Pathways for Nutrient Loss to Water;

Slurry and Fertilizer Spreading

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Summary

There are almost 150,000 farms in Ireland and these contribute substantial quantities of N and P to inland and coastal waters. Some of these nutrients are carried from wet soils by overland flow and by leaching from dry soils. Farm practice can reduce the loss from farms by judicious management of nutrients. Improvements are required to diminish export of nutrients without impairing operations on the farm. Literature regarding nutrient loss from agriculture was reviewed in this project and maps were prepared to predict best slurry spreading times around Ireland. Two further maps were prepared to show slurry storage requirement on farms.

Water pollution by phosphorus occurs when P is carried from the soil surface by overland flow. Both P at the soil surface and overland flow must be present for pollution to occur. The critical concentration of P in surface water is 0.01 to 0.03 mg/ l. This is low compared to P levels in soils, which have risen steadily over the past 45 years from 1 to 8 mg/l. Data reported below show that the concentration of P in overland flow varies from the critical level in surface water to 30 mg/l or 1000 times greater than the safe level. Overland flow is common in Ireland and Gleeson's map (Sherwood, 1992) shows the distribution of soils most likely to produce surface runoff by infiltration excess or high water table level. Most surface runoff is generated rapidly from limited source areas. Management practices can contribute to nutrient loss by the timing and rate per hectare of nutrient applications and by allowing traffic and livestock onto land under wet conditions.

Nitrogen as nitrate is lost in water draining freely from dry soils in autumn and winter. A level over 11.3 mg/l N in drinking water can be harmful to babies up to six months old and it may also have a role in the promotion of cancer. The limit for eutrophication in estuaries is much lower at 2.6 mg/l N. Crops require excess N as fertiliser to achieve optimum economic yields. Nitrate represents only 2% of the N in the soil, but this is the form that is most available to plants and it is most easily lost to groundwater through leaching.

Improvements to farm management can do much to reduce losses of N and P. Reducing the amount of N in the soil in autumn and having crops actively growing from September onwards limits losses. Applying slurry

early in the growing season allows the nutrients to be used up by plants. Nutrients obtained from the breakdown of organic matter can be used up at this time. If slurry must be surface spread during a period when overland flow is normally expected, it should be done under the most favourable soil and weather conditions possible. Incorporation of slurry and P fertiliser reduces the risk of nutrient loss in overland flow. Reducing P input to land and especially restricting slurry spreading on wet soils in winter reduces P losses. Diffuse losses of P will become more significant as point sources reduce.

Data from a former project was reviewed. This included nutrient loss data for slurry and fertiliser to overland flow which was monitored on three sites in the vicinity of Johnstown Castle, Co. Wexford. Each site had six plots 2 m by 30 m long with a tank in which overland flow was recorded by depth measurement. Three plots were treated at three different application rates of pig slurry, one plot was treated with cattle slurry, one with fertiliser and one acted as control. Measurements showed that N and BOD in water were highest when a storm occurred just after spreading and that concentrations decreased over a period of about 10 days. Several weeks were required for P concentration to reduce to a level of 1 – 2 mg/l. The loss of nutrients from fertiliser was always less than from slurry with corresponding amounts of N and P. The statistical analysis of the nutrient concentration data proposed in this project was not possible. Some data were missing and overland flow was variable across plots. Overland flow was shown to be a factor which could affect the relationship between nutrient treatment and water solution effects. Comparisons between plots are not reliable. Overland flow at the three sites was concentrated in the months October to March with the highest values in January/February. Phosphorus content in runoff from two sites was summarised but comparisons between treatments were not consistent.

The Fertiliser Use Study (Coulter et al, 2002) recorded the application rate of fertilizers on 1130 farms around Ireland. The survey showed that many farmers with moderate stocking densities of cattle applied N to their fields at higher rates than recommended. However in 2004 Teagasc recommended an increase in the N rates for grassland in line with the latest research results. This eliminated the difference. In Tillage, excess N or P is applied to most crops. While this may be of concern in some catchments it is not a problem overall. Application of slurry to silage ground was not included in the survey but outline calculations suggest an excess application of P on an annual basis. This deficiency in the survey may be eliminated in the next issue.

Animals are housed in winter and the resulting slurry is spread on land. This sometimes caused pollution so local governments introduced by-laws to restrict spreading. In this project, maps were prepared based on rainfall. These provide useful information and show where restrictions could be placed to best effect. Assumptions were made about soil, air temperature and rainfall. The third parameter was taken to be the most relevant in predicting slurry-spreading opportunity. The rainfall data were analysed using a set of rules to identify spreading opportunity. Each rule sets a maximum rainfall threshold for a day. Thresholds varied from 0.5 to 2.5 mm/day. A string of several rules was termed a “filter”. Tests on the shape and length of the filter indicated that an offset V-shape of 8 days duration was best. The number of safe spreading days per year was calculated for each location. Years with a spreading probability exceeding 0.1 were considered spreading years. The ratio of spreading years to total years in the analysis was plotted for all points on 12 monthly maps of slurry spreading opportunity. There are more spreading opportunities in the eastern two thirds (5 to 6 years in 10) than in the western parts of Ireland (3 to 4 years in 10). This method based on rainfall can provide useful data to predict slurry-spreading opportunity anywhere in the world. It must be used in conjunction with other data regarding slope and soil moisture to provide site-specific information.

When animals are housed for winter, slurry must be stored until it can be spread on land without risk of nutrient loss. However, variability in rainfall and other parameters demand long storage periods in some parts of the country but not in others. Periods of 16 to 24 weeks are currently recommended. Two methods have been developed to indicate the distribution of storage period requirement throughout Ireland. One method uses the data from the approach described above and the principle that if it is not possible to spread, then the slurry must be stored. Maps for 5-month and 6-month winters were plotted. Storage periods from 4 to 24 weeks were predicted with the longest periods in the wettest areas to the north and west. The second method used several variables to calculate storage times. The basic storage period for an area was calculated from rainfall and evapotranspiration. This was adjusted using five factors based on soil properties and farm management. The resulting information shows the impact of soil condition and farm practice on slurry storage requirement. A map was plotted for a range of climate values but with other factors set to control conditions. Storage periods on the map range from 17 to 27 weeks.

1. Introduction

Pollution of lakes, rivers and ground water may occur from agricultural sources in various ways. Farm management practice, technology and soil can each contribute to the problem. An increase in intensification of agricultural practices has mirrored a decline in the water quality of Irish lakes and rivers. Many of the 146,000 farms in Ireland contribute to nutrient loss. These have an average size of 30 hectares and contribute in total about 100 kt N and 4.5 kt P each year to inland and coastal waters. These values are very much higher than the estimated background loads, 5.6 kt N /yr and 0.36 kt P/yr, which would probably exist in the absence of farming (Stapelton, *et al.,* 2000). Therefore agriculture appears to have a significant part to play in improving our environment. Sustainable approaches toward maximizing farm income and minimizing losses to the environment must take priority when formulating policies for agriculture in the future.

Soils have a range of properties such as texture, structure and nature of horizons etc. Soils that tend to retain water have a high risk of generating overland flow. In contrast freely drained soil has a lesser risk of causing overland flow, but it is inclined to leach nutrients which occur in excess in the soil. The soil properties that determine the risk of overland flow include hydraulic conductivity and infiltration capacity. In addition, certain topographical factors such as slope or location in or near flood plains influence the risk of flooding. Occasionally, however, poor farm management will result in the export of nutrients from slurry or fertiliser from the target site via overland flow.

The need to keep animals indoors during winter has given rise to the need to store slurry for several months in the winter. While cattle numbers have fluctuated with Government policy and market values, the provision of slurry storage facilities on farms has not been so flexible. Most stores are concrete tanks under livestock buildings and cannot be enlarged without extending the building. Over-ground stores are more flexible but any extension still requires considerable investment. Growth in herd size or ingress of rainwater can require an increase in slurry storage. Spreading in winter accommodates this but the land is most vulnerable to flooding at this time. Differences in rainfall and soil type around Ireland imply differences in slurry storage requirement. Guidelines for slurry storage did not identify any regional differences in the sizes of slurry storage tanks required on farms at the time this research took place. However recent publications have included recommendations from this project on regional differences in storage requirement (EU, 2005).

The objectives of this work were as follows:

- To critically review information in existing literature and data. This would help to develop an improved understanding of the factors contributing to pollution by P and N.
- To identify regional opportunities for spreading slurry
- To estimate the regional opportunities for storing slurry

These objectives were pursued in the following way. The first target was addressed by literature review, by an in-depth review of the Fertiliser Use Survey (Coulter *et al.,* 2002) and by a revised statistical analysis of nutrient loss data from former trials at Johnstown Castle. For objective 2, a mapping exercise, using detailed rainfall data, indicated the climate risk element of slurry spreading. A similar approach was adopted for the third objective where climate and other data were used to plot maps of slurry storage requirement.

2. Review

The review deals with nutrient loss from agriculture under eight headings. These topics cover issues concerning the soil, climate, machinery and management.

2.1. Overland flow

There are a variety of runoff processes, which may occur under different circumstances depending on soil, site and weather conditions. Hortonian overland flow is caused as a result of infiltration excess. It occurs on soils that are compacted, have high clay content or few macro-pores. Saturation overland flow occurs due to saturation excess. On wet soils, which can be saturated during a short burst of rainfall, immediate saturation overland flow may be expected. Overland flow is much delayed on thick macro-porous soils with a permeable matrix (Naef, Scherrer, & Weiler, 2002). Rapid subsurface flow results where an impermeable horizon of soils or impermeable bedrock on a steep slope is overlaid by shallow soil and an effective system of lateral flow paths.

Accurate determination of infiltration rate is an important factor in the reliable prediction of surface runoff. Water movement through homogeneous sandy soil is relatively uniform, while in silty soil a greater distinction is observed between mobile and immobile water (Barbee & Brown, 1986). Clay soils are likely to exhibit preferential flow through cracks caused by swelling and shrinking (Beven 1981; Bouma & Dekker, 1978). During saturated infiltration tests using a little pond small soil aggregates disintegrated and migrating smaller particles quickly formed a seal on the soil surface within a short period. Slaked clay particles are gel-like and seal the soil surface causing an extremely small infiltration coefficient. During rainfall the slaking of aggregates is enhanced by the kinetic energy of the raindrops causing fine soil particles to detach on impact and move about clogging pores. After a drying period the newly formed seal consolidates to form a crust. McIntyre (1958), Haraldsen and Sveistrup (1996) also demonstrated reduced infiltration rate on grassland. Smith *et al.,* (2001) showed how slurry solids loading could be critical to the risk of surface ‘sealing’ or capping and the generation of overland flow.

Frozen soil generally has a low conductivity and is prone to overland flow in heavy rain. If soil is saturated before freezing it develops a constant but very low conductivity. Soil moisture content below saturation at freezing allows a higher conductivity in the matrix. Percolating rainfall may melt ice in small pores allowing water to flow at normal rates in the soil. However, if the soil is very cold the rain may freeze so that the soil becomes as impermeable as if it had been saturated before freezing (Gray & Male, 1981).

Contaminated runoff originates through transfer of chemicals at the soil or slurry surface to overland flow. This transfer occurs through a variety of processes, (a) the mixing of rain water with the soil solution and slurry solution; (b) the dissolution of chemicals present in a solid form; (c) the desorption of chemicals adsorbed to the soil, or (d) the adsorption of chemicals to eroded soil or slurry particulates. Infiltrating water mixes with chemicals in a spatially limited mixing layer of the soil matrix (near to the surface), and the degree of interaction between rainwater and soil water usually depends upon depth, a concept known as non-uniform mixing (Ashraf & Borah, 1992). Transport of contaminants along the soil surface occurs through both connective means and by dispersion. Chemical routing is determined by the soil roughness coefficient, the slope, the dispersion characteristics of the solute or particles and the surface distribution of the pollutant. Undulations on the soil surface may generate source or sink fluxes of water and chemicals.

2.2. Soil Drainage Properties

Soil is an important reservoir of fresh water. The amount of water in soil equals one third of all freshwater in lakes, including artificial reservoirs and is one order of magnitude larger than that in riverbeds (Dyck & Peschke, 1983). Transport of water-soluble materials occurring naturally or under human influence is linked to hydrologic processes and these in turn are controlled by the soil.

Soils are classified according to their morphological features, genesis and soil forming processes. They are grouped into Great Soil Groups to simplify their analysis. Within a group, soils have the same nature, arrangement and degree of expression of horizons in the soil profile. These are further simplified in the soil map in AGMET (1996), which illustrates the distribution of soils in Ireland

Mulqueen and Gleeson (1982) conducted a study to examine the relationship between geology and land drainage. The results indicated that glacial geology has wide-spread influence on drainage problems. The predominant features were produced by the Midlandian Glaciation and to a lesser extent the Munsterian Glaciation. As the glaciers melted they left behind till and outwash deposits in the form of moraines, eskers, drumlins, valleys and plains. These glacial features often contain layers of sand and gravel that promote the flow of water from high to low ground in undulating and rolling landscapes. This occurs primarily along end moraines of glaciers. Drainage problems of a similar nature are associated with mountains and hills with permeable rocks. Glaciation often resulted in a transfer of drift from one rock type over another. This has produced drainage anomalies when for example iron pans developed on Carboniferous karst limestone at Castlecoote (Roscommon).

Soils with thick unstructured plastic impervious layers with a high proportion of fine particles (fine sand, silt or clay) are often associated with Namurian shale and limestone. They are also associated with drumlins as in Monaghan, Cavan, Leitrim and Clare.

Impervious layer soils are associated with some old red sandstone formations. Generally soils derived from ORS formations do not have the extremes of low permeability associated with Namurian shale. These impervious layered soils are characterised by a thin top soil (80-400mm) resting on a tight very slow-draining clay, silt or fine sand. Measured permeability can be as low as 10^{-5} m/day.

Soils derived from many rocks are intrinsically permeable when located in suitable topography. These include ORS and Silurian sandstone and shale, most Carboniferous limestone, schist, gneiss and granite (Aldwell, 1980). In these, weathering can result in the formation of pans. These include iron and silica pans and calcareous pans on limestone-derived sands and gravels.

Closely packed strata characterize soils with impervious layers, with bulk densities up to 1620 kg m^{-3}. Permeability is very low and if drains are to be effective in this horizon, the soil must be loosened. The layers deeper than 1 to 1.5 m are less tight and more permeable with slow inflow through small cracks. Sometimes there is groundwater seepage present as springs or diffuse seepage.

In hilly and mountainous areas, the permeability and the accumulated strata of the rocks determine the hydrology of adjacent low lying land in that they determine the nature and amount of surface runoff and deep seepage. For example, soils on highly fissured cavernous limestone are free of drainage problems except where the ground surface intercepts the water table as in hollows or where pans form. Rocks of low permeability result in perched or high water tables (Mulqueen & Gleeson, 1982). This is especially noted where the soil cover is thin. Granites and some old red sandstone are good examples of this. These are mainly carboniferous limestone and Namurian shale. These strata are covered by thick deposits of glacial drift, which dominate the drainage. However in some areas such as the Burren and south Galway there are extensive areas where the limestone has only thin if any soil cover. A number of these sites exhibit classical characteristics of karst limestone. In general these areas are dry because rainfall percolates freely to the groundwater table except where the ground dipped below the ground water table.

The risk of contamination of groundwater is partly dependent on soil type. Soil associations where the probability of groundwater contamination occurring is high, include areas where thin soil cover over fissured bedrock is prevalent, or where soil cover is thin or non-existent. The risk is reduced in certain areas where the soil cover is thin or where coarse textured soil covers fissured bedrock. Soil associations where the probability of groundwater contamination is low include areas where soil cover is generally deep or where soil has low hydraulic conductivity. In areas of high altitude and in low-lying blanket peat the contamination risk is very low.

2.3. Spreading Criteria

Good farming practice under Irish conditions has been defined as *'...common sense farming which cares for the environment and meets hygiene and animal welfare standards'* Allied to this, compliance with nutrient management is governed by law, in particular; The Local Government (Water Pollution) Act, 1977 Water Quality (Standards for Phosphorus) Regulations, 1998 (Government of Ireland, 2003), and the Local bylaws on the regulation of agricultural practice, where they apply. Over 18 EU Directives including the Nitrate Directive 91/676EEC and the Water Framework Directive 2000/60/EC support these.

The current code of good farming practice recommends that slurry, dung-stead manure and chemical nitrogen should not be applied in the months of November and December. There is a significant risk of causing water pollution by spreading slurry if heavy rain is forecast in the next 48 hours, if land is frozen or snow-covered, if the land slopes steeply towards rivers, streams or lakes, or the slurry is to be spread on exposed bedrock. P is easily lost to water from fertilizer spread on the soil surface. Incorporating the fertilizer in the soil reduces or eliminates this loss (Baker and Laflen, 1982).

Many researchers have tried to identify the optimum conditions for the application of organic manures with the emphasis varying from soil trafficability, nutrient cycling to the environmental implications of overland flow, nitrate leaching and ammonia volatilisation. Many of the models developed have been used for the estimation of workdays for carrying out field operations.

Attempts to estimate soil moisture deficits relating them to precipitation and potential evapotranspiration for agricultural purposes have been conducted. Brereton & Keane (1982) related grass yield to irrigation. They extended this information countrywide using the ratio actual: potential evapotranspiration. Gardiner (1986) used the parameters Cumulative Soil Moisture Deficit (CSMD) and Winter Rain Acceptance Potential (WRAP), to describe soil water relations with emphasis on return to field capacity.

2.4. Nitrogen

Nitrate leaching to field drains or deep groundwater has a serious impact on pollution of waterways and on public health. Infants up to six months old are most vulnerable to high nitrate concentrations in drinking water supplies. There are concerns too about the possible role of nitrates in the promotion of cancers (DAFF, 1996). The European Union has therefore set a permitted limit of 50 mg/l nitrate in potable water. The limit for eutrophication is 2.6 mg/l in coastal waters. Faecal coliforms may accompany nitrates from animal slurries or manures. The emphasis must be on seeking to eliminate the sources responsible for contamination.

The intensification of agriculture has led to significant environmental consequences, including excessive fertilization, as indicated by the difference between the nutrients imported to farms and the amount exported as food. Field experiments have shown that cereals must be fertilized with an excess of 25 kg N/ha on a loamy soil and 60 kg N/ha on sandy soils to achieve the economic optimum yields (Engels, 1993).

Globally N fertilization has increased from about 32 Mt N in 1970 to 80 Mt N in 1990. Nitrogen fertilizer use is expected to increase to approximately 140 Mt/y by 2050, with two thirds of this being applied in developing countries (Galloway *et al.,* 1995).

Nitrogen exists in the soil in different forms or pools. These include nitrate (NO_3^-), ammonium (NH_4^+), organic matter and plants. The nutrient is added to the soil by fixation from the air and by addition in the form of chemical fertiliser and slurry. Nitrate is the primary source of N for plants. It represents about 2% of the N in the soil but it is replenished on an ongoing basis by mineralisation and nitrification of organic matter. It is soluble and easily leached from the soil. This represents a considerable risk as substantial quantities of NO_3^- leach to groundwater each year. Losses are particularly significant in winter when most drainage takes place and crops are not available to use the nutrient (Zebarth *et al.,* 1996). Nitrate may also be lost from the soil through denitrification, a microbial process where NO_3^- is reduced to gaseous compounds, primarily N_2 and N_2O. This process is facilitated by saturation conditions in the soil.

Nitrogen efficiency may vary considerably depending on the ammonium – N content of the organic manure, the rate of nitrogen mineralisation during the growing season, the application conditions, and the type of crop. The potential for nitrate leaching from rotations with organic manure is considered larger than from rotations with mineral fertilizers (Thomsen *et al.,* 1993), but the type of organic manure does not affect losses (Eriksen *et al.,* 1999). Trials have shown that spreading of manure, in January and February tends not to cause nitrate leaching in excess of that from untreated controls (Pain and Smith, 1993). Application of dairy cattle manure to the soil in the autumn cannot be recommended because of the high risk of leaching. When applied at this time little fertilizer value is derived from the manure in the following year (Zebarth *et al.,* 1996). Good management practices such as avoiding autumn N application and eliminating over fertilization will reduce nitrate leaching (Beckwith et al., 1998).

Two complementary approaches are necessary to control nitrate loss *(*Lord *et al.,* 1999). The quantity of nitrate in soils in autumn and winter must be reduced and nitrate uptake by plants in this period should be maximized. The first objective entails control on nutrient application rates and timing. Nitrogen inputs above the economic optimum increase post harvest nitrate residues (MacDonald *et al.,* 1989). Autumn cultivations are often avoided or delayed and this can reduce nitrate mineralisation (Davies *et al.,* 1996). The second approach involves the use of cover crops which are effective provided sufficient growth is made before winter (Shepherd & Lord, 1996). They are more effective than winter cereals because they are sown 1 – 2 months earlier and require less cultivation.

Rainfall events immediately after manure application are associated with nutrient runoff losses but eventually the quantity and potency of the manure declines to a level where the effect is insignificant. The decline in potency arises due to breakdown of slurry components by microbial action and volatilisation of ammonia. The quantity of slurry also declines because it is washed into the soil by rain (Sherwood, 1992). Increasing slurry application rate and, in particular slurry solids loading, increased solids and NH_4^+-N losses via surface runoff. Losses appeared to increase substantially when slurry application rate exceeded approximately 50 m^3/ha. Sealing of the soil surface by slurry solids appears to increase any nutrient loss (Smith *et al.,* 2001).

2.5. Phosphorus

Enrichment of surface water by diffuse P is a cause for concern in many countries. In the Irish Republic, a gradual and steady decline in river quality has largely been attributed to P enrichment from diffuse sources (Lucey *et al.,* 1999). In Germany during the period 1987-89, diffuse pollution from agriculture to water was about 78% of P export (Werner, 1997) while in the UK, 40% of total P inputs to water were from diffuse sources in the recent past (Morse *et al.,* 1993). Much of this P is from livestock sources. Recent legislation focuses specifically on P and requires improvements in water quality within a ten-year period. For rivers, the P target is a median unfiltered MRP of <0.03 mg/l. A critical P concentration for triggering eutrophic effects in lakes can be as low as 0.02 to 0.035 mg/l (OECD, 1982). This is reflected in guidelines for water quality adopted by some countries. In Ireland the average soil test P has increased 10 fold throughout the past 45 years, from < 1mg/kg Morgan’s P in 1950 to > 8 mg/kg Morgan’s P (Tunney *et al.,* 1997). The EPA has adopted a soil P threshold of 15 mg/kg Morgan’s above which there can be no land application of manure from intensive pig operations (EPA, 1996). Phosphorous losses from agricultural soil to surface water are mainly due to the excessive accumulation of available P in soil as a result of long-term inputs of fertilizer P (Frossard *et al.,* 2000). The P present in the soil solution represents only a small fraction of plant needs and the remainder must be obtained from the solid phase in the soil. Various processes are involved in soil P transformation and these are discussed below.

Virtually all the P in the soil solution is there as phosphate PO_4. Both organic and inorganic phosphates are always present. Most P is in the solid phase. The processes involved in soil P transformation are precipitation-dissolution and adsorption-desorption. These control the transformations of P between inorganic and organic forms (Frossard *et al.,* 2000). Desorption makes phosphate available to plants but it is also the process that makes it vulnerable to leaching. The turnover or flux of P through the soil microbial biomass is widely acknowledged to be an important factor that determines the availability of P in the soil-plant system. The particles involved in P transport include: *Particulate matter* $>0.45\ \mu m$ and *Clay* $<0.02\mu m$
P concentrations in crops and forages are variable and depend on soil fertility, plant maturity, plant species and climate (Underwood, 1981; Minson, 1990). Temperate grasses contain more P than tropical grasses and more mature forage has lower P contents with the lowest P contents measured in summer probably due to light intensity and/or water shortages (Minson, 1990).

Generally the concentration of P in water percolating through the soil profile is small due to the sorption of P by subsoil deficient in the nutrient. Exceptions occur in acid organic or peaty soils where the adsorption affinity and capacity for P are low due to the predominantly negatively charged surfaces and the bonding of organic matter to Al and Fe (Sims et al., 1998). Similarly, P is susceptible to movement through sandy soils with low P sorption capacities and through soils that have become waterlogged, leading to the conversion of insoluble Fe (III) to soluble Fe (II). Soils with preferential flow through macro-pores and earthworm holes also permit downward movement of P (Bengstrom *et al.,* 1992; Sharpley and Syers, 1979). Phosphorous losses from undisturbed ecosystems occur by leaching at very low rates (Walker & Syers, 1976; Frossard *et al.,* 1989, and Letkeman *et al.,* 1996).

Surface runoff is usually generated very rapidly from limited source areas with the water in contact with the P-rich soil surface. Flow expands and contracts quickly during a storm as a function of rainfall and soil moisture conditions. As this is the main mechanism by which P is exported it is clear that P export is negligible if surface runoff does not occur. Particulate P represents 60 – 90% of the nutrient in overland flow from tillage land (Sharpley *et al.,* 1992) but the dissolved form dominates under grass or forest cover. Sources of sediment P in streams includes eroding surface soil, stream banks and channel beds

Heavy clay rich soils usually contain cracks and other large pores through which water can move rapidly, a process described as channelling or bypass flow (Bouma and Dekker, 1978;). Large pores with smaller surface to volume ratio and faster flow have less capacity to absorb P. Furthermore P carried on material detached from the soil matrix can move only through the larger pores. Drains in heavy clay soil create channels in the soil allowing P rich water to flow to rivers and lakes. In tillage most P in bypass flow is attached to suspended soil material while flow in soil channels under grassland contains most dissolved material (Addiscott and Thomas, 2000 and Haygarth *et al.,* 1988).

The critical concentration of dissolved P is difficult to identify because the sensitivity of natural waters is variable. Sharpley and Rekolainen (1997) suggested that the critical value is of the order of 0.01 mg/l to 0.03 mg/l. P enrichment of P sensitive coastal waters in North Carolina has been linked to outbreaks of Pfiesteria, which produces a neurotoxin that is lethal to fish (Burkholder *et al.,* 1997). Also drinking water supplies throughout the world may experience periodic massive surface blooms of cyanobacteria (Kotak *et al.,* 1993). These blooms may kill fish and make water unpalatable. When they die the bacteria release toxins in the water that can kill livestock and pose a serious health hazard to humans (Lawton and Codd, 1991; Martin and Cooke, 1994).

P losses from agricultural soils may be minimized by reducing P availability in excessively fertilized soils, by lowering P inputs, by increasing the P sorption capacity of soil or by increasing P removal in produce as appropriate. There is strong evidence that the higher the soil P level, the higher the P loss to water (Tunney *et al.,* 2000) so soil P should be no higher than required for agronomic efficiency. Both total and soluble P loss can be related to slurry solids loading and while much greater P losses can arise following slurry application, these losses can be reduced to near those of untreated land, simply by reducing application rate. A significant increase in losses can occur when application rate exceeds 2.5 to 3.0 t/ha solids loading (Smith *et al.,* 2001) The use of amendments such as

Fe oxides, alum and coal combustion by products to increase the sorption capacity of soil may be a useful strategy to reduce soil P in high fertility soils (van der Molen *et al.,* 1998; Shreve *et al.,* 1995 and Stout *et al.,* 1998). Data from long-term field experiments can be used to derive precise relationships between soil available P, P inputs and P removal. These may allow the calculation of the P input required to achieve optimum levels of water-soluble P. Sibbesen & Sharpley (1997) listed the requirements for P efficient cropping systems in temperate zones. These included better understanding of the science involved, plants that make better use of P, rotational cropping systems that are efficient in the use of P and appropriate measures to protect soil and water resources from excess P.

2.6.1 Slurry spreading and storage systems

There was an estimated 60Mt of agricultural waste in Ireland that required treatment in 1998 (Stapelton, Lehane, and Toner, 2000). Of this, 35 Mt was cattle slurry, 20 Mt was dirty water while pig manure, poultry manure and silage effluent each amounted to 2.5 Mt or less. Therefore most spreading systems should be capable of spreading cattle slurry but there is also considerable work for irrigators spreading waste with low solids content.

Spreading systems consist of a transport unit and a spreading mechanism. Typically transport units include the vacuum tanker, pumped tanker or umbilical hose with pump. Slurry distribution systems can be fitted to most transport units. Self-propelled irrigators cannot be used with injectors.

With the broadcast spreader the slurry is forced under pressure through a nozzle while with the other spreaders slurry passes through a series of pipes before reaching the ground. Broadcast slurry spreaders that are equipped with a splash plate, have poor distribution patterns with coefficients of variation of more than 30% (Steffens and Lorenz, 1993). New equipment such as band spreader, trailing hoses and injection techniques, reduce variation to an acceptable level, but at higher cost. The band spreader lays slurry gently on the ground or on the crop in strips or bands but the trailing shoe spreader parts the crop to leave the slurry on the soil surface.

Trials compared the broadcast applicator to other spreaders. Injectors place the slurry below the soil surface at 50 mm (shallow injection) or 150 mm depth (deep injection). Shallow and deep injection techniques, may cause damage to the sward under unfavourable ground conditions. These machines are expensive and require more power by the pulling tractor than other techniques. The trailing shoe technique reduces exposure of the slurry to the air and minimises draught requirement from the tractor. It seems more promising for general use in agriculture but further research is necessary.

Slurry spreading is part of a system. McGechan and Wu (1998) examined environmental and economic implications of some slurry management options. They found that; (a) losses of N by leaching are high where the store is too small and slurry is spread during the winter, (b) losses are extremely high where slurry is spread repeatedly on the same area of land over the winter period and this cannot be justified on economic or environmental grounds, (c) reducing mineral fertilizer applications to allow for nutrients in slurry offers economic and environmental benefit, but in the case of injection only a small proportion of the additional costs can be recouped through the reduction in requirements for mineral fertilizer.

Slurry storage must be adequate to hold all the waste liquids with high organic content produced on the farm during the housing period. The slatted underground tank is the most common slurry store used in Ireland. It is protected from rain and the slurry is more concentrated than in other stores. In the UK aboveground bolted steel circular tanks are the most common type of store. They are more exposed to the weather but they can be covered relatively easily. Lagoons are used in the UK and in Southern and Eastern Europe. They are generally uncovered and are very exposed so emissions of ammonia during much of the year are likely to be increased (Huijsmans, 2003). In addition to any flows from the farmyard, these stores must accommodate all the rain that falls within the embankment and safety fencing is necessary. Dung-steads are common in the UK and these can accommodate quite liquid slurry. The most liquid fraction of the material oozes out through boards and the solid fraction is retained. Both fractions are stored and spread separately.

The risk of overflow in slurry storage arises from both management effects that are largely predictable and weather sources which are not. Any tank receiving dirty water or rain is affected by the variability of rainfall. A freeboard of 300 mm is required at all times in a lagoon in the UK (NRA, 1991). Perhaps on Irish farms spare slurry storage capacity of a month or more should always be available. Jia *et al.* (2004) studied over-flows of slurry stores in North Carolina and they suggested that in wet years the crop nitrate limits should be relaxed so that slurry could be spread more frequently.

Slurry treatments reduce difficulties at spreading. Agitation can break up the top crust on slurry in store and mix the settled solids through the liquid to allow it to be pumped into a tanker. Separation of slurry solids from liquid can be achieved by sedimentation or by mechanical separation through a sieve. The latter method is more effective, removing dry matter, nitrogen and phosphorus from the slurry liquid. Benefits of the process include improved flow properties of the slurry and nutrient reduction but the solid and liquid fraction must be stored and spread separately. Anaerobic digestion is the most important treatment method. It is widely used in China and India but it is practised to a lesser extent in Europe. The process involves the promotion of anaerobic activity in the slurry. The benefits include biogas production, odour reduction and improved flow properties. Aeration involves the use of an aerator to introduce air to slurry for aerobic digestion. Short duration treatment is used to reduce odour, and prolonged treatment also reduces unwanted ammonia, organic load and pathogens (Burton and Turner, 2003).

2.6.2 Fertilizer spreading

Fertilizer is one of the most important inputs in animal and crop production and there are approximately 84,000 fertilizer spreaders in Ireland. This compares to 31,000 slurry tankers (C.S.O., 2000). The fertilizer spreader itself plays a very important role in efficient fertilizer use. There are two basic design types on the market, the oscillating spout and the spinning disc. The spread pattern of the fertilizer spreader depends on the physical properties of the fertilizer as well as the design and adjustment of the spreader.

The popular Vicon© spreader with oscillating spout operates at bout widths of 6 to 12 m. Other manufacturers include Abbey, Cosmo, Agrex, Anfer and Eurospond (Goulding Chemicals, 2002). Spinning disc type spreaders are widely used. The single disc type is used for grassland applications at widths of 6 to 12 m (Goulding Chemicals, 2002). They tend to have an asymmetrical spread pattern and bouts need considerable overlap to overcome this. Twin disc machines give a more uniform spread pattern. Some models have modifications to prevent fertiliser entering drains or streams. Manufacturers of disc spreaders include, Teagle, Wessex, Sulky, Cosmo, Cavallo and Bogballe. Under tillage systems the ‘window of opportunity' for spreading tends to be shorter than that of grassland. The need for higher work rates has resulted in farmers using wider bout widths.

3. Overland flow trials by Sherwood and Fanning (1976 - 1981)

3.1. Introduction

In most countries there is a growing awareness of the high amenity value of clean water. Agriculture is often blamed for increasing the eutrophication status of surface water. Land spreading of animal manures in indiscriminate fashion is a practice that causes one of the biggest outcries. In the mid 1970s, literature data on runoff of nutrients from land spreading of animal manures were very scarce and this study reported by Sherwood and Fanning (1981) was undertaken to provide new information about the factors involved. The data from the 1970's trial were revisited in this project to apply statistical analysis to determine, if possible, clear relations between treatments and their effect on water quality.

3.2. Materials and Method

Experimental plots were located on three grassland sites in Co. Wexford. The Castlebridge site consisted of acid brown earths, associated with gleys, regosols and podzols and was poorly drained (permeability 0.03 m/d). The Hoarstone site had a gley soil, and this was influenced by surface water impedance. It was moderately drained (permeability 0.12 m/d). Associated soils include grey brown podzols primarily. At the third site, Burrells, the soil was wet and of mineral origin. Gleys, influenced by surface water impedance dominate the area and these are associated with grey brown podzols. The estimated permeability is 0.08 m/day. The slope of all three sites is 10°.

Six experimental plots measuring 30 m by 2 m were isolated within each site. Each plot had a berm of timber at the side and a metal strip at the top end. At the lower end, gutters were installed to channel the runoff into a metal reservoir 1.83 m x 0.91 m x 0.38 m high. Water samples were tested for PO_4^-, Total P, NO_3^-, NH_4^+, Total N, K, Na, pH, BOD and COD. The depth of water in the collecting chamber was used to determine the quantity of runoff from each plot. Samples were taken randomly after significant rainfall events. Slurry was chopped to allow it pass through a 38 mm pipe, which was used to apply the slurry manually to the plots.

Each plot received a different treatment (Table 3.1). These treatments were applied one to three times each year from 1979 to 1981. The application dates were chosen to give maximum information about runoff or infiltration. Variation in the volume of water from the Hoarstone plots was excessive. Therefore instead of applying three different rates of pig slurry to the plots at each site, in September 1979 and January 1980, only one rate of pig slurry (45 m^3/ha) was applied to Plot Numbers 3, 4 and 5 so that the effect of different volumes of runoff could be assessed.

Table 3.1. Nominal application rates used on the treatments at the Castlebridge, Hoarstone and Burrells sites

PLOT	APPLICATION RATES
Plot 1	No treatment
Plot 2	Cattle slurry @ 45 m^3/ha
Plot 3	Pig slurry @ 22.5 m^3/ha
Plot 4	Pig slurry @ 45 m^3/ha
Plot 5	Pig slurry @ 90 m^3/ha
Plot 6	Fertilizer 120 N, 42 P and 51 K

The experiment also suffered from variability in the quality of the slurry, which ranged from 2 – 9% dry matter. The treatments were always measured in terms of hydraulic load and this often resulted in very different amounts of nutrients at the two sites.

3.3. Results and Discussion

Soil type was seen to affect overland flow through the influence of soil permeability on the volume of runoff water. Average annual rainfall over the four years was 1,093 mm and mean potential evapotranspiration 536 mm. The mean annual runoff measured at Castlebridge was 210 mm or four times the 50 mm flow that was recorded at Hoarstone. This ratio is the inverse of that given above for infiltration rate at the two sites. Despite the difference in flows similar numbers of events occurred at each site but the volume was always greater at Castlebridge. Measured flows at Burrells reached 200 mm in one year but missing data prevented the calculation of a reliable average.

Time was the most important factor covering the amount of BOD, NH_4^+-N and PO_4-P in runoff water. The concentrations of all three parameters were highest in runoff water resulting from storms which occurred immediately after slurry application. The concentration decreased steadily with time thereafter. This phenomenon can be illustrated by losses during very heavy rainfall in January 1980, 2 days after an application of 3.7 t/ha (DM) of pig slurry at Castlebridge. Losses were as high as ~ 1,600 and 255 mg/l for BOD and NH_4^+-N respectively in the runoff water. These concentrations were approximately 10% of those in the slurry applied. Three days later a second storm caused further loss but at lower concentrations of 114 BOD and 34 mg/l. Generally losses reduced to acceptable level in about 10 days. The rapid reduction in BOD is due to the action of soil bacteria. A frosty period in January 1977 allowed high BOD in overland flow several weeks after spreading.

Phosphorus behaved a little differently. There was a relationship between the rate of slurry P applied and the concentration of PO_4-P in the runoff water. In the range 0 to 30 mg/l, an increase in the amount of P applied caused an increase in the loss of P in overland flow. While the concentrations reduced through several rainfall events the differences persisted. Also P decreased more slowly than BOD or NH_4^+, taking several weeks to reach a concentration of 1 to 2 mg/l. Most phosphorus runoff occurred following winter application, which is a reflection of the larger volumes of water, collected from more runoff events. It is evident from the graphs shown in Sherwood and Fanning (1981) that the relationship between rate applied and the amount in runoff, tended to be exponential rather than linear.

Other information in Sherwood and Fanning (1981) included the comments that; total phosphate concentration in the water was always only slightly higher than orthophosphate concentration, that the pattern of nutrient loss from cattle slurry was very similar to that from pig slurry and that the nutrient loss from fertiliser was always less than from slurry with corresponding amounts of N and P.

In this later project inspection of the overland flow data showed many gaps in the record. Periods of months existed when no data were recorded. On many occasions peak overland flow values were lost as tanks overflowed. Such data can support trend analysis of nutrient concentration in overland flow and this has already been published (Sherwood and Fanning, 1981).

Regression analysis of the overland flow data showed that it was too variable to be dismissed as a factor affecting nutrient content of the water. Therefore relations between treatments and nutrient concentrations could not be established and nutrient loads cannot be calculated. Analysis in this project was confined to further identification of trends in nutrient loss from the plots.

A summary of the Johnstown data showed that overland flow was greatest at Castlebridge where up to 335 mm of flow occurred in one year. Flow was concentrated in the period October to March inclusive with the highest values in January and February. Phosphorus is the most important nutrient affecting eutrophication. Table 3.2 is a summary of P concentration in overland flow over the monitoring period (Sept ’76 to July 81). Data are given for sampling events at only two sites. Data for dates when treatments changed temporarily were excluded as also were data from Burrells as treatments there were not consistent. The P data were highly skewed with a small number of very high values. A meaningful average was difficult to obtain, even where a transformation was used. The median is not so vulnerable to extreme values as the average so the former statistic is used to summarise P concentrations over a period approaching 5 years (Table 3.2).

Table 3.2. Median phosphorus concentration (mg/l) in overland flow from plots treated with slurry and fertilizer (Sept '76 to July '81)

Site	**N**	**Treatment**					
		1 Pig (High)	2 Pig (Med)	3 Pig (Low)	4 Cattle	5 Fertilizer	6 Control
Hoarstone	73	1.45	1.68	1.63	0.74	0.56	0.32
Castlebridge	69	2.70	0.73	0.64	0.29	0.52	0.15

The nominal application of P on plots 1 to 6 was 250, 150, 110 kg/ha in pig slurry 120 in cattle slurry and 42 kg/ha P in fertilizer respectively. The data in Table 3.2 suggest a trend with reducing concentrations of phosphorus from the high pig application in plot 1 to control in plot 6. The trend is not entirely consistent. Plot1 at Hoarstone had a relatively low concentration of P although application rate of pig slurry was high and cattle slurry at Castlebridge gave a lower concentration than fertilizer despite an apparent higher application of P in the cattle slurry. Variability in overland flow and/or variation in treatments over the years may account for these anomalies.

3.4. Conclusion

The data from the trials at Castlebridge, Hoarstone and Burrells give an indication of the relative nutrient contribution that slurry and fertilizer can make to surface water. It was not possible in this project to improve on the analyses presented in Sherwood and Fanning (1981) due to the variability of overland flow data and missing values.

4. Fertilizer use study

The loss of nutrients from agriculture is associated with the excess application of N and P to grass and crops. The Fertilizer Use Survey (FUS) records the actual application rates of fertilizer on farms (Coulter et *al.,* 2002). This provides an opportunity to assess whether nutrients are applied in excess on farms and, if excess exists, to calculate its magnitude. This supports the main objective in this project namely to identify the main factors contributing to eutrophication from agriculture. If excess nutrient is applied on farms then eliminating this excess might offer a relatively easy method to reduce nutrient loss. Recommended fertilizer application rates offer the optimum economic return. Higher rates will incur increased cost and additional risk of environmental damage but may not guarantee greater return.

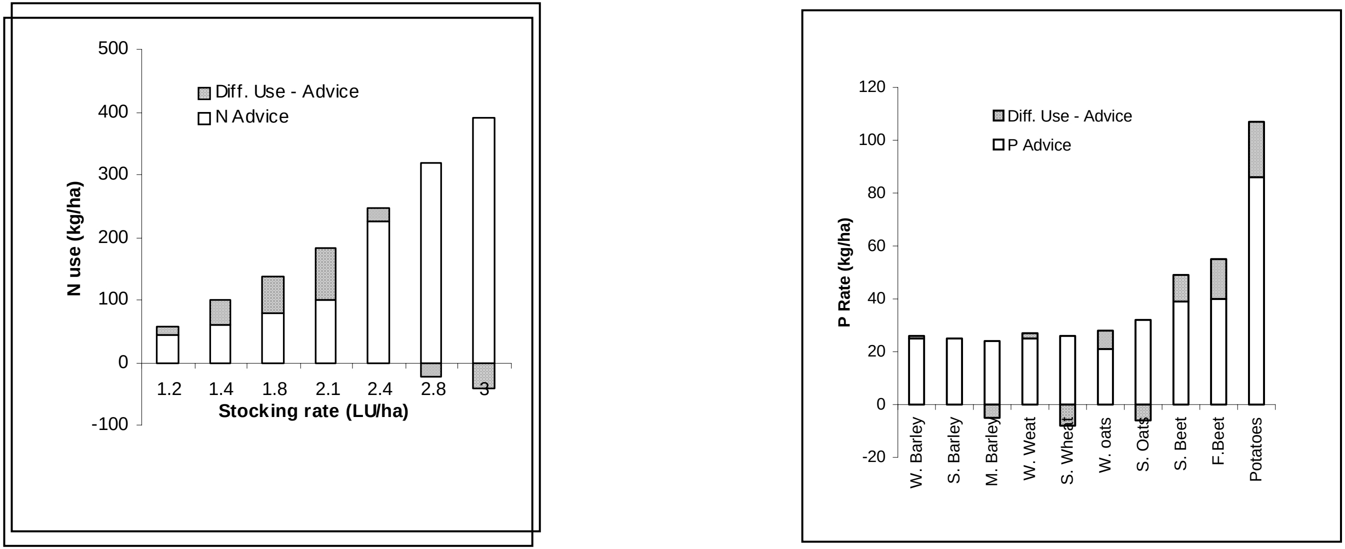
4.1. Method

The FUS was based on the National Farm Survey. Farms that were included in the survey were selected using information from the CSO Census of Agriculture. They were classified into six main farming systems namely: dairying, dairying with other enterprises, cattle, cattle rearing, cattle with other enterprises, mainly sheep and tillage systems where each system refers to the dominant enterprise in the group. The data were analysed using an SAS statistical package to provide data relating to N, P and K fertilizer use on farms along with other farm management parameters. The potential use range of soils was also taken into account. The results of the FUS were validated by comparing fertilizer rates in the survey with national figures for the consumption of farm nutrients. Differences between the two data sets were less than 1%.

The data in the FUS was presented in 80 tables so in this report only a summary can be given. Data relating to fertilizer application were plotted for the main enterprises. Plots for two of these are shown below. The FUS used data from 1130 farms chosen randomly around Ireland. It was assumed that the distribution of activity among farms in the survey was similar to the distribution in all farms in Ireland. Using the percent of total area under crops and grassland (Fingleton and Cushion, 1998) national excess application was calculated.

4.2. Results and Discussion

Grassland is the dominant farm activity covering over 90% of farmed land. Nitrogen use in grassland was generally close to or below recommendations with the exception of mainly dairy farms. On these farms, at low to medium stocking rates (1.4 to 2.4 LU/ha), application rates were substantially in excess of recommendation in 2000. In Fig. 4.1 the rates advised by Teagasc are plotted along with the difference between usage and advice



(a) (b)

Fig. 4.1 Fertilizer usage (tops of bars) compared to advice for; (a) N usage on mainly dairy farms and (b) P usage on tillage farms.

The data in Fig 4.1(a) show a strong relationship between stocking rate and usage (r =0.99) whereas the correlation between advice and usage is not so strong (r = 0.94). This suggests that dairy farmers were disinclined to follow Teagasc advice in 2000 at these stocking rates. Teagasc recommendations were revised in 2004 and substantial changes were made in relation to N application to grassland and to sugar beet. The changes in advice for grassland would almost eliminate the excess application of N on Dairy farms if these recommendations were applied in 2000. Developments in research in relation to rates and timing of fertilizer application are given as the reason for the changes. This is part of an ongoing process at Teagasc. Only on a very small number of dairy farms with high stocking rates did applications exceed 300 kg/ha, the level above which N-leaching is likely to occur. Phosphorus use in grassland was largely in line with recommendation.

Tillage crops cover a relatively small area of Irish agricultural land. In the FUS this amounted to 6.4 % but Fingleton and Cushion (1998) indicated a value of 10.4%. This divergence is probably due to differences in interpretation as to what constitutes tillage. Lack of consistency between the FUS and national data may also be a factor. In this review only one value for N or P usage for each crop has been considered. Relative values are given as a percent of usage. Ten crops were surveyed and of these, two crops (S. Wheat and W. Oats) had N applied at a rate that was 40% in excess of recommendation, six crops (W. Barley, M. Barley, W. wheat, S. Oats, S. Beet, F. Beet) had 20% excess and only two (S. Barley and Potatoes) complied with Teagasc advice. Where more N is applied than is needed by the crop, increased losses to groundwater can be expected especially in autumn.

Greater compliance was evident in relation to P in tillage (Fig 4.1(b)). Of the ten crops only three showed excess application, namely the root crops S. Beet, F. Beet and Potatoes. The excess was 20 to 30% of application. This deviation is probably more serious than the excess use of N as the maximum allowable concentration for P is 500 times smaller than that for N. The poor management of root crops in this context may be due to the fertilizer compounds available for use on crops. Farmers try to spread all the fertilizer required at a given time in a single operation. Compound fertilizers are used. If the compound does not have the exact combination of N, P and K required only one nutrient can be applied at the correct rate.

The others will be too high or too low. For example, in the case of potatoes, N can have a large impact on quality but P is not so important. Therefore in the survey N usage was close to recommendation but P was 25% above the optimum.

The area of land taken up by individual farming activities varies greatly so in Table 4.1 the data have been adjusted to show a national balance for fertilizer application on an annual basis expressed in tonnes. These values are approximate but they give a good indication as to where any problems might lie. National consumption of fertilizer is 410,000 t/y of N and 50,000 t/y of P. In relation to N the largest excess was 20% in dairy grassland. This has been addressed in the most recent recommendations (Coulter, 2004). Values for dry stock were uncertain due to the presence of clover at an indeterminate level in the sward. Fertilizer use with sheep was close to the optimum. Usage on silage ground could not be assessed, as data were not available for slurry application or loss of N through ammonia emission. Tillage had the only unresolved excess. The total quantity was small at 1.6 % of national consumption of N but in catchments with a high proportion of tillage this excess might have a significant effect on quality of groundwater or that of an estuary downstream. Phosphorus usage was within guidelines with the exception of applications on tillage farms. Again at 1 % of national consumption the total quantity is small but in certain catchments the impact of high application rates in a large proportion of fields could be significant. The usage of both N and P on REPS farms was substantially below that on other holdings. Clearly this scheme has much to offer in terms of reducing excess nutrients on farms.

Table 4.1. National usage of N and P compared to Teagasc advice (+ve = excess, –ve = inadequate application).

			Nitrogen		**Phosphorus**	
System	**Sub-system**	**Difference**	**(,000 t)**	**(Nat%)[1]**	**(,000 t)**	**(Nat %)[1]**
Grassland	**Dairy**	**U – A[2]**	83	20	-4.0	-8.1
	Dry stock	**U - A**	-30	-7	-4.5	-9.2
	Sheep	**U - A**	-0.95	-0.2	-0.76	-1.6
	Silage	**U - A**	N.A.	N.A.	N.A.	N.A.
Tillage		**U - A**	6.4	1.6	0.66	1.3
REPS		**R – NR[3]**	-78	-19	-5.4	-11.1

Notes:
1. Percent of national N or P fertilizer consumption in agriculture
2. Use - Advice
3. REPS – Non-REPS

The FUS was relatively large so statistical precision was high. The standard error was quoted for all values except those in the analysis of REPS farms where insufficient data were available. Where quoted, all differences were significant at $P < 0.05$ and over half of values were significant at $P < 0.001$. The statistical error in Table 4.1 is 1 % to 5%. The survey was compared to national data for fertilizer sales to assess accuracy and the difference there was less than 1% for each of the three elements N, P and K.

This review of the FUS has not identified any large-scale excess application of N and P. The high nutrient input in tillage will only be of concern in a small number of catchments. It is perhaps more important that the survey did not deal sufficiently with activity on silage ground. The average application rate of slurry on these areas is approximately 40 m^3/ha. Only a portion of the N remains but about 25 kg/ha/y of P is effectively added to the field. This exceeds P advice for grassland at most stocking rates. Data in the FUS suggests that half of the farmers surveyed did not allow for nutrients in the slurry when deciding fertilizer requirements. Therefore some fields have far more P applied annually than the grass crop can use. It is likely that more information regarding slurry applications will be available in future issues of the FUS. This is important as slurry contains one third of the P available to agriculture. It can be considered a fertilizer. Application rate of fertilizers is only one of several parameters that can affect nutrient loss from farms. Some of these are discussed in other sections of this report.

4.3. Conclusion

The FUS does not highlight any major excess application of N and P on farms. High application rate of P on root crops may be a concern in some areas where the crops concerned are grown. However the absence of precise information regarding the use of slurry on silage ground indicates that more data are required to determine whether the application of nutrients to farmland is in excess of recommendations.

5. Climate Risk Spreading Maps

5.1. Introduction

The predominant agricultural systems found in Ireland are for livestock production based on grass. Animals are housed in the winter to allow controlled feeding of conserved forage and to protect soil resources from trampling damage. This gives rise to the need for storage of slurry and for its disposal by spreading on land. In recent times land spreading has became associated with the issue of pollution by the EPA and the EU (Stapleton *et al.,* 2000). Local governments in six counties have introduced bylaws to limit the spreading of slurry in winter months. Perhaps a method to identify spreading opportunities in winter could be found to benefit farmers and the environment. Using published spreading criteria, rainfall data can be analysed to identify periods of dry weather in the past. Soil data are not available for this purpose. A set of filters could be designed to analyse rainfall data and to prepare a national map of spreading opportunity.

5.2. Method

The method to estimate spreading opportunity from climate depends on two assumptions. Firstly that climate is assumed to be independent of the slurry spreading system and secondly that soil can be grouped under two headings, wet soils and other soils. Climate interacts with slurry spreading but is not affected by it. Other researchers have successfully dealt with soil as only two classes, wet soil and dry soil (Daly *et al.,* 2002; Brereton, 1989). Frozen ground rarely occurs in Ireland so temperature need not be considered. This leaves rainfall as the driving variable in estimating slurry-spreading opportunity.

It is assumed that rain, in the form of free water, provides the main transporting agent for slurry nutrients. It is also assumed that there are rainfall thresholds that relate to the slurry spreading risk (McGechan and Wu, 1998; McGechan and Lewis, 2000). The weather influence on slurry spreading was related to three periods. During the few days before spreading the soil should not be too wet to absorb the slurry. On the spreading day there should be no rain and in the few days after spreading only light rain should fall lest overland flow cause significant pollution. A series of rainfall thresholds were used to integrate rainfall during these three periods.

Daily rainfall was obtained from the Met Éireann archive for the period October to March each year recorded at 100 locations distributed fairly evenly throughout Ireland. Rainfall filters with different shape and duration were compared using actual data for 10 representative locations. The filters examined the rainfall record one day at a time, looking ahead for a period equal to the filter duration. If all days in the rainfall record had less rainfall than the thresholds defined in the filter, the first day of the record was designated a spreading day, otherwise a non-spreading day. The filter then stepped forward one day and repeated the process. The maximum rainfall value chosen for any filter threshold was 2.5 mm and the minimum rainfall threshold was 0.5 mm. Initially the winter safe spreading probability was calculated as the number of predicted safe spreading days divided by the number of days in the record. Then the annual probability was calculated. Where a year had an annual probability exceeding 0.1 it was considered a spreading year. The ratio of spreading years to total years in the weather record was plotted on the maps. Contours with probabilities of 0.3, 0.4, 0.5 and 0.6 correspond to 3 to 6 years in 10 with safe spreading opportunities in winter.

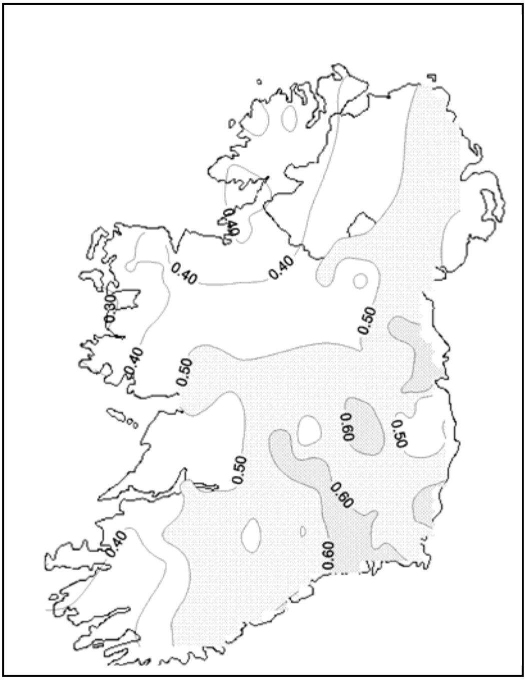
5.3. Results and Discussion

The range of probability of a safe spreading opportunity calculated with each filter was related to both the filter characteristic and the location of the rain gauge. The lowest probabilities were always associated with Glenties in County Donegal where annual rainfall was greatest. The highest probabilities were always associated with Baldonell Aerodrome in County Dublin where rainfall was least. It was decided that a V-shaped filter of 8-day duration was the best for predicting safe spreading probabilities because it provided a good balance between a conservative approach with low risk and the practical need to be able to spread slurry in the winter months.

The filter chosen for creating the spreading opportunity maps had an offset V-shape of 8 days duration (2.5-2.0-1.5-1.0-0.5-1.0-1.0-1.0 mm/d).

The definition of the winter storage period for slurry is important in determining the probability of a safe spreading period. Met Éireann define winter as December to February but the potential housing period is October to March. Therefore maps were drawn for both scenarios but only the map for the latter period is shown in Fig. 4.2.

Fig. 4.2. Map of the probability of safe slurry spreading in Ireland for the period October to March. Mid-grey areas represent 5 years in 10 probability of being able to spread safely.



The map reveals trends in the data. There was a greater probability (5 to 6 years in 10) of being able to spread in the eastern two-thirds of the country than in the vicinity of the western seaboard (3 to 4 years in 10). Some areas in the east and south had probabilities of 7 years in 10. While it is not possible to rigorously test the output of the methodology, the trends and features of the map in Fig. 4.2 are broadly in line with spatial patterns found on maps of wet days (Rohan, 1986), extreme rainfall events (Logue, 1995) and winter rainfall acceptance potential of Irish soils (Gardiner, 1986).

The safe spreading probability maps must be used in conjunction with other information in order to develop site-specific estimates of spreading opportunity in the future. Some areas with steep slopes, wet soils etc. are all permanently excluded from spreading (EU, 2005). It is estimated that of the five counties that currently implement by-laws limiting slurry spreading operations, two have a probability of 4 to 5 years in 10 of spreading slurry safely in winter while the other three have a probability 5 or 6 years in 10.
.

5.4. Conclusions

It can be concluded that it is possible to determine the climatic limitation to safe slurry spreading on the basis of rainfall distributions. The analysis of rainfall data from Ireland with a threshold filter proved an effective means of producing a map of climatic limitation to safe slurry spreading which should be applicable to any part of the world with a similar need to manage slurry at times of the year dominated by rainfall. Future development of this method will consider introducing other parameters such as soil properties and weather forecasts.

6. Slurry Storage Maps

6.1. Introduction

Environmental concerns are guiding farm systems towards sustainability. Fundamental to this development is the farm nutrient budget. This includes identifying spreading lands and calculating application rates that are consistent with environmental restrictions. The amount of storage required for slurry should also be calculated. Guidelines for slurry storage did not identify any regional differences in the sizes of slurry storage tanks required on farms at the time this research took place. However recent publications have included recommendations from this project on regional differences in storage requirement (EU, 2005).

6.2. Method

Two methods were used to determine the slurry storage period required at any location. In the first approach, the need for storage was determined from the method based on rainfall described in chapter 5. This uses the principle that when slurry cannot be spread it must be stored. The periods of interest were defined as (a) October to February and (b) October through to March but only the latter is considered here. For each site, the probability of a weather related spreading opportunity was examined. For a given month, if the probability of a spreading opportunity was less than 0.6 then storage for one month is required. If the probability of spreading was greater, then no storage was allocated for that month.

The second approach is the method of Stettler, Aschmann, & Wilson (2003) which is used in Oregon, USA. This method uses soil, farm management and weather factors to calculate slurry storage period. It involves a two-stage procedure; firstly the basic storage period is calculated from weather data and secondly this is adjusted using soil and management factors described in Table 6.1. The weather parameters include evapotranspiration and precipitation. The parameter ‘L’ denotes the day of the year when ¾ of annual evapotranspiration has occurred and ‘E’ represents the day in spring when evapotranspiration equals precipitation. The basic storage period (SP_b) is given by;

$$SP_b = 365 - (L - E) \qquad \ldots\ldots\ldots\ldots\ldots(6.1)$$

Table 6.1. Values for adjustment factors in Equation 2

Adjustment Factor	Good	Upper average	Lower average	Poor
Soil hydrology (F_o)*	0.75 (Moderate leaching risk)	0.95 (High leaching risk)	0.85 (Moderate runoff risk	1.0 (High runoff risk)
Management level (F_m)	High (0.6)	Med (0.8)		Low (1.0)
Area with hydrology buffer (F_l)	0.8 (100 % buffered)	0.9 (50% buffered)		1.0 (0% buffer)
Nutrient loading (F_n)	0.5 (No added nutrients)	0.75 (50% of crop requirement met)		1.0 (Crop needs met)
Application method (F_a)	0.7 (Injection or incorporation)	0.8 (Slurry, surface applied)		1.0 (Solid manure)

*In the analysis values for F_o in the range shown in this table were taken from Sherwood (1992)

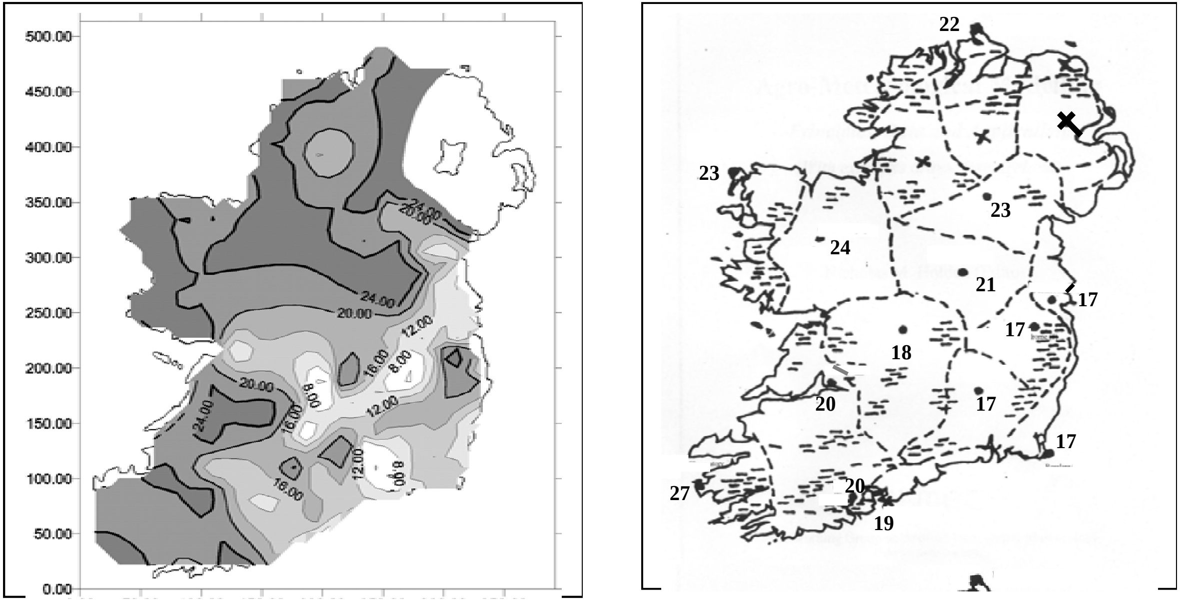
The basic storage period is modified to account for management and soil effects. The resulting expression for adjusted storage (ASP) is;

$$ASP = SP_b \times F_o \times F_m \times F_l \times F_n \times F_a \quad \ldots\ldots\ldots\ldots\ldots \; (6.2)$$

The five adjustment factors in equation 2 above are given in Table 6.1.

6.3. Results and Discussion

One of the maps developed from climate data alone is shown in Fig. 6.1. This is for a 6 month winter period from October to May inclusive. It uses data for over 100 rain-gauging stations so it is a reliable indicator of the impact of rainfall on slurry storage times. The distribution of long and short storage times matches a typical map of rainfall. The range in values is 4 to 24 weeks. This includes shorter times than in the Code of Good Agricultural Practice (EU, 2005). However storage times calculated using climate alone does not include the effects of other factors and the actual storage times required may be different. It is also evident that in some areas a partial winter spreading ban



(a) (b)

Fig. 6.1: Maps of slurry storage requirement (weeks) based (a) on weather data over 6 months (Oct-Mar) and (b) based on soil, weather and management factors (≡ = hill land). No data relating to Northern Ireland was available for either map.

Table 6.2. Influence of individual factors on storage period (weeks).

Synoptic station	**Basic store period (Days) (ASP)**	**Runoff risk factor (O)***	**Actual storage period (weeks)**				
			Control	**Soil hydrology (Fo)**	**Manage-ment (Fm)**	**Buffer (Fl)**	**Nutrient (Fn)**
Factors used†			O:0.8:0.9: 1:0.8	**0.7**:0.8:0.9: 1:0.8	O:**1**:0.9: 1:0.8	O:0.8:**0.8**: 1:0.8	O:0.8:0.9: **0.75**:0.8
Belmullet	278	1	22.8	17.1	28.6	20.3	17.1
Birr	284	0.75	17.5	17.5	21.9	15.6	13.1
C/ment Aero.□	265	0.79	17.3	16.4	21.6	15.3	12.9
Claremorris	329	0.87	23.5	20.3	29.4	20.9	17.6
Clones	290	0.96	22.9	17.9	28.7	20.4	17.2
Cork Airport	308	0.79	20.0	19.0	25.0	17.8	15.0
Dublin A/port□	259	0.79	16.8	16.0	21.0	15.0	12.6
Kilkenny	271	0.75	16.7	16.7	20.9	14.9	12.6
Malin Head	263	1	21.7	16.2	27.1	19.3	16.2
Mullingar	299	0.87	21.4	18.4	26.7	19.0	16.0
Roches Point	270	0.83	18.5	16.7	23.1	16.4	13.9
Rosslare	260	0.78	16.7	16.1	20.9	14.9	12.5
Shannon	270	0.9	20.0	16.6	24.9	17.7	15.0
Valentia Obs. □	331	1	27.2	20.4	34.0	24.2	20.4
Average	**284**	**0.86**	**20.2**	**17.5**	**25.3**	**18.0**	**15.2**

* From "Runoff risk categories of soils" (Sherwood, 1992).

† Sequence of factors used in heading is**:** Fo; Fm; Fl; Fn;

□ Synoptic station names: "C/ment Aero" is Casement Aerodrome, DublinA/port is Dublin Airport and Valentia Obs" is Valentia Observatory.

would be necessary (4-12 weeks storage required) and in other areas a longer duration is appropriate (16-24 weeks).

Actual storage periods were calculated using Equation 2 above and values for factors taken from Table 6.1. The result of this calculation is shown in Table

6.2. This shows the storage periods that would apply in the vicinity of each meteorological station for each combination of factors. For example the storage periods listed under "Control" for Belmullet represent land where the "Runoff risk factor" (F_o) has a value of 1, quality of management (F_m) is medium (value = 0.8), 50 % of the land is buffered against pollution (F_l = 0.9)), 100% of the recommended nutrient levels are applied (F_n = 1.0) and the manure type is slurry (F_a = 0.8). Using this combination of factors a storage period of 22.8 weeks was calculated. In each column to the right of "Control" a single factor is changed to an adjacent value in Table 6.1. This factor is shown in bold in the heading of Table 6.2. In this way the effect of each factor relative to the control is seen. In the column headed "Soil hydrology", a constant value of 0.75 is used for Fo and this represents a dry soil with a risk of leaching.

In the case of an investigation for a given farm, the storage period calculated would be checked against general experience of weather and soil conditions in the locality to ensure a minimal risk of nutrient loss outside the storage period. Data for such a calculation is not available in this case. For all the locations in Table 6.2, grass growth occurs during part of the storage period at each location most years at least.

6.4. Conclusion

The map based on climate (Fig 6.1a) benefits from data from151 rainfall stations but its use is limited due to dependence on only one parameter when clearly several factors are relevant. It is hoped that in future additional parameters can be included. The map based on the method of Stettler, Aschmann, & Wilson (2003) uses 6 parameters but resolution is limited by the availability of evapotranspiration data at only 14 synoptic stations countrywide. Four of the six parameters were calculated in the USA and are unlikely to match Irish conditions exactly. Additional Irish data at a large scale (e.g. county level) would improve the predictions for this country. The method of Stettler, Aschmann, & Wilson (2003) offers the possibility of slurry storage calculations for individual farms. Both maps indicate a range of required storage periods that are longer in the high rainfall areas to the west and north the country and shorter in the east and south.

7. Overall Conclusion

This project dealt with a number of topics related to water pollution from agriculture from which the following conclusions can be drawn.

The overland flow data from Sherwood and Fanning showed the relative contribution of fertilizer and slurry when spread lands are flooded but due to variability in flow over space and time it was not possible to analyse chemical properties of the floodwater.

The use of fertilizer in Irish Agriculture is close to recommendation according to detailed survey data in the Fertilizer Use Survey. The largest percentage deviations from advice are in the tillage sector but as crop acreage is small, the impact on water quality is expected to be evident in only a few catchments.

It is possible to calculate the number of safe spreading days in winter using rainfall data only. The resulting maps reflect reasonably well, other related parameters presented on maps. Probability of winter spreading ranged from 4 years in 10 in the west and north to 6 years in 10 in parts of the east and south.

Slurry storage period can be determined using the spreading data above or alternatively by using six parameters related to weather and farm features. The former method indicated storage periods of 8 to 24 weeks while the latter predicted periods of 17 to 27 weeks. More work is required on each method to allow optimum reliability.

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