as the most significant EU enactment on water management to date, also provides for water management on the basis of River Basin Districts (RBD's).

In an Irish context, the **Water Pollution Act** (1977 and Amended Act, 1990) is the principal legal framework relating to Water Pollution. These Acts make provision for the protection of watercourses by prohibiting the entry of polluting matter to waters, outlining statutory requirements relating to the licensing of discharges to waters and sewers, outlining water quality standards and water quality management plans, outlining nutrient management plans and agricultural bye-laws and detailing civil liability relating to water pollution.

Unlike the European Union which only has a Nitrate Directive, the problem of phosphorus has been specifically addressed by the Irish State with a legislative measure: the **Phosphorus Regulations 1998**. That can be easily understood in a country where nitrate levels are generally lower than in the rest of Europe, due to the predominance of pasture as opposed to tillage as the main agricultural land-use (EEA, 2004), but where eutrophication due to phosphorus is a growing issue. These Regulations set out quality standards for Phosphorus in surface waters particularly rivers and lakes. This a quite unique piece of legislation in Europe in that the set standards can be met either by reaching annual median phosphorus concentrations or by achieving biological status targets, i.e. direct measurements of eutrophication impacts.

1.5 Previous research projects

A number of works have been carried out in Ireland and in other countries to study phosphorus losses from soil to water at the field or plot scale. These studies generally focus on the transfer pathways and mechanisms through the soil matrix. The catchment-based approach is relatively recent and the number of published studies is limited, especially for large catchments.

In 1997, Ireland launched a programme called "Managing Ireland's Rivers and Lakes- A catchment Based Strategy against Eutrophication". As part of this programme, some projects were carried out at the scale of large catchments. So far, results have been published for 2 studies: one about the Lough Derg and Lough Ree catchments (KMM, 2001) and the Three Rivers Project that is dealing with the Boyne, Liffey and Suir catchments (MCOS, 2002). The monitoring and management systems developed for these projects included intensive studies on a number of subcatchments.

As far as the Lee catchment is concerned, a number of studies have already been carried out, especially in the upland Dripsey catchment. The loss of nitrogen, suspended sediment and phosphorus to water (Lewis, 2003) and soil phosphorus (Khandokar, 2003) were investigated in this experimental catchment. A STRIDE (Science and Technology for Regional Innovation and Development in Europe) programme also focused on farm practices and phosphorus loss to water in the Dripsey catchment (Anon, 1995).

1.6 Objectives and Methodology

This study is firstly and mainly based on the water quality samplings carried out in 56 different sites located on the River Lee and its tributaries. The different sites were sampled 8 times over 2 years, during base and storm flow conditions, producing at the end a sort of map of the water quality, notably in term of phosphorus, of the Lee catchment.

The objective was first to gather as much data as possible on the catchment to get a better understanding of the different sources, mechanisms or catchment characteristics which could explain the measurements made in the different rivers. These data are both spatial (land use, intensity of farming, topography, soils, etc) and temporal (essentially rainfall data). A big part of the work was therefore to collect and process the data and then to make them available at the level of the 56 different subcatchments defined by each sampling sites. GIS techniques are extensively used at this stage.

This study was also including the collection of 341 soil samples that were analysed for different parameters in relation to phosphorus. One of the objectives was therefore to analyse the results of these samplings and examine the characteristics of this soil in terms of soil chemical properties.

One of the main objectives was then to investigate the relationships between the phosphorus concentrations in the streams in base flow and storm flow conditions and the different parameters describing the subcatchments. The final step is to model the river phosphorus levels by testing an existing model at the catchment scale and setting up a model for the catchment.

1.7 Layout of the thesis

This thesis is made up of seven chapters. Chapter 1 includes an overview of the impact of phosphorus on the aquatic environment and a literature review on the topic of P transfer from land to water. A detailed presentation of the study area is given in Chapter 2. In addition to the physical description, this chapter also evaluates the environmental condition of the area. Chapters 3 and 4 detail the different data sets and the way they were created. An analysis of the factors influencing the phosphorus losses is presented in chapter 5. Chapters 6 attempts to model the levels of phosphorus in rivers. Finally, a summary of the findings and recommendations for further research are included in Chapter 7. The appendices include some of the computer codes used in the study.

Chapter 2

Study Area Description

2.1 Catchment location

The Lee River catchment is located in the southwest of Ireland (see Figure 2.1). It is totally contained within Cork County. The total catchment area of the basin (including Cork estuary) is 1250 km² but the 56 water sampling sites are included in a smaller catchment area of 1135 km², the 2 most easterly sites being located upstream of Cork City. The study area actually matches with the Lee catchment without its most eastern part.

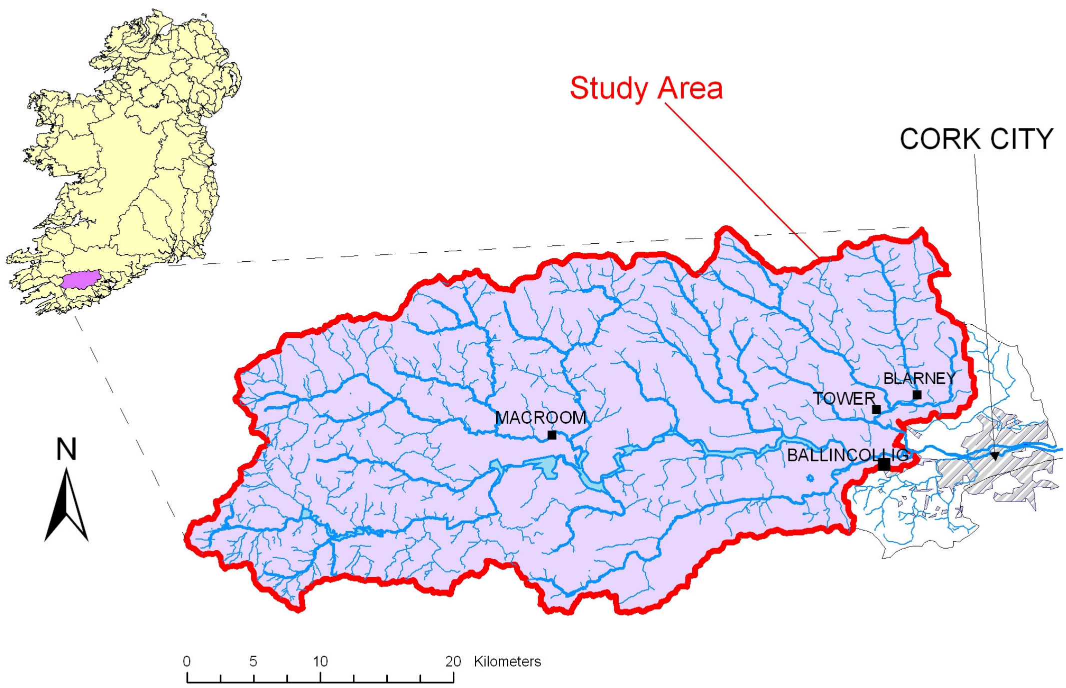

Figure 2.1: Location of the study area.

2.2 Catchment description

2.2.1 Topography

The river Lee basin is bounded to the North and West by ridges 200-250 m high and dominated by a belt of low mountains including (see Figure 2.2):

- the Boggeragh Mountains separating the Lee and Backwater catchments in the North
- the Derrynasaggart Mountains in the North-West of the catchment on the border between county Cork and county Kerry.
- the Shehy Mountains in the south-west, also situated on the Cork/Kerry border.

On the south, however, there is no clear limit to the Lee catchment. Mullaghanish, in the Derrynasaggart Mountains, is the highest point and reaches 649 m above sea level.

The Lee flows through a structurally guided valley in the Devonian sandstone ridge before meeting the river Bride, 10 km west of Cork, which has traversed a wide open synclinal valley floored with Carboniferous limestone.

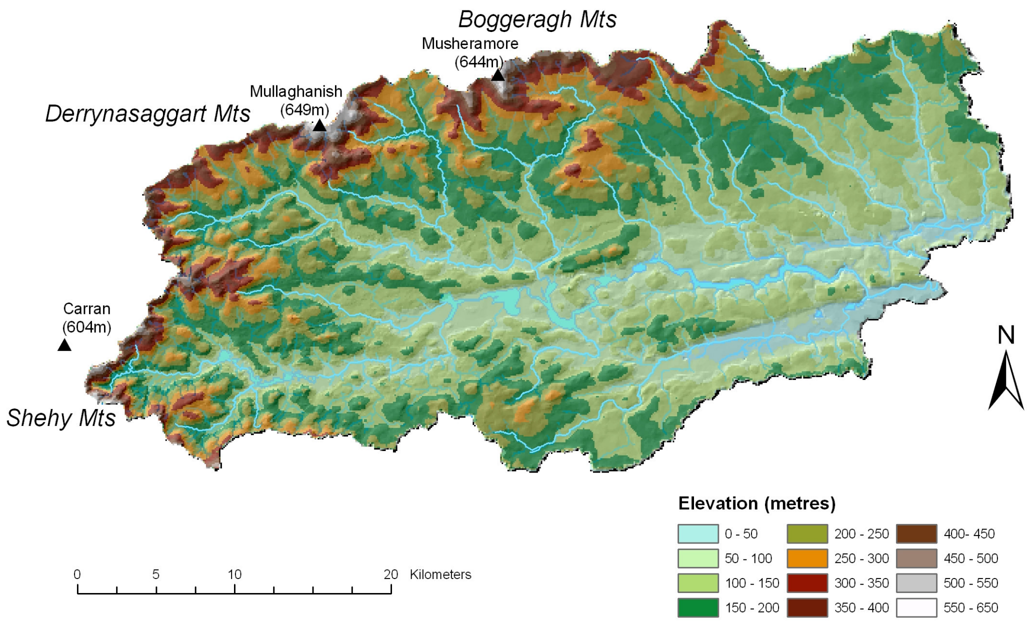

Figure 2.2: Topography of the study area.

2.2.2 Climate

The climate in the area is temperate and humid due mainly to the proximity to the Atlantic Ocean and the presence of the warm Gulf Stream. The annual precipitation varies importantly within the study area. Over the past six years, the average annual precipitation amounted to 2490 mm in Gougane Barra, at the extreme west of the catchment, while it was only 960 mm in the Muskerry Golf Club at the other end of the study area. As it can be seen on the figure 2.3, there is actually a gradient of increasing precipitation from the east to the west of the catchment. This is due both to the topography and the fact that most rainfall comes from the South West, i.e. from the Atlantic Ocean.

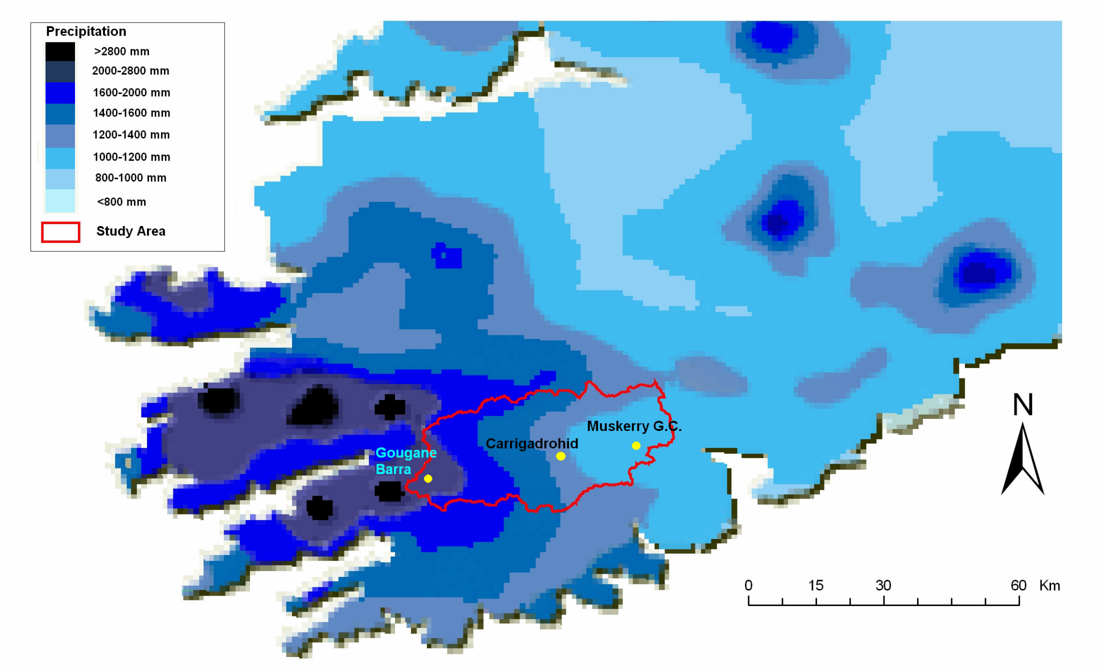

Figure 2.3: 1960-1990 mean annual Rainfall in the south-west of Ireland (adapted from Met Eireann, 2006).

The rainfall regime is characterized throughout the year by long duration events of low intensity (rarely more than 40 $mm.day^{-1}$). Short duration events of high intensity are more seldom and mostly occur in summer (Lawton, 2005). In general, the driest period occurs in late spring and early summer while precipitation reaches a maximum in winter. Figure 2.4 shows daily rainfall depth for Carrigadrohid, located in the middle of the study area, for the year 2005.

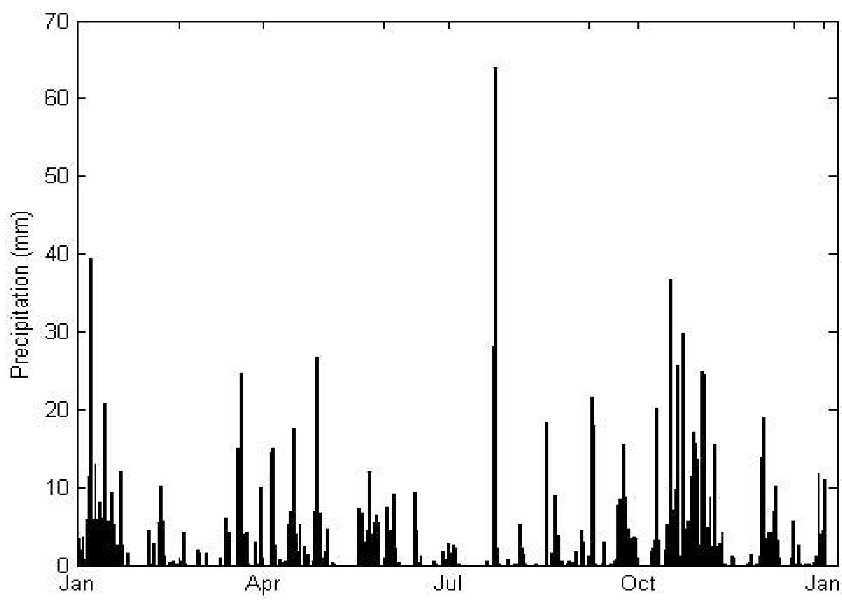

Figure 2.4: Daily rainfall precipitation for the year 2005 at Carrigadrohid.

2.2.3 Soil

In Ireland, a system of soil associations is used to describe soils, based on the Great Soil Group Classification (USDA, 1938). It consists of two or more soils, usually formed from the same type of parent material, which are associated on the landscape in a particular pattern. There are 44 different soil associations in the General Soil Map of Ireland (Gardiner, 1980). Seven of them are present in the Study Area: no 1, 4, 5, 6, 13, 15 and 24 (See Figure 2.5). Each association has a different potential in term of land use.

In the lowland, the prevailing soil is a well drained Brown Podzolic associated with Acid Brown Earth and Gley. These soils have desirable physical qualities of structure, texture, drainage and depth features. They are consequently well suited to arable cropping and grassland. In the wide open synclinal Bride valley, Acid Brown Earth dominates. It is a well drained soil which is very suitable for tillage and grass production (Gardiner (b), 1980).

Where the topography starts to be more rolling, the soil association 6 can be found. It is dominated by Brown Podzolic soils formed mainly from glacial till of predominantly Old Red Sandstone composition. The best use is in pasture, due to the altitude and slope.

In the hilly and mountainous parts of the catchment, peaty podzols are mainly found. This is a rather poor soil depleted of nutrient by heavy rainfall leaching through an organic layer (the podzolisation process). Its potential use, as well as that of the associated Peats and Lithosols, is very limited due to the high elevation, inaccessibility, peaty surface and low nutrient status. They are only suitable for mountain sheep grazing and some forestry. Due to the high rainfall and humidity conditions, blanket peat also accumulated in the area, especially in the upper parts of the mountain ranges. Because of their poor drainage capacity and the adverse physical conditions, the range of uses of blanket peat in agriculture is very limited.

Table 2.1: Soil associations partitioning.

Broad Physiographic division	Soil Associations			% of Total Area
	Nos	Principal Soil	Associated Soils	
Mountain and Hill	1	Peaty Podzols 75%	Lithosols 15%, Blanket Peats 10%	33.6
	4	Lithosols & Outcropping Rocks 70%	Blanket Peats 25%, Peaty Podzolz 5%	1.4
	5	High Level Blanket Peats		5.1
Hill	6	Brown Podzolics 80%	Gleys 15%, Podzols 5%	18.8
Rolling Lowland	13	Acid Brown Earths 70%	Grey Brown Podzolics 15%, Gleys 15%	3.0
	15	Brown Podzolics 60%	Acid Brown Earths 20%, Gleys 20%	36.8
	24	Low level (Atlantic Type) Blanket Peats		1.3

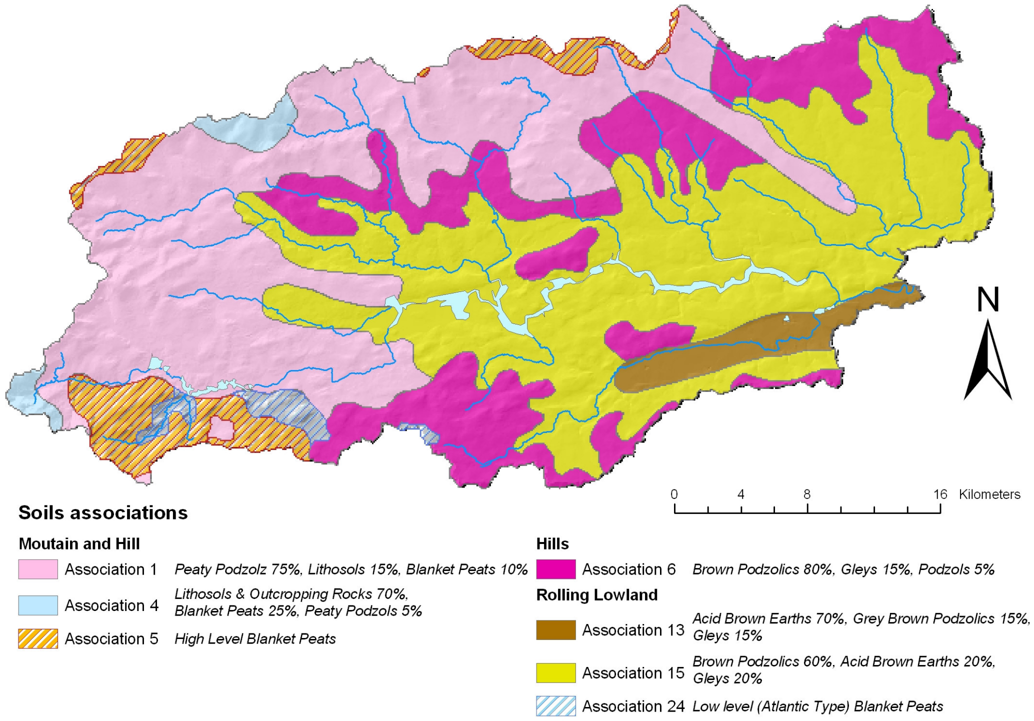

Figure 2.5: Soil associations in the study area (adapted from the General Soil Map of Ireland, Gardiner and Radford, 1980).

2.2.4 Land Use

Information is available through the Corine (**Co-OR**dination of **I**nformation on the **E**nvironment) Land Cover database with different levels of information to describe the different land cover categories. (See Chapter 3 for more information on CORINE database).

Since the large urbanised area of Cork City is not included, the study area is mostly rural. The other urban areas are almost all near Cork city: the medium towns of Tower and Blarney (around 3,000 and 2,000 people respectively) and a part of the town of Ballincollig. Macroom with a population of about 3,000 people is the only medium town elsewhere in the catchment. Overall, the urban fabric covers less than 1% of the catchment area.

Around 70% of land is dedicated to agricultural use with three quarters of this agricultural land under pasture. At the level 4, Corine makes the distinction in the "pasture" category between improved and unimproved grassland. It appears that almost two thirds of the pastures have been subject to improvements to get a more productive grass: reseeding, addition of fertilizers and drainage works. Dairying is the main form of agriculture. In some parts, where much of the land is good quality, farming is quite intensive. This is the case in the Dripsey and Martin catchments and around the Inniscarra and Carrigadrohid reservoirs. A relatively small proportion of the catchment is occupied by arable land (less than 10%). Cereals, particularly barley, are cultivated in the area. Pig industry is generally very developed in

County Cork but the number of piggeries in the catchment is limited compared to other parts of the county, like the Mitchelstown area or West Cork.

In the upper parts of the catchment, i.e. in the west and north-west, agriculture is less common. The land cover is comprised of coarse grassland, moorland and peatland, which limits the use mainly to extensive grazing. It has to be noticed that, according to the Corine database, peat bogs represents more than 12% of the total catchment area (see Table 2.2). In some parts, forestry also covers significant areas and this type of land use is developing for some years with the afforestation campaigns taking place in the county.

Table 2.2: Land Cover Repartition (from CORINE).

Land Cover Description			Percentage		
Level 1	**Level 2**	**Level 3**	**level 1**	**level 2**	**level 3**
Agricultural areas	Pastures	Pastures	51.73	51.73	70.21
	Arable land	Non-irrigated arable land	7.82	7.82	
	Heterogeneous agricultural areas	Land principally occupied by agriculture with areas of natural vegetation	8.87	10.67	
		Complex cultivation patterns	1.80		
Forests and semi-natural areas	Forests	Coniferous forest	7.41	10.46	15.26
		Broad leafed forests	1.25		
		Mixed forest	0.03		
	Scrub and Herbaceous vegetation associations	Transitional woodland scrub	5.92	6.57	
		Natural grassland	0.65		
Wetlands	Inland Wetland	Peat bogs	12.25	12.25	12.25
Water Bodies	Continental Waters	Water bodies	0.82	1.32	1.32
		Stream courses	0.49		
Artificial areas	Urban Fabric	Discontinuous urban fabric	0.55	0.55	0.80
	Mines, Dumps and Construction Sites	Mineral extraction sites	0.23	0.25	
		Construction sites	0.02		
	Artificial vegetated area	Sport and leisure facilities	0.17	0.17	

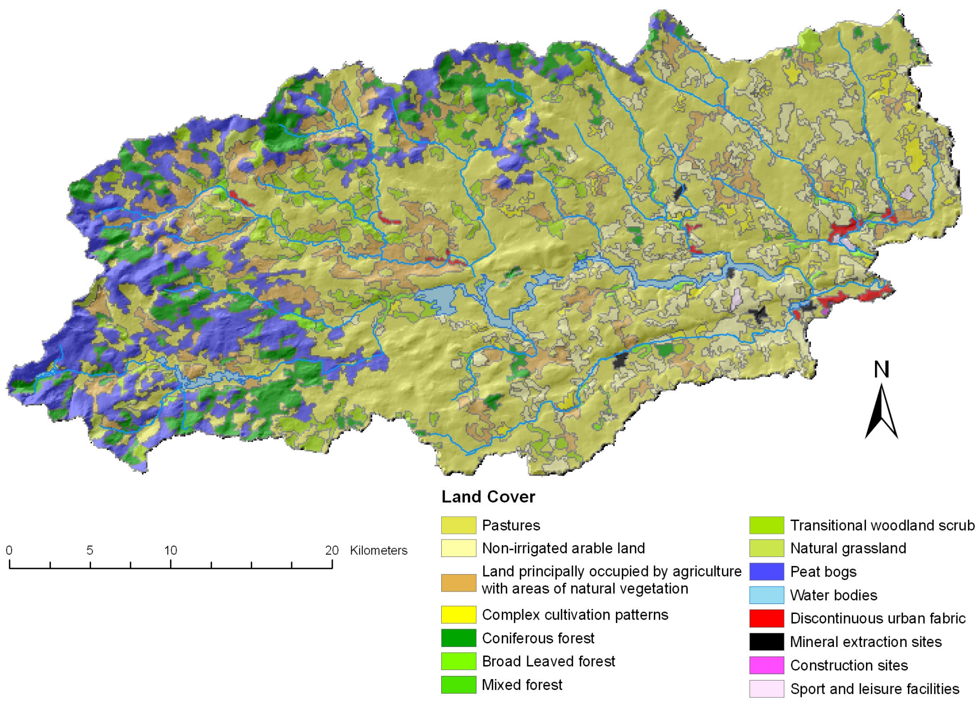

Figure 2.6: Land cover in the study area.

2.3 River System

The river Lee is one of the largest in south-west Ireland. It flows in a west to east direction through County Cork for about 65 km before discharging into tidal waters just upstream of Cork City. The river rises in West Cork, in Gougane Barra, in the Shehy Mountains and flows east to the mouth of Cork harbour at Roche's Point.

Most of the Lee's tributaries join it from the north and are very steep. The principal ones are from east to west (see Figure 2.7):

- the Shournagh and Martin draining an area of about 200 km^2 of hilly land,
- the Dripsey, a fast flowing stream, draining an area of 100 km^2 to Inniscarra Reservoir,
- the Laney, a flashy mountainous stream with a 104 km^2 catchment area,
- the Sullane, another flashy mountainous stream draining a total area of more than 200 km^2,
- and the Toon with a flattish catchment 47 km^2 in area.

From the south the principal tributary is the River Bride which joins the Lee approximately 3km upstream of Ballincollig and drains a very flat catchment 120 km^2 in area. It also holds the largest morainic accumulation in County Cork (Anon, 1995).

In addition, there are three impoundments along the main channel: one small (1.36 km^2) natural lake, Lough Allua (Inchageelagh Lakes) and , two manmade ones, Carrigadrohid Reservoir and Inniscarra Reservoir. They resulted from the development of the Lee Hydro-electric Scheme in the 1950's which significantly affected the aspect of the valley.

- Carrigadrohid Reservoir has an area of 9 km^2 and an approximate volume of 50 million m^3. The catchment area upstream of the dam is 616 km^2
- Inniscarra Reservoir is 5.2 km^2 in area and impounds about 70 million m^3. The catchment area upstream of Inniscarra Dam and downstream of Carrigadrohid Dam is 177 km^2.

2.4 Sampling Sites

In our study, water samples were taken at 56 different river sites covering the whole catchment and consequently representing the different types of land use and soils. The sites were sampled 8 times but the first sampling campaign took place on two different dates with a time interval of 2 weeks. 5 samplings were carried out during storm flow conditions and 3 during base flow (including the first one). Base flow typically occurs during non-storm period and comprises discharge from springs and near-stream seepage. The samplings in storm flow conditions were basically done the morning after a rain event. The dates for the different sampling campaigns are summarised below:

Table 2.3: Sampling Dates.

Conditions	Event No	Date	Code
Base flow	1	11/05/2004	B1a
		24/05/2004	B1b
	2	01/06/2004	B2
	3	27/01/2005	B3
Storm Flow	1	28/10/2004	St1
	2	10/02/2005	St2
	3	06/04/2005	St3
	4	28/04/2005	St4
	5	09/09/2005	St5

The 56 sites were split into 2 different runs, one north and one south so that all the water samples were collected in a few hours and at the same time by two different teams. The names of the sites were derived from the run they belonged to: N1 to N34 for the north run and S1 to S22 for the south run (See Figure 2.7).

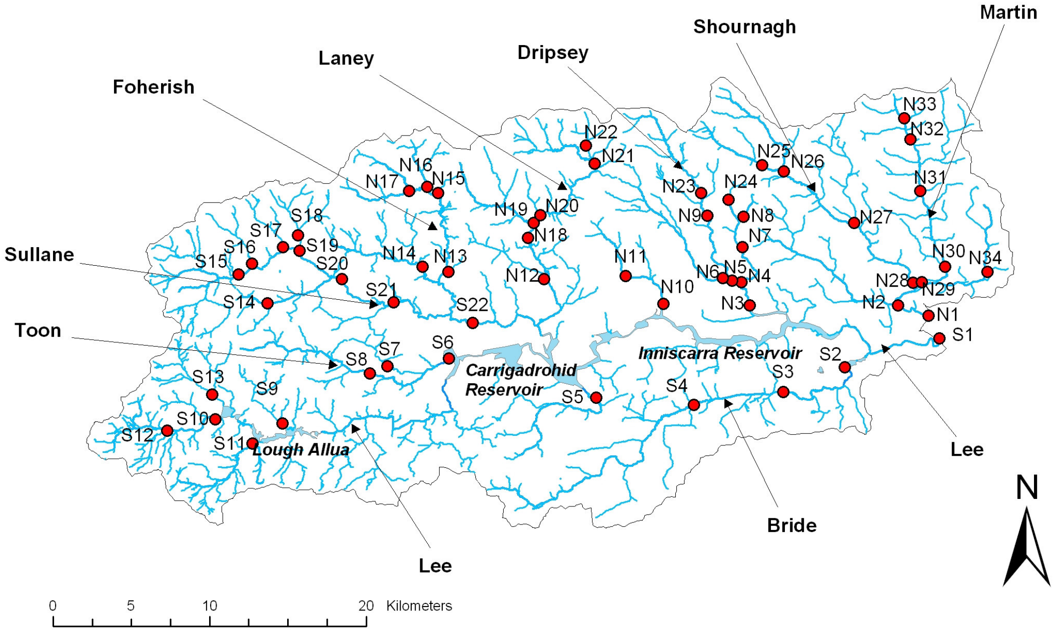

Figure 2.7: Rivers and Water Quality Sampling Sites location.

For each sampling point, a contributing subcatchment was delimited using Arcview (See Figure 2.8). The subcatchments vary in size from 2.1 km^2, for the N15 and N24 sites, to 923 km^2 for S1. But the median subcatchment size is around 22 km^2. Table 2.4 gives some information about the different subcatchment (name, size, elevations).

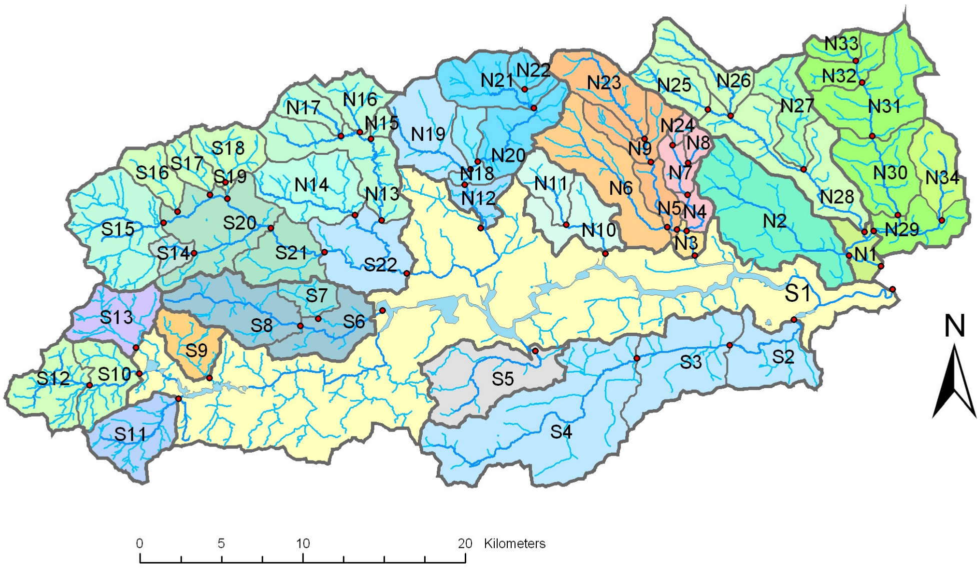

Figure 2.8: The 56 subcatchments.

Table 2.4: Subcatchment presentation.

Sample	Site Name	Catchment Area (km2)	Sampling point elevation (m)	Max catchment elevation (m)
N1	Healy's Bridge	211.9	4	372
N2	Gardes Bridge	44.8	18	200
N3	Dripsey Bridge	82.2	49	434
N4	Site 4	14.9	63	253
N5	Dripsey Castle Bridge	64.3	66	434
N6	Colthurst's Bridge	28.8	70	353
N7	Sexton's Cross Roads	10.7	126	253
N8	Miskella's Bridge	2.9	142	200
N9	Dripsey Lower Bridge	28.1	129	434
N10	Glashagariff Bridge	24.2	58	374
N11	Bealnamorive Bridge	9.2	120	374
N12	Morris's Bridge	73.0	101	644
N13	Garranagappul Bridge	44.5	120	620
N14	Bealahacreagh Bridge	22.8	122	460
N15	Carriganimmy Bridge	2.1	169	385
N16	Keel Bridge	10.4	172	496
N17	Garrane Bridge	7.4	183	571
N18	Clonavick Bridge	66.3	129	644
N19	Awboy Bridge	20.9	139	644
N20	Knocknagappul Bridge	37.5	145	644
N21	Carrigagulla Bridge	21.1	206	644
N22	Aghalode Brige	4.1	232	491
N23	Dripsey Bridge Upper	16.9	147	434
N24	Nad Road Site	2.1	155	253
N25	Downeys' Bridge	10.8	138	372
N26	Ruby's Bridge	13.1	123	367
N27	Ballycraheen Bridge	14.9	75	235
N28	Willison's Bridge	70.2	27	372
N29	Bawnafinny Bridge	89.8	24	279
N30	Blarney Walk Site	63.0	37	279
N31	Wise's Bridge	41.9	72	279
N32	Rathduff	15.1	98	231
N33	Bridge Left of Ballygrogan Bridge	5.1	113	231
N34	North of Horgan's Bridge	13.1	37	199
S1	Bannow Bridge	923.7	0	649
S2	Oven's Bridge	117.7	21	287
S3	Kilcrea Bridge	98.7	38	287
S4	Farnanes Cross	69.3	46	287
S5	Athsolis Bridge	29.0	69	287
S6	Toon Bridge	46.8	65	361
S7	East of Aghacunna	6.3	99	224
S8	Silvergrove Bridge	24.7	96	361
S9	Carrahy Bridge	11.7	89	340
S10	Inchinossig Bridge	31.7	89	552
S11	Bealaphadeen Stream	18.7	90	545
S12	River Lee (C3)	17.0	107	552
S13	Keamcorraghvooh (D3)	16.6	126	534
S14	Gortnascarthy	4.3	172	391
S15	Milleeny Bridge	32.2	144	498
S16	H3/H4	8.9	151	426
S17	West of Ballyvourney	6.4	131	424
S18	Cappagh Bridge	12.3	149	649
S19	Bohill Bridge	12.7	124	649
S20	Poulnabro Bridge	93.7	102	649
S21	Sullane Bridge	109.9	87	649
S22	Linnamilla Bridge	201.3	70	649

2.5 General Water Quality

In a European context, water quality in Ireland can be considered as fairly good and in recent years, there has been a decrease in severely polluted waters. According to the Irish Environmental Protection Agency (EPA), 69% of the total river channel surveyed in Ireland (13,200 km) was in a satisfactory water quality in the period 2001-2003 (Toner, 2005). However, problems of mild pollution and eutrophication are increasing in Irish lakes and rivers. Ireland is facing a worrying decline of the number of its rivers with the highest biological water quality. Eutrophication which is seen as “the greatest threat to the water quality both nationally and within County Cork” (Cork County, 2004) is considered to be due in most cases to excessive phosphorus inputs to waters.

The Environmental Protection Agency is carrying out a biological survey of Irish surface waters for periods of three years. In county Cork, the most recent is the one for 2001-2003. The sites are classified according to a scheme of biotic indices (or quality values). A Q1 value is corresponding to a bad water quality associated with very low macroinvertebrate community diversity, while a Q5 value will describe a good water quality with an absence of pollution affecting the macroinvertebrate diversity. The target river standards specified in the Regulations are based either on minimum Q-values or on median MRP (molybdate reactive phosphorus) values. A high correlation has been demonstrated between the biological Q rating and MRP levels (Bowman, 1996). The Table 2.5 summarizes the water quality assessment scheme in Ireland and the standards for phosphorus in rivers:

Table 2.5: Water Quality assessment in Ireland (adapted from EPA 2006).

Biotic index Q value	Community diversity	Quality class	Quality status	Annual Median MRP(µgP/l)	Standard limit for annual median MRP (µgP/l)
Q5	High	A	Unpolluted	~15	15
Q4-5					20
Q4	Reduced			~30	30
Q3-4		B	Slightly polluted	~45	50
Q3	Low	C	Moderately polluted	~70	70
Q2-3				Usually >100	improvement required
Q2	Very Low	D	Seriously polluted		
Q2-1					
Q1	Little/none				

It appears from this last survey that water quality in Cork is generally good and improving. But at the same time, the decline in the number of the highest biological water quality sites, which is observed at a national scale, is also true for the county.

57 of these EPA sites are included in our area of study. Of the EPA 57 sites, 20 are common with the present study (See Figure 2.9). For the period 2001 to 2003, the bulk of the sites recorded Q4 or Q4-Q5 values, meaning an unpolluted status. However, 7 sites holding

Q3-Q4 were slightly polluted and 2 with Q3 were moderately polluted. There was also one site in Crookstown on the river Bride which recorded a Q2 value, indicating a severe pollution.

This biological monitoring carried out between 2001 and 2003 shows an overall good quality of the waters in the catchment. The few pollution problems are mainly located in the eastern part (Shournagh, Martin) but their importance remains limited. It is interesting to notice that no site was holding the very high quality value Q5.

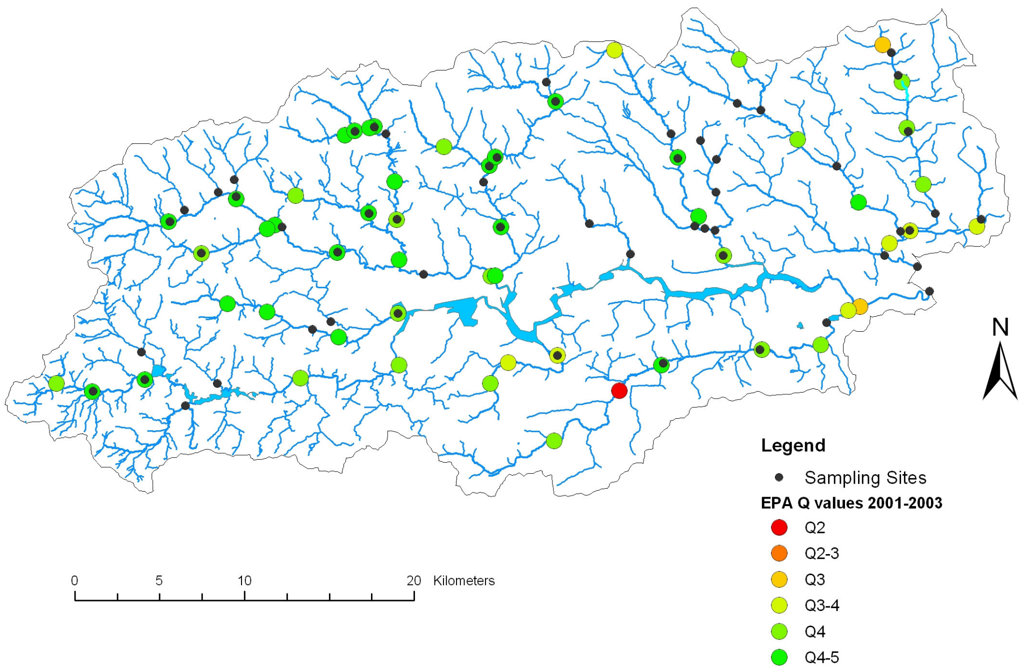

Figure 2.9: EPA water quality monitoring sites in the study area (2001-2003).

Among the 57 EPA sites, 16 were also part of a phosphorus monitoring programme during 2002 and 2003. For each site, a number of samples were taken during this period and analysed for MRP. For 4 of these 16 sites, the median MRP over the period was not compliant with the upper target limit of 30µgP.l^{-1}, corresponding to an unpolluted status. 3 were located on the river Martin, one on the Blarney River which is a tributary of the Martin and one on the Shournagh, downstream of its confluence with the Martin.

From this, it is quite clear again that the eastern part of the catchment is the one likely to present problems in term of water pollution and high phosphorus concentrations.

Lakes:

In this study, no sampling of lake water was carried out. But eutrophication, which is the principal pressure on lake water quality in Ireland, is mainly caused by the inputs of nutrients, through the inflowing rivers and, to a lesser extent, by direct inputs to lakes.

Lake water quality is usually assessed by reference to a scheme proposed by the OECD and using 5 trophic categories: Ultra-Oligotrophic, Oligotrophic, Mesotrophic, Eutrophic and Hypertrophic. To assess the trophic status, 3 parameters are used: total phosphorus, chlorophyll and water transparency. In Ireland, a modified version is used using only the annual maximum chlorophyll concentration (See Table 2.6). In fact, algal pigment chlorophyll is directly related to the inputs of phosphorus to freshwaters.

Table 2.6: Modified version of the OECD trophic classification scheme for lake waters (EPA 2005).

Lake Trophic Category		Annual Max.Chlorophyll (mg/m3)	Algal Growth	Deoxygenation in Hypolimnion	Level of Pollution	Impairment of Use of Lake
Oligotrophic		<8	Low	Low	Very low	Probably none
Mesotrophic		8-25	Moderate	Moderate	Low	Very little
Eutrophic	**Moderately**	25-35	Substantial	May be High	Significant	May be appreciable
	Strongly	35-55	High	High	Strong	Appreciable
	Highly	55-75	High	Probably total	High	High
Hypertrophic		>75	Very High	Probably total	Very high	Very high

For the period 2001-2003, the three main lakes of the study area were assessed by the EPA in term of water quality. Lough Allua was classified as being in the strongly eutrophic category, which is consistent with an already strong level of pollution. The data collected for Inniscarra reservoir indicated a moderately eutrophic status. The larger lake, Carrigadrohid reservoir, was assessed as being mesotrophic but a recent increased phytoplankton growth was noticed.

It is important to specify that both reservoirs have experienced significant improvements in their trophic status compared to the conditions recorded in the 1990's. Inniscarra was for example classified as hypertrophic during the period 1991-1994. This shows the results of actions which have been undertaken in the county, notably the regulation of agricultural practices and the construction or upgrading of wastewater treatment plants.

2.6 Environmental Pressures

The sources of water pollution are generally categorized as being a point source or a non-source point (diffuse source) of pollution. Point sources of pollution occur when the polluting substance is emitted directly into the waterway. A pipe spewing toxic chemicals directly into a river is an example. A non-point source occurs when there is runoff of pollutants into a waterway, for instance when fertilizer from a field is carried into a stream by surface runoff.

In Ireland, discharges from inefficient or overloaded sewage treatment plants as well as industrial effluents are quite often responsible for the occurrence of seriously polluted stretches of rivers (Toner, 2005). But most of the cases of slight and moderate pollution are attributed to agriculture.

In county Cork, as far as phosphorus is concerned, P from agriculture is seen as the main pressure on water quality (Cork County, 2004). At the same time, discharges from some municipal wastewater treatment plants, industries and forestry practices can also contribute significantly to phosphorus loading in rivers in Cork.

2.6.1 Point Sources

The main point sources from which, phosphorus may be lost to water, are usually municipal waste water treatment plants and industrial discharges. Therefore, urban areas can typically be significant sources of phosphorus.

Upstream of Cork city, the Lee catchment is largely rural. Only a part of a city (Ballincollig) is included in the study area and that, just at the outlet of the catchment. There are also three medium towns (Tower, Macroom and Blarney) and several little towns and villages (see Table 2.7).

Table 2.7: Population of the main towns (>150 inhabitants) included in the Study area (CSO Census 2002).

Town	Population
Ballincollig*	14,591
Tower	3,032
Macroom	2,985
Blarney	2,146
Kilumney	522
Coachford	412
Farran	368
Crookstown	320
Dripsey	295
Ballingeary	205
Inchigeelagh	157

only partly included in the study area

The population of the catchment is a bit less than 40,000 inhabitants for a total area of 1,135 km^2, which gives an average density of population around 30 people/ km^2. The western and northern parts of the catchment are the most scarcely populated while the region close to Cork City shows the main pressure in term of population (See Figure 2.10).

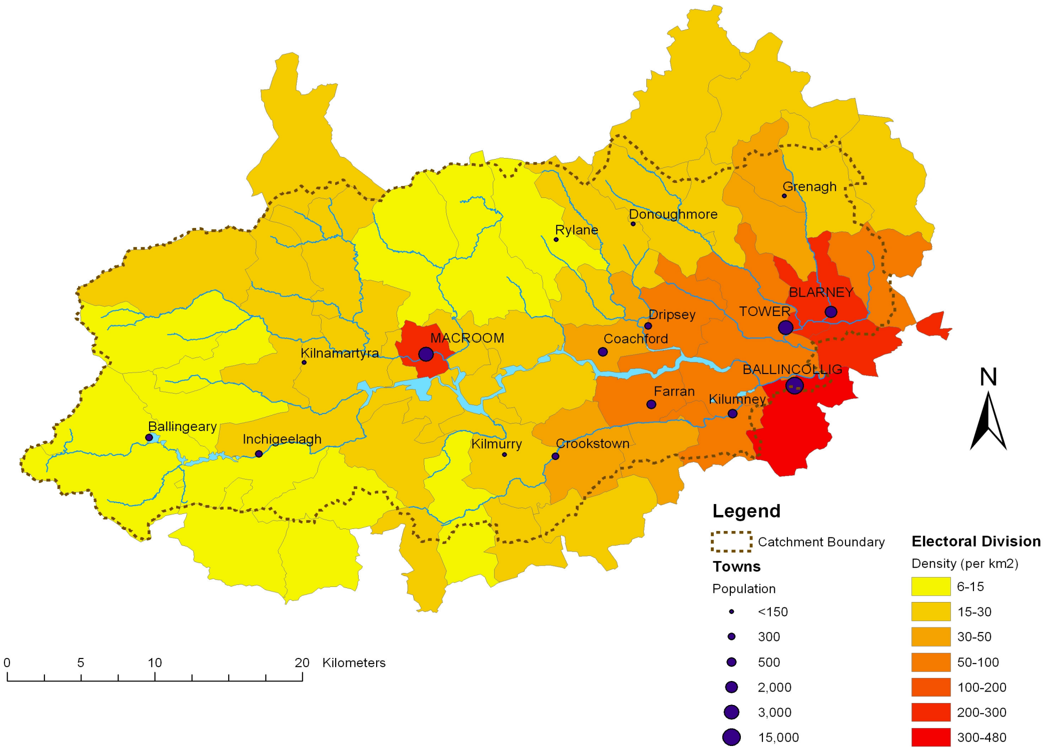

Figure 2.10: Density of population of the different Electoral Divisions included in the study area (CSO census 2002).

Most of the towns and villages have a waste water treatment system (see Table 2.5). Each of the larger towns also has a secondary sewage treatment, with some of them incorporating phosphorus removal stages in the treatment of organic wastes (Macroom, Coachford, Dripsey) (O'Halloran, 1998).

Table 2.8: Municipal Waste Water Treatment Plants in the Study Area.

WWTP	Receiving Water	Pop. Equiv.	Treatment
Ballinagree	Laney	/	/
Coolea	Sullane	80	/
Aghabullogue	Dripsey tributary	100	/
Kilnamartyra	Sullane	100	/
Clondrohid	Foherish	150	/
Kilumney	Bride	150	/
Kerry Pike	Shournagh	250	/
Inchigeelagh	Lee	300	/
Rylane	Dripsey tributary	450	/
Ballingeary	Lee	600	Primary
Coachford	Lee	600	Primary
Dripsey	Dripsey	600	Secondary
Killeens	Blarney	600	/
Cloghroe	Shournagh tributary	600	Secondary
Ballymakeera	Sullane	1800	Primary
Macroom	Sullane	5,000	Secondary
Blarney	Martin	8,000	Secondary
Ballincollig	Lee	15,000	Secondary

A significant part of the population, especially the people living in the countryside, is not connected to a public sewerage system and consequently relies on septic tanks to treat their wastewater. This could represent a potential (diffuse) source of pollution. However, with the drastic reduction in the use of phosphate detergent for some years, this domestic source of P can be neglected considering as well the scattering of the population.

Industrial Discharge:

Discharges from trade and industrial premises need to be licensed by either Local Authorities (under the Water Pollution Act, 1977 and Amended Act, 1990); or in the case of activities with significant pollution potential, by the Environmental protection Agency (EPA) under the Integrated Pollution Control (IPC) Licensing.

Within the study area, there are no large industries which could discharge important quantities of potentially pollutant liquid effluent. There are around 80 licensed discharges, with about 40 sites discharging directly in the rivers and streams. A large number of them are just creameries using water for milk cooling activities. The rest of them are small manufactures, food processing activities, sewage effluent from restaurants and a gravel pits and quarries.

5 sites are regulated under IPC legislation but none of them is discharging effluent in surface waters. 2 pig units in Grenagh and Lissarda have an IPC license for the rearing of respectively 690 and 850 sows (See Figure 2.11). The important quantity of pig manure, which is produced there, is landspread in farms located around the piggeries.

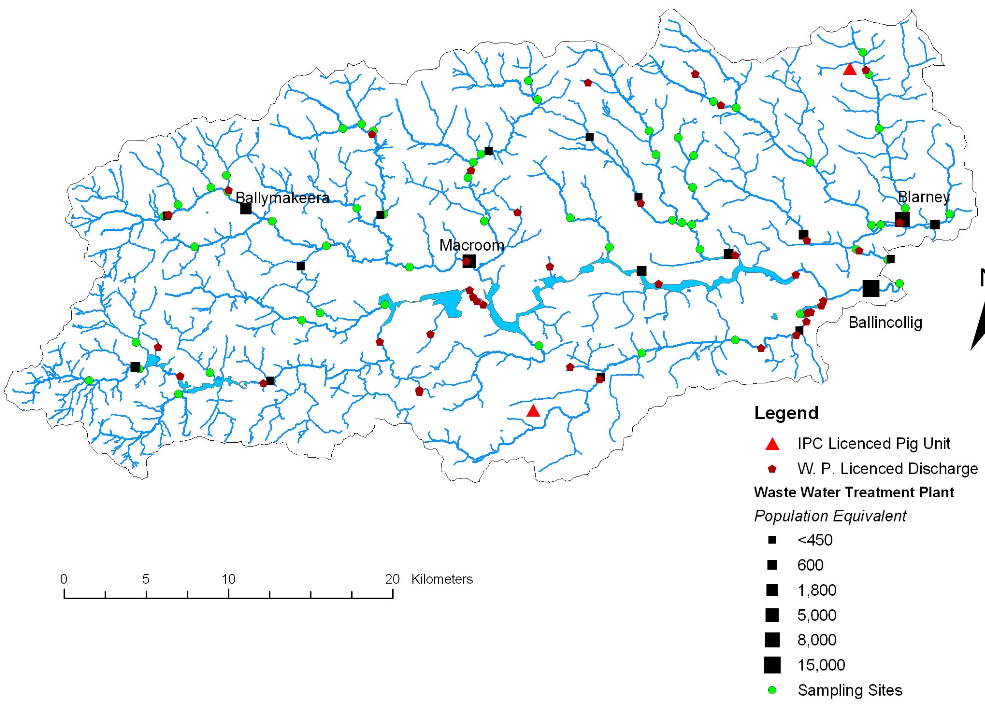

Figure 2.11: Point Source Pressures.

2.6.2 Diffuse Sources

According to the EPA (Brogan, 2001), there is very strong evidence to suggest that nutrient loss from agriculture, including farmyards, is now the single biggest source of pollution problems in Ireland's rivers. Nationally, the EPA estimates that agriculture is the largest source of nutrient inputs to waters with 73 % of all inputs of phosphorus and 82% for nitrates. Locally, agriculture is also identified as the main pressure on water quality in County Cork (Cork County, 2004).

As indicated before, agriculture is by far the main activity in the study area. In 1989, a study by Cork Co. Council concluded that less than 20 % of P discharged over the Inniscarra dam on the river Lee came from non-agricultural sources. With the improvements made in the sewage treatment, it can be assumed that today an even higher proportion of P loss to water can be attributed to natural background and agricultural sources.

Forestry plantations, through the exploitation operations and the potential impact of silt and soil erosion, need also to be considered as a possible environmental pressure on the water quality.

After this attempt to identify the different pressures on water quality, it can be concluded that the study area is mainly under the threat of agricultural activities in term of nutrient loss even if in some locations and some occasions, other causes should be considered as well.

Chapter 3

Data Presentation

3.1 GIS Background

GIS is more than a tool of computer cartography. This computerized information system gives possibilities of storing, manipulating and analyzing spatially indexed information. In this project, a large range of the possibilities offered by GIS were used. It was done using the ArcGIS Desktop® from ESRI which includes a collection of GIS software products (Arcmap, ArcToolBox, ArcCatalogue, and ArcinfoWorksation) to perform various tasks.

3.1.1 Basic concepts

Basically, there are two primary GIS concepts which should be remembered:

- "Features have attributes associated with them"
- "Information is separated into layers"

Two main types of spatial data models exist for storing geographic data digitally: vectors and rasters.

A vector model is a representation of the world using points, lines and polygons:

- Points are good for representing information in which only the location and not the physical shape of the feature is important.
- Lines are suitable to represent many real world features such as rivers or roads.
- Polygons are solid multi-sided shapes representing area features. Everything inside the boundary of a polygon has the attributes associated with the record.

In ArcGIS, the *shapefile* format is one of the main vector data storage format for storing the location, shape and attribute of geographic features. An attribute table is attached to each shapefile. It is a tabular file containing rows and columns: each row represents a geographic feature and each column represents one attribute of a feature.

When dealing with land use, for example, polygons, which are the best way to represent surface, is preferentially used. Space is therefore divided in a number of polygons. Each polygon is associated with a type of land use. If they are not adjacent, several polygons can be associated with the same land use. Then, for each polygon, in addition the type of land use, other information can be attached in the attribute table such as the area, but again everything included inside a polygon has the same attributes. Eventually, all the polygons form together a shapefile which can be visualised as one layer in a map.

Raster data models incorporate the use of a grid-cell data structure where the geographic area is divided into cells identified by rows and columns. A raster can therefore represent any data source that uses a grid structure to store geographic information. Each cell is referenced by its geographic x, y location and is assigned a single value. In ArcGIS, the *Grid* format is the common from of raster. Raster files are efficient for representing continuous change. DEMs (Digital Elevation Model) are an example of digital files in raster form. A DEM describes the terrain and elevation of a given area. Thus, the topographic map presented in the Chapter 2 (Figure 2.2) was obtained by deriving a DEM from the contour lines on digitized maps from the Ordnance Survey (Discovery Series, scale 1:50,000). The delineation of the whole catchment and of the 56 different subcatchments was also performed using a DEM of the study area in addition of other tools.

Both formats of representation (raster and vector) were used in this project. There are advantages and disadvantages for using either the vector or raster data model to store spatial data. It will often depend on the type of data, the transformations needed to be performed and the analyses required.

3.1.2 Methods

In this project, some of the GIS data had to be created from scratch and some was already available in a GIS format but had to be given the right spatial extent so that the information could be used. The objective was actually to make all the information available at the subcatchment level.

To do so, extensive use of the analytical tools included in the ArcGIS software was required. The following geoprocessing operations were combined:

- Dissolving = to merge adjacent lines or polygons that have the same values for a specified attribute.
- Merging = to append adjacent layers into a single layer.
- Clipping = to cookie-cut features and attributes of an input feature layer using a clip polygon.
- Intersecting = to create a new feature class by combining the line or polygon features of an input layer with those of an overlay polygon layer.

These geoprocessing transformations were also combined with sorting operations using a spreadsheet programme (Microsoft Excel ®).

3.2 DATA 1- Catchment's characteristics

3.2.1 Land Cover

3.2.1.1 Presentation of CORINE database

The CORINE Land Cover (CLC 2000) database consists of a geographical database describing vegetation and land use in 44 classes with a minimum mapping element of 25 hectares. It is part of the European Union programme CORINE (CO-ordination of INformation on the Environment) and covers many European countries, including all EU member states. The land-cover information is based on the interpretation of satellite imagery in combination with ground proofing and ancillary information.

The first CLC data base was finalised in the 1990s (CLC1990). Using the year 2000 as reference, an update of the database and a mapping of changes was decided under the project CORINE Land Cover 2000 (CLC2000). This updated database has now been completed in many European countries, including Ireland, and was therefore available for this project. CLC 2000 is said to meet much higher standard in term of data quality than the previous version CLC 1990.

With a scale of 1/100,000, CORINE gives a fair description of the surface and distribution of land units. However, there are limitations to the use of this database. Indeed, the smallest mapped unit in CLC2000 is still of 25 ha. It is therefore very likely that CLC classes include heterogeneous micro-areas of less than 25 ha. As a consequence, CLC should not be considered as a way of delivering a very accurate assessment of surfaces.

3.2.1.2 Classes

Among the 44 classes used in Corine database, 34 are present in Ireland. In our study area, 16 of these 34 classes were identified. A technical guide (Bossard, 2000) gives more details about the characteristics of the different classes (the extent of the class for the study area is reminded between brackets):

- **Discontinuous urban fabric (*0.55%*):** Most of the land is covered by structures. Building, roads and artificially surfaced areas associated with vegetated areas and bare soil, which occupy discontinuous but significant surfaces.
- **Mineral extraction sites (*0.23%*):** Areas with open-pit extraction of construction material (sandpits, quarries) or other minerals (open-cast mines). Includes flooded gravel pits, except for river-bed extraction.
- **Construction sites (*0.02%*):** Spaces under construction development, soil or bedrock excavations, earthworks.

- **Sport and leisure facilities (*0.17%*):** Camping grounds, sports grounds, leisure parks, golf courses, racecourses, etc. Includes formal parks not surrounded by urban areas.
- **Non-irrigated arable land (*7.82%*):** Lands under a rotation system used for annually harvested plants (Cereals, legumes, fodder crops, root crops) and fallow lands, which are not irrigated.
- **Pastures (*51.73%*):** Lands, which are permanently used (at least 5 years) for fodder production. Includes natural or sown herbaceous species, unimproved or lightly improved meadows and grazed or mechanically harvested meadows.
- **Complex cultivation patterns (*1.80%*):** Juxtaposition of small parcels of diverse annual crops, pasture and/or permanent crops.
- **Land principally occupied by agriculture, with significant areas of natural vegetation (*8.87%*):** Areas principally occupied by agriculture, interspersed with significant natural areas.
- **Broad-leaved forest (*1.25%*):** Vegetation formation composed principally of trees, including shrub bush understoreys, where broad-leaved species predominate.
- **Coniferous forest (*7.41%*):** Vegetation formation composed principally of trees, including shrub and bush understoreys, where coniferous species predominate.
- **Mixed forest (*0.03%*):** Vegetation formation composed principally of trees, including shrub and bush understoreys, where neither broad-leaved nor coniferous species predominate.
- **Natural grassland (*0.65%*):** Low productivity grassland which developed under a minimum human interference (not mowed or fertilized). Often situated in areas of rough, uneven ground. Frequently includes rocky areas, briars and heathland.
- **Transitional woodland/shrub (*5.92%*):** Bushy or herbaceous vegetation with scattered trees. It can represent either woodland degradation or forest regeneration/recolonisation.
- **Peat bogs (*12.25%*):** Peatland consisting mainly of decomposed moss and vegetable matter. May or may not be exploited.
- **Water courses (*0.49%*):** Natural or artificial water-courses serving as water drainage channels. Includes canals. Minimum width for inclusion: 100 m.
- **Water bodies (*0.82%*):** Natural or artificial stretches of water.

In Ireland, given the extent of pastures, additional work was carried out in CLC 2000 to subdivide the pasture class into improved and unimproved grassland. Improved grassland is grassland that has been subject to some form of management through various agricultural techniques and fertiliser usage while unimproved grassland is essentially "semi-natural" grassland.

3.2.1.3 Data processing

The CORINE database was available in shapefile format for the whole Republic of Ireland. Such a file contains more than 20,000 polygons associated with one of the 34 land cover classes identified in Ireland.

A number of geoprocessing operations combining the CLC database and the subcatchment delineation shapefiles were executed. The clipping and intersection operations eventually gave rise to several thousands of polygons. These features needed to be merged together according to the land class but also to the subcatchment they belonged to. To perform such a "multi-attribute" merging, a combined use of Arcmap and Excel was necessary, the analytical tools provided by the GIS software not offering such possibilities. The process which was elaborated, even if it was optimised, was relatively time-consuming.

Then, the management of the large outputs (16 land classes * 56 subcatchments = 896 possible groups of polygons) required the use of advanced techniques to eventually obtain the partition of the different land classes in each subcatchment.

As it can be seen from the percentages, the extent of some land cover classes is very limited. It is the case, for example, for all the artificial areas. The scheme of land cover variables which was adopted for this study consequently does not take all the classes into account. In addition, some classes were merged together, sometimes in several different categories at the same time, in order to obtain a number of relevant variables describing the land use. The classification adopted is summarized in Table 3.1. Table 3.2 shows the extent of the different classes in the 56 subcatchments.

Table 3.1: Land Use variables classification.

Land Use Name	Description (Corine classes)
Cultivated	Non-irrigated arable land + Complex cultivation patterns
ImpGrass	Improved Grassland
UnimpGrass	Unimproved Grassland
Pasture	Pastures (***ImpGrass***+***UnimpGrass***)
Agricultural	Non-irrigated arable land + Complex cultivation patterns + Pastures + Land principally occupied by agriculture with areas of natural vegetation
Forest	Coniferous forest +Broad Leaved forest +Mixed forest
Semi-Natural	Transitional woodland scrub +Natural grassland
Peat	Peat Bogs

Table 3.2: Land Use (proportion) for the 56 subcatchments.

Subcatchment	Area(km2)	*Cultivated*	*ImpGrass*	*UnimpGrass*	*Pasture*	*Agricultural*	*Forest*	*Semi-Natural*	*Peat*
N1	211.9	21.0	39.8	24.6	64.4	92.2	5.5	1.8	0.8
N2	44.8	19.0	33.3	31.6	64.9	95.0	4.0	0.6	0
N3	82.2	13.2	39.1	29.8	68.9	84.7	11.2	4.3	3.2
N4	14.9	18.8	46.4	22.0	68.4	97.3	0.7	0	0
N5	64.3	10.5	38.4	32.2	70.5	82.0	13.6	5.5	4.1
N6	28.8	12.8	36.3	42.3	78.6	93.5	3.5	0.4	3.0
N7	10.7	15.7	49.8	20.3	70.1	99.9	0	0	0
N8	2.9	0.7	34.7	27.5	62.1	100	0	0	0
N9	28.1	4.4	40.4	23.6	64.0	68.5	25.1	12.2	6.4
N10	24.2	4.7	41.1	24.6	65.7	79.5	15.8	13.7	4.7
N11	9.2	0	40.8	22.3	63.1	66.8	21.0	15.6	12.3
N12	73.0	0	25.0	11.1	36.1	46.1	31.6	15.3	20.1
N13	44.5	0	27.3	14.4	41.6	54.6	26.6	7.1	17.4
N14	22.8	0	31.1	11.8	42.9	55.2	34.5	30.3	10.2
N15	2.1	0	60.9	1.3	62.1	62.1	0	0	37.9
N16	10.4	0	28.8	18.1	46.8	75.2	11.3	1.8	13.5
N17	7.4	0	19.1	6.9	25.9	33.0	33.0	13.0	26.3
N18	66.3	0	22.8	10.3	33.1	42.7	33.4	15.4	21.5
N19	20.9	0	8.0	9.2	17.2	38.3	25.4	19.5	29.4
N20	37.5	0	29.4	10.3	39.6	42.9	35.0	9.5	21.6
N21	21.1	0	22.4	3.3	25.7	26.0	48.9	8.7	24.2
N22	4.1	0	14.8	0.0	14.8	14.8	51.8	11.4	33.4
N23	16.9	4.6	32.5	18.2	50.7	55.3	34.2	17.0	10.5
N24	2.1	8.7	74.9	14.2	89.3	100	0	0	0
N25	10.8	17.7	49.7	21.7	71.4	93.0	0.9	0	6
N26	13.1	4.1	36.3	25.8	62.2	80.0	12.7	2.5	7.2
N27	14.9	24.5	44.4	27.4	71.9	97.1	3.0	0.7	0
N28	70.2	21.3	40.3	24.4	64.8	92.9	4.8	0.6	2.3
N29	89.8	20.8	44.6	21.9	66.5	92.2	6.6	3.5	0
N30	63.0	16.7	47.1	24.5	71.6	91.3	8.5	5.1	0
N31	41.9	13.9	47.2	23.9	71.0	89.4	10.6	6.9	0
N32	15.1	10.9	49.2	16.8	66.0	81.6	18.4	14.8	0
N33	5.1	0	53.8	17.1	71.0	71.0	29.0	29.0	0
N34	13.1	49.2	25.8	20.5	46.3	100	0	0	0
S1	923.7	7.0	31.2	17.6	48.8	65.2	16.7	7.7	14.9
S2	117.7	21.3	37.7	27.9	65.5	93.8	5.3	2.5	0
S3	98.7	17.2	37.5	29.9	67.5	92.9	6.3	3.0	0
S4	69.3	14.6	41.7	28.7	70.4	92.3	6.6	3.8	0
S5	29.0	7.8	43.8	24.4	68.1	90.6	9.4	2.4	0
S6	46.8	1.0	21.6	12.3	33.9	46.7	23.2	6.8	30.0
S7	6.3	0	33.2	24.6	57.8	86.7	2.4	2.4	10.9
S8	24.7	0	14.7	3.3	18.0	28.3	31.3	6.2	40.4
S9	11.7	0	11.6	5.5	17.1	27.6	22.4	0	50.1
S10	31.7	0	7.1	3.7	10.8	17.3	17.3	2.6	64.1
S11	18.7	0	14.7	7.7	22.4	25.8	22.0	14.8	41.0
S12	17.0	0	5.5	2.4	7.9	7.9	19.3	0.0	70.8
S13	16.6	0	19.1	13.6	32.7	44.8	11.0	13.4	36.9
S14	4.3	0	11.1	3.4	14.5	54.4	0.9	0	44.6
S15	32.2	0	8.4	3.7	12.2	22.3	25.8	2.9	51.9
S16	8.9	0	7.7	4.8	12.5	22.7	37.3	4.0	39.9
S17	6.4	0	0.3	0.0	0.3	35.7	30.2	16.9	33.9
S18	12.3	0	8.7	4.4	13.2	27.5	11.3	24.6	46.2
S19	12.7	0	8.6	5.0	13.6	28.6	11.9	24.2	44.9
S20	93.7	0	12.1	7.9	20.0	38.3	23.0	10.2	36.3
S21	109.9	0	15.8	9.5	25.3	42.3	23.4	12.2	32.2
S22	201.3	0	21.5	11.8	33.3	51.2	24.7	13.8	22.6

3.2.2 Soil & Subsoil

A soil and subsoil mapping project on a county by county basis was recently undertaken by the EPA. The project was originally part of the Forest Inventory and Planning System (FIPS) funded by the Forest Service. But the management of the project was taken over by the EPA as it was seen that the information provided by the project was required to assist in the establishment of an integrated monitoring and management system for all waters within the River Basin Districts, as required under the Water Framework Directive. Soil parent materials, topography and land cover were mapped nationally using remotely sensed imagery. The association of parent materials, topography and land cover with soil type was modelled using GIS, thematic maps and field data. The result gives geographically more accurate results than the General Soil Map but with quite different classifications.

3.2.2.1 Soil

Soil classification is described according to the Irish Forest Soils (IFS) classification which gives qualitative information about the soils hydraulic properties. The soil types modelled fall into the following categories, peat or mineral and the mineral category is further subdivided into acidic or basic, deep or shallow and then well or poorly drained. All the soils in the area are acidic.

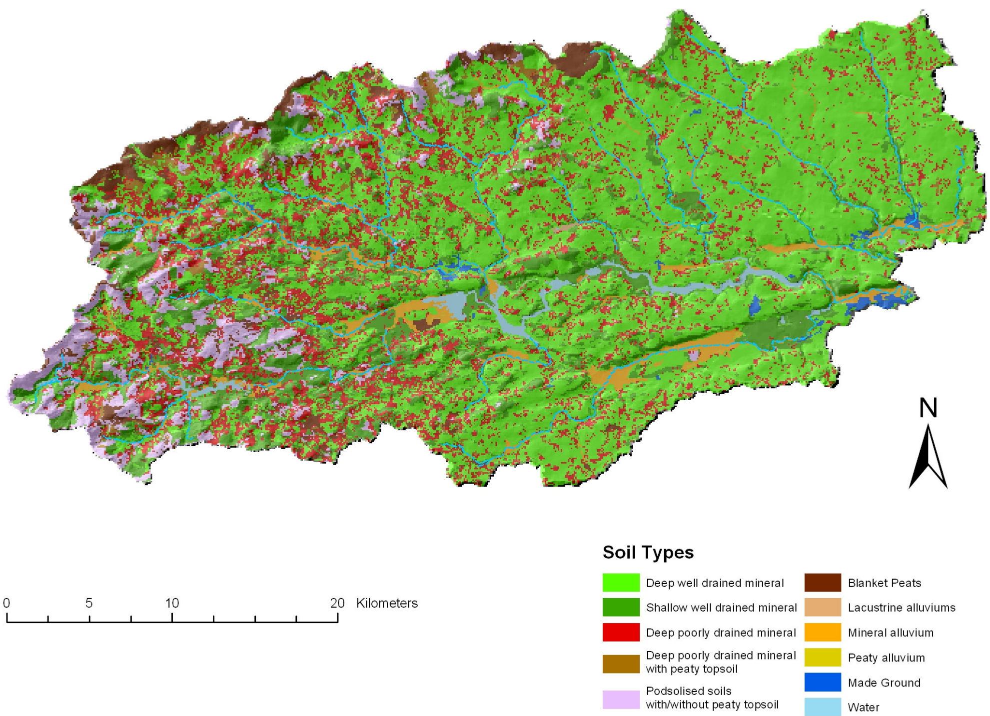

Figure 3.1: Soil types in the study area according to the IFS classification.

Figure 3.1 shows that most of the river Lee basin is covered with well drained mineral soils (about 66%). In term of the great soil groups classification, the deep well drained mineral soils correspond to Acid Brown Earths and Brown Podzolics, and the shallow ones to Lithosols and Regosols. Poorly drained mineral soils, that represent 18% of the catchment soils, appear in patches all over the catchment, but especially in the western part of the catchment.

3.2.2.2 Subsoil

More information about soils can be obtained from the subsoils (also called parent materials) which is the mineral from which the soil is formed. Subsoils are divided in tills (diamictons), glaciofluvial sands and gravels, esker sands and gravels, glaciolacustrine deposits, alluvium, peat, marine deposits, miscellaneous materials, and bedrock at or close to the surface (<1m).

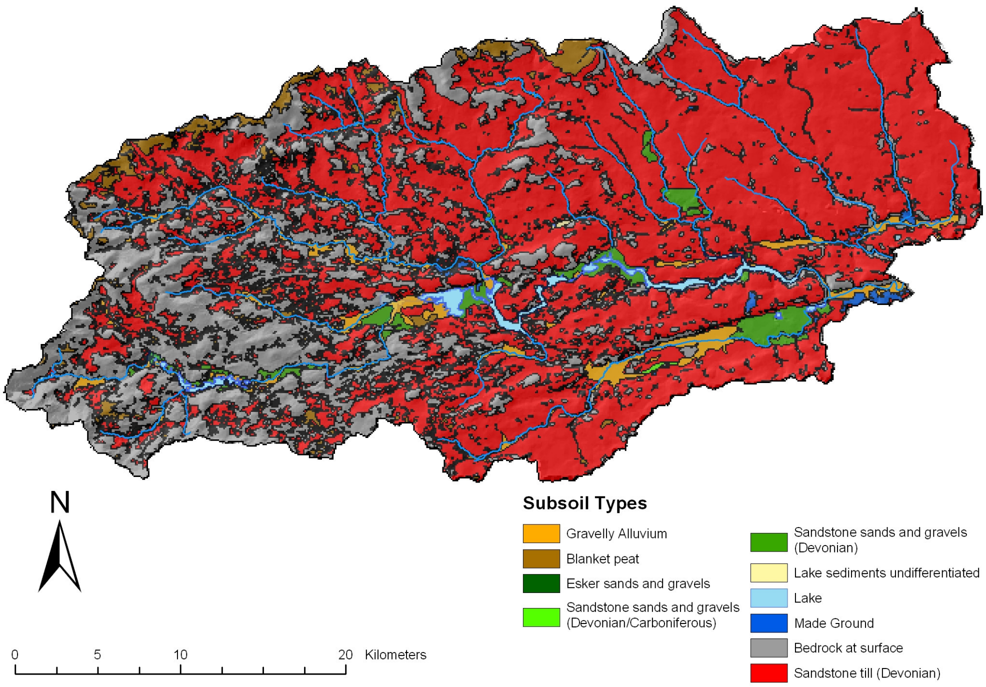

Figure 3.2: Subsoil types in the study area.

Figure 3.2 shows that most of the soils (61%) originate from tills which are sediments deposited by glacier ice. Bedrock at less than 1 meter of the surface also represents (27%) a significant proportion of the subsoils.

3.2.2.3 Data

Different variables representing the most widespread types of soils and subsoils have been defined. They are summarised with their description in Table 3.3. Distribution over the different subcatchments is shown in Table 3.4

Table 3.3: Soil and Subsoil variables classification.

Soil	Description
DeepWD	Deep Well Drained Mineral
ShallowWD	Shallow Well Drained Mineral
WellDrained	Well Drained Mineral (***DeepWD+ShallowWD***)
PoorlyDrained	Deep poorly drained mineral with or without peaty topsoil
Subsoil	**Description**
Till	Sandstone Till (Devonian)
Rock	Bedrock at or close to the surface

Table 3.4: Soil and Subsoils for the 56 subcatchments.

Subcatchment	Area(km2)	Soil				Subsoil	
		DeepWD	*ShallowWD*	*WellDrained*	*PoorlyDrained*	*Till*	*Rock*
N1	211.9	79.64	6.71	86.35	9.51	88.31	7.71
N2	44.8	82.81	5.22	88.02	7.07	89.50	5.62
N3	82.2	68.22	11.31	79.53	11.64	77.45	9.65
N4	14.9	77.46	7.20	84.66	10.90	86.88	2.98
N5	64.3	66.04	12.23	78.27	11.77	75.21	11.12
N6	28.8	73.58	7.35	80.93	13.18	84.51	10.68
N7	10.7	83.77	1.96	85.73	9.05	92.60	2.33
N8	2.9	80.76	3.44	84.19	15.81	96.13	3.79
N9	28.1	60.28	12.31	72.60	11.46	68.68	13.27
N10	24.2	66.79	10.49	77.28	18.09	81.15	15.85
N11	9.2	59.69	8.82	68.52	25.05	79.72	18.08
N12	73.0	47.31	10.33	57.64	24.05	67.77	23.29
N13	44.5	37.98	15.59	53.57	25.34	55.77	30.58
N14	22.8	42.91	10.57	53.49	30.80	63.53	28.48
N15	2.1	37.91	0.47	38.39	23.70	57.73	20.82
N16	10.4	39.46	3.85	43.31	31.76	63.23	17.81
N17	7.4	33.70	6.79	40.49	19.97	51.69	23.40
N18	66.3	44.49	10.68	55.18	25.14	65.93	24.79
N19	20.9	37.55	8.17	45.72	31.01	64.36	29.77
N20	37.5	45.42	12.28	57.70	21.74	63.39	24.06
N21	21.1	41.49	12.07	53.56	18.30	58.14	22.56
N22	4.1	39.61	13.04	52.66	26.33	66.05	16.45
N23	16.9	49.76	15.21	64.97	10.24	56.04	19.41
N24	2.1	89.37	0.48	89.86	0	93.50	0.97
N25	10.8	68.88	12.37	81.26	15.05	78.70	18.66
N26	13.1	64.80	16.30	81.10	15.91	79.29	18.68
N27	14.9	89.47	2.55	92.02	5.90	95.00	2.95
N28	70.2	78.78	8.63	87.40	10.19	87.57	10.39
N29	89.8	80.37	5.10	85.47	10.45	90.16	5.81
N30	63.0	82.62	4.40	87.01	11.43	93.60	4.92
N31	41.9	84.30	2.36	86.66	11.95	95.90	2.84
N32	15.1	83.58	3.18	86.75	11.85	95.22	3.45
N33	5.1	82.85	6.43	89.28	9.75	92.31	6.82
N34	13.1	88.69	3.13	91.82	8.03	96.21	3.67
S1	923.7	42.60	19.31	61.90	19.95	54.94	31.84
S2	117.7	62.41	14.19	76.60	13.44	74.02	10.97
S3	98.7	63.34	11.24	74.58	14.23	75.58	12.17
S4	69.3	64.55	10.83	75.38	16.26	78.21	13.38
S5	29.0	51.83	24.14	75.97	17.92	64.06	30.42
S6	46.8	27.06	27.46	54.52	23.79	38.28	51.62
S7	6.3	45.57	18.83	64.40	33.23	66.27	33.06
S8	24.7	20.45	29.05	49.49	23.81	32.69	58.89
S9	11.7	13.31	26.11	39.42	23.21	20.13	73.70
S10	31.7	11.06	23.99	35.04	16.10	20.17	69.59
S11	18.7	15.14	24.08	39.22	20.12	24.99	66.46
S12	17.0	7.45	27.68	35.13	8.28	10.20	80.29
S13	16.6	25.83	12.73	38.56	21.67	38.22	55.25
S14	4.3	18.50	13.82	32.32	42.39	34.59	60.07
S15	32.2	14.50	27.30	41.80	19.85	27.49	53.48
S16	8.9	30.91	7.16	38.07	31.70	60.47	11.41
S17	6.4	43.04	4.64	47.68	28.96	67.63	15.26
S18	12.3	23.80	5.38	29.18	32.60	49.40	28.74
S19	12.7	24.01	6.02	30.03	32.81	49.13	29.53
S20	93.7	23.90	18.68	42.58	28.66	42.01	42.29
S21	109.9	24.40	20.11	44.51	28.66	40.94	44.48
S22	201.3	30.79	18.85	49.64	27.71	47.22	39.48
Study Area	**1135.6**	**49.51**	**16.96**	**66.47**	**18.00**	**61.17**	**27.34**

3.2.3 Slope

Relief is usually considered as an important component of phosphorus transport to rivers. With Arcmap, it is possible to identify the steepest downhill slope for a location on a surface. This was computed automatically for each cell of the raster elevation grid by taking the maximum rate of change in elevation over the cell and its eight neighbours. The output result is a raster containing the slope in percent at each cell (see Figure 3.3). The higher the slope value is, the steeper the terrain is.

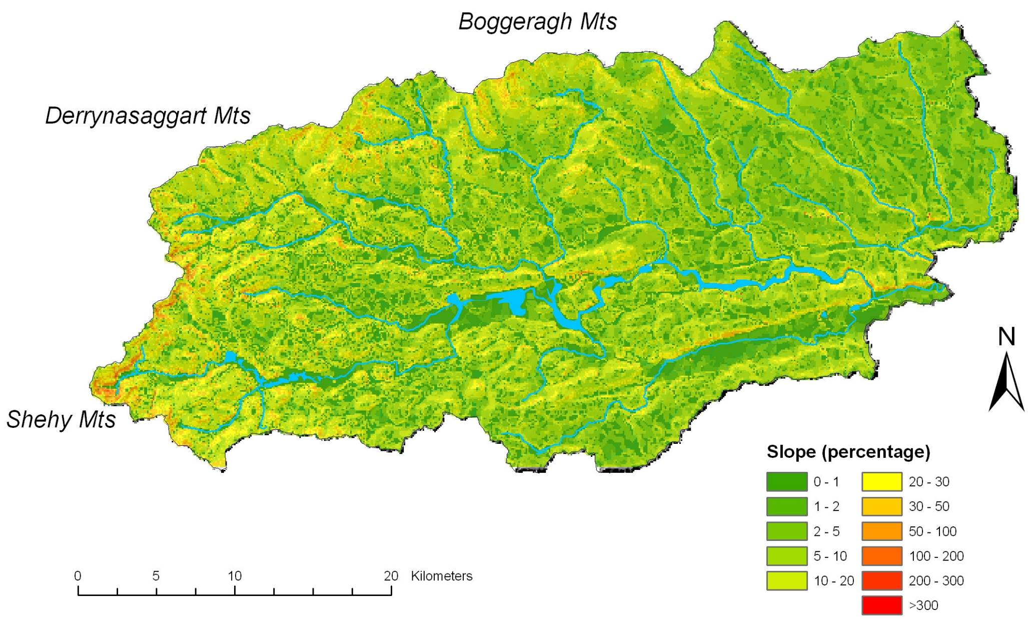

Figure 3.3: Slope in the study area.

In the slope map, steeper slopes are shaded red while flat terrain is green. The steeper slopes are usually located in the western part of the catchment. In the East, slopes are mainly less than 20% (about 11 degrees). An average cell slope was computed for each subcatchment in order to get an indicator of the terrain steepness. The values given in Table 3.5 do not give the average slope of each subcatchment but the mean of the cell slopes within the subcatchment, which gives a better idea of the relief.

Table 3.5: Mean of the cells slope for the 56 subcatchments.

N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19
6.02	6.22	6.71	4.50	7.13	6.44	4.26	3.90	7.95	7.29	7.60	11.03	12.50	9.90	12.39	9.45	14.06	11.40	12.55

N20	N21	N22	N23	N24	N25	N26	N27	N28	N29	N30	N31	N32	N33	N34	S1	S2	S3	S4
11.50	12.39	12.82	9.73	4.46	8.67	7.00	4.43	6.35	5.39	5.08	5.10	5.69	7.11	4.89	9.77	6.74	6.66	6.79

S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22
8.95	8.37	5.32	9.78	8.94	20.27	16.36	24.46	18.13	14.63	16.29	13.01	13.33	17.50	17.31	14.31	13.57	12.24

3.3 DATA 2- Agriculture

3.3.1 Census of Agriculture

A Census of Agriculture was conducted in June 2000 by the CSO (Central Statistics Office) and covered all farms in Ireland with at least 1 hectare of land farmed. It was the first full Census of Agriculture to be conducted since 1991. The Census results contain updated structural information on a wide range of agricultural topics, including: area farmed, area under various types of crops, numbers of livestock and poultry, the farm workforce, ownership and use of farm machinery and the extent of involvement in non-agricultural activities. The data are available on the CSO website (www.cso.ie) at the Electoral Division (ED) level (See Figure 2.10 for the different Electoral divisions included in the study area).

3.3.2 Livestock

The number of livestock and the partition in different types is given for each electoral division by the census of agriculture. The table 3.6 gives an example of the available data.

Table 3.6: Number of livestock in Macroom Urban ED and type of livestock (CSO).

	Bulls	Dairy Cows	Other Cows	Dairy Heifers	Other Heifers	Cattle Male 2+	Cattle Female 2+	Cattle Male 1-2	Cattle Female 1-2	Cattle Male <1	Cattle Female <1	Total Cattle
18005 Macroom Urban	26	555	429	115	44	237	45	477	295	431	354	3008

	Rams	Total Ewes	Other Sheep	Total Sheep
18005 Macroom Urban	4	350	470	824

The data, which represent livestock numbers of various species, uses and ages, could not be directly used. It was necessary to have a common unit to describe livestock numbers that would express the total amount of livestock present as a single figure. The system of livestock unit equivalents (LU) developed by Teagasc for grazing livestock was chosen. With this system, dairy cow is taken as the basic grazing livestock unit (1 dairy cow = 1 LU) and all other grazing stock are then given equivalents. A calf under 6 months is for example considered as 0.2 LU. The Teagasc system of equivalences was adapted so that it can match the livestock categories used by the CSO in the 2000 census (See Table 3.7).

Table 3.7: Livestock Unit equivalence.

Type of Livestock	LU equivalent
Bulls	1
Dairy Cows	1
Other Cows	1
Dairy Heifers	0.9
Other Heifers	0.7
Cattle Male 2+	1
Cattle Female 2+	1
Cattle Male 1-2	0.7
Cattle Female 1-2	0.7
Cattle Male <1	0.3
Cattle Female <1	0.3
Rams	0.2
Total Ewes	0.2
Other Sheep	0.15

According to these equivalences, the number of livestock units was then worked out in each Electoral Division. A number of Electoral Divisions being only partly included in the Study area, further computations were necessary to estimate the amount of livestock. It was decided to consider the area covered by grassland in each of these electoral divisions using the Corine database and to allocate livestock in proportion to the areas of grassland included in the study area. Livestock densities in the catchment are shown in figure 3.4.

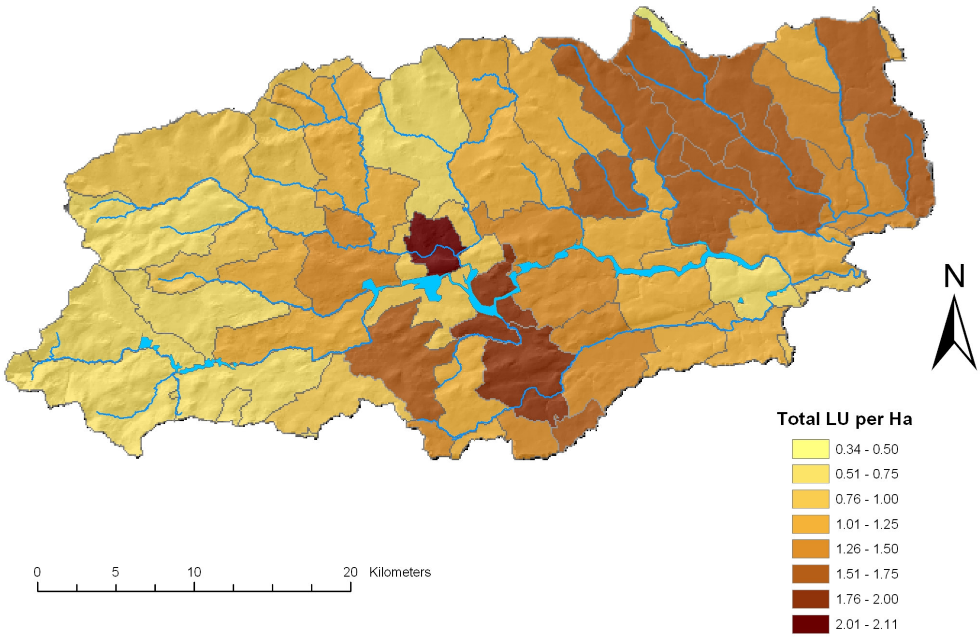

Figure 3.4: Livestock density in the study area.

Then, to allocate the amount of livestock to each subcatchment, similar computations had to be carried out, using the areas of grassland in each subcatchment in comparison to the areas of grassland in the electoral divisions they are included in. To perform these computations, GIS tools revealed again to be a precious help.

3.3.3 Fertiliser

In Ireland, there is no available data about the use of chemical fertiliser at a small scale such as the electoral division level. The data provided by the 2000 census on the area under various types of crops in each ED (See Table 3.8) were consequently used in combination with a survey of the fertiliser use in Ireland (Coulter, 2006). This survey is based on the farm management data for the years 2001-2003 of 1275 farms part of the annual National Farm Survey carried out by Teagasc. Data relating N, P and K fertiliser use for different crops to geographic region and farm characteristics were produced. The data obtained for the South region (Cork + Kerry) were used in this study to estimate the use of P fertiliser in the different EDs. The data provided by this survey (See Table 3.9) had to be adapted to match the results of the 2000 census of agriculture.

Table 3.8: Area farmed (ha) in Macroom Urban ED and type of crop (CSO).

	Area Farmed	Total Wheat	Total Oats	Total Barley	Other Cereals	Total Cereals	Other non-cereal crops	Total Crops, Fruit & Horticulture
18005 Macroom Urban	1234	0	0	3	0	3	2	14

	Total Hay	Total Pasture	Total Silage	Rough Grazing in use	Potatoes	Sugar Beet
18005 Macroom Urban	37	822	348	12	0	10

Table 3.9: P use for grassland and tillage crops in the south region.

Grassland	P (kg/ha)
Grazing	11
Silage	13
Hay	8
Tillage	P (kg/ha)
Cereal Crops overall	22
Sugar Beet	35
Potatoes	39

With these average application rates of phosphorus and the data of the agricultural census, the quantity of P chemical fertiliser used in each electoral division was then worked out. Again, a method had to be found to estimate the fertiliser load in the EDs which were only partially included in the catchment. Quantities of fertilisers were assigned in function of the agricultural areas under different types of land covers by using Corine data base, in combination with the average fertiliser loads for the different types of crops. Thus, areas under heavily fertilised crops (corresponding to the arable land and complex cultivation patterns in Corine) were given more importance in the fertiliser load allocation process than agricultural land under pasture or mixed with areas of natural vegetation. A system of scores was used for this purpose. The scores were obtained by multiplying the areas under the different types of Corine agricultural covers by coefficients proportional to the estimated fertiliser use in these areas. Figure 3.5 shows the relationship between the total fertiliser load (derived from CSO data) and these scores derived from the Corine database for the different EDs. The good correlation (r^2=0.76) tends to show a good agreement between CSO data and Corine data.

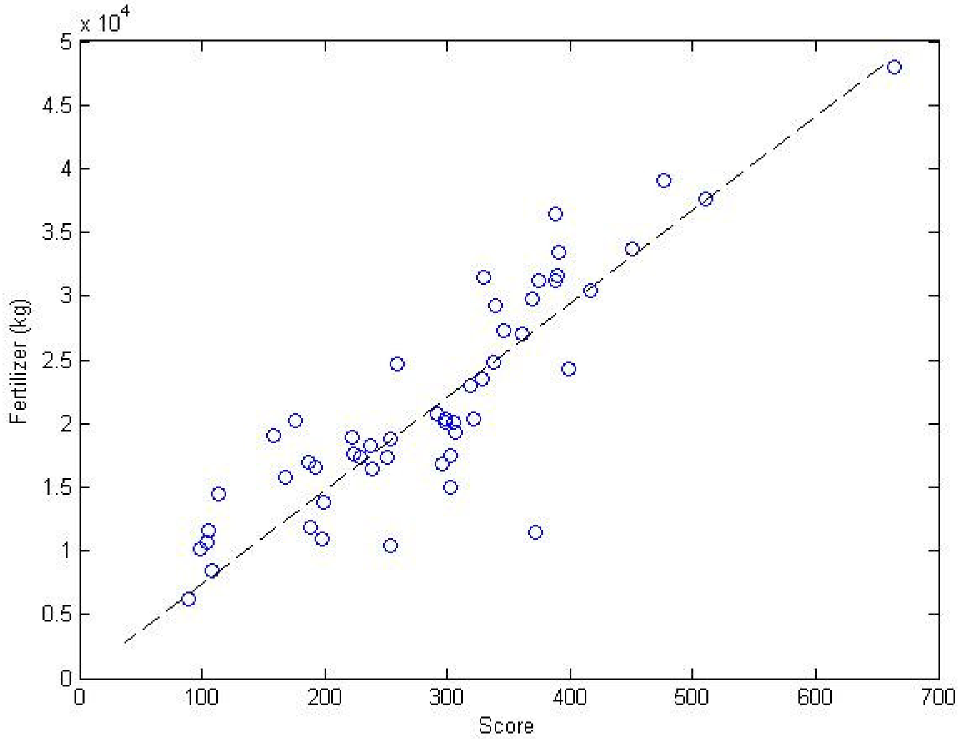

Figure 3.5: Total fertiliser use vs. Corine score in the different EDs.

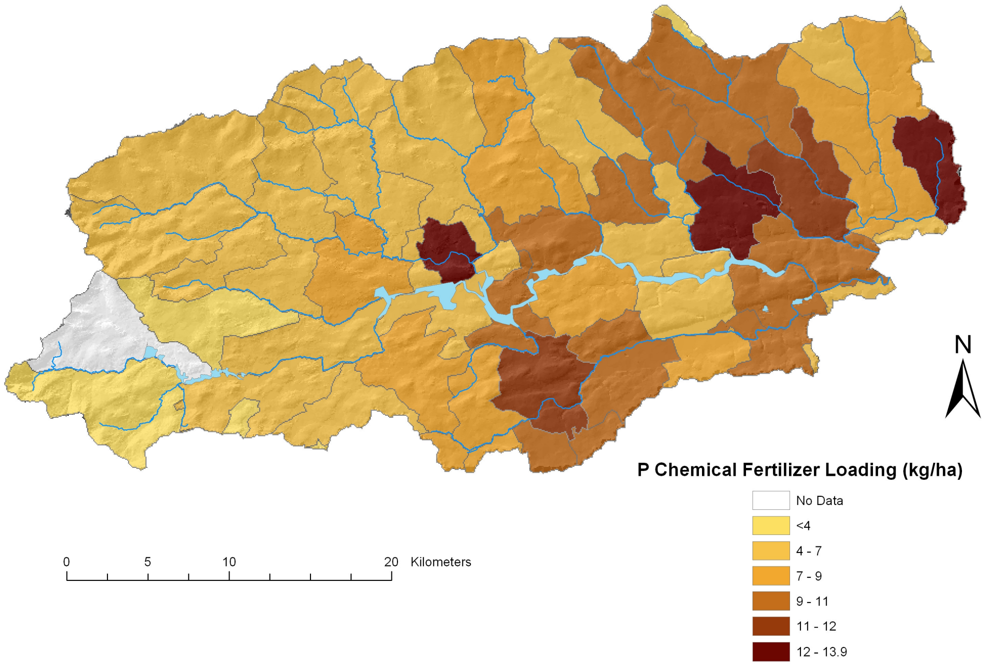

Figure 3.6: Fertiliser (P) use in the study area.

Figure 3.6 shows the results obtained with this method. As it can be seen, there was no data available for one of the Electoral Division (Bealanageary, Macroom Rd) in the CSO census. The linear relationship found previously was consequently used to estimate the use of fertiliser in this electoral division. An annual load of 3.1 kg P/ha was found for this division, which appears to be in line with the neighbour EDs.

Then a similar method based on the combined use of Corine data and fertiliser figures for the different EDs was used to allocate fertiliser application loads for the 56 subcatchments. The results obtained for livestock density and fertiliser use are summarized in Table 3.10.

Table 3.10: Agricultural data for the 56 subcatchments.

Subcatchment	Area(km2)	Livestock density (LU/ha)	Fertilizer (kg/ha)
N1	211.9	1.50	9.84
N2	44.8	1.60	11.42
N3	82.2	1.41	8.87
N4	14.9	1.58	10.60
N5	64.3	1.40	8.48
N6	28.8	1.45	9.45
N7	10.7	1.58	10.61
N8	2.9	1.44	8.80
N9	28.1	1.39	7.36
N10	24.2	1.37	8.60
N11	9.2	1.41	7.87
N12	73.0	0.72	4.42
N13	44.5	0.90	5.01
N14	22.8	0.96	5.53
N15	2.1	1.20	5.96
N16	10.4	1.00	6.67
N17	7.4	0.74	3.14
N18	66.3	0.67	4.06
N19	20.9	0.35	2.63
N20	37.5	0.81	4.64
N21	21.1	0.54	2.87
N22	4.1	0.26	1.44
N23	16.9	1.14	6.12
N24	2.1	2.04	10.89
N25	10.8	1.70	10.12
N26	13.1	1.44	7.37
N27	14.9	1.59	9.71
N28	70.2	1.51	9.87
N29	89.8	1.51	9.11
N30	63.0	1.58	8.40
N31	41.9	1.51	7.73
N32	15.1	1.36	7.00
N33	5.1	1.44	5.72
N34	13.1	1.34	13.89
S1	923.7	1.07	6.60
S2	117.7	1.41	9.73
S3	98.7	1.47	9.54
S4	69.3	1.56	10.28
S5	29.0	1.35	8.99
S6	46.8	0.88	5.36
S7	6.3	1.56	9.69
S8	24.7	0.50	3.03
S9	11.7	0.44	1.46
S10	31.7	0.27	0.71
S11	18.7	0.82	2.47
S12	17.0	0.20	0.30
S13	16.6	1.02	1.54
S14	4.3	0.56	6.08
S15	32.2	0.48	2.79
S16	8.9	0.50	2.80
S17	6.4	0.01	3.29
S18	12.3	1.14	3.27
S19	12.7	1.14	3.39
S20	93.7	0.81	4.63
S21	109.9	0.91	5.12
S22	201.3	0.93	5.46
Study Area	**1135.6**	**1.15**	**7.20**

3.4 DATA 3- Hydrology

3.4.1 Flow

A number of hydrometric gauging stations (staff gauges fitted or not with an autographic water level recorder) are present within the study area. 30 stations were identified in the catchment using the Register of Hydrometric Gauging Stations in Ireland developed by the EPA. Among these 30 stations, several ones are classified as obsolete or inactive, which means that no measurements are currently being taken at these stations. Nevertheless, 20 are supposed to be on operation in the area (See Figure 3.7). 9 are operated by the Electricity Supply Board (ESB) to assist hydro-electric power generation and water level control in relation to dam safety, 8 by Cork County Council and 3 by the Office of Public Works (OPW).

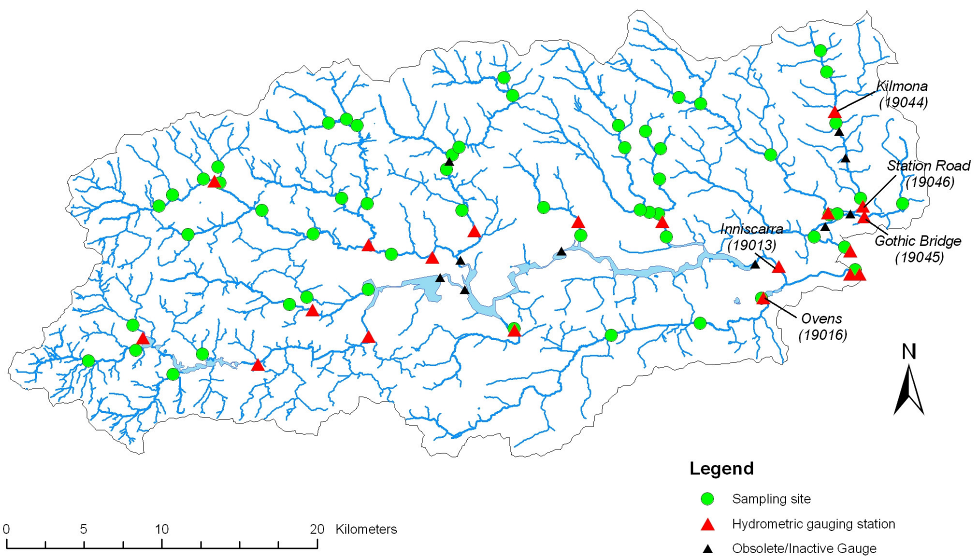

Figure 3.7: Hydrometric Station Network in the study area.

Several requests were made to these different bodies and to the EPA, which is supposed to implement a programme gathering all the hydrometric data in Ireland, but very few data sets were finally obtained. The only substantial piece of data was obtained from the OPW for their 3 stations on the Martin River (Kilmona, Station Road) and the Blarney (Gothic Bridge), which approximately correspond to the sampling sites N31, N30 and N34, respectively (See Figure 3.7). At these stations, water level was recorded every 15 minutes and the results are available in digitized form only from the beginning of 2005 but that, only for Kilmona and Gothic Bridge stations. Unfortunately, there are no really recent and reliable rating curves available for these gauges. Flow was yet calculated at these points using old rating curves

(See Figure 3.8). Some daily mean flows (See Figure 3.9).were also obtained for 2004 and part of 2005 at the station of Iniscarra, on the river Lee, and at Ovens (sampling site S2), on the Bride.

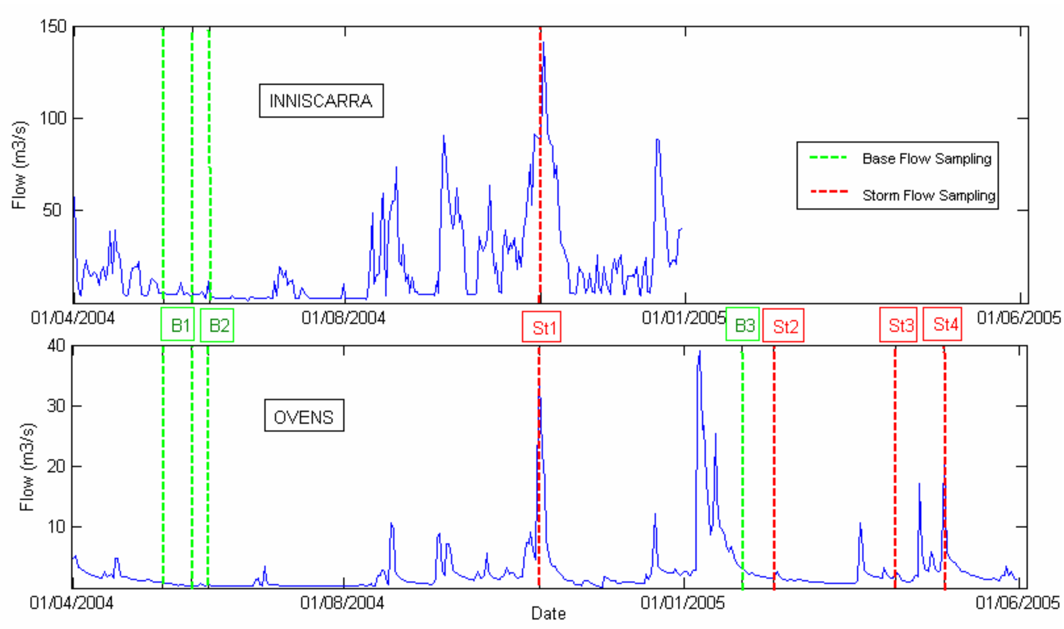

Figure 3.8: Daily Mean Flows at Iniscarra and Ovens.

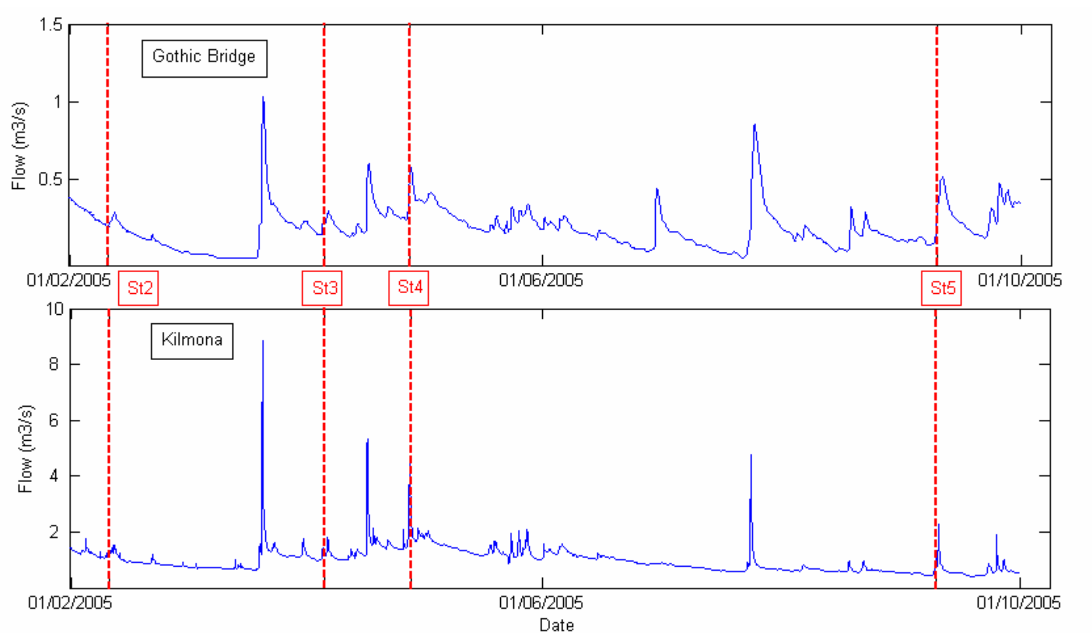

Figure 3.9: Flows at Kilmona and Gothic Bridge.

From figures 3.8 and 3.9, it is noted that the sampling St1 was done during the biggest sampled event in term of flow. Then come St4 and St5, which were carried out in moderate storm flow conditions. St2 and St3 were done during relatively limited storm event. In comparison, for example, at the time of B3 sampling, the flow was more important due to big storms that had occurred some days before. That can also be seen on figure 3.10 which shows more precisely the flows for the OPW gauging stations thanks to the smaller time steps.

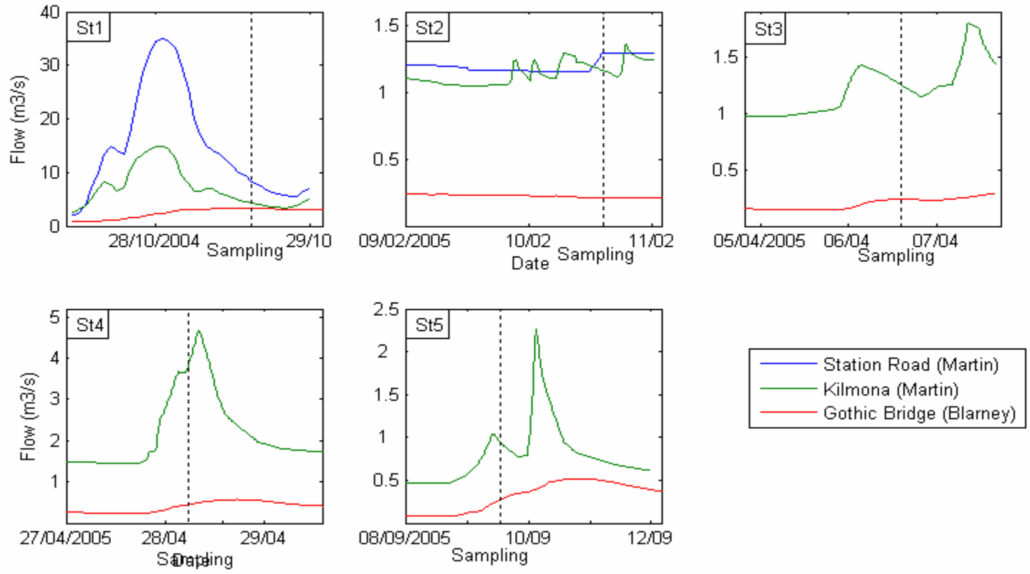

Figure 3.10: Flow at Station Road, Kilmona (partly) and Gothic Bridge for the 5 storm events.

On figure 3.9, it can be seen that the two rivers, while they are geographically close, behaves quite differently in term of flow. The Martin River, although it is bigger than the Blarney, shows a more flashy flow regime. The hydrographs of the Martin River are typically narrower. As a consequence, several samplings were collected on the falling limb of the Martin hydrograph (St1, St3 and St5), i.e. after the peak discharge occurred, while the Blarney was still in the rising limb phase of its hydrograph, i.e. before the peak discharge. This difference in the timing of the sampling in relation to the hydrograph could have an influence on the sampling results. According to the form of phosphorus measured, the timing of the increase in concentration can actually differ. Other sampling results (Baker) suggest for example that total phosphorus peaks on the rising limb of the hydrograph while the maximum soluble reactive phosphorus concentration occurs after the peak discharge.

These flow data unfortunately relate only to 3 sites among the 56 of our study. But the remarks made about the timing of the samplings in relation to the position on the hydrograph should be kept in mind when comparing later the results between them.

3.4.2 Precipitation

Rainfall is a major component in the transfer of phosphorus from land to a watercourse. It was therefore seen as necessary to have access to the amount of precipitation prior to each of the different samplings, notably in storm flow conditions. For our study area, two types of data were available: rain gauges and radar data.

3.4.2.1 Rain gauges data

Within our study area, there are 12 rain gauges operated by the Irish National Meteorological Service, Met Eireann. The details of the stations and the data availability are given in Table 3.11. Among these 12 gauges, only 8 had continuous daily data for the period 2004-2005. The data of the gauges are collected manually by Met Eireann staff. The readings generally cover the period 9 a.m. to 9 a.m. (UTC) the next day. In the tables provided by the Meteorological Service, there is sometimes no reading at a station for one or more days. It is then specified by an indicator code and the following actual reading gives the cumulative total.

Table 3.11: Met Eireann operated rain gauges in the study area

Station Number	Station Name	Grid Reference	Data Availability
1504	RATHDUFF G.S.	W 598 848	almost no data from 2004
2604	BALLYVOURNEY (CLOUNTYCARTY)	W 210 715	yes
2704	GOUGANEBARRA	W 095 660	yes
2804	DONOUGHMORE	W 492 821	yes
3004	BALLINGEARY (VOC.SCH.)	W 150 671	yes
3604	CARRIGADROHID (GEN.STN.)	W 405 720	yes
3704	INISHCARRA (GEN.STN.)	W 545 722	yes
3804	MACROOM (RENANIRREE)	W 201 726	yes
6104	MUSKERRY (GOLF CLUB)	W 580 743	yes
9604	M.BALLINGEARY (MEELIN MTN.)	W 140 716	monthly data only
9704	M.BALLINGEARY (TOOREENANEEN)	W 131 645	monthly data only
9804	M.BALLYVOURNEY (KNOCKACOMMEEN)	W 160 807	monthly data only

UCC Hydromet Research group is also operating 10 rain gauges spread over its research catchment which is located between Donoughmore and Coachford and which corresponds in fact to the catchment N24 of this study. Rainfall is measured on an hourly basis in the different stations. One rain gauge located in Knockane (W 490 770) was selected to complete the network of the Met Eireann gauges. This station actually presents data of good quality and is far enough of Donoughmore where there is already a Met Eireann gauge. The objective was actually to have a network of rain gauges spread all over the study area. Details about the location of the different rainfall stations in the study area are given in figure 3.11.

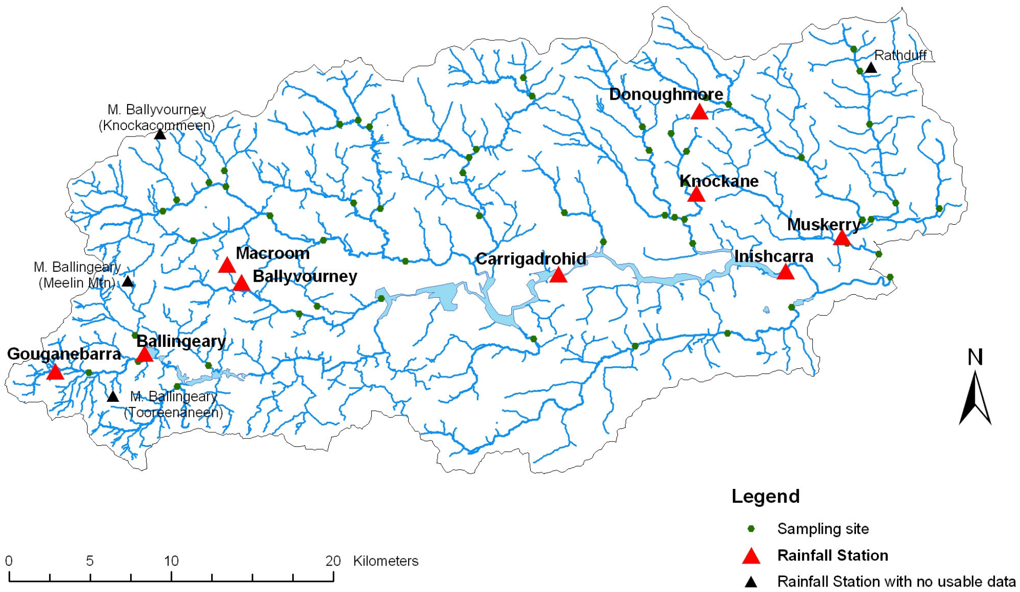

Figure 3.11: Rainfall station network.

As it can be seen on figure 3.11, large parts of the study area are not covered by the rain gauge network. It is especially the case in the South, North-East and North-West of the catchment. But even with a denser network, it would not be possible to fully measure rainfall variations. Rainfall actually varies widely even over short distances and "hot spots" can easily be missed by gauges. In addition, as far as temporal accuracy is concerned, daily measurements does not really give access to the intensity of the different events. For these reasons, it was decided to consider the potential of radar data.

3.4.2.2 Radar data

Met Eireann operates two weather radars, which are located at Dublin and Shannon Airport. These modern radars were installed in the 90's and scan the atmosphere for rainfall every 15 minutes to a range of 240 km with a 1 km resolution. Data are available from Met Eireann for hourly accumulation periods with sensitivity of 0.1mm/hr. The accuracy of the data varies with the type of precipitation (showers, rain, drizzle, etc…) and the distance from the radar. Beyond 100 km from the radar, the accuracy is said to fall off dramatically. The study area lies between 75 and 100 km from Shannon airport. It was therefore decided to use the data provided by the radar located in Shannon.

The files provided by Met Eireann are ASCII (American Standard Code of Information Interchange) files containing a header and the data matrix as shown in figure 3.12. The header gives information about the date, the time and the format of the data. The matrix contains 480 rows and 480 columns, each number corresponding to the amount of rain in millimetres that felt on a 1000*1000 m square during one hour.

```
2005  3 24  4  5    5    5  1  2  480  480
      0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  ...
      0.0  0.0  0.2  0.2  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.0  0.0  0.0  0.0  0.0  0.2  0.2  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.6  0.2  0.2  0.4  0.0  0.2  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.0  0.0  0.0  0.0  0.2  0.2  0.4  0.4  0.4  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.1  0.1  0.1  0.0  0.1
      ....
```

Figure 3.12: Example of a radar rainfall file for the 24/03/2005 from 4am to 5am.

Figure 3.13 shows an example of a radar image as recorded by the rainfall radar of Met Eireann and created by using Matlab®. The image is centred on the radar in Shannon Airport. The Study Area is shown in black contours. The grid refers to the Irish National Grid coordinates. On the right is indicated the scale of rainfall intensity in mm/hour.

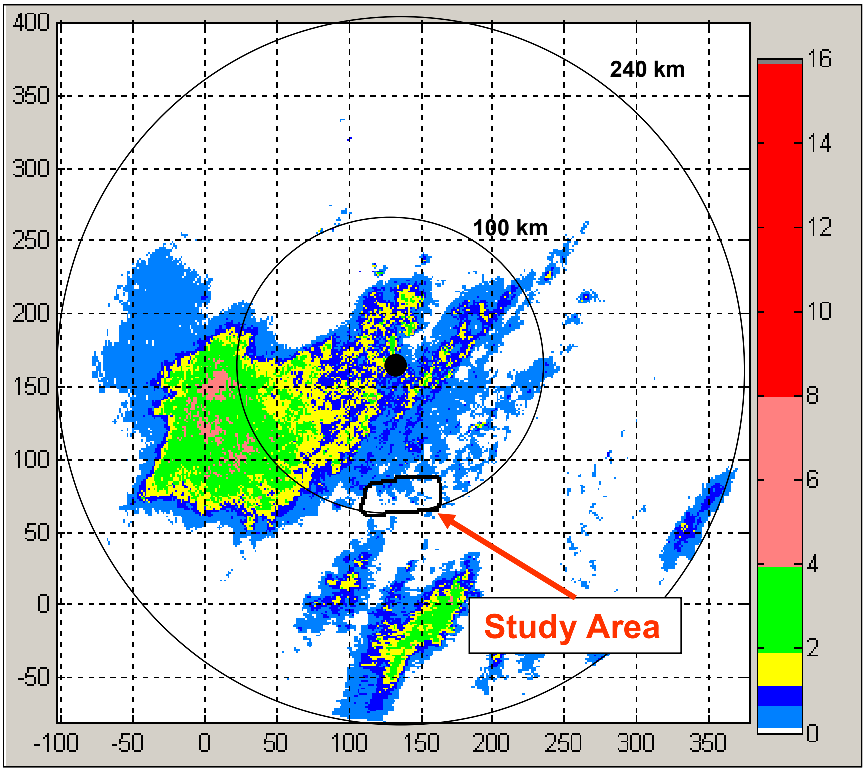

Figure 3.13: Radar Image for the 08/09/2005 from 3pm to 4pm

There is a number of missing hours in the radar data, due either to maintenance operations or radar breakdown. In this study, we are especially interested in the couple of days prior to each of the sampled storm events. In this regard, the last sampling campaign was unfortunately affected by a break of the radar that occurred from 4pm on the 08/09/2005 to 11am on the 09/09/2005, i.e. just during the storm preceding the samples collection.

The accuracy of the hourly accumulation radar products has not been determined by Met Eireann, but they estimate it to be between 50% and 70%. At present, radar data are actually not corrected by ground truth, i.e. using data from rain gauges. Indeed, data provided by rain gauges are usually considered to be more reliable and to give an accurate measurement of the actual rainfall. For the Knockane station, which has hourly data available, comparisons were done between the data provided by the rain gauge and the one provided by the radar at this location. Comparisons were carried out for the 5 storm events that were sampled during 2004-2005 and the results are shown on figure 3.14. It can be seen that the radar detects quite well the different rain events and that the timing between the two types of data is also very good. However, it appears that, most of the time, radar tends to underestimate the precipitation. Heavy rain seems to be more underestimated than light rain. For the 5 events, the average accuracy for the total precipitation is around 55%.

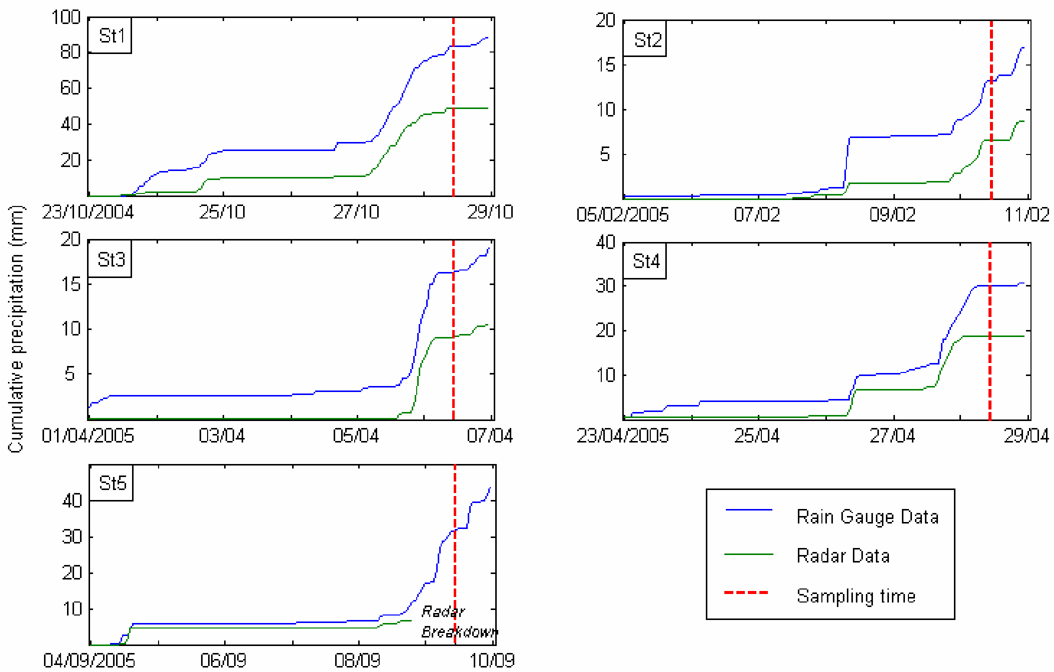

Figure 3.14: Comparison between Radar and Rain gauge data at Knockane.

From that, it can be said that radar has a good spatial coverage – it covers a wide area at a good resolution- and a good temporal coverage with hourly data. However, the rainfall values provided by the radar can only be considered as rough estimates, with important variations, of the actual rainfall amounts. On the other hand, rain gauges give accurate data but for limited areas. In addition, with rain gauges only giving daily data, the temporal coverage can be considered as poor. For these reasons, it was decided to combine radar and rain gauges to improve the accuracy of radar rainfall measurements.

3.4.2.3 Radar correction

What is here in question is a correction of the data provided by the radar and not a calibration of the radar. Calibration would result in absolute bias coefficients for radar data that would not be dependent on the rainfall measurements anymore. Here, radar measurements are compared to rain gauge measurements and corrected accounting for the depth of precipitation observed on the ground. Radar precipitation for a station will be defined as the average precipitation of the 4 pixels surrounding the gauge location, and that, in order to account for the wind causing raindrops to fall outside the pixel where they are measured.

A method, which is usually used to correct radar data (Steinman, 2005), is to calculate a bias coefficient at every station and for each period of time (each day in this case). Then the corrected data matrix is obtained by multiplying the original radar rainfall data matrix by an average daily coefficient corresponding to the mean of all station coefficients. But considering the highly uneven precipitation distribution over the study area, it was decided that a single correction coefficient for the whole catchment would not give accurate enough results.

For every day of interest, the daily radar data (from 9am to 9pm) were corrected by using the bias coefficient determined at a station only over the Thiessen polygon associated to this station. Thiessen (Voronoi) polygons define individual areas of influence around each of a set of points. Their boundaries define the area that is closest to each point relative to all other points. Mathematically, they are defined by the perpendicular bisectors of the lines between all points. Basically, the Thiessen polygon of a rain gauge is the region for which if any point is chosen at random in the polygon, that point will be closer to this particular gauge than to any other gauge.

For this correction purpose, only 8 rain gauges were selected, i.e. those with at least daily data available. In addition, as far as the two very close stations of Macroom and Ballyvourney are concerned, only the Ballyvourney one was kept, considering its better data consistency. The 8 corresponding Thiessen polygons are represented on Figure 3.15. For all the pixels of the radar image which are included in the i^{th} Thiessen polygon, the correction coefficient is defined as:

$$C_i(t) = \frac{Pg_i(T)}{\sum_{t \in T} Pr_i(t)} \qquad (3.1)$$

where, $Pg_i(T)$ is the rain gauge rainfall over the period T (from 9am to 9pm) and $Pr_i(t)$ the radar rainfall sampled at the 4 pixels corresponding to the location of the station i at time *t*.

The corrected value of a pixel is then obtained by multiplying its original value by the coefficient of the corresponding day and corresponding Thiessen polygon. With this method, the data provided by the radar over 24 hours are therefore matching the daily values given by the rain gauges at the locations of these ones.

Then, the average amount of precipitation over each subcatchment was computed by taking into account the possible inclusion of the subcatchments in different Thiessen polygons. To do so, a combined use of Matlab and Arcinfo Workstation was necessary. Matlab was required to handle the high number of radar files, change the format of the data and compute the corrections. The programming possibilities offered by the Workstation were necessary to allocate the rainfall data to the different subcatchments and work out the average amount of precipitation. The programmes written in Matlab language and AML (Arc Macro Language, the programming language of Workstation Arcinfo) are attached in Appendix.

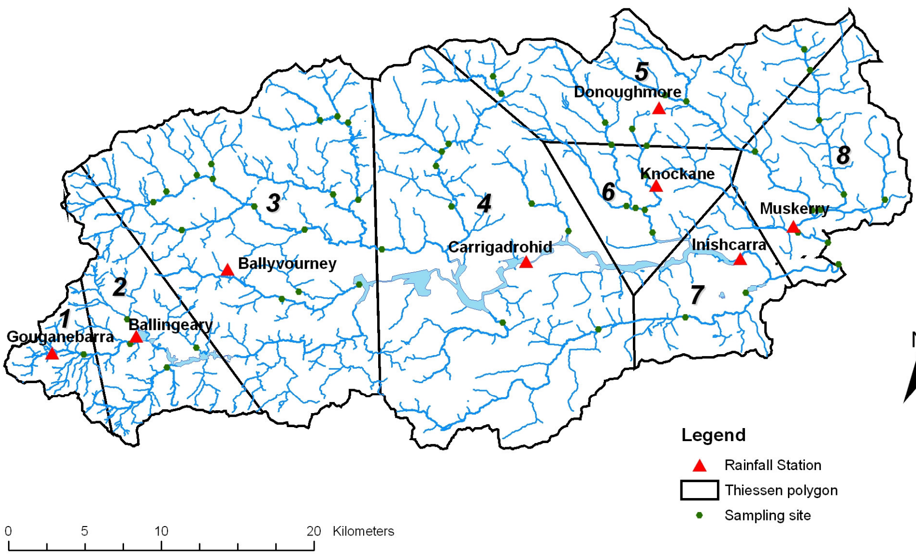

Figure 3.15: Selected rain gauges and corresponding Thiessen polygons.

Figure 3.16 shows the average corrected radar precipitation over the subcatchment S5 for a period of 10 days prior to the 5 samplings in storm flow conditions. The period of time represented on the graphs goes until 9am on the day of sampling. In the case of the subcatchment S5, this is 1 or 2 hours before the samples were collected. It can be seen on the 5 graphs that a storm event, more or less intense, happened each time during the previous 24 hours. It should be remembered that the graphs represent values that are averaged over the subcatchment. Rainfall may have been more intense in some part of the subcatchment and less intense and some others.

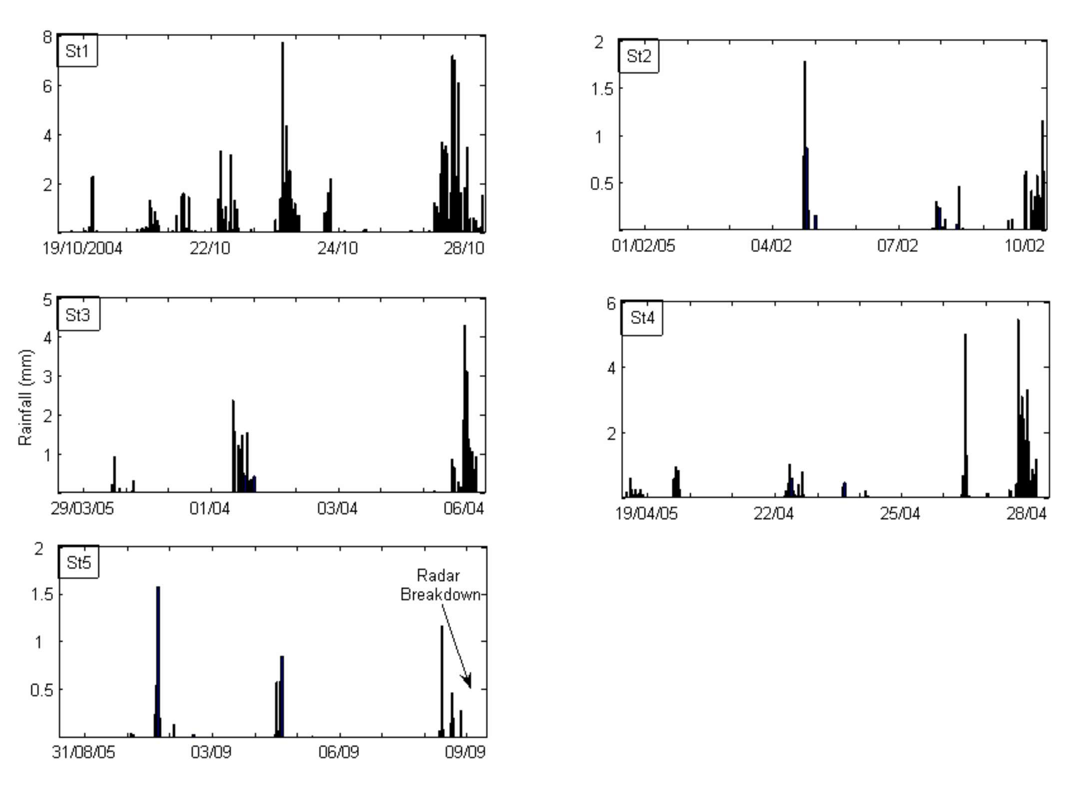

Figure 3.16: Hourly rainfall over subcatchment S5 for the 5 storm flow events.

As far as base flow samples are concerned, the radar was not working from the 18th of May to the beginning of June 2004. There is consequently no radar data available for the sampling B2 and as well the second part of the sampling B1 (B1b). There was anyway only little rain before the base flow samples were collected: almost no rain during the 4 days prior to the sampling for B1 (for both campaigns) and B3. Rain gauge data indicate that, for B2, light precipitations occurred during the days before the sample collection. Figure 3.17 shows the amount of rainfall over S5 for the 10 days prior to the different base flow samples.

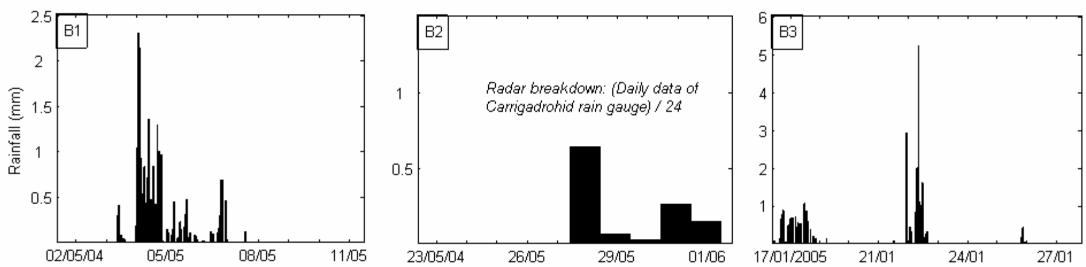

Figure 3.17: Hourly rainfall over subcatchment S5 for the 3 base flow events.

Table 3.12 shows the results obtained for the 56 subcatchments: amount of precipitation and maximal intensity during the 24 hours prior to the sampling (there is no intensity data available for St5 since the radar was not working).

Table 3.12: Rainfall data for the 56 subcatchments.

Subcatchment	Rainfall amount					Rainfall intensity			
	St1	St2	St3	St4	St5	St1	St2	St3	St4
N1	45.66	3.59	10.52	15.65	19.36	6.28	1.56	1.96	5.56
N2	51.75	4.07	11.68	18.61	18.74	7.20	0.84	2.81	4.54
N3	49.83	4.87	13.54	21.29	23.10	6.68	0.91	2.42	3.41
N4	49.68	4.88	13.61	21.40	23.21	6.89	0.34	2.81	3.46
N5	49.66	5.04	14.13	22.08	23.34	5.12	0.58	2.48	2.72
N6	54.16	5.43	14.72	23.91	22.08	6.39	1.10	2.67	3.61
N7	47.00	4.11	11.19	18.12	23.74	6.23	0.97	2.60	3.42
N8	43.90	4.02	11.07	16.94	25.50	6.34	1.06	2.15	2.45
N9	43.29	4.81	14.07	20.98	25.50	5.90	1.10	2.28	2.32
N10	70.45	19.40	23.07	30.15	13.83	9.05	2.03	3.37	9.41
N11	62.65	8.38	19.12	32.55	21.50	7.96	0.90	3.60	6.40
N12	65.38	8.14	19.24	33.11	22.32	7.30	0.80	3.33	5.66
N13	80.56	15.59	18.84	31.19	16.50	8.52	1.82	3.13	4.82
N14	79.52	10.52	17.77	29.06	16.40	9.44	2.15	3.12	5.04
N15	80.66	14.84	18.00	32.26	16.40	9.44	2.15	3.12	5.04
N16	86.28	15.67	18.49	34.87	16.40	9.44	2.15	3.12	5.04
N17	89.97	19.85	20.18	37.23	16.40	7.68	1.76	2.77	4.84
N18	65.56	8.00	18.92	33.10	22.40	6.30	1.29	3.60	6.21
N19	64.34	7.89	18.25	31.82	21.25	7.64	2.50	4.33	8.36
N20	65.20	7.85	18.94	33.23	23.26	7.80	0.92	3.47	5.10
N21	66.84	7.77	18.04	32.95	23.82	6.17	0.85	3.42	5.83
N22	58.58	7.02	16.27	26.37	25.50	6.02	0.88	3.14	3.96
N23	44.06	4.94	14.80	21.94	25.50	5.30	0.80	2.93	3.42
N24	42.97	3.96	11.44	16.90	25.50	5.15	0.80	2.88	2.99
N25	44.89	3.92	12.61	18.89	25.50	5.37	0.98	2.44	3.54
N26	47.18	4.03	12.85	19.17	25.50	5.34	0.98	2.45	3.54
N27	45.02	3.96	10.46	16.80	24.96	5.19	0.75	2.63	3.85
N28	44.98	4.09	11.34	17.22	22.99	5.59	0.82	2.58	3.87
N29	43.39	2.99	9.35	13.03	17.11	6.93	1.00	2.46	4.06
N30	44.23	3.27	9.75	13.18	18.20	5.58	0.63	2.41	2.96
N31	43.55	3.30	9.81	13.10	20.05	5.87	0.88	2.56	3.34
N32	41.54	3.52	10.45	14.72	25.50	5.86	1.10	3.04	3.64
N33	44.12	3.72	10.28	15.08	25.50	6.77	1.27	2.93	3.67
N34	43.44	2.24	8.35	12.46	14.60	5.61	0.56	2.58	2.63
S1	63.11	8.63	17.23	29.48	19.10	8.73	2.52	3.45	5.74
S2	56.92	3.02	15.24	33.66	20.87	8.02	1.33	3.10	3.83
S3	56.44	2.96	15.91	34.88	21.14	8.73	0.75	3.34	5.08
S4	54.73	2.91	17.27	38.81	21.50	6.89	0.84	3.51	4.19
S5	58.44	3.64	18.59	39.12	21.50	7.13	1.15	4.26	5.43
S6	65.40	8.17	16.00	26.38	16.35	8.19	1.72	3.04	3.50
S7	65.01	6.96	16.28	26.92	16.40	8.00	1.01	2.44	2.74
S8	64.76	7.93	15.05	27.37	16.32	9.14	1.08	2.77	2.22
S9	62.67	11.09	19.78	26.25	14.35	7.14	1.29	3.26	2.73
S10	75.93	20.35	25.39	43.15	20.00	8.08	2.47	5.55	4.01
S11	77.96	20.98	22.66	28.99	15.30	8.14	2.71	4.45	3.11
S12	76.33	22.07	27.44	47.21	22.10	11.89	1.36	6.07	3.03
S13	69.18	21.76	24.67	36.65	15.04	10.53	1.90	4.97	2.55
S14	77.61	11.80	15.70	36.64	16.40	10.12	1.08	2.87	2.54
S15	84.31	15.04	17.93	32.18	16.40	10.88	1.22	2.76	2.79
S16	80.46	12.09	15.41	25.69	16.40	8.02	1.97	2.57	3.83
S17	81.84	13.20	16.22	23.01	16.40	8.30	1.84	3.19	3.00
S18	86.42	14.75	16.37	27.23	16.40	8.28	1.83	3.19	2.96
S19	86.49	14.66	16.40	27.26	16.40	8.39	1.72	2.61	2.75
S20	81.96	15.20	18.71	30.18	15.91	7.89	2.07	2.78	3.59
S21	80.01	14.09	18.59	30.18	15.97	7.70	1.52	3.28	3.76
S22	77.75	13.19	18.48	29.57	16.21	7.70	1.52	3.28	3.76

3.4.3 Runoff risk

Surface runoff is often considered to be the dominant mode of phosphorus transport. Surface runoff or overland flow occurs when rainfall exceeds the maximum saturation level of the soil and all the depression storage is filled to capacity. Runoff can also occur more quickly if the rain intensity is greater than the infiltration rate of the soil. However in Ireland, where the rainfall intensities are generally quite low, saturation excess overland flow is more likely to happen than infiltration excess overland flow.

Some work has been done in Ireland to estimate the potential runoff risk of Irish Soils. The soil series in the General Soil Map of Ireland were classified into 13 groups with different runoff risks (Gleeson, 1992). The categories are said to be based on the nature and properties of the soil, site characteristics (slope, vegetation) and rainfall (intensity, amount). But soil types seem to be the main factor. Soil nature is anyway a result from climate, topography, parent material, etc. The scheme which ranks soils from class 1 (highest risk) to class 8 (no risk) is presented in table 3.13.

Table 3.13: Surface runoff risk classification.

class	Description
1	Persistently wet soils in high rainfall areas such as climatic peats, peaty gleys and peaty podzols; high runoff risk.
2	Soils of very low hydraulic conductivity (< 3 mm/day) in the sub-soil.
3	3a. Soils where seepage is prevalent on wet lower slopes. 3b. Soils of low hydraulic conductivity. 3c. Soils of moderately low hydraulic conductivity and some down-slope seepage
4	Basin and cut over peats and adjoining alluvial flat areas.
5	Soils on drier lower hill slopes with occasional seepage and wet hollows in wet weather.
6	Mainly dry soils in low rainfall areas: 6a. Soils at the bottom of slope of undulating topography. 6b. Heavy soils of shaley limestone origin. 6c. Soils in occasional wet hollows in flat to gently undulating topography
7	Dry soils with virtually no runoff risk: 7a. Permeable soils on morainic sands and gravel. 7b. Permeable limestone soils with shallow till cover; some with poor aquifer protection.
8	Soils on thin till cover and poor aquifer protection; no run off risk.

A map showing the distribution of soils with different runoff risk has been published (Gleeson, 1996) and was partially digitized for the purpose of this study (see Figure 3.18).

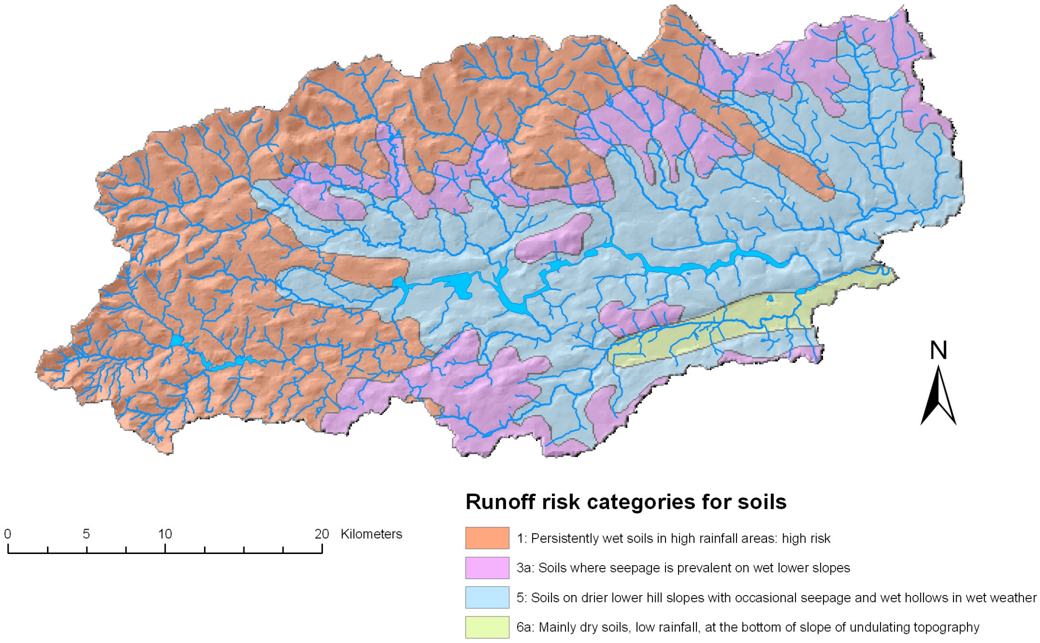

Figure 3.18: Runoff risk in the study area.

Four different risk classes can be found in the study area: 1, 3a, 5 and 6a. The original scheme was therefore simplified into: high, medium, low and very low risk. A numerical score was attributed to each class: respectively 4, 3, 2 and 1. On this basis an average risk was computed for each subcatchment by taking into account the areas included within the different classes. The scores, from 1 (very low) to 4 (high) are summarized in the table 3.14.

Table 3.14: Runoff scores for the 56 subcatchments.

N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19
2.5	2.3	3.0	2.7	3.1	2.8	3.0	3.3	3.6	3.1	3.8	3.8	3.8	3.4	4.0	4.0	4.0	3.9	4.0

N20	N21	N22	N23	N24	N25	N26	N27	N28	N29	N30	N31	N32	N33	N34	S1	S2	S3	S4
4.0	4.0	4.0	3.8	3.5	3.8	3.5	2.5	2.9	2.3	2.4	2.6	2.7	2.8	2.2	3.1	2.1	2.2	2.4

S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22
2.5	3.4	3.1	3.6	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.9	3.8	3.6

Chapter 4

Field Measurements

4.1 Water Quality data

The samples collected in the 56 different sites were analysed for Soluble Reactive Phosphorus (SRP) and Total Phosphorus (TP) and for a number of other parameters: Total Oxidised Nitrogen (TON), Suspended Solids (SS), conductivity, pH, alkalinity, chloride, sodium, potassium, magnesium, calcium and ammonia. The analyses were carried out by the UCC Aquatic Service Unit.

4.1.1 Phosphorus Measurements

Total Phosphorus (TP): includes the amount of phosphorus in solution (reactive) and in particle form. It is measured in milligrams or micrograms per litre ($mg.l^{-1}$).

Soluble reactive phosphorus (SRP): is a measure of orthophosphate in solution, which is the filterable (soluble, inorganic) fraction of phosphorus. The separation of "dissolved" (or "soluble") and "particulate" P phases is based on filtration using 0.45 μm membrane filters. Orthophosphate is the form of phosphorus directly taken up by plant cells. SRP is therefore considered to represent the biologically available fraction of P and is then important in term of eutrophication. It is consequently the form of P that will mainly be considered in this study. Natural concentrations of orthophosphate in freshwaters vary from catchment to catchment depending upon factors such as geology and soil type. Natural ranges are considered to be approximately 0 to 10 μg P/l.

SRP is also referred to as dissolved phosphorus (DP), dissolved reactive phosphorus (DRP) or molybdate reactive phosphorus (MRP). The problem with the latter is that the term MRP is used, ambiguously, in two distinct ways:

- for filtered samples: in this case, MRP is equivalent to SRP measurements
- for unfiltered samples: in this case, MRP is equivalent to SRP plus a fraction of particulate P. (Jarvie, 2002)

Quite surprisingly, the 1998 Irish Phosphorus Regulations do not specify if MRP should be measured on filtered or unfiltered samples.

In some studies, measurements of phosphorus in fresh waters also include Total Dissolved Phosphorus (TDP), which is the total filterable phosphorus, including SRP and dissolved hydrolysable phosphorus. TDP gives access to Particulate Phosphorus (PP) defined by:

$$PP = TP - TDP \qquad (4.1)$$

Particulate P is less available in aquatic systems in the short term, but becomes more available over time.

4.1.2 Results

Table 4.1 shows the results of the analyses for SRP (which is the form of phosphorus we are most interested in) and that for the different subcatchments and sampling campaigns.

Table 4.1: SRP concentrations (mg/l).

	SRP Storm Flow					SRP Base Flow			
Subcatchment	**St1**	**St2**	**St3**	**St4**	**St5**	**B1a**	**B1b**	**B2**	**B3**
	28/10/2004	*10/02/2005*	*06/04/2005*	*28/04/2005*	*09/09/2005*	*11/05/2004*	*24/05/2004*	*01/06/2004*	*27/01/2005*
N1	0.134	0.059	0.063	0.146	0.166	0.025		0.066	0.038
N2	0.166	0.050	0.081	0.190	0.137	0.026		0.063	0.047
N3	0.076	0.023	0.036	0.064	0.051	0.011		0.017	0.022
N4	0.178	0.038	0.072	0.128	0.156	0.015		0.029	0.029
N5	0.056	0.024	0.030	0.052	0.186	0.008		0.013	0.018
N6	0.088	0.034	0.043	0.067	0.286		0.010	0.031	0.020
N7	0.199	0.085	0.081	0.152	1.347		0.011	0.027	0.029
N8	0.189	0.038	0.039	0.097	0.344		0.021	0.041	0.028
N9	0.058	0.018	0.021	0.033	0.099	0.008		0.006	0.013
N10	0.058	0.024	0.019	0.022	0.138	0.009		0.013	0.018
N11	0.023	0.021	0.008	0.012	0.062	0.008		0.006	0.008
N12	0.026	0.030	0.013	0.015	0.034	0.007		0.004	0.007
N13	0.046	0.045	0.026	0.027	0.053	0.008		0.009	0.013
N14	0.038	0.024	0.020	0.036	0.033		0.006	0.006	0.012
N15	0.029	0.099	0.020	0.041	0.029	0.010		0.015	0.017
N16	0.052	0.038	0.020	0.020	0.066	0.008		0.007	0.010
N17	0.015	0.026	0.014	0.011	0.020			0.005	0.008
N18	0.023	0.015	0.006	0.012	0.035	0.006		0.002	0.005
N19	0.020	0.022	0.007	0.008	0.015	0.004		0.002	0.005
N20	0.013	0.007	0.006	0.006	0.020	0.005		0.002	0.004
N21	0.010	0.006	0.004	0.006	0.006	0.002		0.002	0.002
N22	0.003	0.003	0.003	0.001	0.004	0.003		0.002	0.002
N23	0.020	0.010	0.009	0.012	0.019		0.004	0.005	0.008
N24	0.451	0.047	0.036	0.091	0.238	0.021		0.031	0.023
N25	0.069	0.045	0.033	0.073	0.235	0.012		0.024	0.019
N26	0.030	0.051	0.026	0.027	0.112		0.006	0.017	0.022
N27	0.078	0.046	0.021	0.062	0.124	0.015		0.03	0.025
N28	0.089	0.035	0.053	0.090	0.125	0.011		0.042	0.028
N29	0.139	0.059	0.076	0.129	0.184	0.023		0.071	0.043
N30	0.114	0.063	0.072	0.121	0.243	0.031		0.066	0.043
N31	0.104	0.061	0.064	0.109	0.205			0.061	0.041
N32	0.089	0.063	0.052	0.090	0.122		0.016	0.026	0.035
N33	0.083	0.065	0.076	0.103	0.116			0.03	0.050
N34	0.108	0.101	0.102	0.129	0.344		0.089	0.14	0.066
S1	0.135	0.028	0.031	0.078	0.116	0.009	0.009	0.01	0.026
S2	0.128	0.022	0.032	0.131	0.051	0.007		0.014	0.023
S3	0.108	0.018	0.047	0.130	0.084			0.014	0.021
S4	0.084	0.021	0.050	0.110	0.079	0.008		0.02	0.026
S5	0.067	0.020	0.036	0.073	0.083	0.007		0.018	0.025
S6	0.019	0.009	0.008	0.012	0.003	0.003		0.001	0.010
S7	0.055	0.021	0.018	0.042	0.034			0.002	0.024
S8	0.014	0.007	0.007	0.008	0.006			0.007	0.022
S9	0.004	0.007	0.003	0.003	0.006	0.003		0.002	0.003
S10	0.004	0.002	0.003	0.002	0.006	0.005		0.001	0.002
S11	0.010	0.010	0.006	0.005	0.020		0.004	0.003	0.004
S12	0.002	0.001	0.002	0.002	0.006		0.003	0.002	0.000
S13	0.016	0.023	0.017	0.013	0.018		0.004	0.004	0.007
S14	0.015	0.007	0.012	0.010	0.011		0.005	0.003	0.005
S15	0.006	0.009	0.012	0.007	0.014	0.004		0.003	0.004
S16	0.015	0.012	0.005	0.007	0.006		0.005	0.004	0.004
S17	0.008	0.022	0.017	0.017	0.020		0.009	0.01	0.012
S18	0.006	0.015	0.012	0.013	0.018		0.010	0.014	0.010
S19	0.008	0.010	0.010	0.009	0.013	0.010		0.018	0.009
S20	0.009	0.012	0.017	0.012	0.013	0.006		0.007	0.011
S21	0.017	0.014	0.016	0.013	0.015	0.007		0.121	0.010
S22	0.025	0.015	0.018	0.018	0.019	0.007		0.009	0.013

In Figure 4.1, the SRP concentrations at all sites for the different sampled events are shown. Some values (the circled ones) differ more or less markedly from the other values in the same campaign or at the same site. To explore further these discrepancies, some descriptive statistics were carried out in relation to the different sampling campaigns and are shown in Table 4.2.

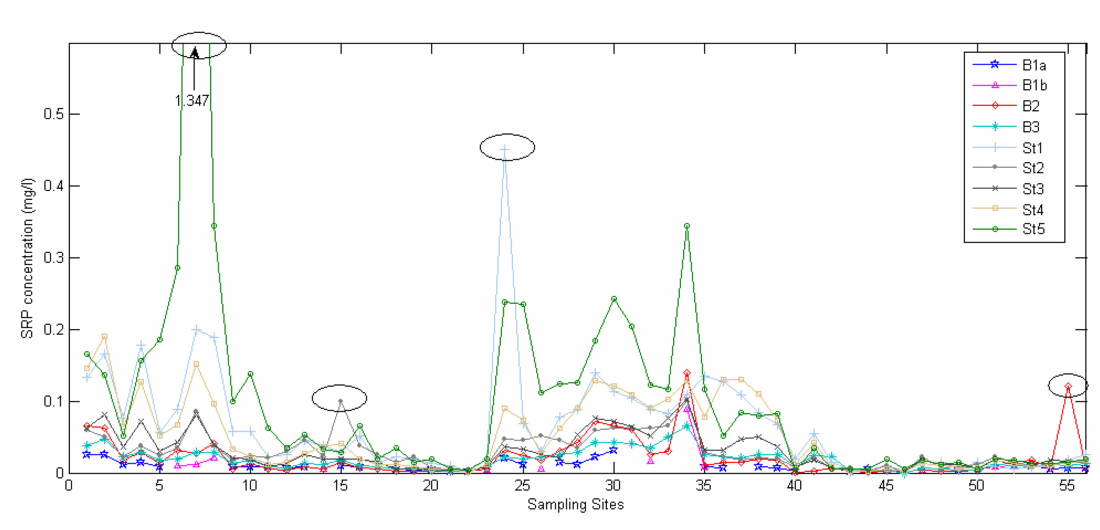

Figure 4.1: SRP concentrations at the 56 sites.
(site 1=N1, site 34=N34, site 35=S1, site 56=S22)

Table 4.2: Descriptive Statistics for the different sampling campaigns.

	Sample	N	Minimum	Maximum	Mean	Std. Deviation	Mean + 3 StdDev
Storm Flow	SRP St1	56	0.002	0.451	0.065	0.075	0.289
	SRP St2	56	0.001	0.101	0.030	0.024	0.101
	SRP St3	56	0.002	0.102	0.029	0.025	0.104
	SRP St4	56	0.001	0.19	0.052	0.050	0.203
	SRP St5	56	0.003	1.347	0.107	0.191	0.680
Base Flow	SRP B1a	35	0.002	0.031	0.010	0.007	0.031
	SRP B1b	16	0.003	0.089	0.013	0.021	0.076
	SRP B2	56	0.001	0.14	0.021	0.028	0.106
	SRP B3	56	0	0.066	0.018	0.014	0.061

Statiscally, outliers are often operationally defined as values that are falling outside about ±3 standard deviations of the mean of the sample population. A maximum admissible value can therefore be defined and is indicated in the last column of Table 4.2. Thus, in storm flow conditions, 2 samples appear to be deviating significantly from the other values belonging to the same sampling campaigns: N24 during St1 and N7 during St5. Deleting these cases would result in a loss of information when calculating for example the average SRP concentration in storm flow conditions at these two sites. Concentrations actually tend to be high at this site in storm flow conditions. But at the same time, considering them without any change would bias the results. It was therefore decided to take the same concentration for N24 as the one at N8 (0.189 mg/l), which is the neighbouring subcatchment with similar characteristics. For N7, an average value between the upstream sites (N24 and N8) and the downstream site (N4) was estimated (0.224mg/l). As far as N15 during St2 is concerned, the SRP concentration is just at the limit of the admissible range but is too different from the other storm flow concentrations. It was therefore replaced by the average concentration in storm flow at N15.

In base flow conditions, the sample taken at S21 during B2 is outside of the admissible range and differs too much as well from the other samples at the same site. The average concentration in base flow was consequently used instead. As far as N34 is concerned, since the three values for B1b, B2 and B3 were consistently high, they were kept the same.

The degree of correlation between the different sampling campaigns was investigated using SPSS 14.0 (all the statistical analyses were carried out using this software). A Spearman's correlation, which is a non-parametric statistic, was preferred to a classical Pearson's one. This test is based on the ranking of the variables without making any assumptions about the frequency distribution of the variables. Here, we are actually more interested to see how the different sites react and rank between each other than to compare the values themselves. The correlation matrix is given in Table 4.3. In all the statistical analyses, the significance of the results will be denoted by symbols *, **, and *** for significance levels of 0.05, 0.01 and 0.001, respectively (ns indicates a non-significant result).

Table 4.3: Correlation matrix of Spearman's Rho values for the different sampling campaigns.

	SRP St1	SRP St2	SRP St3	SRP St4	SRP St5	SRP B1a	SRP B1b	SRP B2	SRP B3
SRP St1	1 (N=56)								
SRP St2	0.78 *** (N=56)	1 (N=56)							
SRP St3	0.90 *** (N=56)	0.84 *** (N=56)	1 (N=56)						
SRP St4	0.94 *** (N=56)	0.80 *** (N=56)	0.96 *** (N=56)	1 (N=56)					
SRP St5	0.89 *** (N=56)	0.83 *** (N=56)	0.87 *** (N=56)	0.85 *** (N=56)	1 (N=56)				
SRP B1a	0.82 *** (N=35)	0.86 *** (N=35)	0.84 *** (N=35)	0.82 *** (N=35)	0.84 *** (N=35)	1 (N=35)			
SRP B1b	0.67 ** (N=16)	0.82 *** (N=16)	0.85 *** (N=16)	0.88 *** (N=16)	0.80 *** (N=16)	/ /	1 (N=16)		
SRP B2	0.74 *** (N=56)	0.74 *** (N=56)	0.86 *** (N=56)	0.81 *** (N=56)	0.77 *** (N=56)	0.85 *** (N=35)	0.93 *** (N=16)	1 (N=56)	
SRP B3	0.87 *** (N=56)	0.79 *** (N=56)	0.93 *** (N=56)	0.92 *** (N=56)	0.81 *** (N=56)	0.84 *** (N=35)	0.89 *** (N=16)	0.84 *** (N=56)	1 (N=56)

The correlation coefficients between the different pairs of events are highly significant: the significance values are all lower than 0.001 except for the pair (St1, B1b). The degree of correlation appears to be strong between the events with the same type of flow conditions. Among the storm flow events, all the correlation coefficient are actually greater than 0.78

and, among the base flow events, none are lower than 0.84. Considering the good correlation between the different sampled events, it was decided that, when the temporal effects would not need to be considered, it would be possible to work with the average values of the parameters for both types of flow conditions (base and storm flow). The average SRP concentrations for the 56 different sites and for storm and base flow are shown in Figure 4.2.

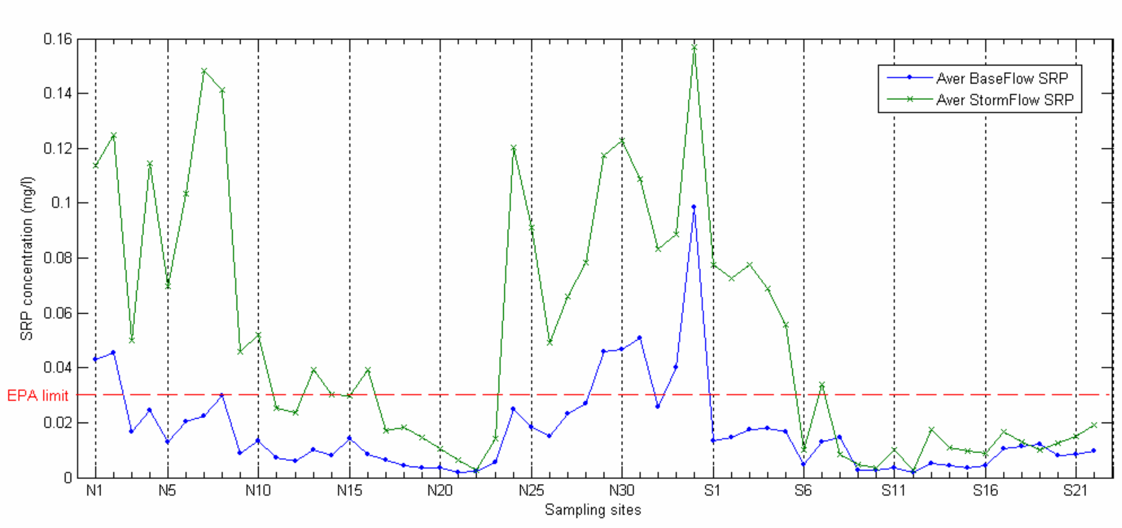

Figure 4.2: Average SRP concentrations for the 56 sites in base and storm flow conditions.

4.1.3 Analysis of results

It can be seen from Figure 4.2 that, in base flow conditions, 7 sites are above the annual EPA limit for median MRP set at 30 µg/l. It is therefore very unlikely that these sites comply with the target over the whole year. The sites in question are N33, N31, N30 and N29 on the Martin, N34 on the Dripsey and N2 and N1 on the Shournagh downstream of its confluence with the Martin (See Figure 4.3). It is obvious again that the Martin is facing some serious problems in term of water pollution. During storm events (see Figure 4.4), the Martin river still shows high concentrations of phosphorus but so do other rivers in the study area, like the Dripsey, the Bride and the Shournagh.

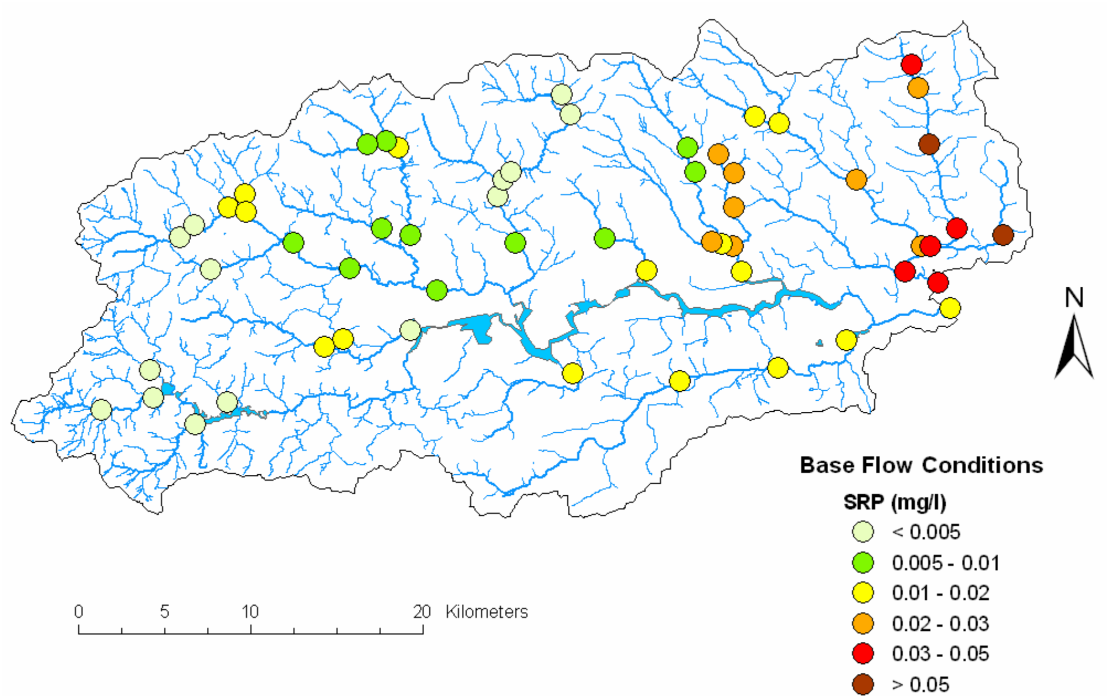

Figure 4.3: Average SRP in Base Flow conditions.

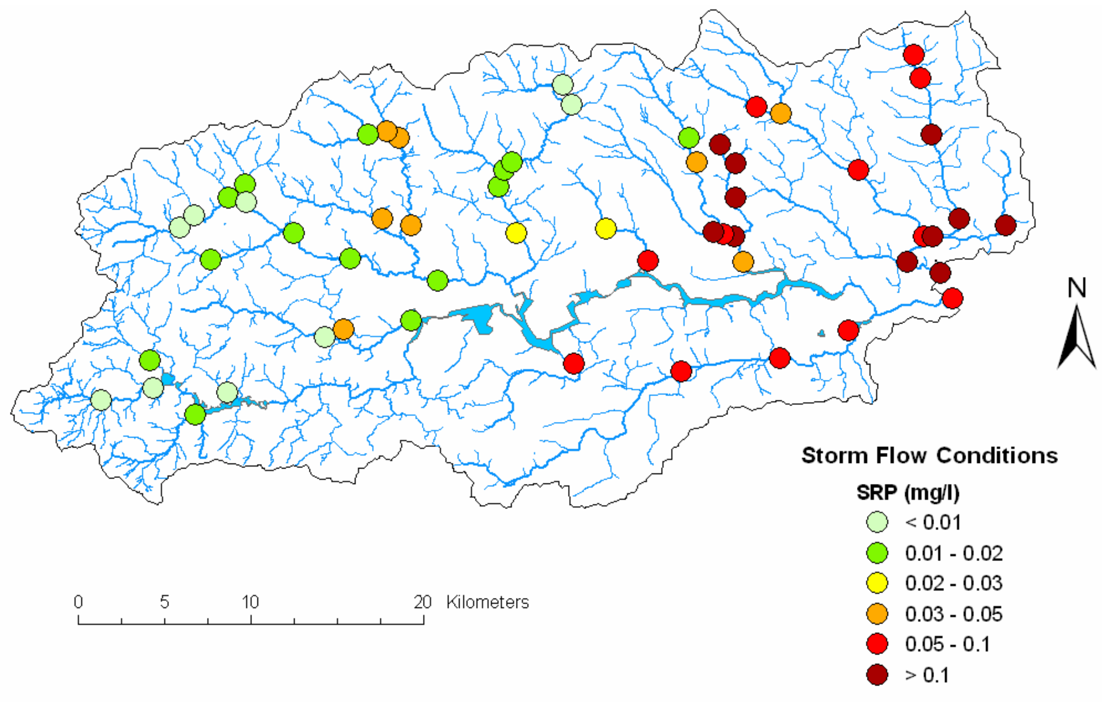

Figure 4.4: Average SRP in Storm Flow conditions.

Except for 2 sites (S8 and S19), the average SRP concentrations were always higher on average during storm flow than during base flow conditions, typically about 3 times higher on average (See Figure 4.2). It should be remembered that storm flow conditions are associated with higher discharge in the rivers. Depending on the size of the river and the type of flow regime, it can be said that discharge could typically be up to 20 times higher in storm flow. As a result, the phosphorus load in the rivers and the exports from the subcatchments are much greater during these events.

The fact that SRP concentrations are mostly increasing with increased discharge is probably due to the nature of phosphorus sources. If the point sources were more important than diffuse sources, an increased river discharge would then dilute the pollution load and maybe cause a decrease in concentration of soluble reactive phosphorus. In a comparison of concentration versus discharge relations for streams of different sizes and locations around the world (Meyer, 1988), it was found that while TP consistently increased as discharge increased, SRP concentrations increased, decreased or remained constant.

A correlation between average SRP concentrations in both types of condition can be noted in Figure 4.5, but should be interpreted carefully in view of:

- the limited number of events sampled and
- the difference in amplitude of the concentrations between the different events (especially during storm flow).

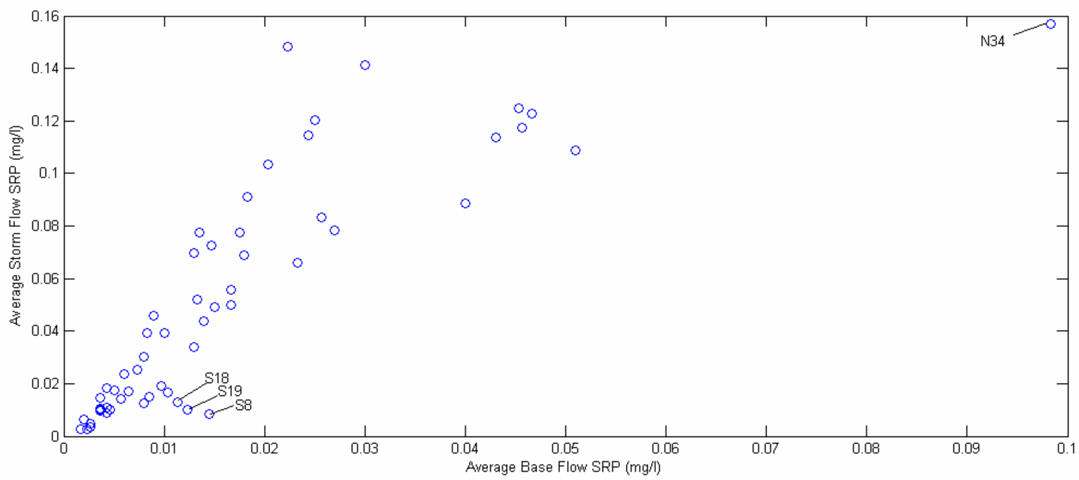

Figure 4.5: Relationship between average SRP concentrations in base flow and in storm flow.

This result first suggests that the majority of the sites were apparently not affected by a significant point source pollution which would have “skewed” the concentrations in base flow. The sites S8, S18 and S19 showing very low average SRP concentrations, their divergence from the general trend is not really significant. But N34, which is consistently showing high base flow values and is therefore falling outside the main pattern, could be considered as potentially affected by a point source pollution.

This relationship between base and storm flow tends also to show that, in term of soluble reactive phosphorus concentration in the river, the different subcatchments seem to react in a similar way to the occurrence of rainfall events. In the previous chapter, some concerns were raised about the timing of the sampling in relation to the position on the hydrograph (sample collected before, at, or after the peak discharge). With this result, it seems that the timing of the sample collection did not have too much influence on the SRP concentrations.

4.2 Soil Chemistry data

4.2.1 Methods

Soil samples were taken about every 2 km on a grid network covering the whole catchment. The locations are shown in Figure 4.14. The 341 samples were analysed for available P and K, P desorption and organic matter. The tests were carried out by Teagasc at the Johnstown Castle Laboratories, in Wexford.

Morgan's P

Plant available P was measured using the agronomic Morgan's P test (Morgan, 1941). This reagent (sodium acetate at pH 4.8) is also the one used as a national Irish soil test to assess the fertility status of agricultural soils. A volume of soil being analysed, the result is then expressed in mg P/l.

Iron-Oxide Paper Strip P (P FeO)

This test, first developed by Menon et al. (1988), is used as an indicator of labile inorganic P, and involves shaking soil solution with an iron-oxide-impregnated paper strip, which acts as a constant sink for labile inorganic P. The unit of P FeO is mg P/kg soil.

Organic Matter

Organic matter (OM) was measured by loss on ignition and the results are expressed as percentage weight loss.

4.2.2 Testing Soil for P

Many different extraction procedures are currently in use to estimate the phosphorus status of soils. Soil P tests were initially developed for agronomic purposes. But nowadays, methods tend to be divided into three categories: agronomic P tests, environmental P tests and total P tests, each one having a different purpose.

- Environmental Soil P tests only extract the portion of soil P which is easily lost through surface runoff or subsurface flow. Therefore very mild extractants are used in an attempt to simulate overland flow concentrations.
- Agronomic tests have been designed as an indicator of plant available P for crop growth and fertilizer recommendations. They consequently use stronger extractants than environmental tests.

- Total P tests use very strong extractants and heating to extract the more recalcitrant forms of soil P.

P status:

Soil phosphorus testing in Ireland uses Morgan's reagent from samples taken to 10 cm depth for agronomic recommendations. A number of other European countries use Olsen P (0.5 molar sodium hydrogen carbonate at pH 8.5) as a standard Soil Test P (STP) method. The Irish Agriculture authority (Teagasc) has developed a P index classification depending on the level of available P in soil (or P status). The ranges are shown in the following table:

Table 4.4: Soil P index system (Teagasc, 2004)

Soil P Index	Soil P ranges [Morgan's P] (mg/l)		Response to fertilizers
	Mineral Soil	Peat	
1 - Very Low	0.0 - 3.0	0 - 10	Definite
2 - Low	3.1 -6.0	13 - 20	Likely
3 - Medium	6.1 - 10.0	21 - 30	Unlikely/Tenuous
4 - Sufficient/Excess	above 10.0	above 30	None

Higher ranges have been used for peat than for mineral soils because of its inability to bond with or store P. But from an environmental point of view, Teagasc advises not to build up the soil P level too high in peats, since P tends not to accumulate and is readily leached or washed out each winter.

Depending on the agricultural use, a soil P index is set as a target. For grassland, which is the main land use in Ireland, it is generally said that no P should be applied on a soil with concentrations above 10 mg/l. It is also suggested (Tunney, 2001) that the optimum grassland production is reached for a Morgan's P of 4 to 6 mg/l and that the level of soil P should be at the lower end of this range for good water quality.

P desorption:

Iron oxide strip P (P FeO) was originally developed, and is still used in some countries, as agronomic STP methods; other countries use it for environmental testing. It actually simulates long-term desorption using a sink for P. This test provides a rigorous quantification of short-term desorbable P (Van der Zee, 1987). It was initially thought to primarily represent bioavailable, dissolved inorganic P (Menon, 1988; Van der Zee, 1987). However, it was found later that, whilst it was effective at extracting almost all dissolved inorganic P from soil solutions, much of the dissolved organic P fraction was extracted too. Thus the P FeO test provides a good indication of desorbable, though not necessarily inorganic, phosphorus.

4.2.3 Raw Data

4.2.3.1 Morgan's P

The frequency distribution of the Soil P test (Morgan's) is shown in Figure 4.6. The average STP for the 341 soil samples is 11.6 mg.l^{-1}. It is higher than the national average which was 8.5 for 2003-2004 according to Teagasc but quite consistent with the results at the county level (See Table 4.5). A higher proportion of samples with STP>10 mg.l^{-1} can also be noticed in the study area compared to the county.

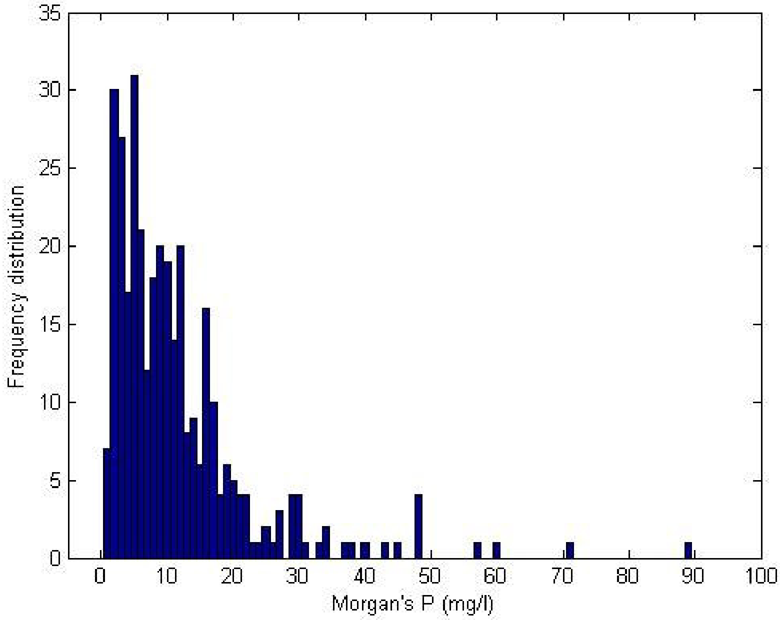

Figure 4.6: Soil P Test (Morgan's P) distribution (341 samples).

Table 4.5: Soil P Test samples Repartition and Comparison.

	No of samples	Mean P mg/l	Percentage of Samples with Phosphorus Content			
			0-3	3-6	6-10	>10 mg/l
Study Area	341	11.6	14.1	22	19.9	44
County Cork *(Teagasc)*	2574	10.5	9	25	29	37
Ireland *(Teagasc)*	90284	8.5	15	34	26	26

4.2.3.2 Organic Matter

The frequency distribution of the Organic Matter content is shown in Figure 4.7. The average percentage of OM for the 339 soil samples is 14.2%.

Peat soil is often described as a soil containing at least 30% of Organic Matter. With this definition, around 10 of our samples were taken in peat soil.

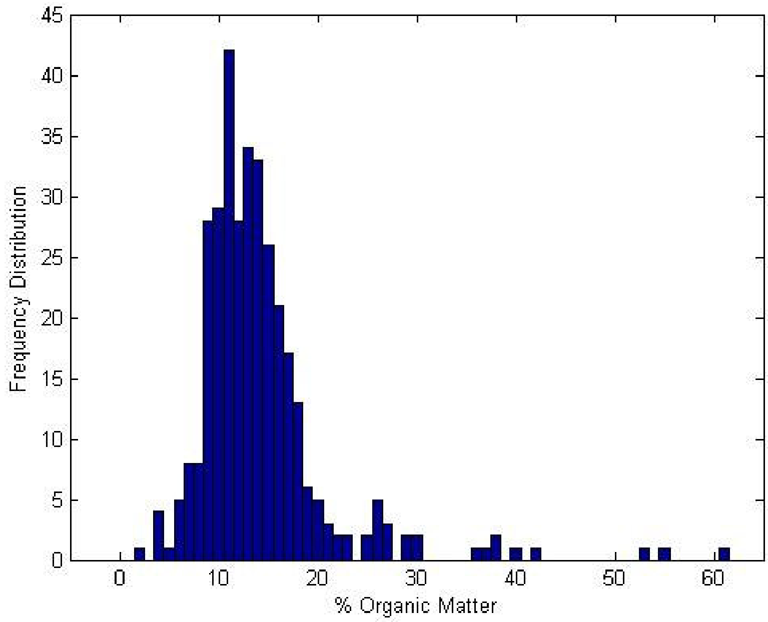

Figure 4.7: Organic Matter content distribution (339 samples).

4.2.3.3 P Desorption

As indicated in the description of the soil test methods, P FeO is expressed on a weight of soil basis (mg $P.kg^{-1}$) while the unit used for Morgan's P test is mg $P.l^{-1}$. This makes the comparison between both tests difficult. For example, when testing for desorption, a smaller volume of soil will be analysed for a dense mineral soil than for a light peaty soil. It was therefore decided to express phosphorus desorption data on a soil volume basis to make the units compatible with the Morgan's P test and take into account the large variation in bulk density across mineral and peat soils.

To do so, the soil bulk density was necessary but was not measured when carrying out the different tests. It was then decided to use a pedotransfer function based on ignition loss to estimate the soil bulk density. The percentage of ignition loss is actually equivalent to the organic matter content. The relation is given in equation (4.2) (Jeffrey, 1970):

$$BD = 1.482 - 0.6786 \log(\%IgL) \tag{4.2}$$

where,

BD is the bulk density in g/ml,

%IgL is the percentage of ignition loss.

The results for P desorption expressed in mg $P.l^{-1}$ are shown in a frequency distribution graph (Figure 4.8). The average P FeO is 22.8 mg P/kg.

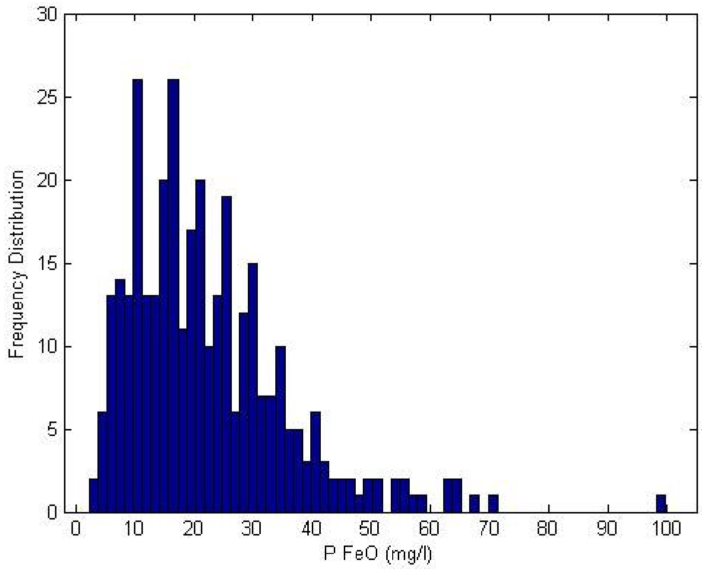

Figure 4.8: P Desorption (FeO Paper Strip P) distribution (339 samples).

4.2.4 Analysis

As indicated in a study about the major Irish agricultural soils (Tunney, 2002), P desorption appears to be related to the Morgan's STP in the soil. In addition, strong linear relationships between P FeO and bioavailable P have also been recorded in surface runoff (Sibbeson, 1997).

On Figure 4.9, the P desorption clearly increases with the amount of phosphorus available in the soils, which would tend to show that high P status soils desorb more P to solution than low P status soils. The quite good relationship can be seen on Figure 4.9, even if the points are too dispersed to get a high correlation (R^2=0.51).

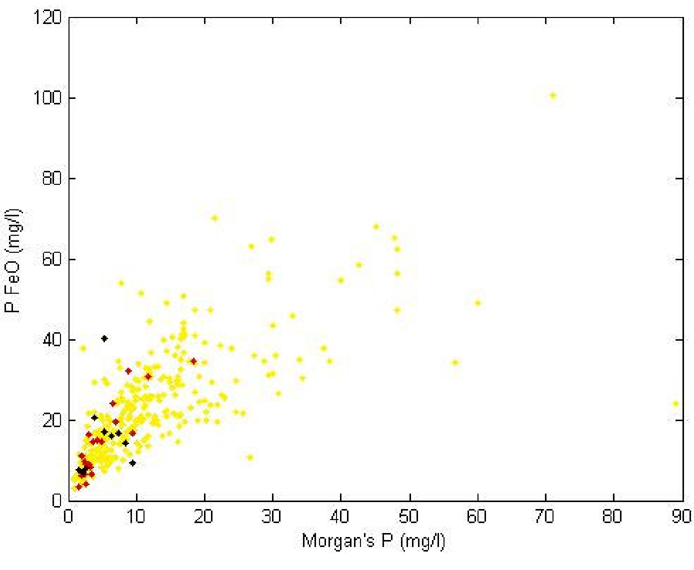

Figure 4.9: P FeO vs. STP (Morgan's P), + OM content [yellow<20%, red=20-30%, black>30%].

Another result of this study does not seem to be verified here. Tunney (2002) indicated that soils with high organic matter content had lower P FeO compared to mineral soils at similar STP levels. From Figure 4.9, it can be seen that the red and black points corresponding to the higher OM content are not concentrated at the bottom of the cloud of points as it could be expected. Thus, it can not be concluded here that organic matter inhibits desorption capacities of soils.

This graph suggests in fact that soils with a high OM content tends to have a low P status. It can be seen well on the next graph (Figure 4.10). Two clear trends are noted:

- Soils with a high OM content (>20%) all have a low P status,
- Soils with a high P status all have a low OM content (<20%).

For the rest of the samples, low OM and low P status are associated.

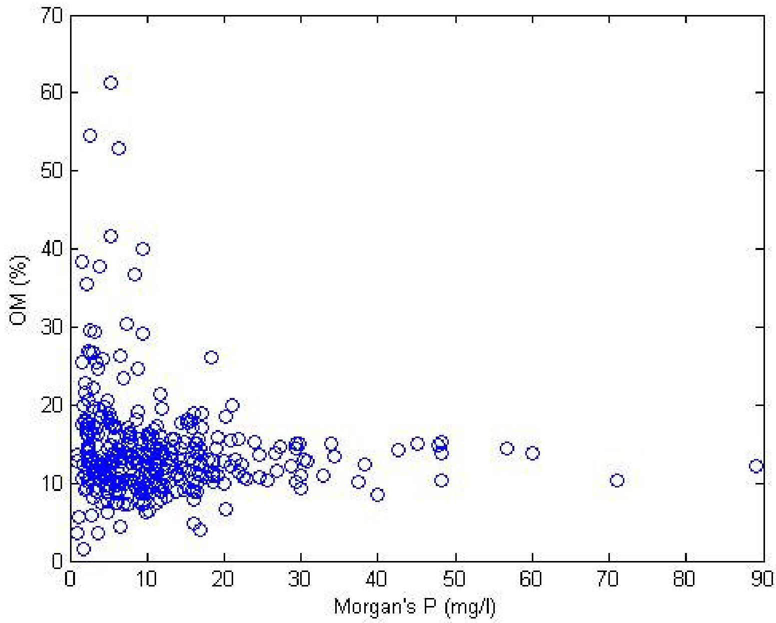

Figure 4.10: OM content vs. STP (Morgan's P)

This result is explained in the literature by the adverse effect of organic matter on P adsorption (Daly, 1999). In acidic conditions, soils with high Iron and/or Aluminium content generally have a greater potential to adsorb P. This is explained by the fact that P is held in the form of iron and aluminium phosphates. But it has been found that OM was competing with P for sorption sites and that sorption sites were also eliminated by organic acids present in soils. This competitive effect associated with the removal of Fe and Al by the organic ions would consequently explain the reduction in P retention for soils with high organic matter content.

From this, we can remember the fact that peat soils seem to have a poor capacity for storing P and that the concept of P build-up used for mineral soils does not really apply in the case of peat soils. If P is applied as fertilizer to peat soils, then it is likely to remain in the soil solution or as readily-available P if not immediately taken up by crop. In the case of a rainfall event associated with overland flow, surplus P could be lost to water.

4.2.5 Spatial Interpolation

Our soil data were collected as point data so the next step is to transform them into spatially continuous data. The prediction of values between actual sampling points is called interpolation. This transformation is a way to produce a map of the different soil properties we are interested in: Soil P, P desorption and Organic Matter.

The interpolation techniques commonly used in agriculture include Inverse Distance Weighting (IDW) and Kriging (Kravchenko, 1999). Both methods estimate values at unsampled locations based on the measurements from the surrounding locations with certain weights assigned to each of the measurements. The problem is that, usually, soil sampling for agronomic purpose is made at field scale on 100 m grids for instance. Here, 341 samples were taken to cover an area of 1135 km^2, using a 2 km grid (1km in a part of the Dripsey catchment). At least, the fact that the sampling was done based on a regular grid is likely to increase the precision of the interpolation compared to a totally random sampling (Burgess, 1981). As a consequence, the selection of an interpolation method was then critical.

There are two types of interpolation techniques: deterministic and geostatistical. The deterministic ones, such as IDW, are based on mathematical functions while the geostatistical ones, such as Kriging, rely both on statistical and mathematical methods. Three of the most "popular" method of interpolation are presented here:

Inverse Distance Weighting: this method is based on the premise that data points are weighted by the inverse of their distance to the estimation point. This approach has the effect of giving more influence to nearby data points than those farther away.

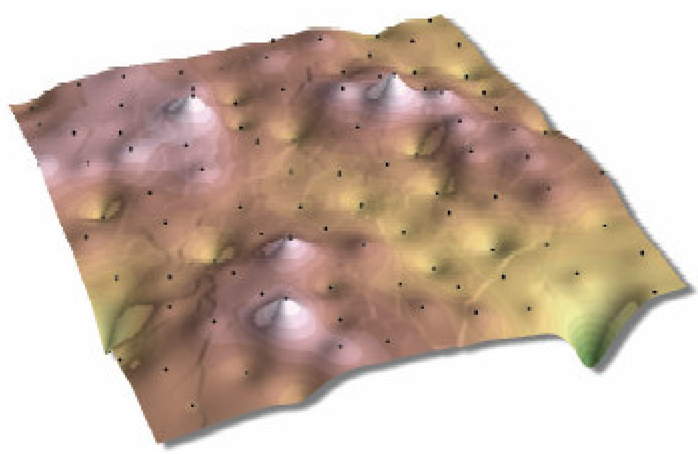

Figure 4.11: Example of Inverse Distance Weighting Interpolation (ESRI, 2004).

Natural Neighbour: this method of interpolation, said to be one of the most robust, is based on the same basic equation as the one used in IDW interpolation. It produces a conservative result by finding weighted averages, at each interpolation point, of the functional values associated with the subset of data that are natural neighbours of each interpolation point.

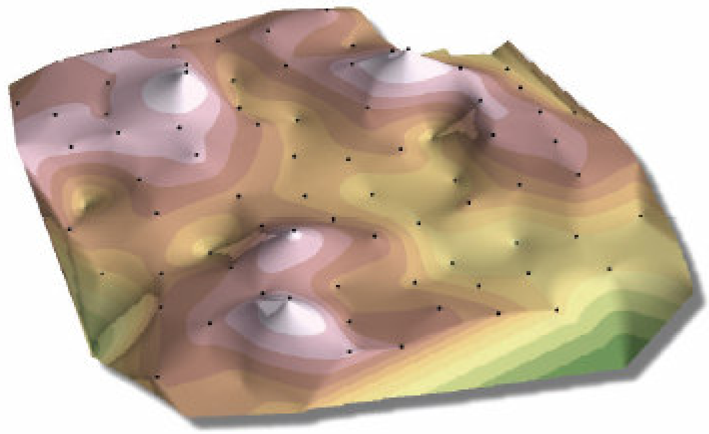

Figure 4.12: Example of Natural Neighbour Interpolation (ESRI, 2004).

Kriging: this method assumes that the direction or the distance between sample points reflects a spatial correlation that can be used to explain variation in the surface. The predicted values are derived from the measure of the statistical relationship amongst the measured points (autocorrelation) using weighted average technique.

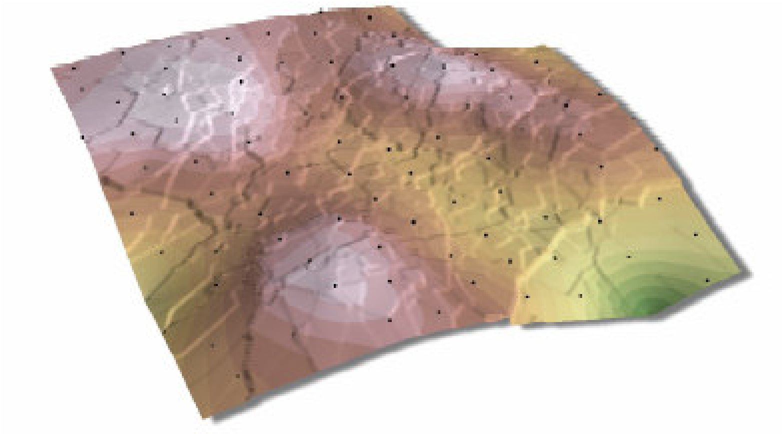

Figure 4.13: Example of Kriging Interpolation (ESRI, 2004).

As it can be seen on the different illustrations, Kriging tends to smooth the data quite heavily and avoid the "bulls eyes" around high and low values. Considering the lack of spatial accuracy of our dataset and the occurrence of some very high values (especially in the case of Morgan's P), the Kriging method, which essentially gives the general trend of the data, was selected.

The spatial interpolation tools available in ArcView were used to perform the ordinary Kriging interpolations. The results are shown in the figure 4.11, 4.12 and 4.13. With the Kriging method, the resulting surfaces do not pass through the input points. It is especially true for the extreme values. It explains that the ranges of the values are narrower after interpolation. As far as organic matter is concerned, for example, it is not possible any more to locate peat soils with the threshold of 30% organic matter content. Due to the smoothing of the interpolation, the limit value has actually been pulled down.

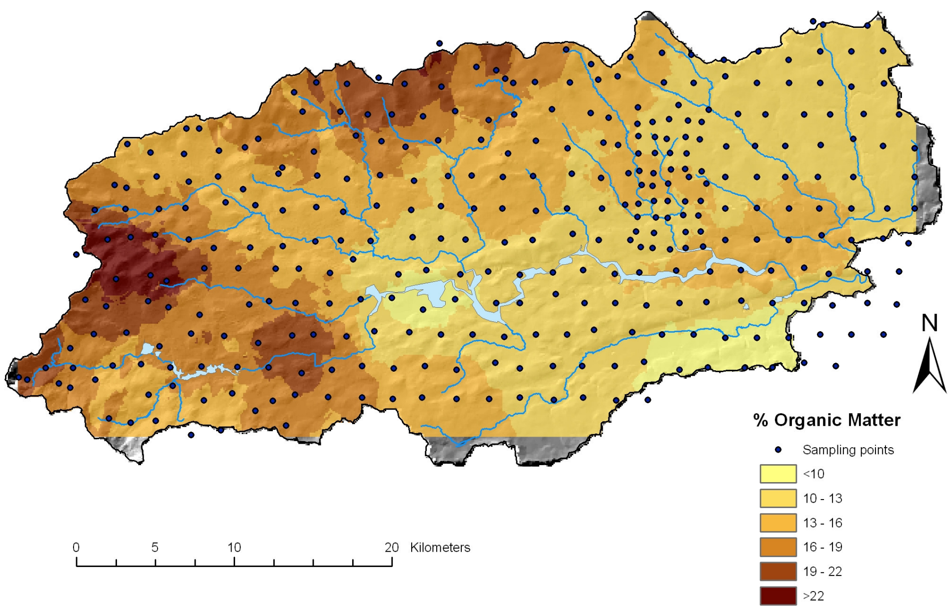

Figure 4.14: Organic Matter Content.

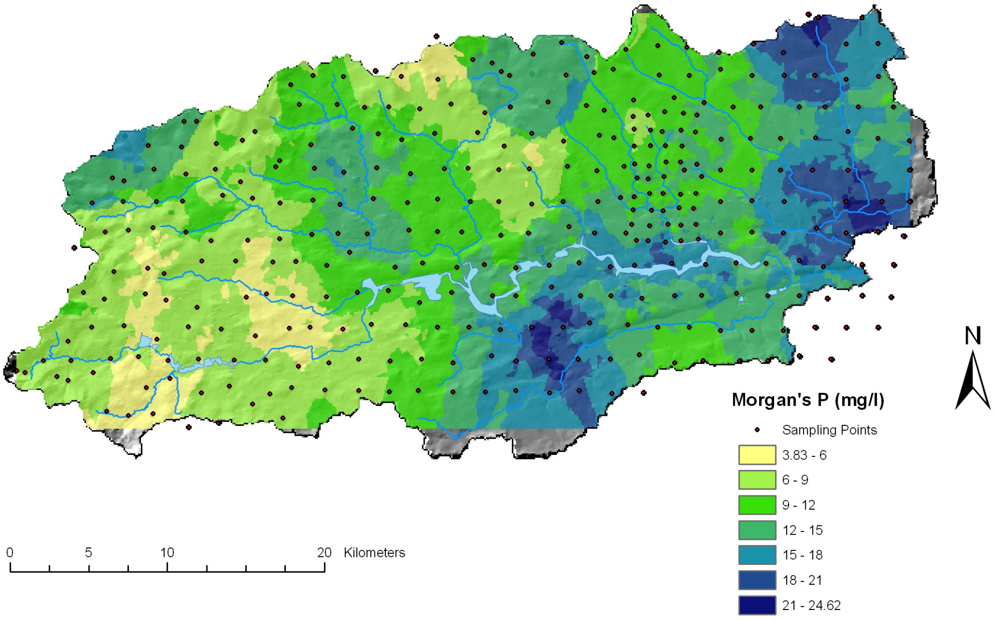

Figure 4.15: Soil Test Phosphorus (Morgan's P).

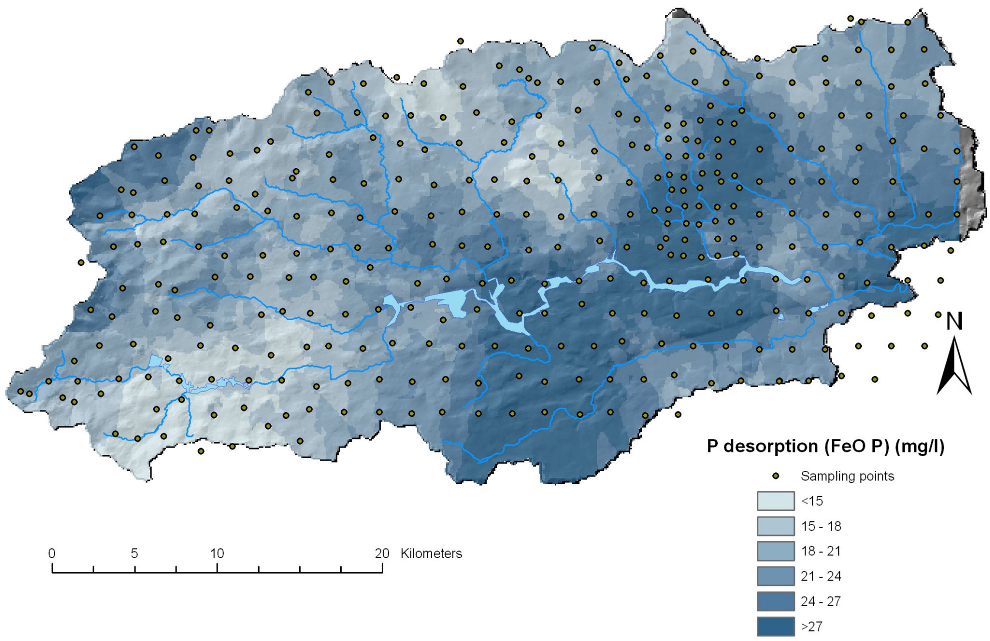

Figure 4.16: Phosphorus Desorption (FeO P).

In figure 4.14, we can see that the soils with a high organic matter content are located where we could expect them, that is to say in the western part of the catchment mainly where the peat bogs are located.

For Morgan's P, the high status P soils can mostly be found in the Martin catchment and in the region of Crookstown south of the Lee. The higher desorption values are also in this latter area and as well in the Dripsey catchment.

It should be remembered that the first aim of these maps is to give a general trend in the distribution of the different soil properties. These maps should not be taken as precise indicators of soil characteristics. There are actually many parameters that can locally influence the sampling. Even within a single field sampled results can vary a lot: for instance, a sampling carried out in a part of a pasture where the cattle tends to gather can give very high values of soil P which might be very different from the rest of the area. We should be even more careful when the sampling is done with a 2 km grid, as it is the case here.

However, to have access to such a recent soil database is also a great chance. Indeed, a project like the Three Rivers Project (MCOS, 2002) had for example only access to the soil P levels averaged over 10 km squares provided by Teagasc. For our project, that would only mean about 10 different values to cover our study area of 1135 km^2.

From these maps, the mean value for each of the 56 subcatchments and for each of the soil properties has been calculated and is shown in Table 4.6.

Table 4.6: Soil properties of the subcatchments.

Site	Morgan's P (mg/l)	P FeO (mg/l)	OM content (%)
N1	15.2	23.5	12.2
N2	13.6	26.0	13.0
N3	11.6	22.9	13.5
N4	10.9	26.8	12.7
N5	11.7	21.9	13.8
N6	11.7	21.8	13.1
N7	10.7	26.0	12.5
N8	11.7	27.9	12.1
N9	12.0	20.3	14.7
N10	9.1	18.4	13.5
N11	6.8	14.8	14.6
N12	9.5	17.1	17.1
N13	10.5	18.2	17.6
N14	11.2	19.3	15.5
N15	9.3	16.2	19.8
N16	9.5	17.1	19.3
N17	9.6	18.1	17.1
N18	9.5	17.0	17.4
N19	8.7	15.8	18.3
N20	10.2	17.6	17.4
N21	10.2	17.7	18.8
N22	12.7	18.4	18.6
N23	12.7	19.8	15.4
N24	10.0	24.5	12.1
N25	10.5	19.7	13.3
N26	10.3	18.5	12.9
N27	14.2	19.8	11.4
N28	12.9	21.8	12.1
N29	17.6	23.3	11.8
N30	17.5	22.2	11.9
N31	17.8	21.0	12.1
N32	19.6	20.3	12.3
N33	20.5	20.7	12.5
N34	14.9	24.0	11.0
S1	10.7	21.7	14.8
S2	14.9	27.3	11.1
S3	15.3	28.0	11.7
S4	16.6	29.4	12.5
S5	13.5	28.5	12.8
S6	6.9	18.3	17.6
S7	7.5	17.9	15.9
S8	6.5	18.8	18.3
S9	6.3	17.0	18.7
S10	7.2	18.5	17.9
S11	5.1	12.7	15.6
S12	7.3	18.7	18.8
S13	7.1	22.0	21.7
S14	7.2	19.2	20.2
S15	10.3	22.4	19.7
S16	14.5	24.6	14.2
S17	11.8	21.3	14.1
S18	8.9	17.9	15.9
S19	8.9	17.8	15.9
S20	9.9	20.7	17.3
S21	9.5	20.4	17.0
S22	10.3	20.0	16.5
Study Area	**11.5**	**22.0**	**14.4**

Chapter 5

Analysis of Data

5.1 Variables

In the previous chapters, we have been creating a number of variables relating either to the observed values of phosphorus concentrations at the different sampling sites or to the characteristics of the corresponding subcatchments. In term of statistical analyses these different variables can be grouped into 2 categories: dependent and independent variables.

5.1.1 Dependent Variables

Statistically speaking, a dependent variable is defined as the factor, which is observed and measured in a study in order to determine the effect of the independent variables. The dependent variable can be considered as the response of the observed phenomenon. Thus, in the case of our study, the dependent variables are the measured SRP concentrations in the river.

In other studies about phosphorus losses, different types of variable are used to describe phosphorus in river: median concentration (Hughes, 2005; Magette, 2002), flow-weighted seasonal average concentration (Daly, 2002), median concentration multiplied by flow (MCOS, 2002). For our study, in view of the poor quality and quantity of the flow data available in the Lee catchment and of the limited number of samplings made during the 16 months between the first and last campaigns, it was not possible to calculate phosphorus loads in the rivers or average concentrations over particular periods of time.

In this study, an important number of sites (56) were sampled more or less at the same moment and that, at a limited number of occasions. This way of sampling gives in fact a series of pictures, at given times, of the P status in the rivers for the two types of flow conditions: base and storm flow. The analysis of the results will consequently be conducted with a spatial approach. Working directly with the instantaneous concentrations or the concentrations averaged over both types of events should therefore not be a problem.

As far as the phosphorus losses are concerned, the advantage of this way of sampling is that, in storm flow conditions, all the samples were generally taken between 6 and 12 hours after the rain event occurrence. Even with a regular sampling, one could not be sure to have samples coinciding with flood conditions, unless the sampling is really intense (more than one sample per day). For example, the sites monitored by the EPA are sampled around 12 times per year. With such a frequency, it is therefore very unlikely that the studies using this source of data could be able to analyse the phosphorus exports in storm flow conditions. The only objection to our approach, which has already been raised previously and partially answered in the precedent chapter, is about the difference in the time of sampling between the different sites: at the time of sampling, the SRP concentration at one site was actually maybe at its maximum while it was already decreasing at another site.

Here, the dependent variables are essentially the average SRP concentrations during base and storm flow conditions. When attempting to assess the effect of rain on phosphorus losses, the SRP concentrations for each storm event will also be used. Table 5.1 summarizes the different dependent variables.

Table 5.1: Dependent variables and their description.

Variable	Description
SRP Storm	Average SRP (mg/l) concentration for the 5 storm flow events
SRP Base	Average SRP (mg/l) concentration for the 3 base flow events
SRP St1	SRP concentration (mg/l) for the first storm flow event
SRP St2	SRP concentration (mg/l) for the second storm flow event
SRP St3	SRP concentration (mg/l) for the third storm flow event
SRP St4	SRP concentration (mg/l) for the fourth storm flow event
SRP St5	SRP concentration (mg/l) for the fifth storm flow event

When plotting the frequency distribution of SRP Storm and SRP Base (See Figure 5.1), it appears quite clearly that there is a positive skew among the values: there is a majority of sites with low SRP concentrations.

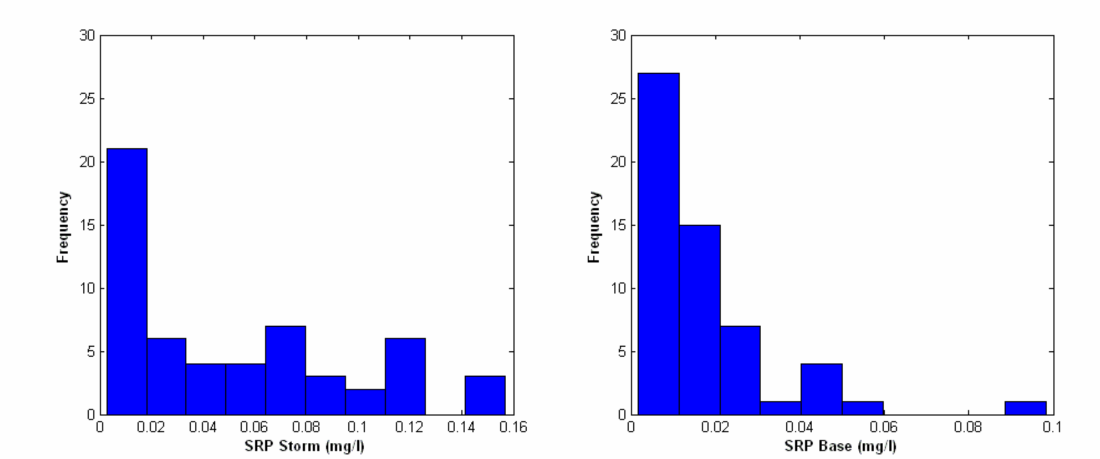

Figure 5.1: SRP Storm and SRP Base frequency distributions.

Because of these positive skews, the above distributions are closer to lognormal distributions than to normal distributions. The non-normality of the data can represent a problem when applying statistical tests. A Log transformation was therefore applied to transform the variables and reduce the positive skews. The frequency distributions of *Log(SRP Storm)* and *Log(SRP Base)* are shown in Figure 5.2 with the normal curves.

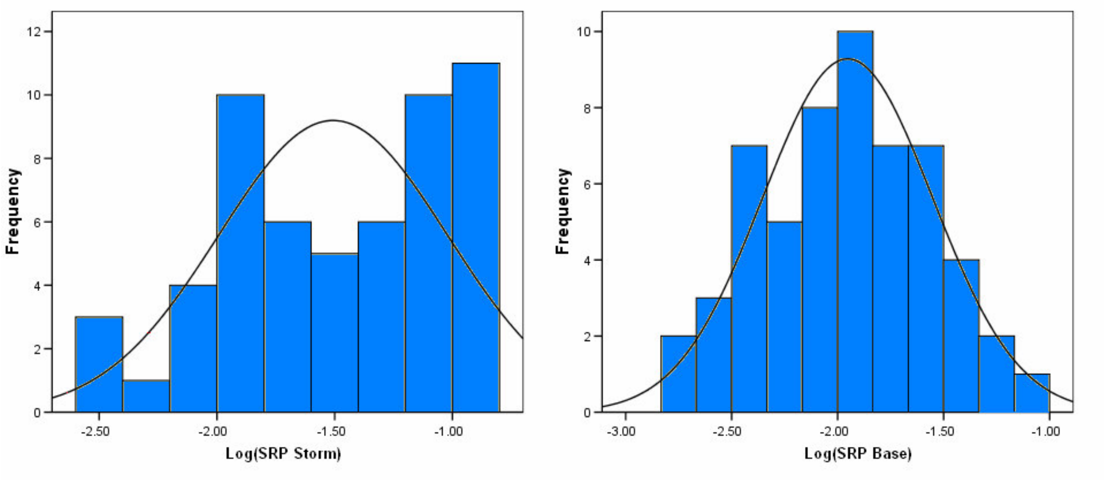

Figure 5.2: Log(SRP Storm) and Log(SRP Base) frequency distributions.

Figure 5.2 shows that the distributions look much closer to normal distributions than before, especially in the case of *SRP Base*. A Kolmogorov-Smirnov test was performed to test the normality of the distribution. The test was non-significant for *Log(SRP Base)*, indicating that the distribution is not significantly different from a normal distribution, i.e. it is probably normal. However, for *Log(SRP Storm)*, the test remains significant even if the Log transformation has improved things a lot.

5.1.2 Independent Variables

An independent variable is a factor which is evaluated to determine its relationship to an observed phenomenon. In a research study, it can be seen as one of the antecedent conditions, which is presumed to affect a dependent variable. So, here, the independent variables are all the variables which are known or thought to have an influence on phosphorus loss.

As seen before, the factors contributing to P loss from agricultural land to surface waters can be grouped as source and transport factors. Among the variables determined in the previous chapters, the source factors are:

- Soil P levels with the Morgan's P test
- Chemical Fertiliser loading
- Organic Fertiliser loading with the density of livestock

Some variables, such as the organic matter content and the soil P desorption, are not directly source factors but are linked to them. Then, there are the transport factors:

- Slope of the terrain
- Runoff Risk
- Amount of precipitation
- Rainfall intensity

Finally, a number of variables can not be considered as source or transport factors but are known or are expected to have a potential impact on P losses. These are all the variables in relation to the land use/land cover and to the types of soil. The set of independent variables with their description is shown in Table 5.2.

Table 5.2: Independent variables and their description.

Variable	Description
Morgans P	Average soil P level using Morgan's P test results (mg/l)
Fertiliser	Annual chemical fertiliser loading (kg/ha)
Livestock	Livestock density (LU/ha)
PFeO	Average P desorption using iron-oxide paper strip P test results (mg/l)
OMcontent	Average organic matter content (in %)
Slope	Mean of the cell slopes over each subcatchment (in %)
Runoff	Runoff Risk score, decimal number comprised between 1 and 4.
Rain1, 2, 3, 4, 5	Amount of precipitation during the 24h prior to sampling for St1, 2, 3, 4, 5
Intensity1, 2, 3, 4, 5	Maximum rain intensity during the 24h prior to sampling for St1, 2, 3, 4, 5
Agricultural	Proportion of the subcatchment dedicated to agricultural use
Pasture	Proportion of the subcatchment covered with pasture
Impgrass	Proportion of the subcatchment covered with improved grassland
Unimpgrass	Proportion of the subcatchment covered with unimproved grassland
Cultivated	Proportion of the subcatchment dedicated to cultivation
Forest	Proportion of the subcatchment covered with forest
SemiNatural	Proportion of the subcatchment covered with semi-natural areas
Peatland	Proportion of the subcatchment covered with peat bogs
WellDrained	Proportion of the subcatchment with a well-drained soil
DeepWD	Proportion of the subcatchment with a deeply well-drained soil
ShallowWD	Proportion of the subcatchment with a shallow well-drained soil
PoorlyDrained	Proportion of the subcatchment with a poorly drained soil
Till	Proportion of the subcatchment with till subsoil
Rock	Proportion of the subcatchment with rock subsoil

5.2 Relationships between subcatchment characteristics

Before studying how the independent variables affect the dependent variables, the relationships within the independent variables were investigated. To do so, the different data sets were combined in a Pearson correlation analysis. For the moment, the variables concerning the single events, i.e. the rain data, are not taken into account.

The Pearson's correlation coefficients *r* are shown in Table 5.3. They refer to linear correlations, the directions of which are denoted by positive and negative signs (+/-). An *r* of +1.00 means for instance that there is a perfect direct relationship while an *r* of 0.00 indicates the complete absence of a relationship. The closer *r* is to -1.00 or +1.00, the stronger the relationship.

Table 5.3: Correlation matrix of Pearson's r values for all subcatchment data (n=56)

	Pasture	*Agricul-tural*	*Cultivated*	*Imp Grass*	*Unimp Grass*	*Forest*	*Semi Natural*	*Peat Land*	*Livestock*	*Fertilizer*
Pasture	1									
Agricultural	0.92 ***	1								
Cultivated	0.57 ***	0.72 ***	1							
ImpGrass	0.94 ***	0.82 ***	0.46 ***	1						
UnimpGrass	0.85 ***	0.87 ***	0.61 ***	0.63 ***	1					
Forest	-0.59 ***	-0.74 ***	-0.59 ***	-0.50 ***	-0.58 ***	1				
SemiNatural	-0.32 *	-0.43 **	-0.46 ***	-0.26 ns	-0.34 *	0.56 ***	1			
PeatLand	-0.89 ***	-0.91 ***	-0.62 ***	-0.80 ***	-0.84 ***	0.41 **	0.16 ns	1		
Livestock	0.92 ***	0.90 ***	0.60 ***	0.86 ***	0.80 ***	-0.70 ***	-0.25 ns	-0.82 ***	1	
Fertilizer	0.85 ***	0.96 ***	0.78 ***	0.75 ***	0.82 ***	-0.71 ***	-0.44 **	-0.87 ***	0.87 ***	1
DeepWD	0.87 ***	0.89 ***	0.72 ***	0.81 ***	0.76 ***	-0.49 ***	-0.24 ns	-0.92 ***	0.81 ***	0.84 ***
ShallowWD	-0.46 ***	-0.51 ***	-0.39 **	-0.49 ***	-0.30 *	0.33 *	-0.06 ns	0.54 ***	-0.49 ***	-0.47 ***
WellDrained	0.88 ***	0.89 ***	0.73 ***	0.79 ***	0.81 ***	-0.47 ***	-0.32 *	-0.91 ***	0.80 ***	0.85 ***
PoorlyDrained	-0.66 ***	-0.58 ***	-0.65 ***	-0.63 ***	-0.56 ***	0.36 **	0.38 *	0.55 ***	-0.58 ***	-0.54 ***
Till	0.80 ***	0.83 ***	0.63 ***	0.74 ***	0.70 ***	-0.40 **	-0.13 ns	-0.90 ***	0.75 ***	0.79 ***
Rock	-0.71 ***	-0.72 ***	-0.55 ***	-0.67 ***	-0.60 ***	0.28 *	0.06 ns	0.84 ***	-0.67 ***	-0.71 ***
Runoff	-0.73 ***	-0.82 ***	-0.79 ***	-0.59 ***	-0.78 ***	0.56 ***	0.33 *	0.77 ***	-0.70 ***	-0.80 ***
Slope	-0.83 ***	-0.87 ***	-0.60 ***	-0.75 ***	-0.75 ***	0.43 **	0.31 *	0.90 ***	-0.76 ***	-0.84 ***
MorgansP	0.53 ***	0.54 ***	0.56 ***	0.49 ***	0.46 ***	-0.15 ns	-0.02 *	-0.64 ***	0.46 ***	0.48 ***
PFeO	0.47 ***	0.60 ***	0.55 ***	0.36 **	0.52 ***	-0.46 ***	-0.43 **	-0.52 ***	0.47 ***	0.59 ***
OMcontent	-0.72 ***	-0.78 ***	-0.72 ***	-0.62 ***	-0.73 ***	0.48 ***	0.19 ns	0.79 ***	-0.74 ***	-0.78 ***

	Deep WD	*Shallow WD*	*Well Drained*	*Poorly Drained*	*Till*	*Rock*	*Runoff*	*Slope*	*MorgansP*	*PFeO*	*OM content*
DeepWD	1										
ShallowWD	-0.68 ***	1									
WellDrained	0.96 ***	-0.44 **	1								
PoorlyDrained	-0.70 ***	0.24 ns	-0.77 ***	1							
Till	0.97 ***	-0.77 ***	0.88 ***	-0.53 ***	1						
Rock	-0.88 ***	0.82 ***	-0.76 ***	0.45 ***	-0.95 ***	1					
Runoff	-0.77 ***	0.30 *	-0.82 ***	0.61 ***	-0.69 ***	0.58 ***	1				
Slope	-0.86 ***	0.45 ***	-0.88 ***	0.50 ***	-0.84 ***	0.75 ***	0.74 ***	1			
MorgansP	0.70 ***	-0.50 ***	0.66 ***	-0.50 ***	0.70 ***	-0.71 ***	-0.72 ***	-0.54 ***	1		
PFeO	0.51 ***	-0.22 ns	0.55 ***	-0.47 ***	0.46 ***	-0.46 ***	-0.69 ***	-0.46 ***	0.57 ***	1	
OMcontent	-0.85 ***	0.47 ***	-0.85 ***	0.64 ***	-0.80 ***	0.74 ***	0.81 ***	0.74 ***	-0.69 ***	-0.60 ***	1

In table 5.3, it can be noted that a great number of independent variables are highly correlated between each other. This can be easily understood when considering the fact that climate, topography, soil type, land cover and land use are intimately related. Soil formation is actually influenced by topography and climate, which are as well related (topography and elevation have an impact on precipitation). Then, these 3 factors influence the use of land man will have and the type of management he will apply.

In addition, in the Lee basin, the characteristics of the catchment tend to follow an East-West distribution. All the agricultural activities are mostly concentrated in the East where the soils have desirable features and the topography is gentle. In contrast, high elevation, steep slopes, poor climatic conditions and bad quality soils limit the use range of the lands located in the western part of the catchment. The pressure on these lands in term of fertiliser application or cattle rearing is consequently less important.

A number of examples can be given to illustrate further these relationships. For instance, the different types of agricultural land use are all highly correlated with the well-drained types of soils. For instance, Figure 5.3 shows the relationship between the proportion of land dedicated to agriculture in each subcatchment and the proportion of well-drained soils. The positive correlation is quite high, $r = 0.89$ ($p<0.001$). Thus, it suggests that agriculture is predominantly present where the soils are well drained. It is a known fact that soils with good drainage characteristics actually suits better to arable crops and grassland. However, one should be careful when interpreting such relationships including variables relating to proportion of lands. Nothing indicates, here, that agricultural areas are actually located where the well-drained soils are, even if it is probably the case. The relationship just indicates that both proportions- agricultural land and well drained soils- are increasing proportionally.

In the same way, another restriction concerns the strong negative correlations that sometimes exist between variables. *PeatLand* and the different types of agricultural land use are for example strongly negatively associated ($r = -0.89$ for *Pasture* and $r = -0.91$ for *Agricultural*). But it should not be interpreted too quickly as a causality effect but rather by the fact that peat land and agricultural land exclude each other: peat bogs have a very limited agricultural use range due to their elevation, organic nature and wetness.

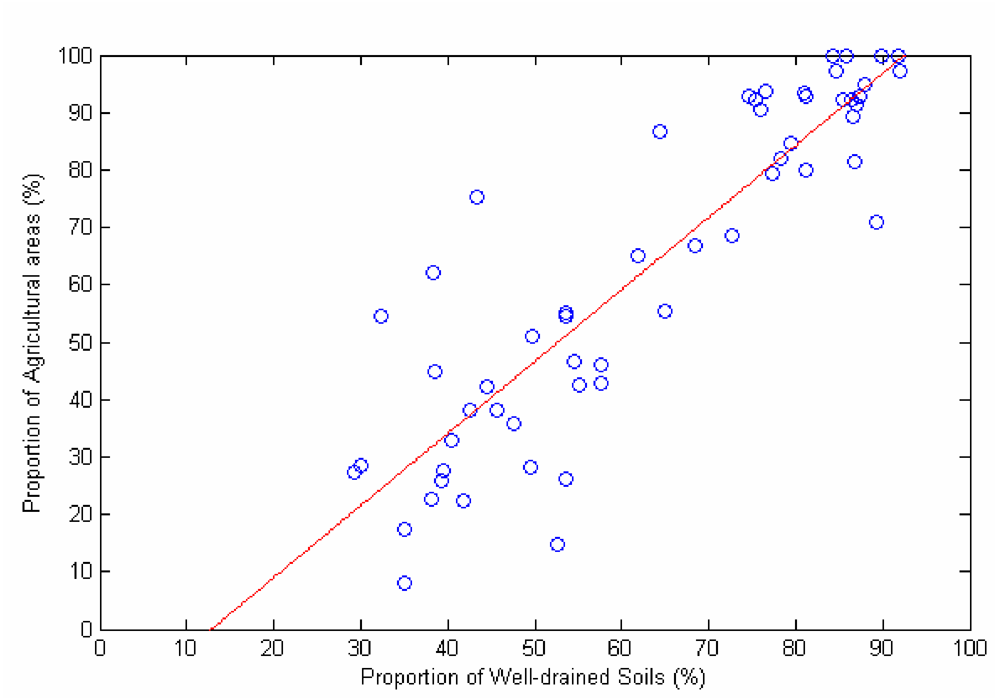

Figure 5.3: Relationship between Agricultural land use and Well-drained Soil in proportion of the subcatchment areas.

For some cases, high correlations can be partially due to the way variables have been constructed. For example, it can be noted in Table 5.3 that there is a strong positive relationship between *Pasture* and *Livestock* ($r = 0.92$) or between *Fertiliser* and *Agricultural* ($r = 0.96$). The number of livestock units and the amount of fertiliser were actually allocated to the different subcatchments using Corine land cover data. But it was used only to allocate these quantities from the Electoral division level to the subcatchment level, which are not so different in size and location: 55 EDs included in the study area for 56 subcatchments. Therefore, this allocation process had maybe an effect at a local scale but the overall partition between subcatchments was not affected. As a conclusion, it can be said that the density of livestock in each subcatchment is, all the same, significantly related to the proportion of land covered with pasture.

The following are a number of information points also given by the correlation matrix:

- There is a significant positive relationship between the average organic matter content of the soil and the proportion of land covered by peat bogs, $r = 0.79$ ($p<0.001$). This indicates that the soil samplings and the following spatial interpolations gave satisfactory results.

- The proportion of land covered with peat bogs correlated positively with the mean of cell slopes ($r_S = 0.90$ ***) and the runoff risk ($r_S = 0.77$ ***). The formation process of peats can explain that trend. Blanket peat accumulated under conditions of high rainfall and humidity. Such conditions prevail in mountains due to altitude and associated adverse climatic conditions.

- *Forest* and especially *Semi Natural* variables show a lot of low correlation coefficients except between each other (r = 0.56 ***). These two land cover types which are quite similar can actually be found in the same areas. An explanation for the low values of the coefficients is the fact that these variables have a number of zero values since there are no forest or semi-natural areas in many subcatchments.

The fact that there are many high correlations between independent variables should be remembered and will be important when we will try to distinguish later the individual influences of each one on the response variables.

5.3 Relationships between subcatchment characteristics and River phosphorus levels

Correlation coefficients between SRP values in base and storm flow and the different independent variables were derived using a Pearson correlation analysis (see Table 5.4). The single events and the corresponding rain data are not included in the analysis for the moment. Both transformed and non-transformed phosphorus data were included in the analysis.

Table 5.4: Correlation table of r values for all subcatchment data (n=56)

	SRP Storm	*Log (SRP Storm)*	*SRP Base*	*Log (SRP Base)*
Pasture	0.77 ***	0.88 ***	0.50 ***	0.73 ***
Agricultural	0.87 ***	0.94 ***	0.64 ***	0.84 ***
Cultivated	0.78 ***	0.69 ***	0.81 ***	0.73 ***
ImpGrass	0.70 ***	0.79 ***	0.45 **	0.66 ***
UnimpGrass	0.71 ***	0.80 ***	0.47 ***	0.66 ***
Forest	-0.67 ***	-0.67 ***	-0.51 ***	-0.65 ***
SemiNatural	-0.41 **	-0.28 *	-0.25 ns	-0.22 ns
PeatLand	-0.78 ***	-0.89 ***	-0.57 ***	-0.76 ***
Livestock	0.77 ***	0.86 ***	0.56 ***	0.80 ***
Fertilizer	0.84 ***	0.89 ***	0.67 ***	0.82 ***
DeepWD	0.88 ***	0.89 ***	0.71 ***	0.82 ***
ShallowWD	-0.57 ***	-0.60 ***	-0.49 ***	-0.57 ***
WellDrained	0.85 ***	0.85 ***	0.68 ***	0.79 ***
PoorlyDrained	-0.68 ***	-0.56 ***	-0.54 ***	-0.52 ***
Till	0.81 ***	0.85 ***	0.66 ***	0.79 ***
Rock	-0.70 ***	-0.77 ***	-0.55 ***	-0.70 ***
Runoff	-0.80 ***	-0.78 ***	-0.72 ***	-0.80 ***
Slope	-0.76 ***	-0.81 ***	-0.58 ***	-0.74 ***
MorgansP	0.62 ***	0.61 ***	0.62 ***	0.65 ***
PFeO	0.63 ***	0.57 ***	0.44 **	0.54 ***
OM content	-0.79 ***	-0.79 ***	-0.66 ***	-0.80 ***

5.3.1 Agriculture

Agriculture is known to be one of the main causes of eutrophication in Ireland through the diffuse phosphorus losses (Toner, 2005). It was indicative to note that the proportion of land dedicated to agriculture (pasture + arable land + land with a mix of agriculture and natural areas) in the different subcatchments correlated very well with the average SRP concentration at each site. With values of r = 0.87 for the non-transformed concentrations and r = 0.94 for the transformed data, the correlation was especially good in storm conditions. In base flow, the Log-transformation also raised the degree of correlation between both data sets but the relationship remains weaker than in storm flow. The value of r = 0.94 obtained for storm conditions, if squared, corresponds to a R^2 of 0.89. This value of R^2 tells how much of the variability within the *SRP Storm* variable can be explained by the *Agricultural* variable. Thus, we can say that, in storm flow conditions, the proportion of agricultural land accounts for 89% of the variability in the concentration of soluble reactive phosphorus. In Figure 5.4, the lines that best fits the data (non-transformed and Log-transformed dependent variable) are shown.

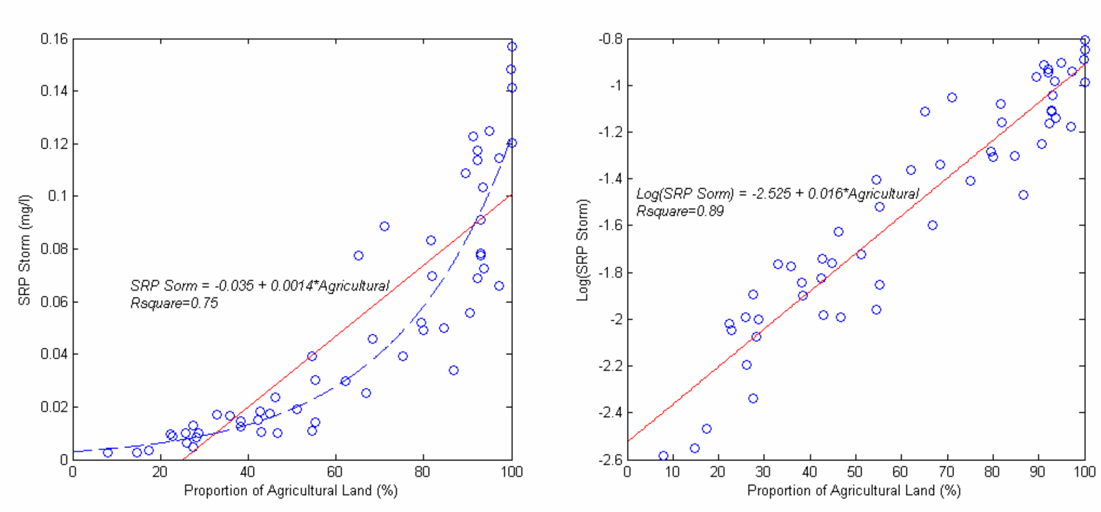

Figure 5.4: Relationship between the proportion of Agricultural land (*Agricultural*) and the average Storm flow SRP concentrations (*SRP Storm* & *Log (SRP Storm)*).

It can be seen in Figure 5.4 that, with non-transformed concentrations, the line does not fit really well the shape of the point distribution. The points seem to follow an exponential trend as shown by the dashed line. As a consequence, the fact of taking the logarithm of the SRP concentrations was really beneficial for the goodness-of-fit of the linear model. This model, which explains almost 90% (R^2=0.89) of the SPR variance, is given by the equation:

$$Log(SRPStorm) = -2.525 + 0.016 * Agriculture \quad (5.1)$$

As far as base flow conditions are concerned, the correlation between *Log(SRB Base)* and *Agricultural* is weaker (see Figure 5.4) but still explains 70% (R^2=0.70) of the variability of the Log-corrected SRP concentrations. The relationship is given by Equation (5.2).

$$Log(SRPBase) = -2.698 + 0.012 * Agriculture \qquad (5.2)$$

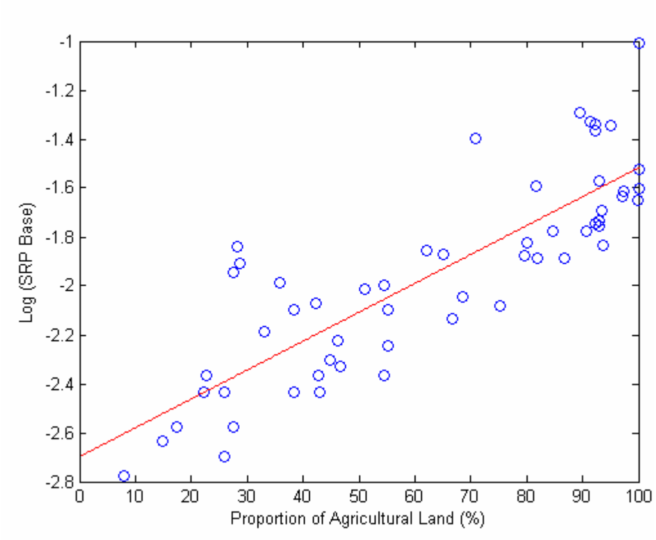

Figure 5.4: Relationship between the proportion of Agricultural land (*Agricultural*) and the average Base flow SRP concentration (*Log (SRP Base)*).

5.3.1.1 Pastures

In the case of pastures, there is again a strong positive relationship between the SRP concentration (corrected) and the proportion of the land covered with pasture in each subcatchment (See Figure 5.4). It is easily understandable when considering the fact that pastures account for three quarters of the agricultural land. However, the variable Pasture explains less variability within the dependent variable than *Agricultural* did. Equations (5.3) and (5.4) give the relationships between *Pasture* and the corrected SRP concentrations. Again it can be noted that linear model fits better the storm flow conditions than the base flow conditions.

$$Log(SRPStorm) = -2.338 + 0.018 * Pasture \qquad (R^2{=}0.77) \qquad (5.3)$$

$$Log(SRPBase) = -2.523 + 0.012 * Pasture \qquad (R^2{=}0.53) \qquad (5.4)$$

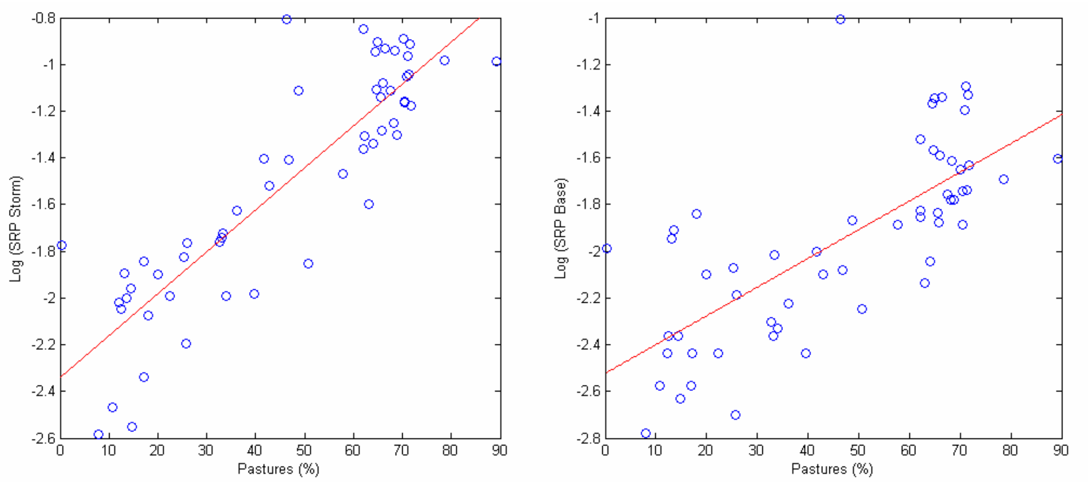

Figure 5.5: Relationship between the proportion of Pasture and the corrected average SRP concentrations in storm and base flow.

Another result about pasture land use is that the correlation analysis shows no difference between improved and unimproved grassland in term of goodness of prediction. The correlation coefficients are actually almost equal for *ImpGrass* and *UnimpGrass* in both types of flow conditions. It seems that improved grasslands could export more P since all the sites with the highest SRP values are those corresponding to the subcatchments with the higher proportion of improved grassland. But these subcatchments are generally also the more agricultural. It is actually quite difficult to distinguish the influence of each factor only with bivariate correlations.

5.3.1.2 Cultivated Land

As far as cultivated land is concerned (arable land and complex cultivation patterns), the correlation coefficients are not as good as previously and the Log-transformation did not increase the value of the r coefficients. It is probably due to the structure of the *Cultivated* variable itself. More than half of the subcatchments do not actually include this type of land use and give therefore a number of zero values in the variable.

Nevertheless, the graphs of Figure 5.6 provide interesting information about the relationships between the SRP concentrations and the extent of cultivated areas. First, it can be noted that the subcatchments without cultivated land give almost all low SRP values (see the concentration of points in the lower-left part of the graphs). It is especially the case in storm flow conditions: except for 2 cases (N8 and N33), all the subcatchments with absence of cultivated land gave SRP concentrations less than 0.04 $mg.l^{-1}$. Then, among the subcatchments actually including cultivated land, a positive relationship can be observed.

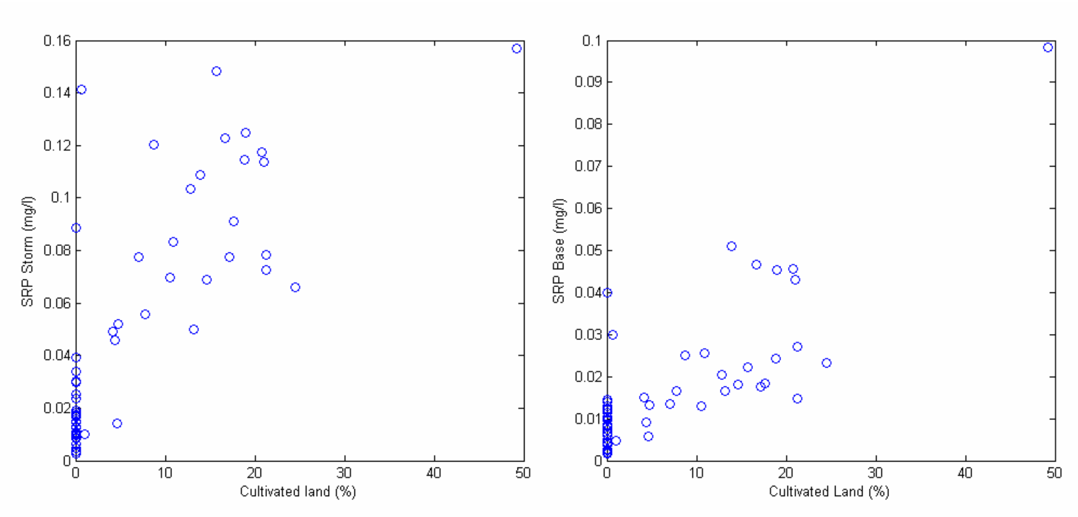

Figure 5.5: Relationship between the proportion of Cultivated Land and the average SRP concentrations in storm and base flow.

Thus, it seems that the response in term of SRP concentration is quite dependent on the presence or not of cultivated areas: SRP values are for the subcatchments not including any cultivated areas and then SRP values are increasing with the proportion of cultivated land. The hypothesis that the mean of the SRP concentrations coming from subcatchments with *Cultivated* = 0% differ significantly from the mean of the SRP concentrations coming from subcatchments with *Cultivated* > 0% was tested using an independent *t*-test and a Mann-Whitney (U) test, which is the non-parametric equivalent of the independent *t*-test. The results of both tests indicated a significant difference between the two means. As it could be expected from Figure 5.5, the difference was more significant in storm flow than in base flow (See Table 5.5).

Table 5.5: Testing for difference between SRP Storm and SRP Base, Grouping parameter = presence or not of cultivated areas.

	SRP Storm	**SRP Base**
Mann-Whitney	U= 47.5	U= 66.5
Significance	p=1.69E-08	p=9.78E-08
T-test	t= -8.47	t= -4.58
Significance	p=5.01E-10	p=6.41E-05

However, when looking at the *Agricultural* variable versus SRP concentrations, we did not notice any diverging trends which could have been caused by the presence or not of cultivated areas within the different subcatchments. In fact, as shown in Figure 5.6, all the subcatchments including cultivated areas are already those with the higher proportion of other agricultural areas. But it seems that the inflection and the slope increase around 60-70% could be caused by the occurrence of arable lands.

In the previous chapter, the site N34 was detected as an outlier in base flow: it was consistently showing high SRP values compared to the other sites. In Figure 5.6, N34 is still falling outside of the main pattern, but the proportion of cultivated land in this subcatchment could provide an explanation. N34 actually includes 49.2% of cultivated areas (31.9% of arable land + 17.3% of complex cultivation pattern), which is double of the second more cultivated subcatchment, N27 (24.5%).

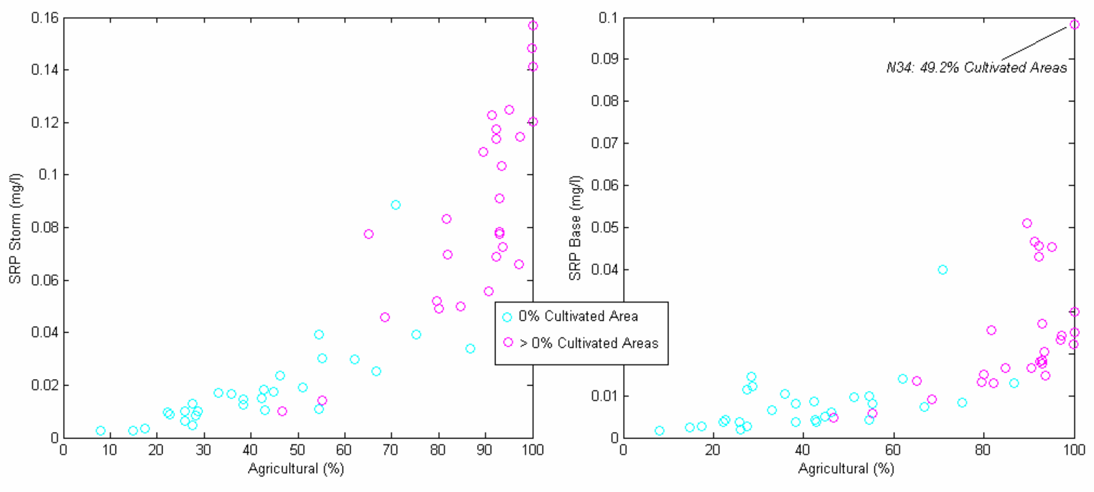

Figure 5.6: Relationship between the proportion of Agricultural Land and the average SRP concentrations in storm and base flow + occurrence or not of cultivated areas.

5.3.2 Natural Areas

5.3.2.1 Forested Areas

Table 5.4 indicates a negative correlation between the proportion of forested areas and the corrected SRP concentrations at the different sites. The correlation is too weak (r = 0.67 in storm flow and r = 0.65 in base flow) to consider *Forest* as a single reliable predictor of the SRP concentrations. Indeed, the points shown on Figure 5.7 are relatively dispersed. The observation of both graphs provides yet interesting information.

The land use *Forest* actually seems to act as a buffer variable. For very limited forest cover, the SRP concentrations range from low to very high values. But, then, the larger the forest cover is, the lower the SRP concentrations are. The red dashed lines on Figure 5.7 could be seen as sorts of maximal possible SRP concentrations. There is actually some evidence in the literature that forested watersheds tend to conserve P (Wickham, 2002). On the other hand, this negative relationship could simply be due to the fact that, when the proportion of forested areas increases, the proportion of agricultural land automatically decreases.

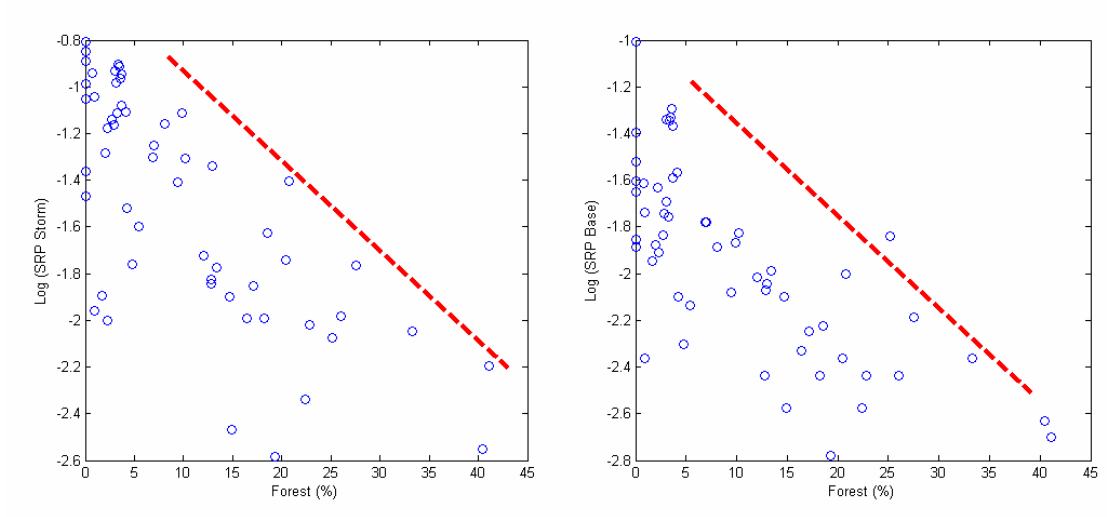

Figure 5.7: Relationship between the proportion of forested area and the Log-transformed SRP concentrations.

Semi-natural areas which represent an intermediate state between forestry and agricultural land also show a negative relationship with the SRP concentration in water. But in this case, the significance of the correlations is really too low to draw any conclusions.

5.3.2.2 Peat Lands

The correlation matrix gives strong negative relationships between the land cover category *PeatLand* and the transformed SRP concentrations: r = -0.89*** for storm flow and r= -0.76*** for base flow. But as we saw before, there is a really good negative correlation between *PeatLand* and *Agricultural*. So it is likely that the observed correlation (See Figure 5.8) is due more to the absence of agricultural activity than to the presence of peat bogs. Peat soils are actually known to be unable to store P (Daly, 2002) so if fertiliser was applied in these areas it would be washed away and transferred to the streams.

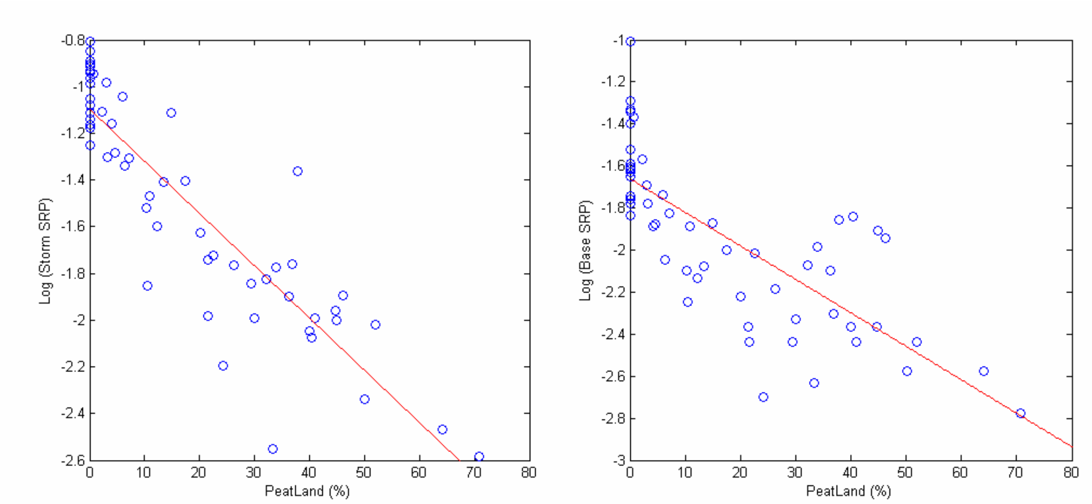

Figure 5.8: Relationship between the proportion of Peat Land and the Log-transformed SRP concentrations.

5.3.3 Management factors

We saw before that both the livestock densities and the amount of fertiliser which is applied in each subcatchment are intimately related with the proportion of land dedicated to agriculture. Logically, the variables *Fertiliser* and *Livestock* are therefore showing high correlationship with the SRP concentrations (See Figure 5.9) but *Agricultural* remains the best predictor. *Fertiliser* appears to be a slightly better predictor than *Livestock*. The degree of correlation is again better in storm flow conditions. It has to be noted that the status of N34 is well explained by the variable *Fertiliser* because of the high application rate observed in this subcatchment. (5.5) to (5.8) gives the relationships with the corrected SRP concentration

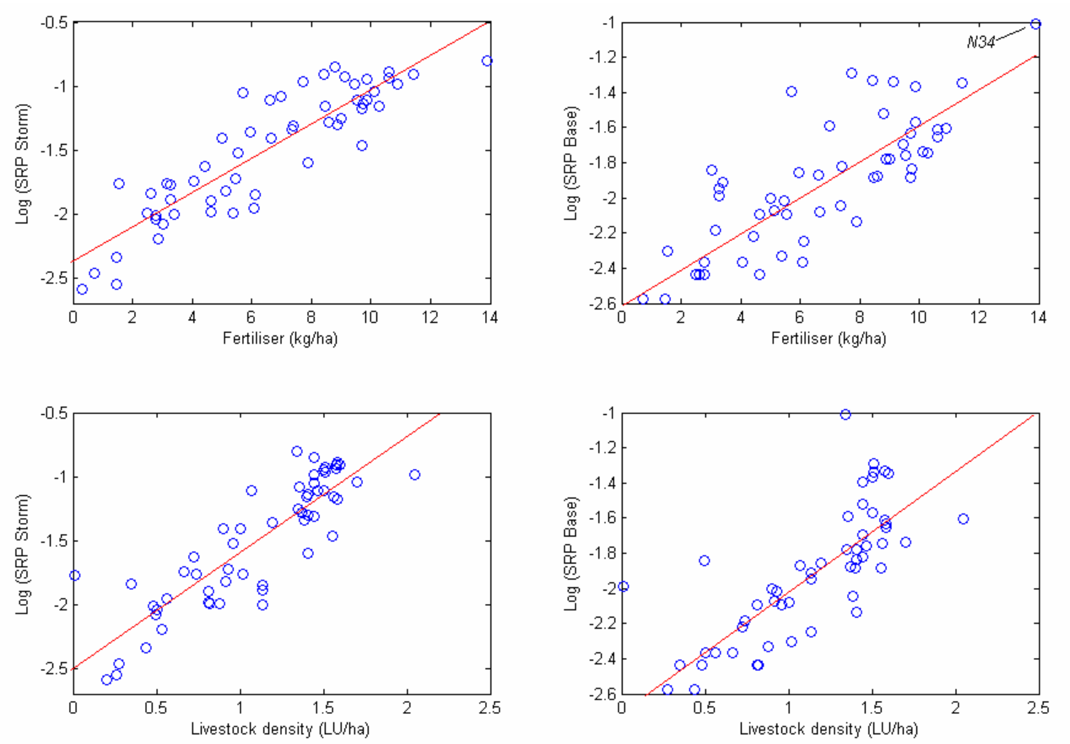

Figure 5.8: Log-transformed SRP concentrations vs. Fertiliser use and Livestock density.

$$Log(SRPStorm) = -2.373 + 0.134 * Fertiliser \quad (R^2=0.79) \qquad (5.5)$$

$$Log(SRPBase) = -2.611 + 0.102 * Fertilizer \quad (R^2=0.67) \qquad (5.6)$$

$$Log(SRPStorm) = -2.499 + 0.904 * Livestock \quad (R^2=0.75) \qquad (5.7)$$

$$Log(SRPBase) = -2.707 + 0.687 * Livestock \quad (R^2=0.63) \qquad (5.8)$$

5.3.4 Soil Phosphorus

Many studies have reported that high levels of phosphorus in soils increase the risk of phosphorus loss to water. The coefficients obtained in the correlation analysis for *MorgansP* are r = 0.61 and r = 0.65 in storm and base flow respectively. It is interesting to note that this variable is a better predictor in base flow. These values of r are not so high; they correspond to R^2 of about 0.4. Therefore, less than half of SRP variability is therefore explained by the soil test P. Nevertheless, the clear positive relationships noted in Figure 5.9 between the level of soil test P and the concentration of soluble reactive phosphorus in water is a very satisfactory result. STP values were actually the result of experimental work on the field and of a number of assumptions concerning the way data were collected and then transformed. This result shows at least that the methods that were used to determine the average soil P levels give coherent results.

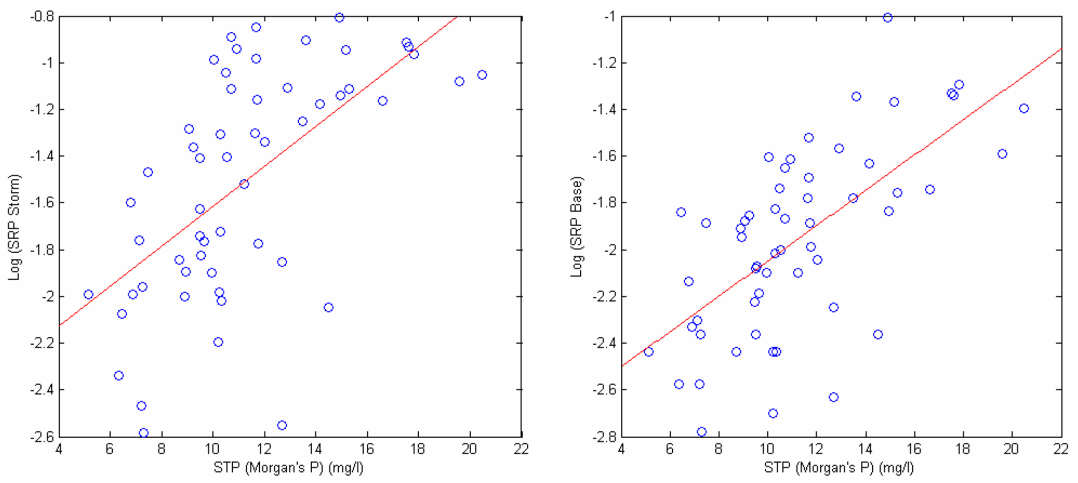

Figure 5.9: Log-transformed SRP concentrations vs. Soil Test Phosphorus (Morgan's P).

Phosphorus desorption (*PFeO*) also appears to show a fairly positive correlation with SRP. This is in agreement with what we could have expected: a higher desorption capacity leads to higher phosphorus losses. However, it is more difficult to interpret the good negative correlation between the organic matter content and SRP concentration. Organic matter is actually supposed to inhibit the retention capacity of soils and therefore promote P losses. The explanation could be that no P is applied to soils with a high %OM, which is quite plausible since these soils are generally not exploited for agriculture.

5.3.5 Transport factors

As far as *Runoff*, *Slope* and the different variables about soil type are concerned, the results provided by the correlation analysis are at the opposite of what we could have expected. Indeed, Table 5.4 shows strong negative correlations for *Runoff*, *Slope* and *Poorly Drained*. One would have expected that an increased runoff would have cause greater transfer of P to the streams. In the same way, the impeded drainage of poorly drained soils could be thought to promote overland and subsurface flows, which are the main pathway for P transfer. But it does not seem to be the case here.

If we consider the whole study area, it appears that the transport factors are high in the west and in the belt of upland areas. There, the slopes are steep and the soils poorly drained. But as far as the sources of P are concerned, i.e. agricultural activities essentially, they are mainly located in the centre, in the south and in the east of the catchment. In fact, areas with the highest transport potential do not coincide with source areas for phosphorus. In the literature on diffuse P loss (Sharpley, 2003), the coincidence of a nutrient source and a pathway is referred to as a Critical Source Area (CSA). The concept is represented with a scheme in Figure 5.10.

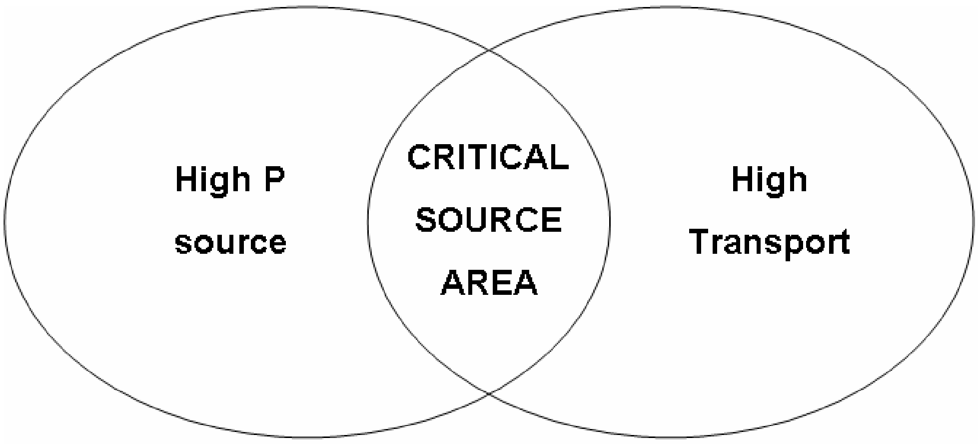

Figure 5.10: The concept of critical source area.

Figure 5.11 illustrates very well the opposite effects of agriculture and transport factors (slope and runoff risk) on the SRP concentrations. Agriculture is actually dominating for small slopes and runoff while it is very limited when the slopes and runoff risks are high. It is therefore difficult to distinguish the real influence of transport factors. But since the relationship is at the opposite of what we could expect, it is likely that these factors have a very limited influence.

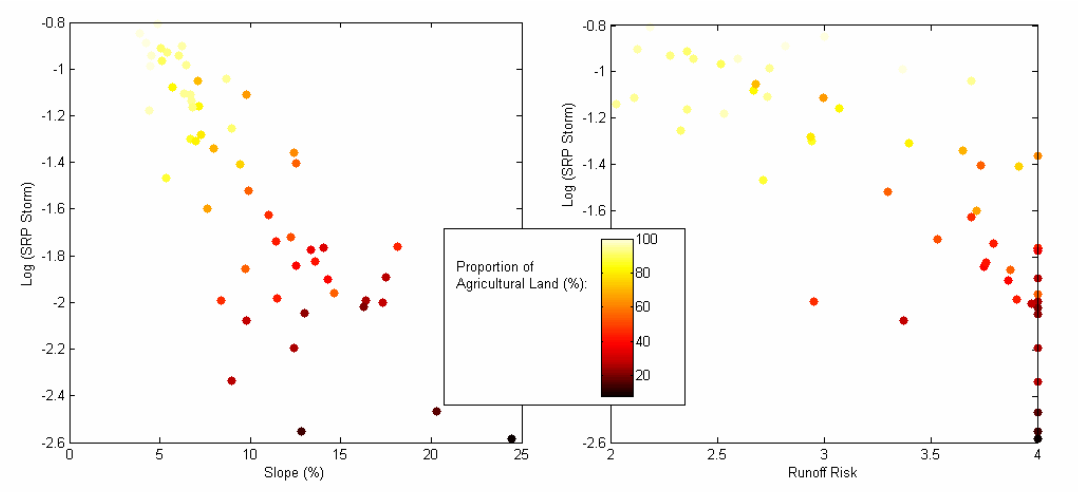

Figure 5.11: Log-transformed SRP Storm concentrations vs. Mean cell Slope & Runoff Risk +proportion of agricultural land.

To confirm the hypothesis that transport factors had little influence, semi-partial correlations were carried out. They were including the SRP concentration in storm flow, one of the transport factors (*Runoff*, *Slope* or a soil type variable) and a control for *Agricultural*, since it is one of the best predictor for SRP levels. This type of correlation is a way to hold constant the effects of *Agricultural* and to look only at the relationship between *Log (SRP Storm)* and the transport variables. But at the end, none of the semi-partial correlations gave significant results. When looking at Figure 5.11, it is actually difficult to detect any clear trend among the subcatchments with similar proportion of agricultural land (i.e. the points with the same colour).

Figure 5.12 shows the type of graph we could have obtained if the areas with sources of P had been more mixed with the areas with transport potential. On an environmental point of view, the non-coincidence between these two types of areas is of course a good thing. If it was not the case, the Lee catchment would actually face some serious problems in term of water quality. But for the interest of this study, this parting between source and transport has unfortunately hidden the role of transport factors.

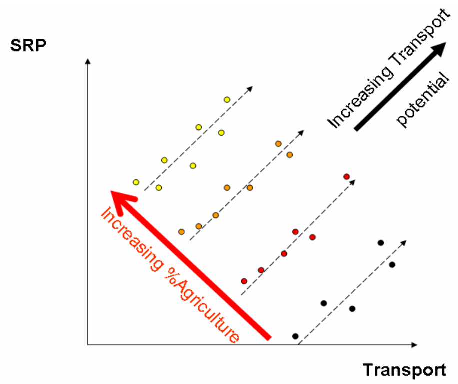

Figure 5.12: Ideal Relationship between SRP and Transport factor when considering the proportion of agricultural land.

5.4 Influence of precipitation

Dissolved phosphorus can be transported via three major pathways: surface runoff, subsurface flow and leaching to groundwater. These pathways are dynamic both in space and in time and depend on factors such as antecedent moisture, topography (that was studied in the previous part) and rainfall intensity, magnitude and duration (Heathwaite, 2000).

5.4.1 Spatial variation

The relationship between SRP concentrations and precipitation was first investigated at the catchment scale to see if the distribution of SRP values was dependent on the amount and/or on the intensity of rainfall that fell on the different subcatchments. For each of the different storm events, the concentration in Soluble Reactive Phosphorus is plotted against the amount of precipitation during the 24 hours prior to the sampling (Figure 5.13) and against the maximal rainfall intensity during these 24 hours (Figure 5.14).

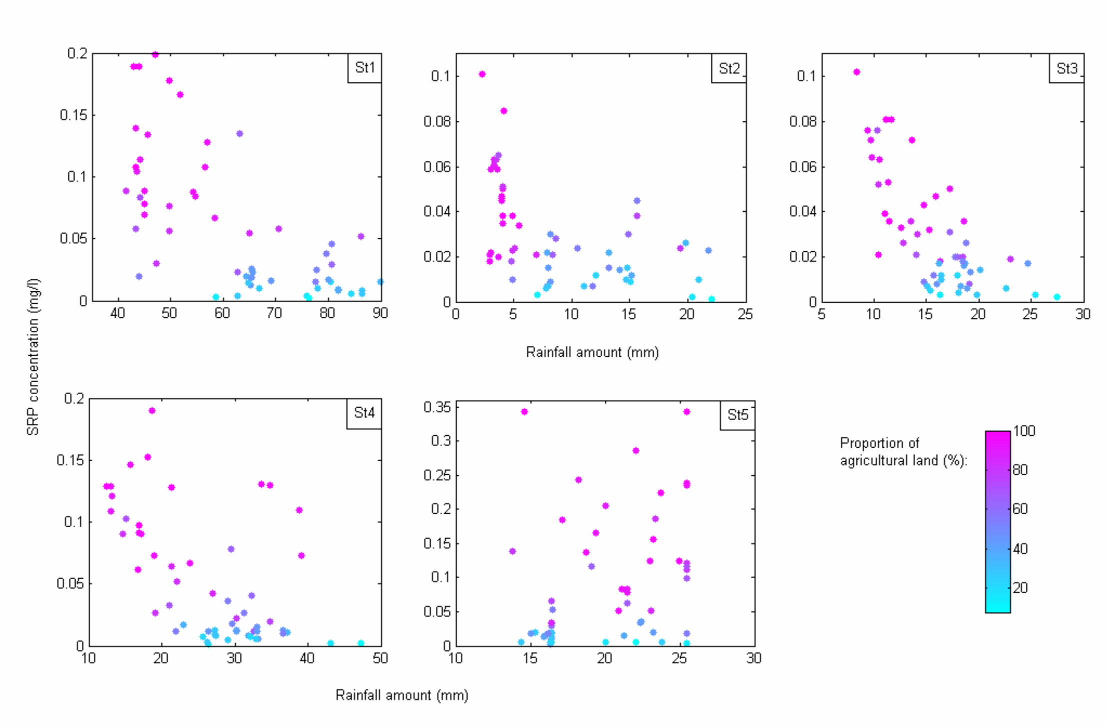

Figure 5.13: SRP concentrations vs. amount of rain for the 5 storm events.

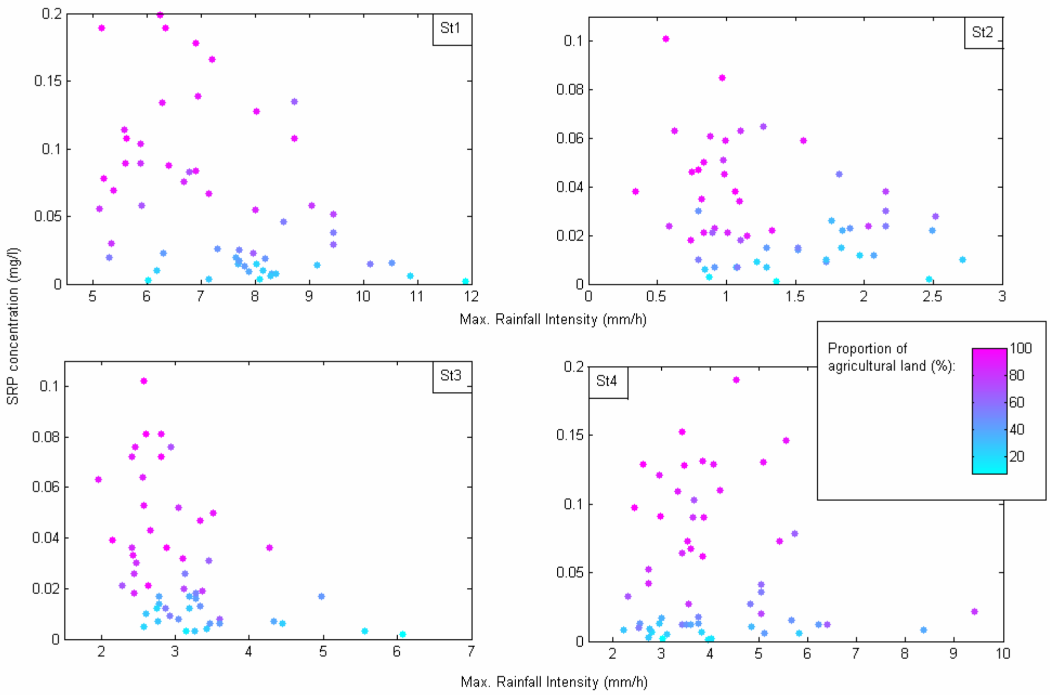

Figure 5.14: SRP concentrations vs. maximal rainfall intensity for the 4 storm events.

Again, it seems that the influence of precipitation is not discernible due to the partition of the different factors -source and transport- at the catchment scale. One would actually expect that higher amounts of rain and stronger intensities would enhance the phosphorus exports. But it is an opposite relationship which is obtained even if it is not as clear as it was with the other transport factors. As we saw in Chapter 2, there is a gradient of increasing precipitation from the East to the West which is at the opposite of the distribution of increasing agricultural activity. It seems again that the proportion of agricultural land is dominant. In the different graphs, the domination of the agricultural effect is actually quite clear with the colour gradation in the different graphs.

To try to isolate the effect of the sole precipitation, semi-partial correlations controlling for the effect of *Agricultural* were carried out. The idea was to see, for subcatchments with similar proportions of agricultural land, how SRP concentrations vary with precipitation. The results indicated some positive and some negative relationships between SRP concentrations and the rainfall amounts/intensities. But like in the previous part, the significance levels were much too low to indicate that the relationships could have any chance of being true.

5.4.2 Temporal variation

After having compared the different subcatchments between themselves, the idea is now to see the potential influence of precipitation by comparing the storm events between themselves.

In Figure 5.15, are shown the SRP concentrations for the different storm events, with the corresponding precipitation amounts and maximal rainfall intensities. Storm No 5, which occurred in September 2005, is associated with the highest values of SRP. As far as rainfall amount is concerned, this event did not rank first. The first storm event (Storm 1) is clearly the one associated with the largest amounts of rain in the previous 24 hours. However, the corresponding SRP values, even if they are high, are in most of the cases lower than Storm 5. In term of rain intensity, Storm 1 is showing the highest values of the four recorded events. The radar had actually a breakdown on the day the last storm occurred. So it unfortunately prevents us from comparing Storm 5 with the other events in term of rain intensity. Nevertheless, the hourly data provided by the rain gauge located at Knockane in the Dripsey catchment can at least gives us an idea of the rain intensity during Storm 5. The values for the different storm events at Knockane are summarized in Table 5.6.

Table 5.6: Rain data at Knockane.

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5
Rainfall amount	56 mm	4.2 mm	11.4 mm	19.4 mm	20 mm
Max Rain Intensity	5.4 mm/h	1.0 mm/h	2.0 mm/h	2.2 mm/h	6.2 mm/h

From Table 5.6, it is clear that Storm 5, even if it was not the most important event in term of rain amount, was the most intense one. It seems therefore that rainfall intensity could be the key driver of phosphorus losses from soil to water. In the literature, the P losses via all hydrological pathways are actually said to be dominated by heavy rainfall events (Schuman, 1973; Tunney, 2000).

In addition, a seasonal effect could also play a role in the magnitude of the P losses. It is actually reported that highest losses tend to occur following the first storm event after a dry period, which can often be the case in late summer and autumn (Jennings, 2003). For instance, Heathwaite (2000) measured the highest concentrations during autumn storms in a grazed catchment. In our study, Storm 5 and Storm 1, which occurred respectively in September and October, are actually the two events that produced the greater exports. Then, the losses over the winter and spring could decrease as the supply of potentially mobile phosphorus is exhausted.

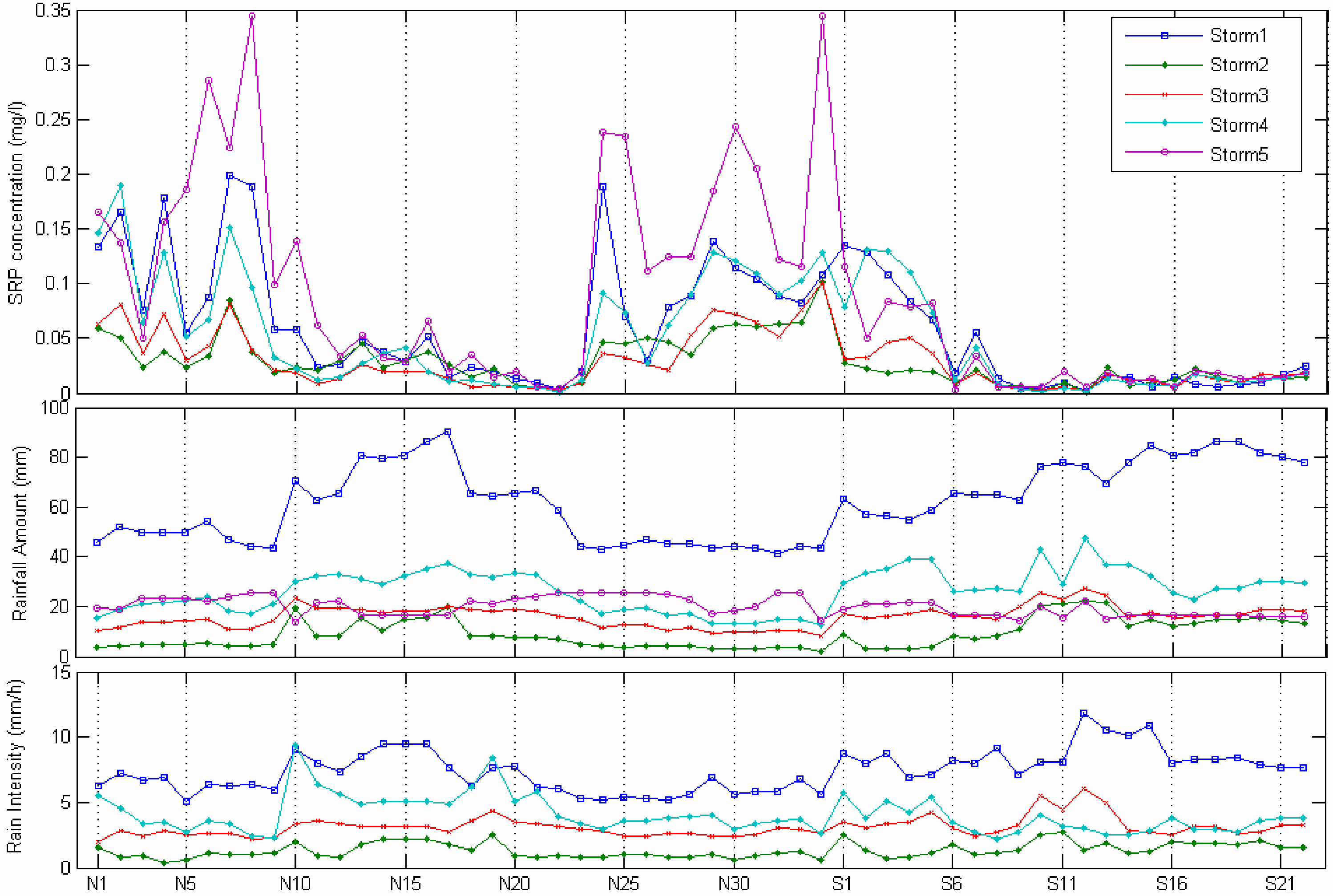

Figure 5.15: SRP concentrations, Rain amount and Rain Intensity for the 56 subcatchments (N1->N34, S1->S22).

Attempts were made to relate the SRP concentrations with the intensity of rainfalls, as this factor was thought to be the main diver of P losses. Correlations involving the ranks and the values of rain intensity and SRP concentrations were carried out. But with only data for 4 different events, it is difficult and risky to draw any conclusions. For a majority of the sites, there was a positive relationship between the intensity of rainfall and the SRP concentrations but only a few of them really showed a correlation as illustrated on Figure 5.16 for N3, N29 and S1. As it can be seen on Figure 5.15, there is a high variability in the SRP results and it is therefore difficult to link them with the rain intensities. It is especially the case for the upland subcatchments with very low SRP concentrations. For these sites, it appears that there is no link between intensity of precipitation and SRP concentration in the river.

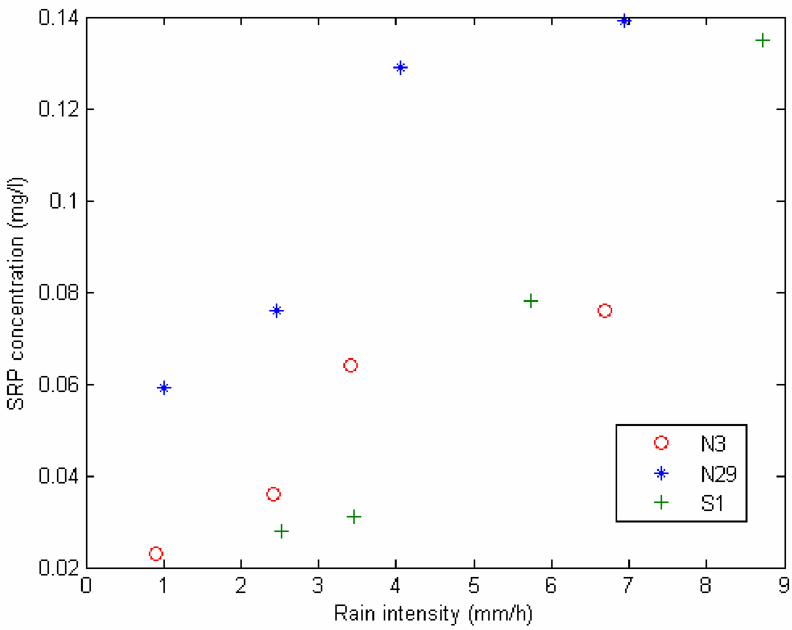

Figure 5.16: Relationship between SRP concentration and Rain intensity for the sites N3, N29 and S1.

5.5 Discussion

In this chapter, the main result is the strong relationship between the proportion of land dedicated to agriculture in each subcatchment and the SRP concentrations measured at the corresponding sites. A number of other source factors (Soil P, fertiliser application, livestock density etc) were also found to correlate well with SRP. The different independent variables predicted better the SRP concentrations in storm flow than in base flow. The modes of transfer that are involved in the two types of flow conditions are different: in base flow, surface runoff does not play any role and dissolution is then more important. It may explain that the level of soil P was found to be a better predictor of SRP in base flow.

SRP concentrations in subcatchments including large natural areas were low. The question is: is it due to the limited extent of agricultural areas or to a conservation of phosphorus by these areas? As far as forested areas are concerned, they are known to trap nutrients and are often utilised as buffers or riparian zones around streams or water bodies to reduce P inputs from agricultural land. This is true as long as forestry activities are not taking place. Post-planting fertilisation and clearfilling can actually lead to enrichment of the run-off water (EPA, 2004). Concerning peat bogs, the poor capacity of peat soils to hold phosphorus tends to indicate that the low level of SRP recorded in the areas covered by peat bogs is essentially due to the absence of agricultural activities.

Whereas source factors were in general correlating well with SRP, transport factors did not give the expected results. Increased transport potential did not result in increased phosphorus transfers even when holding constant the effect of the best source predictor. The non-coincidence of areas with high transport potential and source areas seems to be the main reason. The effect of precipitation was clearer on a temporal than on a spatial point of view. But the limited number of sampled events did not allow us to really investigate the action of rainfall in the transfer of P to water.

Chapter 6

Modelling River Phosphorus levels

6.1 RÉALTA Model

6.1.1 Presentation of the model

This model was developed by the company Kirk McClure Morton, who were consultants of the "Lough Derg &Lough Ree" catchment study. The objective was to identify the areas likely to present risk in term of phosphorus loss to surface waters. *Réalta* is also part of an EU project EUROHARP designed to quantify nutrient losses from diffuse sources across 17 study catchments in Europe. It is currently been compared with 8 other models either based also on nutrient export coefficient approaches (*Moneris, N-LES*) or on more process orientated models (*SWAT, TRK*). *Réalta* is intended to become one of the Irish tool to implement the Water Framework directive at the River Basin District scale.

Based on the use of Geographical Information Systems, *Réalta* links water pollution potential with a set of physical characteristics and management practices. Contrary to many models, it requires limited data input, which is in line with the poor quantity of data available at the scale of entire river catchments. The factors considered in evaluating the potential for loss and transport of phosphorus from agricultural systems are as follows:

- Runoff Risk to Surface Waters.
- Land use.
- Soil Phosphorus Levels.
- Mineral Fertiliser Loading.
- Organic Fertiliser Loading (cattle, sheep).
- Organic Fertiliser Loading (Intensive Agricultural Enterprises – pigs, poultry).

A ranking scheme is developed whereby each of the phosphorus loss indicators is subdivided into zones of relative risk, each of which has a numerical value for scoring purposes. The relative importance between factors is also represented by a further scoring system or "weighting".

A "score" or "rank" for a given combination of factors affecting loss and transport of phosphorus is developed in two steps:

1. Multiply the weight of each factor by the relative risk associated with the magnitude of each factor; and
2. Sum all of the products derived in Step 1.

Eventually, the resulting composite map establishes the range of potential agricultural risk areas across the catchment.

The ranking scheme developed for predominantly grassland catchments in Ireland is presented in Table 6.1. The total scores used to derive the potential risk classes are presented in Table 6.2. Land use data is in fact used only to distinguish between agricultural and non-agricultural areas. Non-agricultural areas are not taken into account by the model. The REALTA model assumes an equal bias across catchments for factors known to have a significant bearing on P loss from agriculture such as farmyards condition, management of land spreading activities and precipitation.

Table 6.1: *Réalta* Phosphorus Ranking Scheme (Kirk McClure Morton, 2001).

Factor	Factor Weighting	Risk Class	Score
Chemical Fertiliser Loading	12	1. 0-9 kgP/ha	0.8
		2. 9-11 kgP/ha	1.6
		3. 11-14 kgP/ha	2.4
		4. 14-19 kgP/ha	3.2
		5. >19 kgP/ha	4
Organic Fertiliser Loading (cattle, sheep, poultry)	24	1. 0.0-1.0 LU/ha*	1
		2. 1.0-1.5 LU/ha	1.5
		3. 1.5-2.0 LU/ha	2
		4. >2.0 LU/ha	4
Organic Fertiliser Loading (piggeries)	24	1. low potential	0.8
		2. moderately low potential	1.6
		3. moderately high potential	3.6
		4. high potential	4
Soil Phosphorus Levels	16	1. 0-5 mg/l **	1
		2. 6-9 mg/l	2
		3. 10-14 mg/l	3
		4. >15 mg/l	4
Runoff Risk to Surface Waters	24	1. very low risk	1
		2. low risk	1.5
		3. medium risk	2.5
		4. high risk	4

*Unit LU/ha = livestock units/hectare
** Morgan's P

Table 6.2: Score used to derive Potential Risk classes (Kirk McClure Morton, 2001).

Total Score	Potential Risk Class
0	Non-agricultural areas
0 - 120	Index 1 Low Risk
120 - 200	Index 2 Medium Risk
200 - 280	Index 3 High Risk
>280	Index 4 Very High Risk

6.1.2 Model implementation

The application of the *Réalta* model was based on the model description available from Euroharp and on the information found in the Lough Derg & Lough Ree Report (KMM, 2001). The data corresponding to the 5 factors involved in the model were gathered in different GIS layers that were combined to obtain the risk map.

6.1.2.1 Chemical Fertiliser Loading

Phosphorus chemical fertiliser loading was estimated using data from the 2000 Census of Agriculture in combination with a 2006 survey of fertiliser use as explained in Chapter 3. In the *Réalta* model, the chemical fertiliser factor is expressed in kg per hectare farmed. The data were kept at the Electoral Division level at which they are produced in the Census since the model was designed for this spatial resolution. Figure 6.1 shows the "chemical fertiliser loading" layer with the different risk classes. Only the four first classes are represented in our study area. The fifth class with loadings > 20kg P/ha was not noted in the catchment.

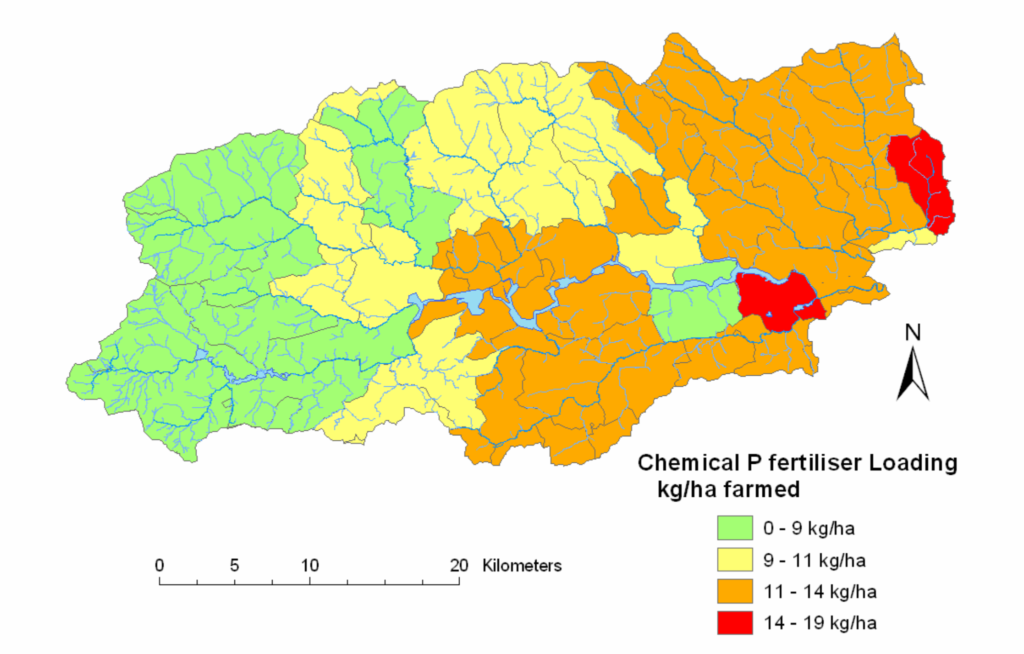

Figure 6.1: Chemical P Fertiliser Loading.

6.1.2.2 Organic Fertiliser Loading (cattle and sheep)

In the model, the organic fertiliser loading associated with cattle and sheep is expressed in term of livestock unit per hectare. Livestock numbers were established based on the data from the Census of Agriculture and then converted into LU/ha as explained in section 3.3.2. Data shown on Figure 6.2 are again at the ED level.

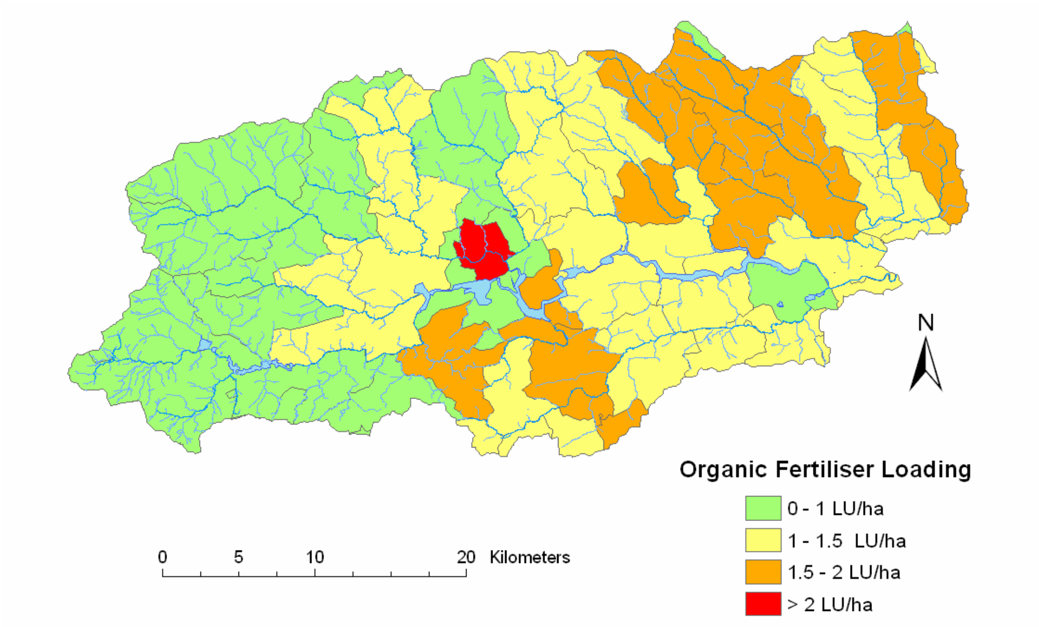

Figure 6.2: Organic Fertiliser Loading (Cattle & Sheep).

6.1.2.3 Organic Fertiliser Loading (piggeries)

As indicated in chapter 2, two pig units are currently licensed by the EPA under IPC license for intensive agricultural activity. Information is available from the EPA through the application and inspection documents. The first piggery is located in Grenagh in the North East of the Study area. The annual production of 9,600 m^3 of slurry is essentially landspread within a 12 km radius from the unit. The second pig unit is in the South of the catchment in Curraglough, Lissarda. About 15,000 m^3 of slurry are produced annually and are landspread in the area around Crookstown, Kilmurry and in the south, outside of the catchment.

Using this information and the methodology used for the "Lough Derg & Lough Ree" catchment study, a map showing areas where pig slurry is potentially landspread was developed (see Figure 6.3). Considering the distance between both piggeries and their size, only the "low" and "moderately low" risk classes were used. It was assumed that the risk was greater near the piggeries by creating two-tiered buffers around them. The area of influence of the Curraglough pig unit is larger to account for the larger number of pigs. The rest of the study area is in the category "not classified".

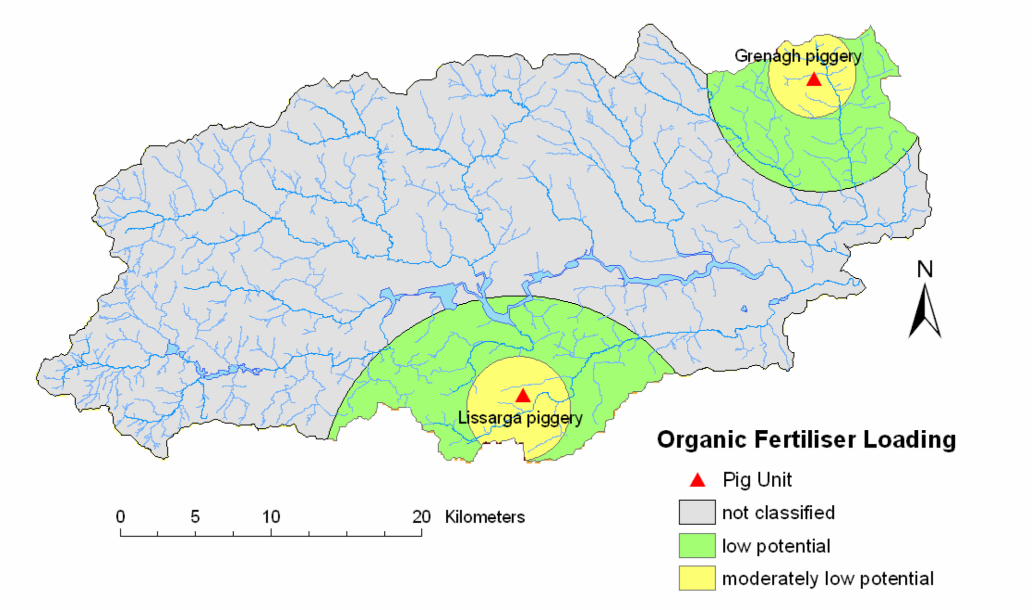

Figure 6.3: Estimated Organic Fertiliser Loading from the two Piggeries.

6.1.2.4 Soil Phosphorus levels

For this factor, soil phosphorus levels obtained from our field samplings were used. They were re-classified into the 4 risk classes used in the model to obtained Figure 6.4 (See Chapter 4 for further details of site sampling).

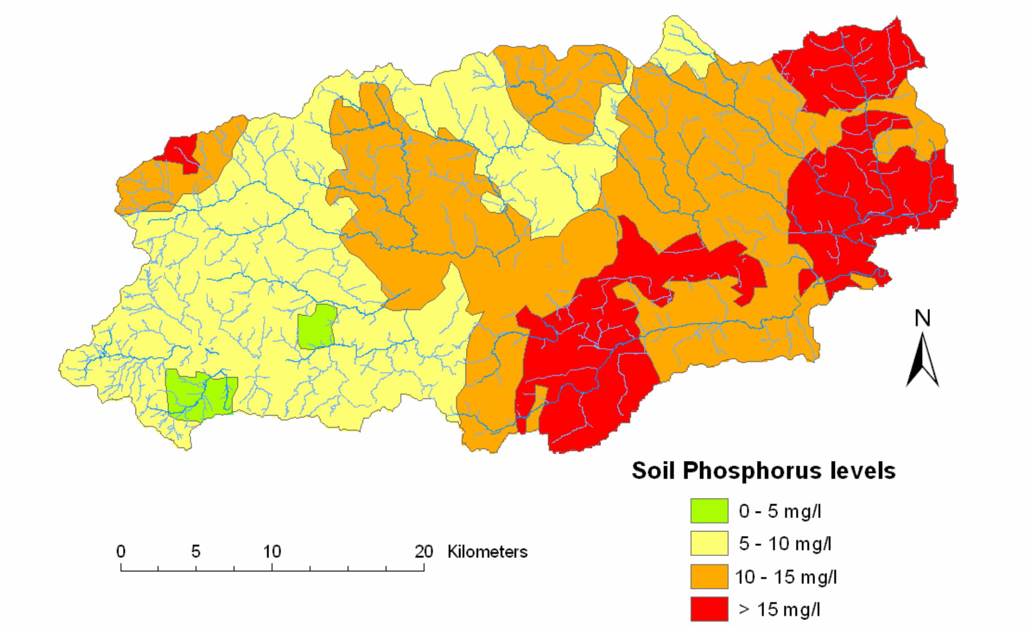

Figure 6.4: Soil Phosphorus levels.

6.1.2.5 Runoff Risk to surface waters

The *Réalta* model uses the runoff risk map developed by Gleeson (1992) and described in section 3.4.3 of this thesis to take account of the physical characteristics likely to influence the transport of phosphorus to surface waters. Gleeson's original eight risk classes are simplified into high, medium, low and very low runoff risk as shown in Table 6.3. The "very low" risk class is not represented in the study area, as shown in Figure 6.5.

Table 6.3: *Réalta* and Gleeson's risk classes equivalences.

Gleeson's Risk Class	Réalta Risk class
1 & 2	Very low risk
3a, 3b, 3c & 4	Low Risk
5, 6a, 6b & 6c	Medium Risk
7a, 7b & 8	High Risk

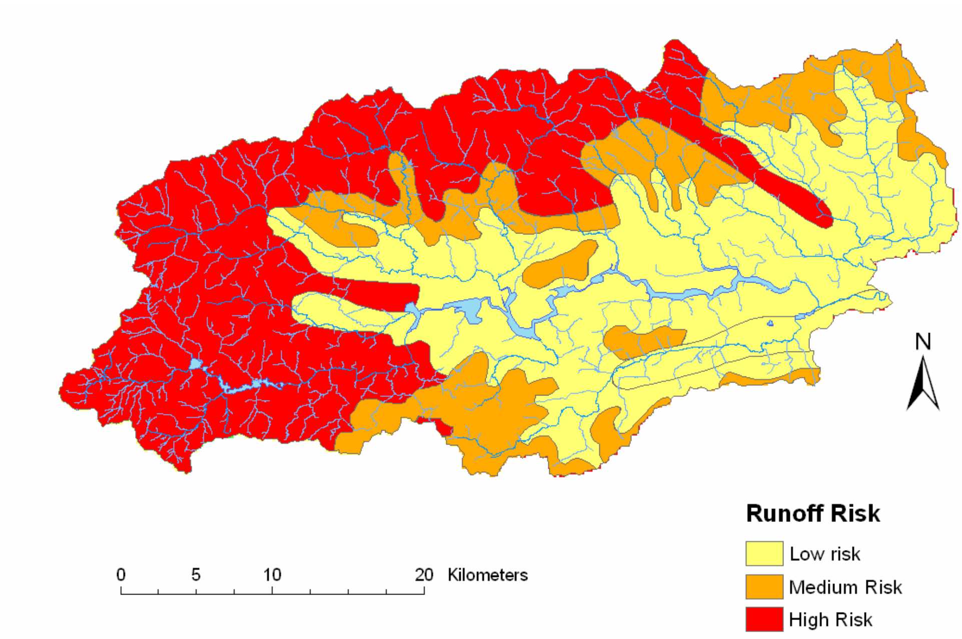

Figure 6.5: Runoff Risk to Surface waters.

6.1.3 Results

The 5 maps were first converted into raster layers with a resolution set at 100m x 100m square cells. Each cell was assigned a score corresponding to the area where they are located. The rasters were then weighted and combined using the functions offered by the spatial analyst tool included in Arc Map. The output layer ([PHOSPH_RISK]) is defined using the definition of the *Réalta* model:

$$[PHOSPH\_RISK] = [CHEM\_FERT]*12 + [ORGA\_CATTLE]*24 + [ORGA\_PIG]*24 + [SOIL\_P]*16 + [RUNOFF]*24 \quad (6.1)$$

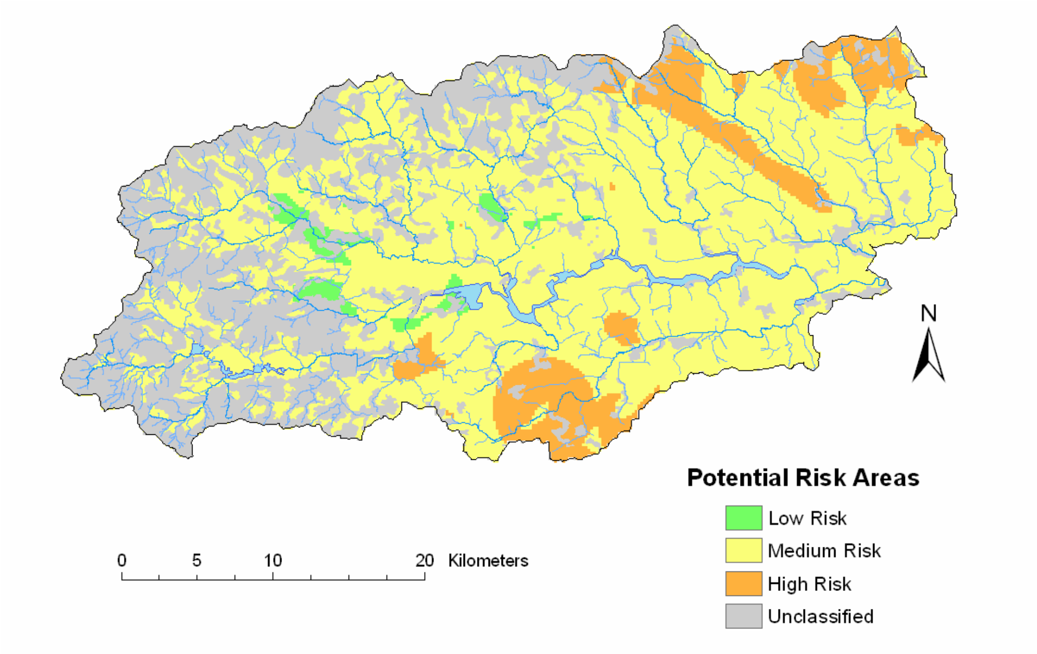

Figure 6.6: Potential Agricultural Risk Areas in terms of P loss to Surface waters.

Figure 6.6 shows the potential agricultural risk areas based on the scores presented in Table 6.3. The grey areas are the non-agricultural areas, which are not taken into account by the model. Most of the catchment is included in the "Medium Risk" category. There are no areas of "Very High Risk" It is noticeable that the "High Risk" areas seem to be heavily influenced by the effect of the two piggeries and of the Runoff risk factor.

As far as the factor for "Organic Fertiliser Loading (Pigs)" is concerned, it is certainly less relevant in the case of Lee catchment study area than it could be in the Lough Derg and Lough Ree catchments. 68 pig units are actually included in these latter two catchments covering an area of 10,600 km^2. In comparison, there are 2 units in our 1136 km^2 study area, which gives a piggery concentration almost four times lower. In addition, the two pig units are holding an IPC license, which means that the land proposed for slurry spreading has been submitted to the approval of the EPA in terms of suitability and sufficient area. It was therefore decided to reduce the weighting of this "piggeries" factor by two thirds, from 24 to 8 and to spread the remaining weighting proportionally amongst the other four factors.

Concerning the runoff risk, this factor appears to be too crude even for a large area like the Lee catchment. As it was noticed in section 3.4.3, soil type is in fact the main parameter used to establish the runoff risk categories and local topography is almost not taken into account. It was therefore decided to include the influence of terrain slope in the "Runoff risk" factor. To do so, cell slopes were classified into 4 categories based on values found in the literature and presented in Table 6.4. Each of these slope categories was given a coefficient between 0.25 and 1, with 1 corresponding to the steepest slopes and 0.25 to the more gentle ones. The “Runoff Risk” factor was then multiplied by this “Slope” factor in order to make it more accurate on a local basis.

Table 6.4: Slope categories and associated coefficients.

Slope (%)	Risk class	Coefficient
<5	very low risk	0.25
5-10	low risk	0.5
10-20	medium	0.75
>20	high risk	1

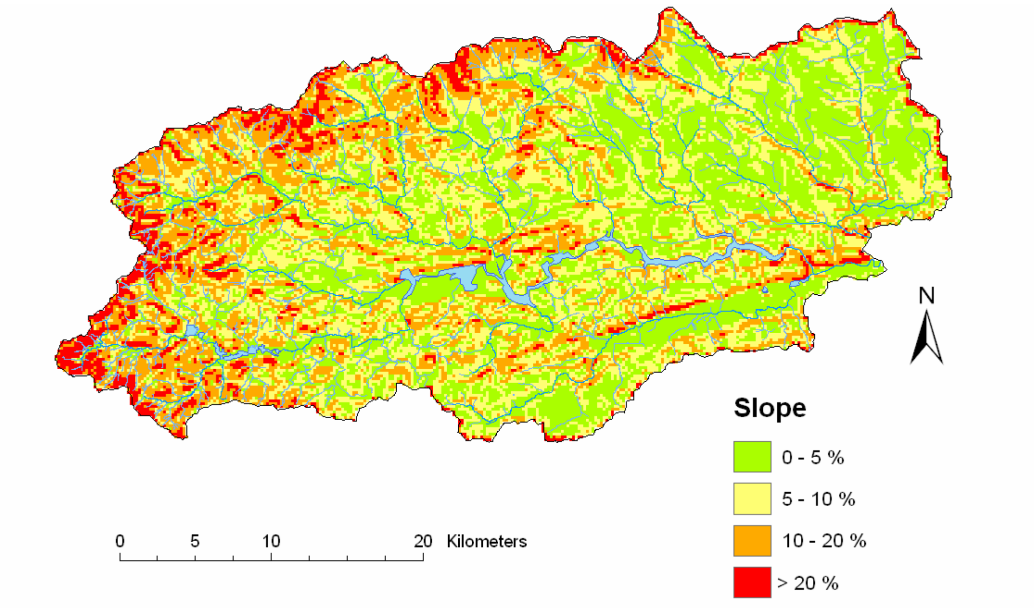

Figure 6.7: Slopes.

The output layer ([PHOSPH_RISK]), which is shown in Figure 6.8, is now defined by Equation (6.2). In addition, as a majority of the land was falling in the “Medium Risk” class, this class was subdivided into medium/low and medium/high risk (See Table 6.4).

$$[PHOSPH\_RISK] = [CHEM\_FERT]*16 + [ORGA\_CATTLE]*28 + [ORGA\_PIG]*8 + [SOIL\_P]*20 + [RUNOFF]*[SLOPE]*28 \quad (6.2)$$

Table 6.4: Score used to derive Potential Risk classes.

Total Score	Potential Risk Class	
0		Non-agricultural areas
0 - 120	1	Low Risk
120 - 160	2	Medium/low Risk
160 - 200	3	Medium/high Risk
200 - 280	4	High Risk
>280	5	Very High Risk

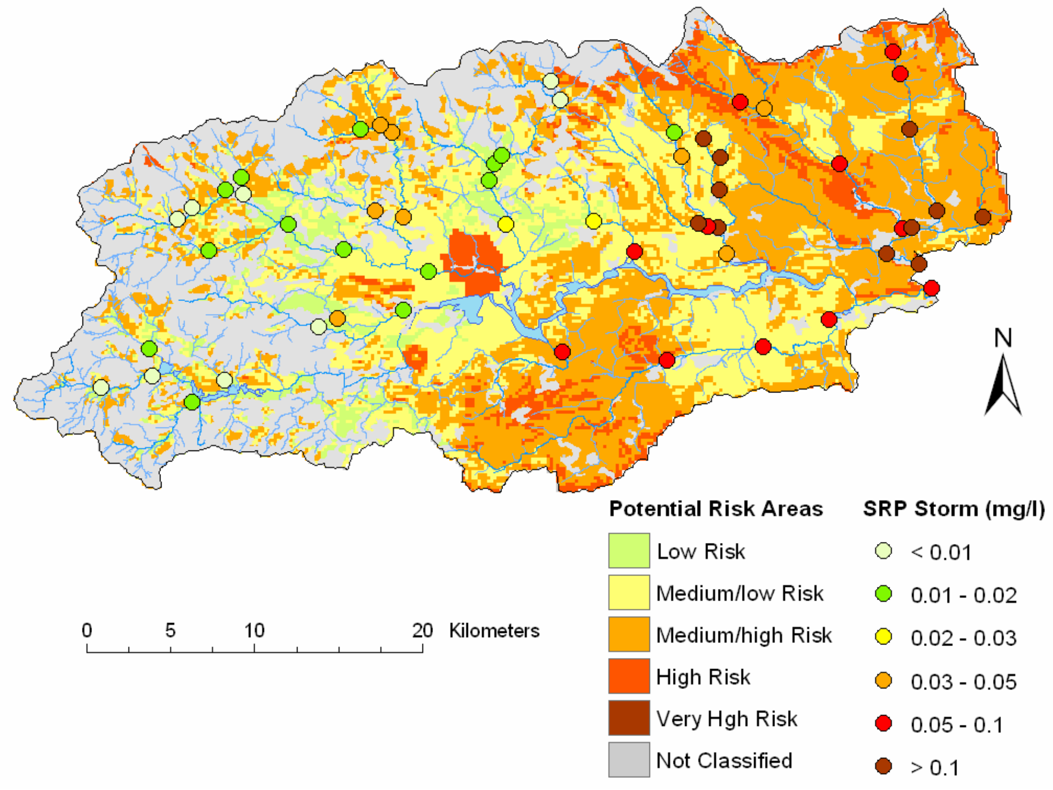

Figure 6.8: Potential Agricultural Risk Areas and measured SRP concentrations.

In Figure 6.8, the potential risk areas and the average measured SRP concentrations of our study are shown. There are some areas classified as "High Risk" but none as "Very High Risk". The areas showing the higher risks of P loss are located in the Shournagh and in the Martin catchments and in the south of the Carrigadrohid Reservoir. This is in line with the high phosphorus concentrations measured there. The Dripsey River, in spite of high SRP concentration, seems to show lower risks. The lower risks are generally found in the West of the Study area where the levels of phosphorus are generally low. But it is also in this part that much of the catchment is not agricultural and therefore not classified.

It would be interesting now to compare more accurately the risk areas and the phosphorus concentrations measured at the 56 different sites. In the "Lough Derg & Lough Ree", the different monitoring sites were allocated a risk based on the risk cell in which they were falling. This approach is very different from what has been done previously in this study. Until now, the predictors for SRP were always based on the whole contributing catchment. Here, only the location of the site is taken into account. In fact, the difference has to be attenuated since 3 of the 5 factors (the ones related to fertiliser) are based not on point data but on averaged data over larger area, such as electoral divisions.

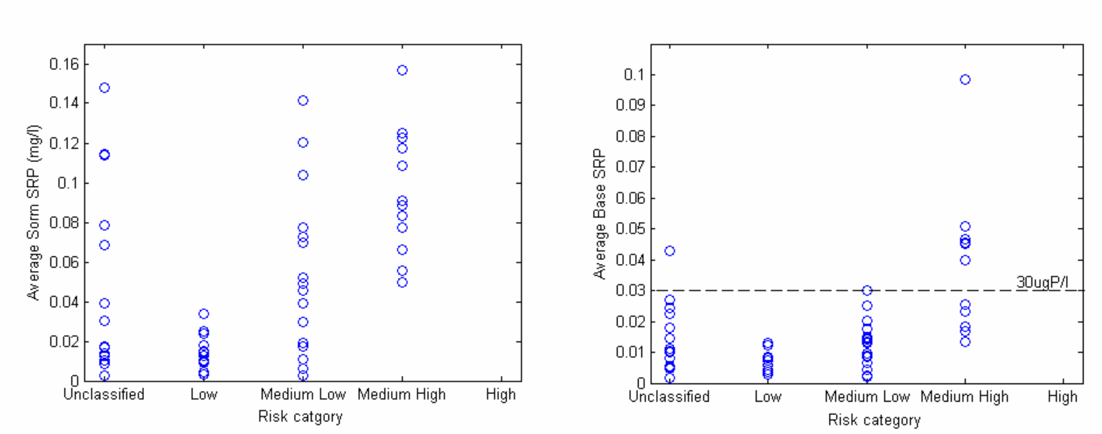

Figure 6.9: Comparison between potential Agricultural Risk and SRP concentrations.

Based on the cell in which it was falling, each sampling site was allocated a "risk". The results are presented in Figure 6.9 with the corresponding average SRP concentrations for storm and base flow conditions. It is noticeable that the greater the risk is, the higher the SRP values. The calculation of average SRP concentrations for each risk class confirms this trend. However, it is noted that there is a great variation of the phosphorus data within the same risk classes. As far as the "Medium Low" category is concerned, the SRP concentrations range for example from 0.003 to 0.14 mg/l. Sites from the Dripsey catchment are, in this case, showing the highest SRP values. A positive point is the fact that, in base flow, all the "low" and "medium low risk" sites are below the value of $30\mu gP.l^{-1}$ while the 7 sites showing higher values are in the "medium high risk".

6.1.4 Discussion

The main advantage of this model is that it is using factors based on information that is accessible. Even if the gathering and treatment of the data is time consuming, the data needed are available with reasonable accuracy (in the case of soil P, we used our own data) Indeed a majority of mathematical models require detailed information on site hydrology, drainage, soil chemistry, etc… At the scale of a large catchment, gathering such data is just not possible. The *Réalta* model essentially assesses the vulnerability of a particular area to phosphorus loss using a rational means.

This model can therefore be a useful tool to indicate areas likely to cause water pollution problems. However the main weakness is that it does not take account of upstream waters. For example, a large proportion of a catchment may be at "high risk", but the water sampling sites corresponding to that catchment may fall into a "medium risk" cell. Therefore the station would be classed as "medium risk" and not be representative of the catchment draining to that station. The amount of P flowing from the upstream areas to a monitoring site is actually an important factor to consider. But on the other hand, taking account of the upstream areas can lead to overestimation of the risk, when for example these areas are showing steep topography but are not associated with potentially dangerous activities in terms of source of P.

Another characteristic of this model is that non-agricultural areas are not included in the analysis. As a consequence, many areas of the catchment are not classified. This can be seen as a weakness but at the same time, if all the peat bogs were included, they would be likely to show high risks of P loss due notably to the importance of the runoff factor in these areas. But it would generally not be consistent with the actual phosphorus status of the streams flowing through these areas.

6.2 Multiple Regression: Land Use Model

So far, we only looked at simple linear regressions, in which the outcome -the SRP concentration- is predicted using the equation of a straight line. The unknown parameters in the equation are calculated by fitting a straight line to the data, for which the sum of the squared differences between the line and the actual data points is minimized. This method is known as the method of least squares. Multiple regressions is a logical extension of these principles to situations in which several predictors are used. Therefore, for every extra predictor that is included, a coefficient has to be added: each predictor variable has its own coefficient, and the outcome variable is predicted from a combination of all the variables multiplied by their respective coefficients plus a residual term:

$$Y = (b_0 + b_1X_1 + b_2X_2 + \ldots + b_nX_n) + \varepsilon \tag{6.3}$$

Y is the outcome variable, b_i is the coefficient of the *i*th predictor (X_i) and ε is the difference between the predicted and the observed value of Y. The model fitted is more complicated but the basic principle remains the same as in simple regression. The objective is to find the linear combination of predictors that correlate maximally with the outcome variable.

Until now, we have considered each independent variable at a time and it was therefore difficult to evaluate the own contribution of each parameter. In addition, the accuracy of the prediction was also reduced It would be interesting, for example, to know, in terms of land use, what is the respective contribution of each type of land use.

6.2.1 Presentation

The variables *Impgrass* (Improved grassland), *Unimpgrass* (Unimproved grassland), *Cultivated*, *Forest*, *Peatland* were entered into a multiple regression analyses. As we saw in Chapter 5, the variable *Cultivated* does not concern all the subcatchments and seems to play an important role in the SRP variations. It was therefore decided to split the analysis into two analysis based on the occurrence or not of cultivated areas. The two groups are called "*Culti*" and "*NoCulti*" and comprise 27 and 29 subcatchments, respectively. Figure 6.10 shows the different subcatchments according to the presence or not of cultivated areas. It is noted that there is a clear difference between the North-West of the study area and the rest of the Lee catchment in terms of the subcatchments belonging to the *Culti* or *NoCulti* groups.

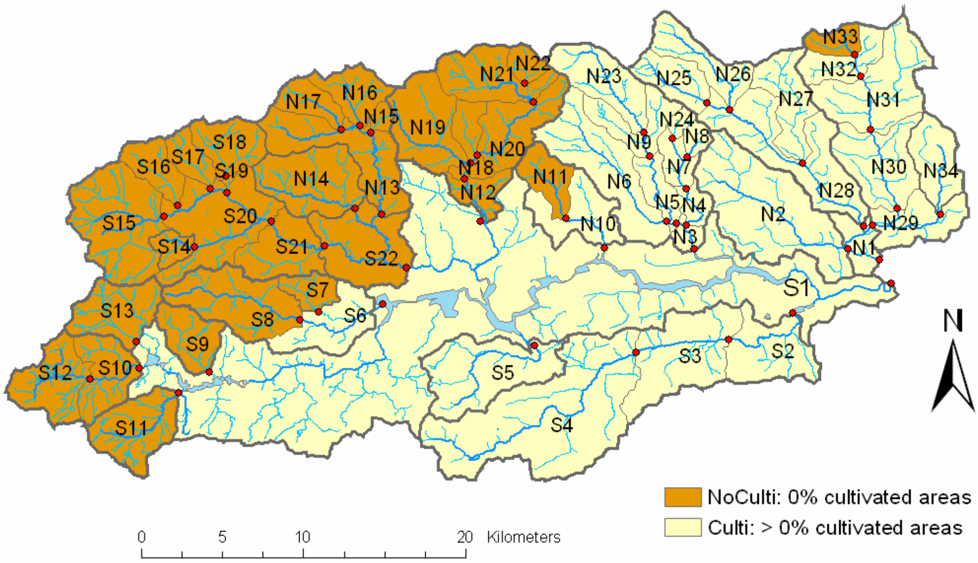

Figure 6.10: The two groups of subcatchments, *Culti* and *NoCulti*.

6.2.2 Multicollinearity

First, a multiple regression was carried out by entering directly the 5 independent variables (or 4 for the *NoCulti* group, since the *Cultivated* variable is null in this case) and *Log(SRPStorm)* as a dependent variable into SPSS. The goodness of prediction of the proposed model was acceptable. But a detailed study of the results showed that only two variables were making a significant contribution to the model, *PeatLand* and *Forest*. The coefficients associated with the other variables were too low to produce any significant variation in the value predicted by the model. This non-significant contribution to the model was also confirmed by *t*-tests.

In fact, as we saw in Chapter 5, there are many high correlations amongst the independent variables. Here, in particular, *PeatLand* is so highly correlated (negatively) with *ImpGrass*, *UnimpGrass* and *Cultivated* that it becomes impossible to distinguish their individual influences on the response variable. *PeatLand*, which is the best individual predictor of *Log(SRPStorm)* among the four variables, is consequently the only one to be kept by the model and makes the most significant contribution, with *Forest*, to the prediction of the result. The other variables, even if they might account for a lot of the variance in the outcome, are almost not taken into account by the model since most of this variance is already accounted for by *PeatLand*. This problem, which occurs in multiple regressions when there is a strong correlation between two or more predictors, is known as multicollinearity.

If there is, for example, a perfect collinearity between two predictors (they have a correlation coefficient of 1), it becomes then impossible to obtain unique estimates of the regression coefficients since there are an infinite number of combinations of coefficients that would work equally well. More generally, multicollinearity can typically have the following unwanted effects (Dallal, 2001):

- Regression coefficients will change dramatically according to whether other variables are included or excluded from the model.
- The standard errors of the regression coefficients will be large.
- In the worst cases, regression coefficients for collinear variables will be large in magnitude with signs that seem to be assigned at random.
- Predictors with known, strong relationships to the response will not have their regression coefficients achieve statistical significance.

6.2.3 Factor Analysis

In general, the purpose of a factor analysis is to reduce a large set of data into a smaller subset of variable by identifying a number of underlying dimensions, known as factors or latent variables. Then, factor scores, which are linear combinations of variables, indicate the scores of the different cases (subcatchments, here) on the subset of factors. Thus, factor analysis can be used to overcome collinearity problems. If such an analysis is carried out on the predictor variables, it will actually reduce them to a subset of uncorrelated factors. The multiple regression can then be rerun but using the factor scores as predictor variables instead of the independent variables themselves.

A factor analysis was therefore carried out with the Principal Component Analysis method using SPSS. The factors were rotated using the varimax method in order to improve the interpretability of factors. Rotation actually maximizes the loading of each variable on one of the extracted factors whilst minimizing the loading on all other factors. It is then clearer to distinguish which variables relate to which factors. The factor analysis was first carried out on the *Culti* group. The outputs will be explained for this first analysis.

The first part of the factor extraction process is to determine the linear components within the data set (the eigenvectors) by calculating the eigenvalues from the correlation matrix of the 5 variables. In Table 6.5, we can see that, before extraction, 5 linear components are identified by SPSS within the data (as many as there are variables). The eigenvalues associated with each factor represent the variance explained by that particular linear component. So, factor 1 explains 47.84% of total variance. We can see that the first three factors explain more than 90% of the variance. These three factors were therefore extracted. In the third part of the table (labelled *Rotation Sums of Squared Loadings*), the eigenvalues of the factors after rotation are displayed. Factor 1 now accounts for 33.54% of variance, factor 2 for 30.92% and factor 3 for 25.66%.

Table 6.5: Total Variance explained for *Culti*.

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.39	47.84	47.84	1.68	33.54	33.54
2	1.23	24.52	72.36	1.55	30.92	64.46
3	0.89	17.76	90.12	1.28	25.66	90.12
4	0.37	7.30	97.42			
5	0.13	2.58	100			

Table 6.6 shows the rotated component matrix, which is a matrix of the factor loadings for each variable onto each factor. It is noted that *Cultivated* loads particularly highly on factor 1. *Forest* also appears to have a significant importance to factor 1 but its loading is opposite. The variables that load highly on factor 2 and factor 3 are respectively *ImpGrass* and *UnimpGrass*. *PeatLand* has each time a significant contribution to the factors.

Table 6.6: Rotated Component Matrix for *Culti*.

	Component		
	1	2	3
Cultivated	-0.969	0.075	0.004
ImpGrass	0.018	-0.970	-0.151
UnimpGrass	-0.084	0.066	0.983
Forest	0.700	0.443	-0.285
PeatLand	0.490	0.632	-0.461

Eventually, in Table 6.7, the component score coefficient matrix is shown. Factors scores are calculated from these coefficients instead of simply using the factor loadings, which could be a solution as well. This matrix is obtained by multiplying the matrix of factor loading (Table 6.6) by the inverse of the correlation matrix. In doing so, the factor loadings are adjusted to take account of the initial correlations between variables. Differences in units of measurements and variable variance are consequently stabilized. This method is called the regression method. Equation (6.4), (6.5) and (6.6) shows how these coefficient scores are used to produce factor scores for factor 1, 2 and 3.

Table 6.7: Component Score Coefficient Matrix for *Culti*.

	Component		
	1	2	3
Cultivated	-0.74	0.27	-0.25
ImpGrass	0.18	-0.71	-0.16
UnimpGrass	0.18	0.09	0.85
Forest	0.35	0.16	-0.06
PeatLand	0.11	0.34	-0.26

$$Factor\ 1 = -0.74\ Cultivated + 0.18\ ImpGrass + 0.18\ UnimpGrass + 0.35\ Forest + 0.11\ PeatLand \quad (6.4)$$

$$Factor\ 2 = 0.27\ Cultivated - 0.71\ ImpGrass + 0.09\ UnimpGrass + 0.16\ Forest + 0.34\ PeatLand \quad (6.5)$$

$$Factor\ 3 = -0.25\ Cultivated - 0.16\ ImpGrass + 0.85\ UnimpGrass - 0.06\ Forest - 0.26\ PeatLand \quad (6.6)$$

The same work was done for the *NoCulti* group. Two main components were identified. In Table 6.8, it can be seen that *PeatLand*, *ImpGrass* and *UnimpGrass* load highly on factor 1 while *Forest* is the variable that loads highly on factor 2. Table 6.9 shows the component score matrix from which the factor scores are calculated.

Table 6.8: Rotated Component Matrix for *NoCulti*.

	Component	
	1	2
ImpGrass	0.831	-0.120
UnimpGrass	0.862	-0.206
Forest	-0.048	0.991
PeatLand	-0.919	-0.296

Table 6.9: Component Score Coefficient Matrix for *NoCulti*.

	Component	
	1	2
ImpGrass	0.36	-0.09
UnimpGrass	0.37	-0.16
Forest	0.00	0.88
PeatLand	-0.41	-0.28

6.2.4 Results

The variables that were collinear were combined into factors and the uncorrelated factor scores can be used in the multiple regressions. The results of these analyses are presented in Table 6.10 and 6.11, for *Culti* and *NoCulti*, using *Log (SRP Storm)* as the dependent variable. The coefficients of the models are shown with their standard errors in the first column. In the second column, the t-tests which are all associated with significance value less than 0.05 indicate than the predictors are all making significant contributions to the models. With R^2 values of 0.726 and 0.755 for *Culti* and *NoCulti*, it can be said that both models fit well the *Log(SRP Storm)* values corresponding to these reduced groups (n_{Culti}=27 and $n_{NoCulti}$=29).

Table 6.10: Multiple regression results for *Culti*.

	Coefficients		t-test	
	B	Std. Error	t	sign.
(Constant)	-1.489	0.089	-16.74	2.23E-14
Factor 1	-0.020	0.003	-6.27	2.12E-06
Factor 2	-0.016	0.003	-4.89	6.14E-05
Factor 3	0.013	0.005	2.85	9.07E-03

R^2=0.726

Table 6.10: Multiple regression results for *NoCulti*.

	Coefficients		t-test	
	B	Std. Error	t	sign.
(Constant)	-1.723	0.044	-39.25	1.13E-24
Factor 1	0.025	0.003	8.90	2.25E-09
Factor 2	-0.007	0.003	-2.64	0.014

R^2=0.755

However, these coefficients are not very instructive as they are, since they relate to the factors and not to the variables themselves. The models were therefore transformed so that the equations show the influence of the different variables:

<u>*Culti*</u>:

$$Log\ (SRP\ Storm) = -1.489 + 10^{-3}(7.14*Cultivated + 5.85*ImpGrass + 6.23*UnimpGrass - 10.44*Forest - 11.21*PeatLand) \qquad R^2=0.726 \qquad (6.7)$$

<u>*NoCulti*</u>:

$$Log\ (SRP\ Storm) = -1.723 + 10^{-3}(9.84*ImpGrass + 10.70*UnimpGrass - 6.48*Forest - 8.32*PeatLand) \qquad R^2=0.755 \qquad (6.8)$$

It is noted that, in storm flow conditions, *Cultivated*, *ImpGrass* and *UnimpGrass* act as “sources” of P while *PeatLand* and *Forest* act as “sinks”, as far as this model is concerned. For both groups (*Culti* and *NoCulti*), improved and unimproved grasslands appear to play a similar role in the transfer of P. The unimproved appears to be more likely to export P. This result may seem surprising since the "good" pastures are more intensely exploited. But it is confirmed elsewhere in the literature (Jordan, 2000; McGuckin, 1999). It could be due to the undrained and compacted nature of the soils associated with non-improved grasslands, which ensures that P remains in the surface layer, limits the possibility of adsorption down the profile and encourages surface runoff. Cultivated lands is the type of land use which plays the most important role in terms of P source as shown by the coefficient associated with *Cultivated*. In this case, it is a known fact that higher losses are generally reported from soils under arable cropping than for low-intensity grassland (Sharpley, 1997). Figure 6.11 shows a comparison between the observed and the predicted *Log (SRP Storm)* values. The goodness-of-fit for *Culti* and *NoCulti* is slightly the same with R^2 values of 0.73 and 0.76 respectively.

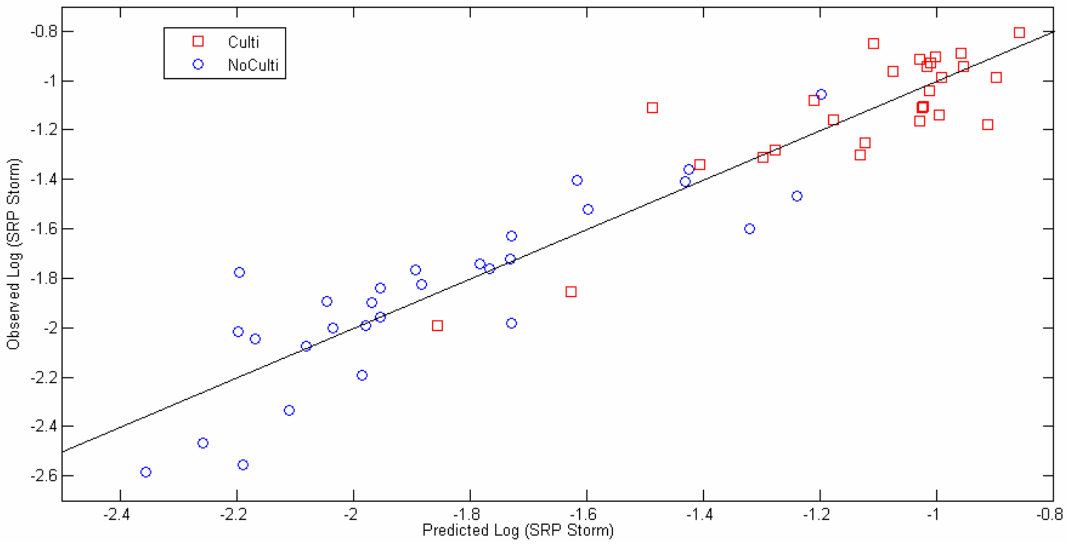

Figure 6.11: Observed *Log (SRP Storm)* values vs. Predicted *Log(SRP Storm)* for *Culti* and *NoCulti* groups.

In base flow, the value of R^2 is dramatically lower at 0.39 for the *NoCulti* group. It seems that for the streams in the West of the catchment, land use is not a good predictor any more when it comes to base flow conditions. Other parameters, such as underlying geology or the nature of the soil, could explain better the level of phosphorus observed in surface waters, which are anyway in the range of natural concentrations (less than $10\mu gP.l^{-1}$).

For the *Culti* group, R^2 remains good with a value of 0.68. The details of the model, in base flow, for this group of the catchments including cultivated lands are presented below:

Culti:

$$Log\ (SRP\ Storm) = -1.827 + 10^{-3}(13.71*Cultivated + 2.40*ImpGrass - 0.71*UnimpGrass - 10.62*Forest - 7.76*PeatLand) \qquad R^2=0.675 \qquad (6.7)$$

It is noticeable that, in this case, the proportion of cultivated land is the dominant factor, in terms of phosphorus sources. The role played by the percentage of good pasture is limited. In addition, it appears that unimproved grasslands are now acting as “sinks” in this model while in storm flow, they were greater exporters than the improved grasslands. Since precipitation and surface runoff are not playing any role in this case, it is normal than the fertilised pastures that hold more phosphorus within their soil matrix export more P.

6.2.5 Discussion

In this multiple regression model, the cultivated lands and the improved grasslands were found to act as “sources” of P while forestry and peat land appeared to act as “sinks”. The status of unimproved grassland was dependent on the climatic conditions, acting as a “source” in case of a rain event and as a “sink” the rest of the time. However, the terms “source” and “sink” should not be misunderstood. They mean that an increase in the proportion of cultivated land or improved grassland is likely to cause an increase in the level of SRP measured at the outlet of the catchment while an increase in the proportion of land covered by forestry or peat bogs will result in lower SRP concentrations. It does not mean that the land use identified as “sinks” actually trap phosphorus even if, in the case of forested ecosystems, a conservation of P is actually often reported in the literature (Attiwill, 1993). Another restriction concerns the land use “peat land”. Strictly speaking, it is not a land use but rather a land cover since this type of land can be dedicated to extensive grazing, exploited for peat or left as natural areas. As far as the Lee catchment is concerned, peat lands generally have no particular use or are associated with very light agricultural activities. If it was not the case and if application of manure and fertilizer were occurring, the status of peat land would be perhaps very different in terms of phosphorus losses, since peat soils do not have the capacity to fix or store applied P (Daly, 2005).

Chapter 7

Conclusion

7.1 Conclusion

In this study, phosphorus losses from soil to water were investigated in the River Lee catchment in Ireland. For most of the area, the phosphorus levels measured in the streams do not show signs of severe pollutions. However, in the East of the catchment, where agriculture is more present, concentrations of Soluble Reactive Phosphorus (SRP) measured at several river sites exceeded regulatory values.

In this mostly rural catchment, agriculture appears to be the main pressure in terms of phosphorus losses. The influence of other sources (waste water treatment plants, industries, urbanised areas, etc) was evaluated but the pressure of these sources was not considered as potentially dangerous as agriculture activity. With extensive improvements brought to farmyards, diffuse field sources are now representing the bulk of P losses to surface waters.

The results of 341 soil sample analyses showed that 44% of the samples collected in the catchment had Morgan's STP (Soil Test Phosphorus) greater than 10 $mg.l^{-1}$, which is above the agronomic requirements and is therefore likely to increase the risk of P losses. The phosphorus desorption capacities of soils appeared to increase with STP level. In addition, high organic matter soils turned out to hold little quantities of phosphorus. It is in line with the poor capacity of these soils to store P, which is often reported in literature.

A number of data sets were created with the help of GIS tools to describe land use, agricultural practices, soil types, topography and precipitation. When comparing these parameters with the SRP concentrations measured in storm and base flow conditions, a number of relationships were highlighted. The best predictor of the SRP levels revealed to be the percentage of land dedicated to agriculture, i.e. arable land, pasture and agricultural land including limited natural areas. This variable explained 89 % of the variance observed amongst the log-transformed SRP data in storm flow. Livestock density, fertiliser application, soil P levels all showed good positive correlation with the measured soluble phosphorus concentrations. As far as transport factors (rainfall, runoff) are concerned, it was very difficult to evaluate their contribution. The areas with a high transport potential, i.e. those subject to high precipitation and showing steep relief, do not coincide with the source areas of P. The transport factors are therefore not "triggered". When trying to investigate the role of rainfall on a temporal point of view, we had insufficient number of sampled storm flow events. However, it can be said that loss of phosphorus is dominated by rainfall events of high hourly intensity rather than high rainfall amounts resulting from continuous low intensity events.

Réalta, the Irish phosphorus model, was evaluated on the Lee catchment. It gave interesting results, but also showed weaknesses. This model is actually based on a local approach and contribution from the subcatchment draining the sampling sites are not taken into account. A model based on a multiple regression approach was built as part of this thesis to predict SRP levels from land use. It gave some interesting results about the contribution of the different types of land use in terms of P loss. First, land use was found to be a better predictor in storm flow conditions than when precipitations were not involved. Cultivated land appeared to be the dominant predictor of SRP concentrations. Improved grassland turns out to be also a major contributor. In contrast, phosphorus levels decreased with increasing proportions of forestry and peat land. The status of unimproved grasslands seems more ambiguous, acting as a source in storm flow and as a sink in base flow. This may be due to the nature of the soil which favours a washout of P when precipitation occurs.

From that, a number of recommendations can be made for the Lee catchment:

- Applications of P fertiliser and manure should be reduced especially in areas where Soil Test P show levels already higher than the agronomic requirements (>10 mg/l). These applications build up soil P to unnecessary levels and increase the risk of P losses. In addition, direct wash-off to the streams can also happen if rainfall occurs just after the spreading.
- Phosphorus application should absolutely be avoided in the upland areas of the West. This part of the catchment actually presents the higher transport potential. In addition, there is a significant proportion of peat soils, which are known to be unable to fix phosphorus. If phosphorus was applied, it would be washed out during rainfall events.
- Forestry cover has increased for a few years in County Cork and further afforestation campaigns are planned. Forestry activities (post-planting fertilisation, clearfelling) and the fact that plantations are often established on soils with a very poor capacity to hold phosphorus could lead to an increase of the risk of P loss to water if forestry industry was developing in the Lee catchment.

7.2 Suggestions for further research

1) The study should be continued and more samples should be taken. A greater number of results in both types of flow conditions would improve the knowledge about the phosphorus status of the different streams included in the study area. A better understanding of the temporal mechanisms involved in the P transfers could also be gained. Indeed, the effects of precipitation and the seasonal patterns involved could not be properly examined in this study due to the limited number of sampling campaigns during storm flow conditions.

2) Some weaknesses concerning the sampling strategy were underlined. Within the study area, rivers of different sizes and with different types of flow regime are actually represented. It is therefore likely that the water quality response may vary a lot between the different sites in terms of temporal pattern. With single samplings for each event, it is not possible to capture this dynamic nature of the phosphorus transfers. A continuous monitoring of the phosphorus concentrations is something very difficult to set up. But monitoring the flow at the different sampling sites could be an interesting first step. It would give the possibility to study the dynamics of the phosphorus transfers, especially in the case of the flashier streams, for which the peak concentrations are especially difficult to catch. It would also be the way to compare the different sites between themselves in terms of P loadings on given periods of time instead of using instantaneous concentrations, which are maybe not the most representative variables.

3) The methods that were used in this study to develop the different data sets are based on information which is, in most of the cases, available all over Ireland. By following a similar process, it could be possible to investigate water quality in other catchments for which water quality data are available. Comparisons could then be made between catchments presenting different characteristics.

4) New parameters could be integrated in the modelling of P losses. Based on the fact that P exports generally come from a small portion of a catchment which often corresponds to the area around the stream, it could be interesting to work on a way to weight the different parameters according to their distance from the stream.

5) Great efforts were put into the exploitation of radar data. Even if the results obtained in terms of P losses were not those expected, experience was gained in the use and calibration of such data over specific areas. Such an experience can be useful for diverse type of projects.

6) The water quality analyses carried out for this study provides the measures of a number of parameters other than Soluble Reactive Phosphorus (SRP). There is material for further studies: the Total Phosphorus concentrations could be integrated in the study of phosphorus losses and nitrate leaching could be investigated for example through the concentrations of Total Oxidised Nitrogen (TON).

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Appendix

Appendix A: Matlab Codes

```
% To determine the average hourly rainfall over the 56
subcatchements

clear
% Select Time Period
DateStart='18/10/2004/00';
DateEnd='28/10/2004/24';

daystart=datenum(DateStart,'dd/mm/yyyy');
dayend=datenum(DateEnd,'dd/mm/yyyy');

numbday= dayend-daystart+1;

for i=1:numbday

    for j=1:24
        %load radar data
       RadarDirectory='C:\Documents and
       Settings\VesnaJ\Desktop\Radar\2004-2005\';
       RadarFile=['snn240-',datestr(daystart+(i-1)+(j-
       1)*1/24,'yyyymmddHH'),num2str(rem(daystart+(i-1)+(j-
       1)*1/24,1)*24+1,'%02.0f'),'01_pcr.rra'];
        filename=[RadarDirectory,RadarFile];
        zipfilename=[filename,'.zip'];

        %check if radar file exists
        if exist(zipfilename)<1
             disp(strcat('file: ',RadarFile,' does not
exist'));

        else
        unzip(zipfilename);
        B=dlmread(RadarFile,'',1,0);
        A=flipud(B);
        delete(RadarFile);

       %transform the matrix data into an ASCII file
     recognized by Arcinfo
        copyfile ('header.txt','header2.txt');
       dlmwrite('header2.txt', A, '-append', 'roffset', 1,
     'delimiter', ' ');
        copyfile ('header2.txt','C:\WorkSpace');
        delete('header2.txt');
```

```
        %launch programme in Arcinfo Workstation
        cd C:\WorkSpace
        system ('arc "&r matlab3.aml"');
        delete('header2.txt');
        cd C:\MATLAB701\work

        end
    end
end
```

Appendix B: Arcinfo Codes

To be used in combination with the previous Matlab Code

```
/* convert Ascii file to a grid
Asciigrid header2.txt raingrid2 FLOAT

/* Do loop for all thiessen
&do thies = 9 &to 9 &by 1

/* Do loop for all north catchments---------------------------
&do ind = 34 &to 34 &by 1

&if [exists SUBcatchthiess\%thies%n%ind%.shp -file] &then &do
/* use gridclip function with the catchment polygon using a
precision of 100m
&type %thies%n%ind%
grid
setcell 100
gridclip raingrid2 rout2 cover catchment/%thies%n%ind%
quit

/*Export statistics (mean value) to file
&DATA ARC INFO
ARC
SELECT ROUT2.STA

EXPORT ../raintest/%thies%n%ind%rainmean.txt ASCII MEAN

Q
STOP
&END

kill rout2

&end
&else
&type no %thies%n%ind%
&goto stopju
&label stopju
&end

/* Do loop for all south catchments---------------------------
&do ind = 22 &to 22 &by 1

&if [exists SUBcatchthiess\%thies%s%ind%.shp -file] &then &do
/* use gridclip function with the catchment polygon using a
precision of 100m
&type %thies%s%ind%
grid
setcell 100
gridclip raingrid2 rout2 cover catchment/%thies%s%ind%
```

```
quit

/*Export statistics to file
&DATA ARC INFO
ARC
SELECT ROUT2.STA

EXPORT ../raintest/%thies%s%ind%rainmean.txt ASCII MEAN

Q
STOP
&END

kill rout2

&end
&else
&type no %thies%s%ind%
&goto stopju
&label stopju

&end
&end
kill raingrid2
&return
q
```

To be used to calculate the average values of Soil P, Soil OM, Soil PFEO, Slope, Runoff at the subcatchment level

```
 /* Do loop for all north catchments--------------------------
 &do ind = 1 &to 34 &by 1

 /* use gridclip function with the catchment polygon using a
precision of 100m
 grid
 setcell 100
 gridclip Soil P/Soil OM/ Soil PfEO/ Slope/ Runoff routn%ind%
cover Catchment/n%ind%
 quit

 /*Export statistics to file
 &DATA ARC INFO
 ARC
 SELECT ROUTN%ind%.STA
 EXPORT ../max.txt ASCII MAX
 EXPORT ../min.txt ASCII MIN
 EXPORT ../mean.txt ASCII MEAN
 EXPORT ../stdv.txt ASCII STDV
 Q
 STOP
 &END

 kill routn%ind%
 &end

 /* Do loop for all south catchments--------------------------
 &do ind = 1 &to 22 &by 1

 /* use gridclip function with the catchment polygon using a
precision of 100m
 grid
 setcell 100
 gridclip Soil P/ Soil OM/ Soil PfEO/ Slope/ Runoff
routs%ind% cover Catchment/s%ind%
 quit

 /*Export statistics to file
 &DATA ARC INFO
 ARC
 SELECT ROUTS%ind%.STA
 EXPORT ../max.txt ASCII MAX
 EXPORT ../min.txt ASCII MIN
 EXPORT ../mean.txt ASCII MEAN
 EXPORT ../stdv.txt ASCII STDV
 Q
 STOP
 &END

 kill routs%ind%
 &end
 &return
```