Environmental RTDI Programme 2000–2006

Impact Assessment of Highway Drainage on Surface Water Quality

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Synthesis Report

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Prepared for the Environmental Protection Agency

by

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WATER QUALITY

The Water Quality Section of the Environmental RTDI Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in this area. The reports in this series are intended as contributions to the necessary debate on water quality and the environment

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1 Introduction

1.1 Background

It has long been known that the road density in Ireland is high for the size of the population and thus, for many years, the vehicle density per kilometre of road was also small. Moreover, in spite of relatively high rainfall in many parts of the country and *ad hoc* methods of road drainage, the environmental impacts of road run-off were usually small and/or temporary. In the last 20 years, however, the road-building programme has increased in intensity and the length of dual carriageway/motorway has also dramatically increased. Vehicle ownership and traffic densities have correspondingly climbed. In response, new transport infrastructure, such as in TRANSPORT 21, has a significant new roads component and an environmental remit. Apart from the requirements of environmental EU directives, there is a clear intrinsic need to determine if the changing quantity and quality of road run-off will pose a problem for the receiving environment. In Ireland, there is a wide diversity of road types, ranging from the boreen to the motorway and there is an equal diversity in receiving environments, ranging from peatlands to limestone hills with little or no soil cover. However, from considerations of traffic densities and carriageway areas, it is likely that dual carriageways will pose the most immediate problems. It is also important to consider the diversity of potential receiving environments.

Previous research has shown that highway run-off can contain a cocktail of potential pollutants, with more than 30 substances found in highway discharges in a study undertaken by CIRIA (1994) and reiterated in a report by Hird (1999). The impact of the pollutants on adjacent watercourses, including groundwater, can be very site specific, and is a function of the nature of the road and the traffic it carries, management systems, drainage systems and hydrological conditions amongst others. Some sites may be more sensitive than others. For example, sensitivity is increased if a watercourse is a spawning site for salmon such as occurs near Gorey, Co. Wexford, or a water supply such as Lough Mourne in Donegal. More difficult to assess is groundwater which frequently occurs near the ground surface in Ireland although overlying subsoils, where they exist, may afford some protection.

Some criteria for assessing impacts on such receiving environments have been available for some time, such as the Drinking Water Regulations or permissible contaminant levels in salmonid rivers, but within the EU, the emphasis on the approach to criteria selection has been changing. The Water Framework Directive (WFD) aims at establishing concentration levels in the aquatic environment mainly in so far as they affect the prevailing ecology. Thus, in any proposed road drainage site, it is necessary to first establish a baseline ecology from which acceptable levels of drainage discharge and quality can be determined. Moreover, the approach will be catchment based, so that a potential drainage site will have to be set in the context of local catchment ecology and hydrology. It is important to identify pragmatic and cost-effective measures for mitigation of run-off rates and quality in this context.

The ongoing development of the national road network in Ireland, and in particular highly trafficked dual carriageways and motorways, will require careful planning and knowledge of impacts and how they can be minimised. The principal drainage systems used in Ireland are filter drains, positive drains (closed pipe – with/without gullies), lined and unlined interceptor drains, shaped concrete channels and soakaways (with or without outfall pipes). Grit collection systems and petrol/oil interceptors are sometimes used where surface water may be discharged to sensitive streams/rivers. Pollution can occur directly from discharge of polluted water and sediment during rainfall and even indirectly during gully cleaning operations. A study completed by WS Atkins (Atkins, 1998) has identified gully cleaning operations and the subsequent disposal of arisings as a major threat to watercourses adjacent to highways.

Under these considerations, the development of sustainable drainage systems has been the subject of research and implementation for some time in Europe and North America. This development includes the use of swales, reed beds/wetlands and permeable surfaces, in addition to the commonly used filter drains and detention ponds.

There is an increased awareness among engineers, planners and decision makers of the importance of flood estimation in the light of a recent flood-prone decade and the predicted effects of climate change, increasing population, incursion of developments into marginal lands, expanding infrastructure and public awareness of climate change issues. Run-off prediction from roadways has been studied for over 30 years (Swinnerton *et al*., 1973; Overton and Meadows, 1976) to the extent of providing practical methodologies (in which one of the present partners, TCD, was involved) for use in drainage design. However, the rainfall run-off design flood methodology should be re-examined and possibly re-calibrated for Irish conditions, particularly in the light of the forthcoming reworking of design flood and rainfall estimation in the current Flood Studies Update programme, managed by the Office of Public Works.

1.2 Objectives

The project objectives were:

1. Review existing practice with respect to road drainage design and maintenance (quantity and quality) for rural dual carriageways and motorways in Ireland and the assessment of any environmental impacts of such run-off. Set this practice in the context of current practice elsewhere in Europe.

2. Identify suitable candidate sites (maximum 15) for monitoring flow and physical/chemical quality of road drainage waters. Specify appropriate equipment for automated measurement of flows and sample collection at these sites as a prelude to selecting at least two for detailed monitoring.

3. Set up and operate at least two representative road drainage sub-catchments with instrumentation for monitoring rates of run-off and corresponding quality for a range of indicative parameters.

4. Analyse flow, rainfall and quality data, through the use of modelling, so as to be able to predict likely run-off peaks, volumes and quality from predetermined design rainstorms.

5. Assess the impacts of road run-off on the sediments, vegetation, macroinvertebrates and fish in the receiving water.

1.3 Organisation of the Project Work

The project work can be divided into five stages: (i) review, (ii) impact studies, (iii) detailed site monitoring, (iv) treatment options (review and monitoring), and (v) analysis and conclusions. This report mirrors that structure.

Review: The current research literature on road run-off generation, constituents and environmental impacts was reviewed. The current situation in Ireland was assessed from the researchers' direct experience and using a questionnaire survey of Local Authorities. In addition, the results of studies of the situation in Europe were incorporated in the review.

Impact studies: This involved field investigation, sampling and laboratory analysis. Impacts on surface waters are assessed in relation to sediment, vegetation, macroinvertebrates and fish.

Detailed site monitoring: Three sites were selected for intensive storm event monitoring and comparison. They included different drainage systems and treatment options.

Treatment options: Various treatment methods are discussed and assessed, both from the technical literature and from this project's own results.

Analysis and conclusions: Conclusions and recommendations are given in the final section.

2 Review

2.1 Scientific Literature

Highway run-off has been identified as a significant source of diffuse pollution contaminating receiving waters since the early 1970s (Hedley and Lockley, 1975; Laxen and Harrison, 1977; Smith and Kaster, 1983; Gjessing *et al.*, 1984; Hoffman *et al.*, 1985). It can contain significant loads of de-icers, nutrients, heavy metals, polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene, xylene, and methyl *tert*-butyl ether (MTBE). Ellis *et al.* (1987) estimated that drainage from highway surfaces contributes as much as 50% of the total suspended solids, 16% of total hydrocarbons and between 35% and 75% of the total pollutant inputs to urban receiving watercourses in the UK. Regular highway operation and maintenance activities are the most common sources of these pollutants.

The impacts of highway run-off on receiving streams are described in terms of the water quality or biological changes induced by the toxicity levels exhibited or both. Maltby *et al.* (1995a) documented that small streams receiving run-off from the British M1 Motorway had higher pollutant concentrations in both the sediment and overlying water and less diverse macroinvertebrate assemblages downstream of the highway run-off discharging point. Maltby *et al.* (1995b) and Boxall and Maltby (1997) subsequently showed that these elevated concentrations had toxic effects on aquatic organisms. The toxicity observed was due to the hydrocarbons, copper and zinc contained in the sediment, 65% of which was due to the PAHs: pyrene (45%), fluoranthene (16%), and phenanthrene (3.5%) alone. In a separate study, Shinya *et al.* (2000) reported that mutagenic activity was associated with PAHs in the particulate fraction of the run-off water and that the three predominant PAHs (pyrene, fluoranthene, and phenanthrene) made up about 50% of the 15 total quantified PAHs.

Barrett *et al.* (1998) and Wu *et al.* (1998) found that highway run-off was generally similar to urban run-off and did not contain appreciably higher levels of heavy metals and hydrocarbons. In contrast, Marsalek *et al.* (1999) showed that 20% of the samples from heavy-travelled, multi-lane, divided roads with a traffic count of more than 100,000 vehicles per day showed severe toxicity responses compared to 1% of the corresponding urban storm water run-off. It may therefore be necessary to make a distinction between the two, particularly on the basis of traffic count. The UK Design Manual for Roads and Bridges (DMRB-UK, 1998) expects pollution impacts on receiving waters mainly from roads with more than 30,000 average annual daily traffic (AADT), although the level of pollution associated with roads carrying more than 15,000 AADT could be of concern. In the USA, the 30,000 AADT cut-off is used to determine whether a given road requires a certain type of run-off treatment system before discharging to receiving streams. According to these criteria, the M50 in Ireland which has an AADT between 60,000 and 80,000 would require run-off treatment facilities. Most other national primary roads and motorways in Ireland have less than 30,000 AADT at most of their sites.

Both surface and subsurface waters are susceptible to contamination from road run-off, surface waters being more vulnerable. The impact on groundwater is generally low due to absorption, immobilisation by the soil, bacterial degradation and storage effects. The risk can however be higher in karst areas where the run-off may drain directly into the aquifer with little or no natural attenuation (Stephenson *et al.*, 1999). Once these water resources are polluted, the water poses a threat to public health, either through consumption of the water or body contact, the cost for treatment increases and the aquatic environment is impaired or destroyed (Overton and Meadows, 1976).

2.1.1 Highway run-off constituents and their impacts

Highway run-off constituents are known to vary from place to place depending on the rainfall characteristics, nature and intensity of traffic and the drainage system used. This calls for a site-specific study to ensure technically defensible interpretations of study results and to develop effective control strategies that minimise the impacts on the receiving aquatic environment. Heavy metal elements, PAHs, VOCs, such as benzene, toluene, ethylbenzene, xylene, and MTBE, are most frequently reported in highway run-off studies. Event Mean (Median)

Concentration (EMC) is often used to report highway run-off quality data and is useful when comparing data from different sites and events and estimating the total pollutant load of an event to the receiving water (Wu *et al*., 1998).

2.1.1.1 Heavy metals

Heavy metals in highway run-off are the most persistent constituents that are never lost from the environment. Metals such as lead, cadmium, copper, aluminium, iron, nickel, zinc, chromium and manganese are some of the ones most frequently reported and come from the wear and tear of vehicle parts (Sansalone *et al*., 1996). For example, tyre wear is a source of zinc and cadmium. Brake wear is a source of copper, lead, chromium and manganese. Engine wear and fluid leakages are sources of aluminium, copper, nickel and chromium. Vehicular component wear and detachment are sources of iron, aluminium, chromium and zinc (Ball *et al*., 1991; Legret and Pagotto, 1999). The concentration of lead in run-off waters in recent years has shown a sharp decrease following the ban of tetra-ethyl lead (TEL), a petrol additive, due to health concerns (Legret and Pagotto, 1999). The mode of transport of the metal ions depends on the nature/type of the metal concerned and the prevailing hydrology. Cadmium, copper and zinc are primarily found in soluble forms and are transported with the water, while iron and lead are mostly attached to sediment particles where the sediment serves as a sink (Sansalone *et al*., 1996). Run-off resulting from short intense rainfall following a long dry period is likely to wash off all forms of the metals deposited on the road surface and may cause severe stress to the receiving stream ecology. The fractionation of the metal into particulate and dissolved phases affects the impact of the run-off since their environmental mobility and bioavailability depends upon the level of aqueous concentration (Mungur *et al*., 1995). Soluble metals usually exert the greatest impact or toxicity on aquatic life. This has implications for the development of control strategies to protect aquatic life.

2.1.1.2 PAHs

PAHs are products of the incomplete combustion of oils and fuels. When released directly into the atmosphere through burning, lower molecular weight PAHs are generally dispersed much more quickly than those of higher molecular weight before returning to the road or surrounding land directly or in rainfall. PAHs enter water directly from the air with dust and precipitation, or particles washed from the road surface by run-off. Most PAHs do not dissolve easily in water but lower molecular weight PAHs are more water soluble than the higher molecular weight PAHs. PAHs are slow to degrade in the environment, and sediments in particular are sinks where these chemicals tend to concentrate. PAHs are of major concern because they are responsible for the larger percentage of toxicity to freshwater organisms. Boxall and Maltby (1997) found that the three predominant PAHs (fluoranthene, pyrene, and phenanthrene) account for a significant proportion of the toxicity (30–120%).

2.1.1.3 The fuel oxygenate MTBE

Since the phasing out of leaded octane additives in petrol in the 1980s, many refineries replaced them with aromatics, a low cost alternative at the time. Towards the end of the 1990s, the introduction of ‘Clean air acts’ in Europe and the USA limited the aromatic content of petrol, and oxygenated compounds such as MTBE became easy options for the refinery industry to reach the new standards. MTBE is used as an octane enhancer to achieve the required octane level and cleaner-burning petrol, thereby reducing toxic exhaust emissions (carbon monoxide and ozone) and improving air quality. It has many attractive properties (such as excellent solubility in petrol) that makes it a good alternative to other petrol components and an ideal substitute for other octane enhancers, e.g. lead. The EU Directive No. 85/536 of 5 December 1985 allows the use of oxygenates such as MTBE as gasoline additives up to 15% by volume without any supplementary labelling. UK refineries add between 0.0% and 10% with an average of 1.08% by volume. The same percentage applies to Ireland since most of the petrol used is imported from the UK. The sole Irish refinery, in Whitegate, “adds less than 1% MTBE to its stocks in winter, a little more in summer” (e-mail from John McDermott, DEHLG, May 2002).

At most commonly observed environmental exposure levels in surface waters (<1.0 mg/l), acute toxicity of MTBE to freshwater organisms is low (Werner *et al*., 2001). However, MTBE has a strong taste and odour that can be detected by humans at relatively low concentrations in water, typically at 5–15 µg/l.

2.1.1.4 Conventional pollutants

Highway run-off contains significant loads of other pollutants such as solids (particulate and dissolved), organic compounds and nutrients that can affect the quality of the aquatic environment. The organic content of road run-off is expressed by biochemical oxygen demand (BOD), chemical oxygen demand (COD) and the total organic carbon (TOC). Phosphorus and nitrogen compounds are essential nutrients for plant and animal growth. Nitrogen and phosphorus compounds are the typically observed nutrients in highway run-off where the application of roadside fertilisers is practised as part of landscaping. Other parameters, such as temperature, pH, dissolved oxygen, and faecal bacteria, are reported in highway run-off studies (Maltby *et al*., 1995a; Barrett *et al*., 1998).

2.1.2 Factors affecting highway run-off contaminant concentrations

Contaminant concentrations in highway run-off are affected by several factors such as the traffic volume, rainfall characteristics, the type of pavement and the nature and type of the pollutant. Pollutant concentrations are also influenced by the dry period preceding the storm, the antecedent storm, and the conditions during the storm event. The relative importance of each factor is dependent on the type of contaminant in question. For example, Irish *et al*. (1998) reported that the solids load increases with the increase in the duration of the antecedent dry period and decreases with the increasing intensity of the previous storm event. Copper and lead are highly influenced by the volume of traffic during a storm, iron is controlled by conditions in the preceding dry period, and zinc is influenced by the traffic count during the dry period and the run-off characteristics of the preceding storm. It is therefore necessary to understand the effect of each factor to effectively control the impacts of run-off.

2.1.3 Assessment of impact of highway run-off

Impact assessment of highway run-off on the receiving aquatic environment involves the measurement of its physical, chemical and biological characteristics and comparing these to previously measured or desired 'baseline' constituent levels and/or aquatic communities. The baseline can be an established standard (guideline) or a measured value of a similar component from a similar (same) site virtually 'unaffected' by human activities. Such conditions are hard to find. The other option is to use the reach of a river upstream from the road drainage discharge point as a reference with which to compare measured constituents downstream of the discharge point (see also Maltby *et al*., 1995a).

The issue of impact assessment of highway run-off on the receiving waters is complicated by environmental factors that are unconnected to road run-off quality (Maltby *et al*., 1995a). The first of these is the habitat change that may result from the altered hydrological regime at the road crossing. Hydrological regime changes are associated with increased flood and reduced low flows that can significantly alter aquatic life habitat. The second is the biological changes that normally occur as a natural characteristic of aquatic ecosystems.

2.1.4 Highway drainage practice and pollution control options

Road drainage practices are primarily designed to remove surface and subsurface water to provide safety and minimum nuisance for the motorist and maximise longevity of the pavement and its associated earthworks (DMRB-UK, 1996). Drainage practices are either surface or subsurface. Some systems such as filter drains have dual functions of surface water run-off control and control of groundwater below the road level. Specific drainage systems include kerbs and gully pots, filter drains, informal verge systems, infiltration pavements, swales and ditches, oil and grit separators, detention or retention ponds, soakaways and infiltration basins, drainage ditches and natural/artificial wetlands. Drainage systems generally perform one or more of the following functions: collection of water, conveyance of water, disposal of collected water, storage of water to reduce peak flows, removal of coarse sediment (CIRIA, 1994).

Almost all established drainage systems remove some of the pollutants that can be physically separated from the run-off water. This is achieved by trapping or settling pollutants with or without a physical structure. Soluble pollutants cannot however easily be treated with conventional drainage systems. The efficiency of these systems is very much limited by their ability to contain, infiltrate and/or biodegrade all of the dissolved pollutants contained in the run-off.

Best management practices (BMPs) are measures that can be taken to reduce impacts of highway run-off constituents on receiving waters and the aquatic life. BMPs are based on principles of sedimentation, infiltration, filtering systems, wetland systems or some form of a combination of these (Scholze *et al*., 1993). BMPs also involve non-structural measures such as cleaning operations and pollution control at source. The realisation of certain vehicle components and fuels as sources of heavy metals, PAHs and some other pollutants may lead to modifications in the composition of tyres, fuel and brake pads (Lee and Jones-Lee, 1993). The ban on leaded fuel is a good example.

The primary objective of implementing BMPs is to enhance the beneficial uses of the receiving waters and protect the downstream aquatic ecosystem by treating the run-off. The pollutants removed from the run-off are disposed in a place where they pose no more threat to surface or groundwater sources (Scholze *et al*., 1993). The problem is that there are no well-established performance criteria to indicate whether or not these BMPs have met their objectives, above all the environmental benefits. Although efficiency may be measured against two criteria (constituent removal and toxicity reduction), the usual approach is based solely on the former.

2.2 Current Road Drainage Practice in Ireland

2.2.1 Roads in Ireland

The total length of roads in Ireland is about 92,500 km (Central Statistics Office, 2002). A total of about 1.9 million vehicles use this network. National primary roads (includes motorways, dual and single carriageways) comprise only 3% of the total road network but carry about 27% of the total road traffic. The total road network carries 96% of passenger traffic and 90% of freight traffic. These figures place Ireland among those countries in the EU with the highest reliance on road transport. The corresponding figures for the EU as a whole are 88% and 72%, respectively.

2.2.2 Legal aspects of road drainage in Ireland

The Fisheries (Consolidation) Act 1959 and The Local Government (Water Pollution) Acts 1977 and 1990 constituted the main national legislation. These Acts empower Local Authorities to prosecute offenders, issue notices of measures to be taken, or seek court orders to discontinue discharges into receiving waters suspected of causing pollution. Local Authorities, however, had both a developmental role and a role in protecting the environment that sometimes resulted in conflicts of the two interests. In 1992, the Environmental Protection Agency Act 1992 was passed and the Agency itself was established the following year. The Act created the concept of Integrated Pollution Control (IPC), in which all types of pollution emitted by a facility are examined together before licensing. This concept has been extended, refined and reintroduced under the Integrated Pollution Prevention and Control (IPPC) Directive (96/61/EC). This directive was adopted into Irish law and enacted as the Protection of the Environment (PoE) Act 2003. The PoE Act came into effect as of 12 July 2004.

2.2.3 Relevant EU legislation

There are a number of EU Directives enacted for the protection of surface and groundwater sources from pollution including: (i) Bathing Waters (76/160/EEC), (ii) Dangerous Substances (76/464/EEC), (iii) Freshwater Fish (78/659/EEC), (iv) Shellfish Waters (79/923/EEC), (v) Groundwaters (80/68/EEC), (vi) Drinking Water (80/778/EEC), (vii) Urban Waste Water Treatment (91/271/EEC), (viii) Nitrates (91/676/EEC) and (ix) Water Framework Directive (2000/60/EC).

2.2.4 Highway drainage systems in Ireland

Drainage practices are classified as surface and subsurface systems based on whether they are used for surface or subsurface drainage. The main types of drainage systems used on rural dual carriageways and motorways in Ireland include: (i) filter (French) drain, (ii) kerbs and gullies, (iii) combined surface water channel and pipe systems, (iv) over-the-edge drainage, and (v) fin or narrow filter (NF) drains.

2.2.4.1 Filter (French) drain

This is the most popular type of drainage system used in rural dual carriageways and motorways in Ireland. It consists of either a porous, perforated or open-jointed non-porous pipe at the bottom of a trench filled with gravel laid at the edge of the pavement or close to it. It serves both purposes of surface and subsurface drainage and is called a ‘combined filter drain’. It is mainly used in cuttings or areas with groundwater problems. It also provides storage of run-off during storms that may help to attenuate flood peaks at the receiving stream due to the time lag between groundwater flow and stormwater flow. Visual inspection suggests that a significant percentage (>40%) of dual carriageways and motorways in Ireland use this system.

A geotextile membrane is used to prevent fine material entering the filter drain while permitting free flow of water into the drainage medium. It limits plant root growth into the filter media and also has some oil retention capacity. Problems associated with the use of geotextile membrane are discussed later in this report. The estimated effective life of filter drains is 10 years after which period the void space is filled with fine material effectively blocking the system. In addition to their primary functions, filter drains can provide some degree of run-off treatment. They can retain some solids and pollutants associated with the suspended solids.

2.2.4.2 Kerbs and gullies

Conventional gullies, incorporating a gully grating and a gully pot, are located at the edge of the road provided with concrete kerbs to facilitate the flow of surface run-off into the gullies. Run-off collected at the gully pots is discharged through a connection pipe into a longitudinal carrier pipe. The carrier pipe then discharges into an outfall. Gully pots serve as a trap for sediment that might otherwise cause partial or total blockage of the carrier pipe or deposition of sediment in the receiving water. Gully pots can have both positive and negative effects on the quality of road run-off depending on the management strategy. They can remove sediments of particle size greater than 300 µm and pollutants associated with solids. Memon and Butler (2002) reported a total suspended solids removal of up to 40%, 20% of COD and 10% of ammonium load. The frequency of cleaning has been shown to have a significant effect on the run-off quality and varies with the contaminant in question. Frequent cleaning (say every week) appears to help reduce dissolved pollutants that originate from biochemical degradation of the sediment during dry periods (Memon and Butler, 2002).

2.2.4.3 Combined surface water channel and pipe system

Combined surface water channel and pipe systems consist of concrete channels, triangular, rectangular or trapezoidal in shape, slip-formed at the edge of the hard shoulder and flush with the road surface and an internal pipe formed within the base of the unit that carries the collected flow. Combined surface water channels have a larger flow capacity, which may reduce or eliminate the need for additional carrier pipes.

2.2.4.4 Over-the-edge drainage

In this system, surface water drains into the grass verge and the water is allowed to drain down the side slopes and into ditches at the base of the embankment. This type of drainage system is used in areas where the embankment is made of granular material which can resist erosion. Over-the-edge drainage is a relatively cheap option if ample granular material is available from cuts and can be obtained at a reasonable cost. Over-the-edge drainage is used in combination with filter drains on major Irish roads.

2.2.4.5 Fin or narrow filter drain

Fin or NF drains are mainly required to drain water that may permeate through the pavement layers and remove groundwater from the road foundation to a sufficient depth. They also prevent the flow of water from verge areas into the pavement layers and foundation. These systems are used independently or in combination with kerb systems or are combined with a surface water channel and pipe system. Since a fin/narrow filter drain is mainly concerned with subsurface drainage, it is not intended to remove pollutants from the drainage water.

2.2.5 Responsibilities of the roads authorities

The National Roads Authority (NRA) is responsible for the national road network, while County Councils manage local and regional roads. The NRA’s main functions, as given in Section 17 of the Roads Act 1993 (as amended), include overall responsibility for the planning and supervision of works for the construction and maintenance of national roads. The impact of road run-off on water quality should be covered in the Environmental Impact Statement for road schemes.

Under current conditions, road drainage is discharged into the nearest watercourse with minimal treatment. Road authorities however are bound to relevant national legislation and EU directives and have the responsibility of protecting the nation’s water from pollution. To this end, the NRA has co-sponsored this research with the EPA to assess the effects of road run-off, under the current drainage conditions, on receiving waters and recommend treatment options to mitigate pollution. Questionnaire responses show that Local Authorities are aware of the pollution potential of road run-off and want to see some form of treatment to be put in place before the water is discharged into receiving waters.

2.3 The European Experience

2.3.1 The POLMIT project

Management of the quality and quantity of run-off from highways has long been a concern of many countries in the EU, particularly those with traffic control problems. This aspect of transport management was recognised as part of a research project under the Transport RTD agenda of the EU 4th Framework Research Programme. The Transport Research Laboratory of the UK coordinated a COST project, entitled *POLMIT – Pollution of Groundwater and Soil by Road and Traffic Sources: Dispersal Mechanisms, Pathways and Mitigation Measures* (Transport Research Laboratory (TRL), 2002), which reported on the European experience to date in the management of highway run-off. This collated material from seven European countries (the UK, Netherlands, Denmark, Sweden, Finland, France and Portugal), derived from the TRL report, forms the basis of the state of the art described in this section. While practice in terms of the removal of run-off from the road varies widely across Europe, it is nowhere consistent and often occurs in an *ad hoc* manner. The deliberate exclusion of direct discharge to surface water enabled a simpler mass balance to be assessed. As revealed by the present investigation, even where direct discharge to surface water is allowed, the pathways involved frequently mean that much of the contamination leaving the road does not necessarily arrive at the discharge point. Moreover, throughout much of Europe, it is apparent that the subsurface environment may be the ultimate receptor for road drainage, rather than surface water.

2.3.2 Sources of contamination

Over the period of the design life of a road, both the road itself and the traffic that uses it are the sources of compounds with potential to contaminate the environment. Much effort in the past has been directed towards understanding how and what concentrations of gaseous and fine particulate material are released into the atmosphere through fuel combustion processes with a view to regulating these emissions at source (Transport Research Laboratory, 2002). The result has been regulation of fuel combustion processes (e.g. catalytic converters) principally with respect to atmospheric emissions.

For the large number of remaining compounds released to the terrestrial environment, direct links between transport emissions and impacts on the environment/public health are more difficult to identify. For terrestrial discharges, past studies have focussed on determining concentrations of pollutants in highway run-off, rather than on concentrations emitted from particular sources. Mitigation measures have been aimed at the treatment of highway run-off rather than at the implementation of source control measures.

The integrated study reported by the Transport Research Laboratory (2002) represents a first attempt in Europe to investigate the complete source–pathway–receptor framework in the context of potential pollution emanating from roads. On the basis of a mass balance approach, the study attempted to assess the quantities of unregulated compounds that are released, what proportion of these emissions enter the local roadside environment, the relative importance of each transport mechanism and where in the environment these compounds are likely to interact. Thus an objective was to identify those pathways by which road and vehicle pollutants are transported into the local roadside environment and any factors which influence the relative importance of each pathway. The proportion of each pollutant released that enters the terrestrial environment was evaluated so as to identify where mitigation measures should be targeted in order to be most effective.

However, in the light of the reported sources of roadside contaminants, no treatment systems currently exist for direct management of contaminants transported by aerial dispersal. Although the reported fluxes do not reflect aerial dispersal as the dominant mechanism of transfer into the local environment, significant quantities of especially zinc and chloride are transported by aerial dispersal. The presence of porous road surfaces was shown to reduce transfer rates by this mechanism although the ultimate pathway for such a route was not investigated. At present, the only practical method of treatment for contaminants transported by aerial dispersal is source control.

3 Surface Water Impact Studies

3.1 Site Selection

A three-stage site selection process was used because of the large number of candidate sites which had to be visited in order to generate a satisfactory list of suitable sites for baseline investigation. (i) Initially, a 'long' list of sites was generated and each visited and inspected visually for suitability. (ii) Sites from the long list which were deemed 'suitable' became sites for the baseline investigation, and water, sediment and macroinvertebrate samples were taken and analysed. For some sites, special investigations of vegetation and fish were also undertaken and some more detailed sediment studies. (iii) Sites used in the baseline investigation were also candidates for the detailed monitoring sites. However, additional sites that became available during the project were also considered.

Following preliminary presentation of the baseline results, it became apparent that most of the chosen sites were already impacted by upstream sources of contamination. It was recommended that some additional, unimpacted, sites be added to the project. With some difficulty, a number of suitable sites were identified and included in the project.

The project team travelled along the major roads leading north (as far as Dundalk), west (up to 75 km) and south (as far as Enniscorthy) and visually identified sites for potential inclusion on the long list. Later in the project, areas in Leitrim, Roscommon and Sligo were investigated in the search for sites without upstream pollution impacts.

The criteria used in the visual selection were:

- The site had to have road drainage entering a river or stream.
- The road catchment area should be significant and identifiable.
- The river or stream should not be too large (too much dilution) or too small (insufficient diversity). Typically, streams with bankfull widths between 2 and 4 m were preferred.
- The sites should not have any additional sources of contamination, e.g. farmyards, draining onto the road or into its drains.
- Accessibility and suitability for monitoring and sampling.
- Type of road drainage system.

Over 46 sites were visually inspected to identify those suitable for studying the impact of road run-off on receiving watercourse and for highway run-off monitoring (Table 3.1). Out of these, 14 sites were identified for water, sediment and biological sampling (Table 3.2) and five sites for road run-off monitoring (Table 3.3).

3.2 Sediment and Water Studies

A baseline study was conducted to establish the background chemical and ecological status of the study sites, record any evidence of changes that occurred during the study period and to determine if road run-off has a detectable impact on the receiving water quality or ecology. At road run-off discharge points, heavy metal (Cd, Cu, Pb, and Zn) concentrations and macro-invertebrate communities upstream of road run-off inflows were compared to those of the downstream. Samples from a control site, a site reasonably free from the possible effect of road run-off, were incorporated to study if any of the study sites are significantly different from the control site. The heavy metals analysed included cadmium, copper, lead and zinc. The nutrients studied were nitrates and phosphates and other parameters including dissolved oxygen, temperature, pH, specific conductivity, non-purgeable organic carbon (NPOC), and total alkalinity. Fourteen small stream sites (from the long list of 46) were selected for this background monitoring (Table 3.2). The Lackan River, a tributary of the Pollaphuca Reservoir in County Wicklow, and which does not receive road run-off, was selected as a control site.

3.2.1 Methodology

At each site, sediment samples were collected from three locations upstream and three locations downstream of the run-off discharge points. The downstream samples were collected beginning from adjacent to the drainage outfall

Table 3.1. Long list of sites surveyed for sampling water sediment and biology.

No.	Name	Road	Assessment
1	River near Newhall	M7	Not suitable
2	River Liffey near Walshes town	M7	Not suitable
3	River Liffey at Greenhills	M9	Not suitable
4	Unnamed river at Hillsborough Bridge	M7 and M9	Not suitable
5	Grand Canal feeder near Ladytown	M7	Not suitable
6	Hartwell River at Tobenavoher Bridge	N7	Suitable
7	Morell River at Morell Bridge	N7	Suitable
8	Kill River at Kill	N7	Not suitable
9	Tributary of Painestown River at Boherphilip Bridge	N7	Suitable
10	Unnamed river at Blackhill	N7	Not suitable
11	Tributary of Slane River at Dunbauin Bridge	N7	Suitable
12	Unnamed river south of Tootenhill	N7	Not suitable
13	Unnamed river at SW of City West Bridge	N7	Not suitable
14	Unnamed river SW of Kingswood	N7	Not suitable
15	Unnamed river at Kingswood	N7	Not suitable
16	Owendoher River NE Newtown	M50	Suitable
17	Little Dargle SE Marley Park	M50	Not suitable
18	Rowanstown at Maynooth Bypass	M4	Suitable
19	Lyreen River Maynooth Bypass	M4	Suitable
20	Unnamed river Turvey Bridge	N1	Not suitable
21	Unnamed river at Daws Bridge	N1	Not suitable
22	Boghall River at Carduff Bridge	N1	Not suitable
23	White River at Dunleer Bypass before exit	M1	Suitable
24	Unnamed river at Dunleer Bypass at exit	M1	Suitable
25	River Dee at end of M1	N1	Not suitable
26	River Glyde south of Castle Bellingham	N1	Not suitable
27	Mattock River before Emerson's Bridge – east of Broomfield	N2	Not suitable
28	Devlin River at Devlins Bridge	N2	Not suitable
29	Balrath River at Balrath Cross road	N2	Not suitable
30	Ballyduff Stream at Arklow Bypass	N11	Not suitable
31	Unnamed stream Enfield Relief Road	N4	Suitable
32	Glen O'Downs Stream	N11	Suitable
33	Glenview Stream	N11	Suitable
34	Doonfin Stream	N11	Suitable
35	Lugdoon Stream	N59	Not suitable
36	Tributary of Unshin at Drumderry	N17	Not suitable
37	Tributary of Unshin at N4	N4	Not suitable
38	Sonnagh Tributary	N5	Not suitable
39	Spaddagh Tributary (two locations)	N5	Suitable
40	Killeen River	N5	Not suitable
41	Mullaghanoe Tributary	N17	Not suitable
42	Stream near Knock Airport	N17	Not suitable
43	Tributary of Lough Arrow	N4	Not suitable
44	Tributary of Lough Key – Tawnytaskin	N4	Not suitable
45	Tributary of River Barrow at Monasterevin	M7	Not suitable
46	Tributary of Ardnaglass Stream	N59	Suitable

Table 3.2. Sites selected for water, sediment and biological sampling.

Site no.	Site name	Monitoring period	AADT/HGV%*	OS NGR	Drainage system
S1	Tributary of Slane River at Dunbauin Bridge (N7)	2002–2003 and 2005	50,729/12.8	N 970 242	Filter drain and over the edge
S2	Hartwell River at Tobernavore Bridge (N7)	2002–2003 and 2005	50,729/12.8	N 925 220	Over the edge
S3	River near Rowanstown at Maynooth Bypass (M4)	2003 and 2005	39,088/7.5	N 934 363	Filter drain
S4	Lyreen River at Maynooth Bypass (M4)	2002–2003 and 2005	39,088/7.5	N 913 370	Filter drain
S5	White River at Dunleer Bypass (M1)	2003 and 2005	24,369/12	O 135 260	Filter drain
S6	Owendoher NE of Newtown (M50)	2003 and 2005	43,624/6.0	O 135 255	Filter drain
S7	Tributary of Painestown River near Boherphilip (N7)	2002–2003 and 2005	50,729/12.8	N 955 235	Over the edge
S8	Morell River near Johnstown (N7)	2002–2003 and 2005	50,729/12.8	N 919 216	Filter drain
S9	Tributary of the Pollaphuca Reservoir**	2003	N/A	O 012 110	N/A
S10	Glen O' Downs Stream (N11)**	2005	34,540/6.8	O 266 105	Filter drain and kerb + linear drainage
S11	Glenview Stream (N11)**	2005	34,540/6.8	O 256 117	Filter drain and kerb + linear drainage
S12	Doonfin Lower Tributary (N59)**	2005	2,513/6.8	G 508 325	Over the edge
S13	Tributary of Ardnaglass Stream at Carrowree (N59)**	2005	2,513/6.8	G 544 330	Over the edge
S14	Spaddagh Tributary (N5)**	2005	5,875/11.3	M 370 979	Over the edge

*2004 data; **control sites.

Table 3.3. Road runoff monitoring sites.

Site no.	Site description	Road	Drainage area (m^2)	Type of drainage system	OS NGR
S1	Kildare Bypass	M7	14,184	Kerb and gully	N 667 113
S2	Maynooth Bypass	M4	9,760	Filter drain/over-the-edge drainage	N 913 370
S3	Maynooth Bypass	M4	1,100	Over-the-edge drainage	N 913 370
S4	Monasterevin Bypass	M7	9,600	Filter drain	N 569 059
S5	Monasterevin Bypass	M7	11,368	Wetland	N 569 059

and further downstream 30 to 40 m apart depending on availability of deposited sediment. The upstream samples were similarly collected from upstream of the road drainage discharge point at similar distances as the downstream side. The top 2–5 cm of the sediment were collected at each point using a plastic scoop and transferred to pre-labelled clean plastic bags. Roadside sediment samples were collected from each side of the M4 Motorway at the Maynooth site.

To study any temporal variation of determinants, six sites, which were sampled at the beginning of the project, were again sampled (for sediment and water) between April and June 2005. Two of the sites were not sampled in the second period because the sites were disturbed by new road construction (the N7 widening). Additional sites, which are considered to be in relatively pristine conditions, were also included this time. Water and sediment samples were taken and analysed using the same techniques for the same parameters as before. Sixteen US EPA-selected PAHs were tested for some sites to add more information to what is already available from the previous period.

3.2.2 Results

3.2.2.1 Comparison of metals in upstream and downstream sediment

Average concentrations of Cd, Cu, Pb and Zn, expressed in µg/g dry weight, of upstream and downstream samples are given in Table 3.4. Concentration ranges are 0.8–4.3 µg/g for Cd, 11.2–53.7 µg/g for Cu, 16.8–45.6 µg/g for Pb, and 65.6–216.9 µg/g for Zn. The levels detected at the river near Rowanstown and the Lyreen River (S3 and S4) are generally higher than at the other sites. Figure 3.1 shows the variation of metals upstream and downstream of the sampling sites.

Some sites exhibited a slight increase in the downstream concentrations although it was statistically significant only at S6 for Cd, S7 for Cu and Zn (at $p = 0.05$). However, the means of all the downstream concentrations were not significantly higher than the upstream sites at $p = 0.05$. All the tested metals showed some degree of correlation to each other (multiple or single), the strongest being a coefficient of determination (R^2) of 0.87 between Cu and Zn and the weakest being 0.38 between Cd and Pb. The multiple correlation of Cd against Cu, Pb, and Zn produced R^2 of 0.59. Sites along the N7 (S1, S2, S7 and

Table 3.4. Average concentrations of metals in sediments upstream and downstream of the sites: first test.

Site no.	Cd mg/g		Cu mg/g		Pb mg/g		Zn mg/g	
	US	DS	US	DS	US	DS	US	DS
S1	2.6	3.2	15.8	16.4	28.6	30.3	70.6	73.0
S2	3.0	2.8	14.0	17.5	21.2	21.0	78.4	89.4
S3	4.0	3.7	38.5	53.7	39.5	38.8	191.8	216.9
S4	4.3	4.1	27.5	24.0	24.3	29.1	136.1	142.2
S5	0.8	0.8	23.3	17.7	34.8	26.0	92.9	70.4
S6	1.3	2.2	15.3	18.7	31.0	33.4	131.6	135.8
S7	2.8	2.7	20.6	30.7	40.6	45.6	99.0	167.7
S8	3.3	2.9	22.0	20.0	30.2	19.4	65.6	73.2
S9	1.7	1.7	11.5	11.2	16.8	18.5	97.4	123.6

US, upstream of discharge; DS, downstream of discharge.

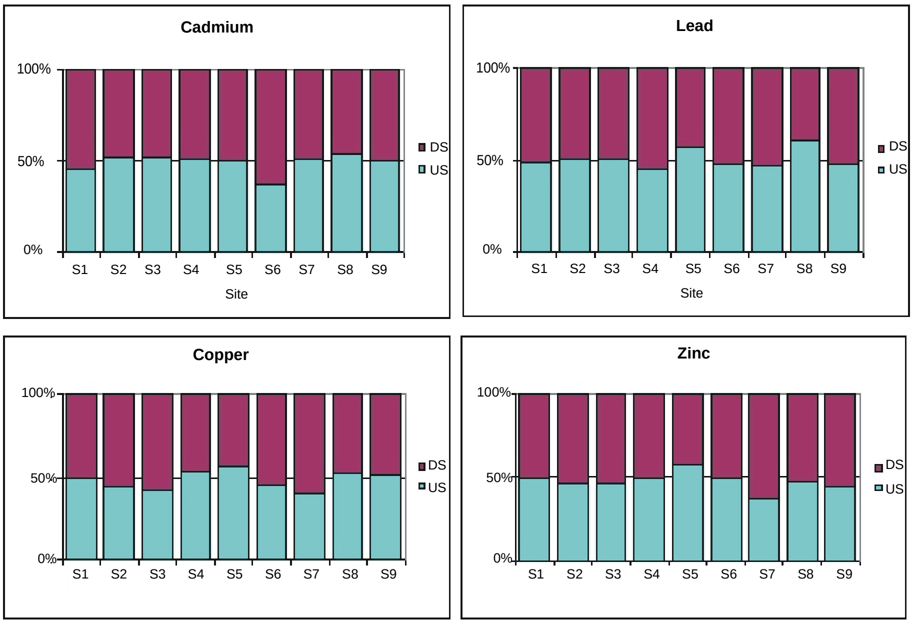


Figure 3.1. Changes in metals in sediments upstream and downstream of outfalls, first test.

S8) showed little variation of metal concentrations among themselves.

Figure 3.2 compares the upstream and downstream concentrations of the four metals for the second period. The overall comparison of upstream and downstream concentrations shows significant variations only in two sites: S6 (Owendoher NE of Newtown) and S12 (Doonfin Lower Tributary). The Owendoher River is crossed by the M50 at the sampling site. This site had a similar history in the previous study too. The Doonfin Lower Tributary is on the N59 in the north-west of Ireland. The stream is found in a valley where road run-off from both sides of the valley drain into the stream from an open drain system. The other sites show such variations in only one or two of the metals tested. S1 (Cu, Pb, and Zn) and S4 (Cd, Pb, and Zn) showed slight increases in three out of the four metals, S5 (Cd and Pb) and S6 (Pb and Zn) in two out of the four metals and S2 (Pb) in only one out of the four

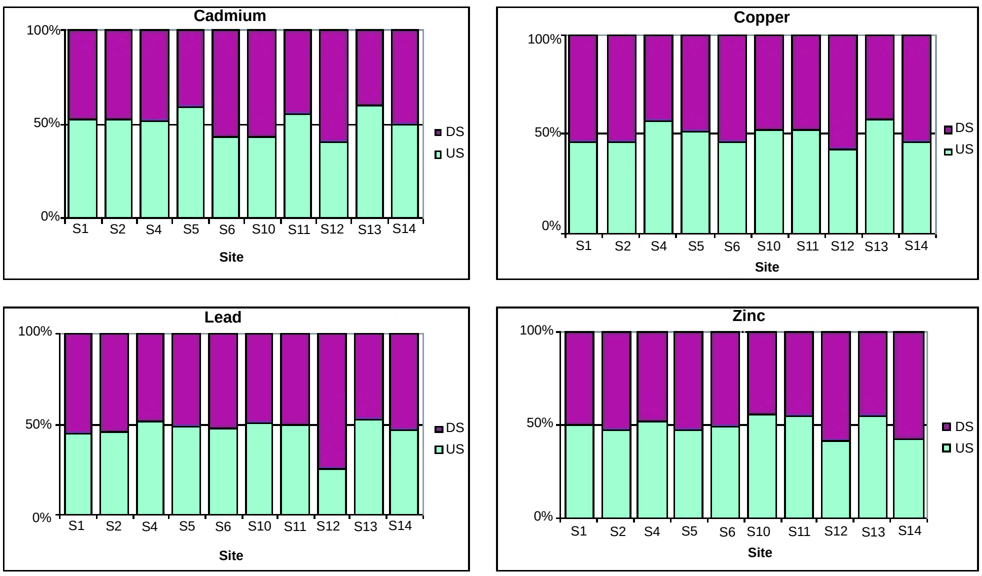


Figure 3.2. Changes in metals in sediments upstream and downstream of outfalls, second test.

metals. The overall comparison of the two periods didn't show a statistically significant difference ($p = 0.05$).

3.2.2.2 PAHs content of the sediment

The PAH content of the sediment is presented in Table 3.5. Sites S6, S10 and S11 show significant differences between upstream and downstream concentrations. S6 is the Owendoher Stream on the M50 and sites S10 and S11 are two sampling sites on the Glen O'Downs Stream along the N11. The Owendoher Stream also had higher heavy metals concentrations in the downstream than in the upstream reaches.

3.3 Vegetation Study

If road run-off is affecting aquatic ecosystems, then the in-stream or riparian vegetation might be expected to respond and to show some signs of the impact. Certain plants can absorb contamination from water through their roots (rhizofiltration). This ability (phytoextraction) can be used to clean up contaminated waterbodies (phytoremediation) or to form organic filters (e.g. constructed wetlands). Trees such as poplar, willow and cottonwood are used for their large water extraction rates. Poplar, cottonwood and aspen have been used to remediate heavy metal contamination, as have mosses such as *Hylocomium splendens* and *Rhytidialdephus loreus* (Mungur *et al.*, 1995; Schutes *et al.*, 2001; Baldantoni *et al.*, 2003). *Apium nodiflorum* (Fool's watercress or European marshwort) has been used as an indicator/accumulator of chromium and nickel and is investigated here as an indicator of cadmium, lead and zinc, more common in road run-off. It is used here because it is commonly found in Irish rivers and has been used in other studies. An aquatic plant, it can be expected to have a high water use and to accumulate metals from the water or sediment. *Apium* grows in colony clumps as it propagates vegetatively.

3.3.1 Sampling locations

Two rivers are studied, the Lyreen (M4: AADT 25,000–30,000) and a tributary of the Painestown (N7: AADT 45,000–50,000). In each case, an outflow pipe brings road run-off directly into the river at the downstream side of each culvert. In each case, samples of *Apium nodiflorum* were collected from (i) up to 50 m upstream of the road, (ii) within 10 m of the road run-off outflow pipe, and (iii) a reach of more than 80 m downstream of the culvert. One to three samples were taken from each population cluster at each location, including samples representative of both banks and the centre of the channel. At least eight plants were taken from each location.

3.3.2 Vegetation study results

The Main Report gives the detailed results. In general, lead concentrations were quite small, but the lowest values were found upstream of the road crossing and highest near the outflow pipe. Downstream concentrations were slightly higher than upstream. Lead concentrations in the roots were significantly higher than in the shoots.

Similarly, copper concentrations were lowest upstream of the road crossing and highest near the outflow pipe. Downstream concentrations were slightly higher than upstream. Concentrations in the roots were significantly higher than in the shoots.

Similarly, cadmium concentrations were lowest upstream of the road crossing and highest near the outflow pipe. Downstream concentrations were slightly higher than upstream. Concentrations in the roots were significantly higher than in the shoots.

Unlike the other metals, zinc concentrations were very high. The roots had higher concentrations than the shoots and the highest concentrations in the Lyreen were found near the outflow pipe and the lowest at the downstream location. In contrast, the highest zinc concentrations in the roots at the Painestown site were at the upstream location and concentrations decrease in the downstream direction. In the shoots however, the highest levels were at the outflow.

The relatively high levels of zinc indicated that (i) there was a source of zinc, and (ii) that *Apium* accumulated zinc well. In contrast, the significantly lower levels of lead, copper and cadmium indicated either that (i) there was not much contamination with these metals, or (ii) *Apium* did not accumulate large amounts of these metals.

3.4 Macroinvertebrate Studies

A total of 28 sites representing 14 streams were sampled between 2002 and 2005. Eight of the streams sampled by Burns (2004) were revisited in April 2005. Six of these streams were resampled for macroinvertebrate fauna (Table 3.6). On visiting the Painestown and Morrell streams, it was noted that due to the major road works the upstream/downstream sites were being impacted by the

Table 3.5. PAHs in the sediment samples.

Compound	S2		S4		S5		S6		S10*		S11*		S12		S13		S14	
	US	DS	US	DS	US	DS	US	DS	US	DS(2)	US	DS(1)	US	DS	US	DS	US	DS
Naphthalene	<1	<1	<1	<1	<1	<1	<1	10	14	<1	<1	14	<1	<1	<1	<1	<1	<1
Acenaphthylene	<1	<1	<1	<1	<1	<1	<1	32	17	<1	<1	17	<1	<1	<1	<1	<1	<1
Acenaphthene	<1	<1	<1	<1	<1	<1	<1	62	178	<1	<1	178	<1	<1	<1	<1	<1	<1
Fluorene	<1	<1	<1	<1	<1	<1	<1	23	53	<1	<1	53	<1	<1	<1	<1	<1	<1
Phenanthrene	<1	<1	50	27	<1	<1	32	187	262	383	<1	262	<1	<1	<1	<1	<1	<1
Anthracene	<1	<1	31	10	<1	<1	12	86	48	45	<1	48	<1	<1	<1	<1	<1	<1
Fluoranthene	<1	<1	85	29	<1	<1	57	573	555	1075	<1	555	<1	<1	<1	<1	<1	<1
Pyrene	<1	<1	74	24	<1	<1	43	527	496	698	<1	496	<1	<1	<1	<1	<1	<1
Benzo(*a*)anthracene	<1	<1	40	18	<1	<1	50	302	297	456	<1	297	<1	<1	<1	<1	<1	<1
Chrysene	<1	<1	64	27	<1	<1	80	339	394	559	<1	394	<1	<1	<1	<1	<1	<1
Benzo(*b*)+Benzo(*k*) fluoranthene	<1	<1	52	17	<1	<1	74	346	434	710	<1	434	<1	<1	<1	<1	<1	<1
Benzo(*a*)pyrene	<1	<1	57	18	<1	<1	59	240	268	405	<1	268	<1	<1	<1	<1	<1	<1
Indeno(*123cd*)pyrene	<1	<1	24	10	<1	<1	37	81	139	296	<1	139	<1	<1	<1	<1	<1	<1
Dibenzo(*ah*)anthracene	<1	<1	13	5	<1	<1	20	44	69	120	<1	69	<1	<1	<1	<1	<1	<1
Benzo(*ghi*)perylene	<1	<1	36	11	<1	<1	52	107	159	392	<1	159	<1	<1	<1	<1	<1	<1
Total	**<1**	**<1**	**526**	**197**	**<1**	**<1**	**516**	**2959**	**3383**	**5139**	**<1**	**3383**	**<1**	**<1**	**<1**	**<1**	**<1**	**<1**

***S10 and S11 are two points on the same stream. The stream crosses the road twice. Note that downstream for S11 is upstream for S10.**

large movement of earth and clearfelling of bankside vegetation. It was decided therefore to abandon sampling these streams. Five new unimpacted sites were selected along the N11, N59 and N5 and were sampled in May/June 2005 (Table 3.6). These new sites were added so that the potential impacts of road-run-off could be assessed in the absence of other anthropogenic inputs.

Macroinvertebrate data are summarised throughout the United Kingdom using the Biological Monitoring Working Party (BMWP) biotic score system. The biological quality is described using the number of BMWP scoring taxa present and the Average Score per Taxon (ASPT) which is derived from the community BMWP score divided by the number of scoring taxa represented. The resulting ASPT value is between 1 and 10.

3.4.1 Biological results

The mean number of taxa at a site ranged from 14 (SL-US05) to 47 (OW-US02) (Fig. 3.3). There were no significant differences in taxon richness between upstream and downstream sites except for one occasion on the Lyreen River in summer 2002.

The mean number of individuals per sample at a site ranged from 169 (PA-DS02) to 2,536 (LY-US202). Independent *t*-tests, comparing the number of individuals per sample at the upstream and downstream sections of each stream, demonstrated that there were no significant differences between the two stretches ($p > 0.05$). Independent *t*-tests demonstrated that there were no significant differences in taxon richness between upstream and downstream sites except for one occasion on the Lyreen River in summer 2002 (LY-US2S02 and LY-DS2S02, $p < 0.05$).

Table 3.6. Details of site locations and macroinvertebrate sampling periods (US, upstream; DS, downstream).

Grid Ref.	Code	Site description and road	2002	2003	2005
O266 105	GD-US	Glen O'Downs Stream south on N11 (US of pipe)		*	
O267 105	GD-DS	Glen O'Downs Stream south on N11 (DS of pipe)		*	
O256 117	GV-US	Glenview Stream on N11 (US of pipe) (Hotel)		*	
O256 116	GV-DS	Glenview Stream on N11 (DS of pipe) in Glen O'Downs Woods		*	
O136 255	OW-US	Owendoher River, US of the M50	*		*
O135 259	OW-DS	Owendoher River, DS of the M50	*		*
0 3017 21030	PP-US	Pollaphuca Reservoir Tributary, US		*	
0 3019 21035	PP-DS	Pollaphuca Reservoir Tributary, DS		*	
G54356 32981	CR-US	Tributary of Ardnaglass Stream at Carrowree, US of the N59		*	
G54281 33020	CR-DS	Tributary of Ardnaglass Stream at Carrowree, DS of the N59		*	
G50803 32480	DF-US	Doonfin Lower Tributary US of the N59		*	
G50815 32512	DF-DS	Doonfin Lower Tributary DS of the N59		*	
M37009 97949	SP-US	Spaddagh Tributary, US of the N5		*	
M36981 98010	SP-DS	Spaddagh Tributary, DS of the N5		*	
N 925 219	HW-US	Hartwell River, US of the N7 at Tobernavoher Br, N of Johnstown	*		*
N 925 220	HW-DS	Hartwell River, DS of the N7 at Tobernavoher Br, N of Johnstown	*		*
N 970 241	SL-US	Slane Tributary US of Dunbauin Br on N7	*		*
N 969 241	SL-DS	Slane Tributary DS of Dunbauin Br on N7	*		*
N 912 369	LY-US	Lyreen River, U/ S of M4 Maynooth Bypass	*	*	*
N 913 370	LY-DS	Lyreen River, DS of M4 Maynooth Bypass	*	*	*
O 055 845	WH-US	Whites River, US of M1 at Dunleer Bypass		*	*
	WH-DS	Whites River, DS of M1 at Dunleer Bypass	*	*	
N 919 214	MO-US	Morell River US of the N7 near Johnstown/Naas	*		
N 918 316	MO-DS	Morell River DS of the N7 near Johnstown/Naas	*		
N 956 234	PA-US	US of N7 on the Painestown Tributary at Boherphilip	*		
N 955 234	PA-DS	DS of N7 on the Painestown Tributary at Boherphilip	*		
N 933 361	RO-US	Rowanstown River, US of the M4 bypass near Maynooth	*		*
N 933 363	RO-DS	Rowanstown River, DS of the M4 bypass near Maynooth	*		*

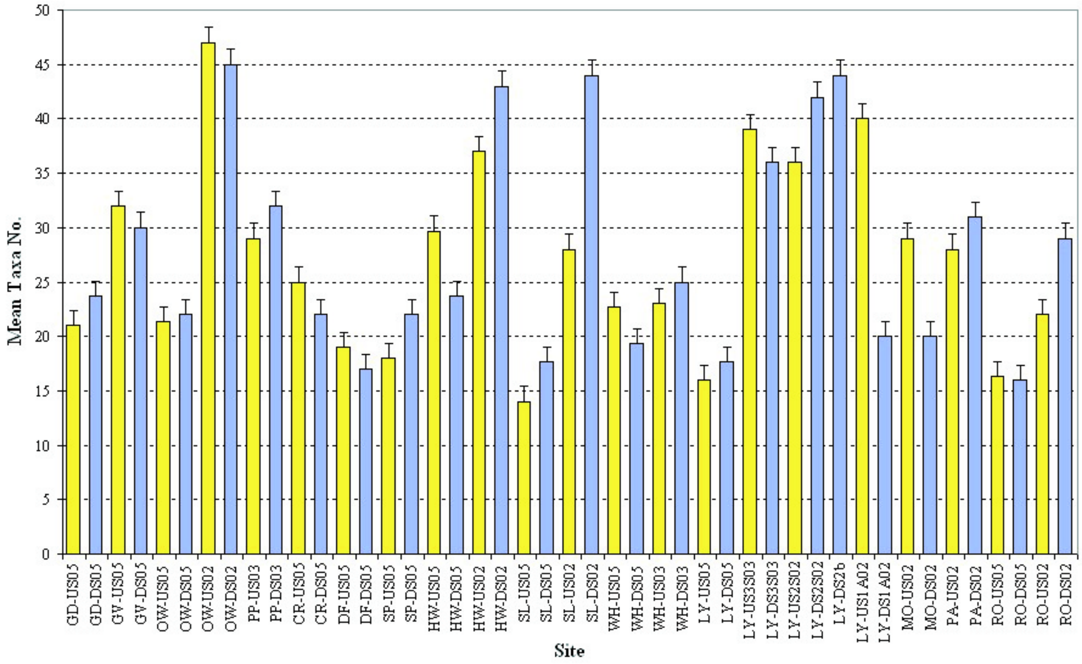


Figure 3.3. Mean number of taxa at each site upstream (yellow) and downstream (blue) with standard error bars.

The Sorensen Similarity Index indicated a high degree of similarity between the sites upstream and downstream of the roadway examined.

A brief examination of the percentage abundance of the major macroinvertebrate taxonomic groups present demonstrated that the abundance of some groups differed between the upstream and downstream sites. The majority of sites however did not differ in the occurrences of these groups (Fig. 3.4).

It should be noted however that the percentage abundance of the Ephemeroptera varied between sites. Lower ephemeropteran abundances were apparent at the Rowanstown and Lyreen sites in particular while the order Plecoptera was not widely represented at many sites. Only two of these streams (Doonfin, DF-US05 and DF-DS05, and the Slane Tributary, SL-US02 and SL-DS02) differed significantly in percentage EPT (Ephemeroptera/ Plecoptera/Trichoptera) abundance between the upstream and downstream sections examined.

3.4.2 Q values

Water quality indices were assigned to both of the sites located upstream and downstream of the roads examined. There were no major differences in quality according to the EPA Q-value rating system between the upstream and downstream sections of each stream. The Q rating system is a biological water quality classification which relates the diversity and relative abundance of key groups of aquatic macroinvertebrates to five basic water quality classes: Q5 – good quality, Q4 – fair quality, Q3 – doubtful quality, Q2 – poor quality and Q1 – bad quality. Only one site scored slightly higher (GV-DS05) in the downstream section and this was probably due to differences in habitat availability. Three streams Whites, Rowanstown and Morrell scored slightly lower in their downstream sections when compared to their upstream counterpart. They however did not differ in their overall quality classification.

In comparing the Q-value ratings between the years, three streams, the Owendoher, Hartwell and to a lesser extent Whites River, all improved in their Q-value rating. The Rowanstown downstream site also improved slightly from serious to moderate pollution status while the Slane Tributary decreased from a classification of slight (2002) to moderately polluted in 2005 (see Main Report for details).

3.4.3 BMWP and ASPT scores

The majority of sites had at least a total BMWP score of 100. Nine of the streams compared had higher BMWP scores in their upstream sections compared to their downstream sections. Independent *t*-tests however

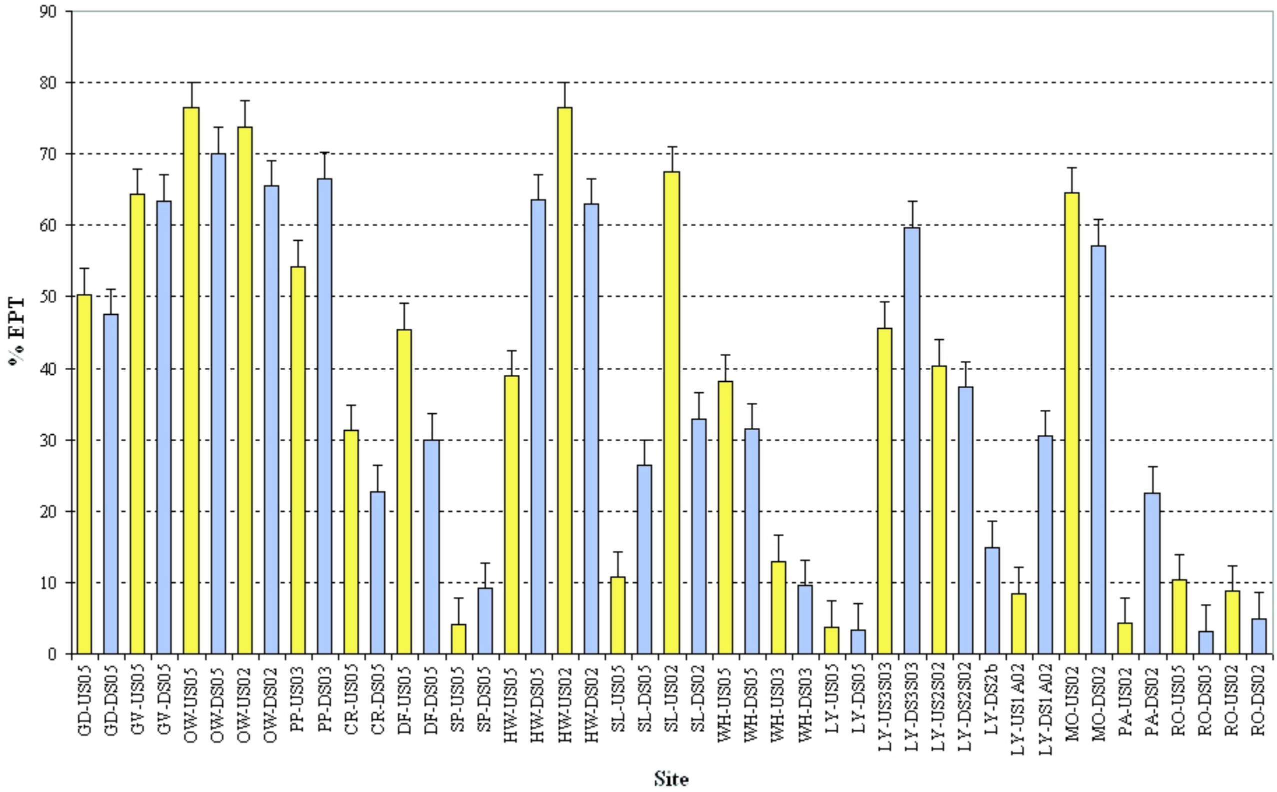


Figure 3.4. Percentage Ephemeroptera, Plecoptera and Trichoptera (%EPT) at each site upstream (yellow) and downstream (blue).

demonstrated that none was significantly different ($p > 0.05$).

The total ASPT scores ranged from 4.44 (RO-DS05) to greater than 7 (OW-US05, OW-DS05). Differences were evident between some of the streams' upstream and downstream sites; however, only four of them demonstrated significant differences when compared using an independent *t*-test (GD-US05 and GD-DS05, PP-US02 and PP-DS02 where the upstream site scored lower and RO-US05 and RO-DS05 and PA-US02 and PADS02 where the downstream section scored lower).

3.4.4 Macroinvertebrate tissues

Due to lack of population densities the analysis was carried out on four pool sites in the tributary of the Painestown River only. The amphipod *Gammarus duebeni* was used in the analysis. The gammarids were collected using the 3-min kick-sampling method, starting downstream and working upstream. Fifty individual organisms were collected at each of the three upstream sites. Only seven gammarids were collected at each of the four pool sites. All were collected with a pond net, from as near as possible to the same sampling points as to that of the sediment.

The mean concentration of the heavy metals recorded in *Gammarus duebeni* at the upstream and downstream sites of the tributary of the Painestown River are given in Table 3.7.

There was an absolute decrease in the concentration of Zn, Cu, and Cd in *Gammarus* tissue in the tributary of the Painestown River downstream of the discharge pipe compared with samples taken from the upstream.

3.5 Fish Studies

Electrofishing was conducted at all sites during the autumn of 2003. Sections upstream and downstream of road run-off outlets were fished separately. The sections ranged in length from 26 to 120 m. Each section was enclosed, using stop nets, to prevent fish from leaving the area being fished, a critical factor in the population estimation procedure. The removal or depletion method, using two successive catches, was used to quantify the population of salmonids present. A visual estimate was made of the relative abundance of the size classes of other species. Brown trout (*Salmo trutta* L.) was the only salmonid encountered and it was present in all but six sites across four rivers (Table 3.8).

There was no consistent pattern with regards to upstream and downstream differences in trout population density. The highest total density figure was 0.6 fish/m^2 at the downstream section of the Hartwell. Two other sites (MO-DS and WH-DS) had reasonable densities *circa* 0.3 fish/m^2. The control sites on the Pollaphuca and the Owendoher (upstream) were *circa* 0.2 fish/m^2, all other upstream sites had extremely poor densities, with values below 0.1 fish/m^2.

Fry densities varied greatly between upstream and downstream for the sites. Both the Hartwell (HW-DS) and the Morell (MO-DS) had much greater densities of fry downstream than upstream. Only one site (SL-US) had a higher biomass of trout fry at the upstream site when compared with the downstream site. There was no noticeable difference in the condition of fish from the various sites. Overall, the analyses of the fish did not reveal a negative impact of road run-off on these biota. One of the major difficulties in the present study was that most sites were already impacted upon by nutrient/organic pollution, making it extremely difficult to isolate possible effects of the road run-off from other pollution effects.

Table 3.7. Mean concentrations of heavy metals in *Gammarus*.

Metal	US/DS	Mean (µg/g)	Standard deviation	Coefficient of variation
Cu	US	71.37	8.41	11.78
	DS	46.10		
Zn	US	89.68	19.2	21.41
	DS	79.00		
Cd	US	0.52	0.006	1.11
	DS	0.40		
Pb	US	2.45	1.19	48.47
	DS	2.50		

US, upstream of discharge; DS, downstream of discharge.

Table 3.8. Catches of brown trout and stickleback.

Site	Code	Brown trout (*Salmo trutta* L.)	Stickleback (*Gasterosteus aculeatus* L.)
Slane US	SL US	35	200-400
Slane DS	SL DS	8–15	
Painestown US	PA US	0–50	100
Painestown DS	PA DS	0–50	100
Hartwell US	HW US	18–0	
Hartwell DS	HW DS	58–0	
Morell US	MO US	25–30	
Morell DS	MO DS	40–100	200
Rowanstown US	RO US	0–30	
Rowanstown DS	RO DS	0–50	100
Owendoher US	OW US	21–0	
Owendoher DS	OW DS	12–0	
Whites River US	WH US	0–5	
Whites River DS	WH DS	23–0	
Pollaphuca US	PP US	18–0	
Pollaphuca DS	PP DS	12–0	
Lyreen US	LY US	8–50	
Lyreen DS	LY DS	0–30	

4 Detailed Study Sites

Of the long-listed sites, five were selected from different locations with relatively easy access from Dublin City for detailed road run-off monitoring. There were two sites on the M4 Motorway at Maynooth Bypass, one site on the M7 Motorway at Kildare Bypass and two sites on the recently opened Monasterevin Bypass on the M7. The first site on the Maynooth Bypass was set up to sample road run-off from a filter drain and the second was to sample direct run-off from the edge of the road. Both sites are on the north-bound carriageway of the M4 Motorway. The Kildare site consisted of a set-up for sampling run-off from a kerb and gully system. The Monasterevin Bypass sites comprise a set-up for monitoring run-off from a filter drain pipe and another set-up for monitoring the constructed wetland adjacent to the River Barrow. The physical description of these sites and monitoring specifications are outlined below.

4.1 Maynooth Study Site

The Maynooth Bypass sampling site is located where the M4 Motorway crosses the Lyreen River near Maynooth Town (OS NGR N 913 370). The drainage system used in the monitoring section is a filter drain and discharges into the Lyreen River through a carrier pipe of 600-mm diameter from both sides of the motorway. The width of the road is 11 m with two lanes and a hard shoulder on each bound. The drainage area contributing to this outfall is about 9,760 m^2.

A second site was set up for direct run-off monitoring. A 100-m length of road was delineated for direct run-off monitoring by cutting the grass verge. The grass verge serves as a kerb to channel the run-off down to the sampling point through a gutter constructed at the end. Water samples were taken from the channel before the water flows into the box.

4.1.1 Rainfall–run-off relationship

The average run-off coefficient for this site was estimated as 0.52 (Fig. 4.1). This value is slightly lower than expected for the type of surface and the drainage system used in the area. The capacity of the filter media to accept water is reduced due to lack of maintenance and excess water runs off to the surrounding soil. During dry

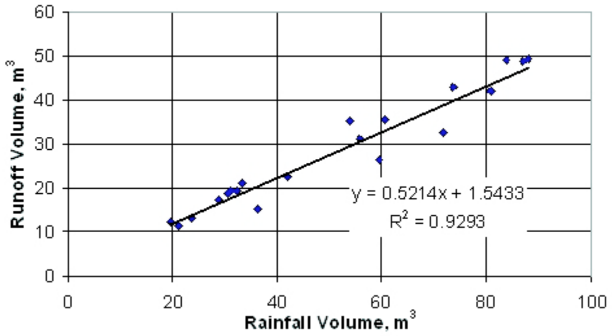


Figure 4.1. Estimating the run-off coefficient for the Maynooth Bypass intensive site.

conditions, there was some flow in the drains. This indicates that the drains intersect the groundwater table and that there is a hydraulic connection. During storm events, when water pressure is much higher in the drain, water may escape from the drains into the groundwater, causing a reduction in the measured run-off coefficient.

4.1.2 Chemical quality of the storm run-off

A summary of the contaminants in the run-off from each site is given in Tables 4.1 and 4.2. Cadmium was rarely present above the detection levels in either the filtered or unfiltered samples. Chloride was measured during winter months to see the effects of road salting on water quality. A value of 367 mg/l was measured from a sample taken on 23 February 2005 from the filter drain site. The corresponding specific conductivity value was 7,592 µS/cm. PAHs were not detected at the Maynooth filter drain site. MTBE and other volatile organic compounds were not detected in any event. Rainfall samples were also analysed for PAHs and other parameters. No PAHs were detected in the rainfall samples.

4.2 Kildare Study Site

4.2.1 Kildare Bypass on the M7

This site was established following the opening of the new 13-km Kildare Bypass Motorway on 6 December 2003. It is a wide median motorway with an AADT of 25,755 with heavy goods vehicles of 12.7%. The type of drainage system used at the site is kerb and gully. This site has the highest annual rainfall compared to the other sites. The

Table 4.1. Flow-weighted mean concentration at Maynooth Bypass (direct run-off).

Determinant	30 Aug 05	11 Oct 05	24 Oct 05	2 Nov 05
TSS (mg/l)	79	69	NA	NA
Total phosphate (mg/l)	NA	0.21	0.11	0.1
NPOC (mg/l)	12	6.26	2.87	1.97
Total cadmium (mg/l)	0.01	0.01	ND	ND
Total copper (mg/l)	0.04	0.04	0.02	0.04
Total lead (mg/l)	0.07	0.07	0.03	0.04
Total zinc (mg/l)	0.15	0.18	0.11	0.17
Filtered cadmium (mg/l)	NA	ND	NA	NA
Filtered copper (mg/l)	NA	0.01	NA	NA
Filtered lead (mg/l)	NA	0.03	NA	NA
Filtered zinc (mg/l)	NA	ND	NA	NA

embankment and subsoil consist of clay. The drainage area under study consisted of a straight 1,200-m length of two-lane east-bound carriageway of total width 11.82 m. The carriageway has cross-longitudinal carriageway slopes of 3% cross-fall and a 0.94% downslope. The highway is surfaced with hot rolled asphalt, and the edge of the hard shoulder is delineated by a 90° sloping kerb face, 90 mm deep. The total area from which run-off was collected was approximately 14,184 m^2.

The drainage system in place is a standard kerb and gully structure. The surface run-off collects at the kerb surface and then discharges to a pipe drainage system via on-line trapped gullies, installed at 20-m intervals. These pipes in turn discharge to a series of sedimentation tanks via prefabricated oil separators. The run-off is then gradually released into Simpson's Stream, which is a tributary of the River Barrow.

4.2.2 Water quality sampling during storm events

Highway run-off samples were collected for 16 storm events from August 2004 to July 2005, and Table 4.3 summarises the minimum, maximum and average results for the 28 determinants that were analysed.

The overall mean total suspended solids (TSS) for the 16 sampled storm events from August 2004 to July 2005 was 425.48 mg/l and is very high. The chloride values are low. As chloride is associated with highway run-off in the winter months in the form of sodium chloride (road salt) and is only spread on the highway on a small number of days, it was hard to detect. Total phosphate values are comparable with other research findings both in America and Europe. The mean value found in this project was 0.46 mg/l which is in between findings of 0.3 mg/l in America and 0.79 mg/l in Europe, respectively. The 16 PAHs analysed had mean values ranging from 0.03 µg/l for fluorene to a high of 1.12 µg/l for fluoranthene. The majority of the PAHs found were comparable with results from the UK (WRc, 2002). The dissolved metals cadmium and lead however are quite high compared to other findings.

4.2.3 Hydrological data

The Kildare site run-off coefficients ranged from 0.52 to 1.84 with a best estimate of 0.95. These results are similar to values reported by Gupta *et al.* (1981), who recorded run-off coefficients in the range of 0.40 to 1.42 from a 100% paved highway in Milwaukee, USA. Although theoretically unexpected, there are a number of practical explanations for recording run-off coefficients above 1; these include snow melt contributing to the run-off, wind steering the rain away from the rain gauge and actual blockage of the rain gauge. In January 2005, run-off coefficients were very high, up to 1.844, for a number of consecutive days. Snow fell on all these days, so a plausible explanation for these high values is the addition of snow melt to rainfall run-off. The average run-off coefficient for the Kildare site was graphically calculated as 0.97 (Fig. 4.2). This value again is similar to reports found in other studies with similar site characteristics such as 100% closed paved area.

4.3 Monasterevin Study Site

Two sites (B and C) were located on the Monasterevin Bypass. One (B) is kerbed with direct run-off (to the wetland) and the other (C) has a filter drain. The Monasterevin Bypass is a section of the M7 Motorway opened in November 2004 with two lanes per carriageway

Table 4.2. Flow-weighted mean concentration at Maynooth Bypass (filter drain site).

	TSS mg/l	Total PO_4 mg/l	Cl^- mg/l	NPOC mg/l	Total Cd mg/l	Total Cu mg/l	Total Pb mg/l	Total Zn mg/l	Filtered Cd mg/l	Filtered Cu mg/l	Filtered Pb mg/l	Filtered Zn mg/l
11 Jun 04	556	0.25	NA	7.12	0.01	0.03	0.06	0.12	NA	NA	NA	NA
27 Jun 04	NA	NA	40.19	NA	0.01	0.04	0.03	0.07	NA	NA	NA	NA
05 Jul 04	NA	NA	NA	NA	ND	0.03	ND	0.11	NA	NA	NA	NA
29/30 Sep 04	65	0.13	15.43	2.38	ND	0.02	0.04	0.09	NA	NA	NA	NA
06 Apr 05	NA	NA	NA	NA	ND	0.02	0.06	0.08	NA	NA	NA	NA
03 May 05	409	0.55	NA	2.91	ND	0.06	0.11	0.37	ND	0.02	0.02	0.01
21 Mar 05	114	0.13	19.38	2.77	0.01	0.02	0.05	0.09	NA	NA	NA	NA
23 Jul 04	32	NA	NA	NA	0.01	0.01	0.08	0.07	NA	NA	NA	NA
28 Jul 05	59	NA	NA	4.31	0.01	0.020	0.04	0.070	ND	ND	0.03	0.020
09 Sep 05	121	0.26	NA	NA	0.01	0.030	0.06	0.110	NA	NA	NA	NA

Table 4.3. Summary of the minimum, maximum and mean values of chemical determinants in highway run-off at the Kildare site.

Determinant (unit)	Minimum value	Maximum value	Mean value
Total suspended solids (mg/l)	4	3325	425.48
Total organic carbon (mg/l)	0.75	47.93	5.77
Chloride (mg/l)	0.87	17.44	4.25
Total phosphate (mg/l)	0.029	3.00	0.46
Total copper (mg/l)	0.008	0.393	0.0895
Dissolved copper (mg/l)	ND	0.031	0.011
Total zinc (mg/l)	0.048	2.36	0.461
Dissolved zinc (mg/l)	ND	0.045	0.035
Total cadmium (mg/l)	ND	0.02	0.008
Dissolved cadmium (mg/l)	ND	0.006	0.0017
Total lead (mg/ l)	0.041	0.485	0.098
Dissolved lead (mg/l)	ND	0.05	0.024
Total PAH (µg/l)	<0.01	84.79	5.29
Acenapthene (µg/l)	<0.01	1.183	0.038
Acenaphthylene (µg/l)	<0.01	0.205	0.035
Anthracene (µg/l)	<0.01	1.749	0.158
Benzo(*a*)anthracene (µg/l)	<0.01	8.147	0.376
Benzo(*b*)+(*k*)fluoranthene (µg/l)	<0.01	7.029	0.343
Benzo(*ghi*)perylene (µg/l)	<0.01	2.936	0.141
Benzo(*a*)pyrene (µg/l)	<0.01	4.789	0.233
Chrysene (µg/l)	<0.01	10.727	0.544
Dibenzo(*ah*)anthracene (µg/l)	<0.01	0.975	0.073
Fluoranthene (µg/l)	<0.01	20.57	1.123
Fluorene (µg/l)	<0.01	0.644	0.030
Indeno(*123cd*)pyrene (µg/l)	<0.01	2.545	0.122
Naphthalene (µg/l)	<0.01	3.048	0.479
Phenanthnene (µg/l)	<0.01	15.082	0.729
Pyrene (µg/l)	<0.01	13.319	0.861

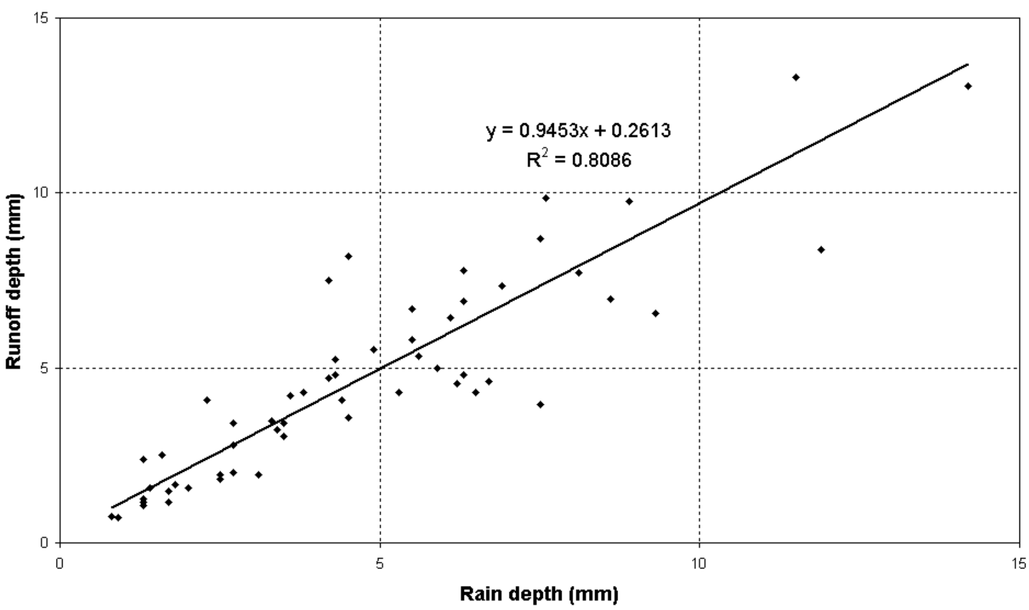


Figure 4.2. Determination of run-off coefficients for Kildare (Site A).

and is 17.5 km in length. The motorway carries an average flow of traffic which is usually between 25,000 and 30,000 vehicles per 24-h day, 12.7% of which are heavy goods vehicles. The embankment and the subsoil consist of clay.

4.3.1 East Monasterevin Bypass – wetland (Site B)

The drainage area consists of a straight 480-m length of west-bound carriageway and 500 m of east-bound carriageway, each of total width 11.6 m. The road is surfaced with hot rolled asphalt and the edge of the hard shoulder is delineated by a 90° sloping kerb face, 90 mm deep. The total area from which run-off was collected was approx. 11,368 m^2. The drainage system in place is a standard kerb and gully where the surface run-off collects at the kerb surface and then discharges to a piped drainage system via on-line trapped gullies installed at 20-m intervals. This is then discharged into a constructed wetland and then into the River Barrow.

4.3.2 Wetland design

To determine the constructed wetland dimensions the hydrology data from the existing Kildare site and constructed wetland guidelines from The Halcrow Group and Environment Agency (EA) in England were used. The rainfall for a 60-min storm event with a 1-year return period was estimated to be 16.0 mm. The wetland was designed to store such a rainfall for at least an hour. The catchment area draining into the wetland is 11,368 m^2 so a wetland 20 m long by 14 m wide and a maximum depth of 0.6 m and a longitudinal slope of 1% was specified (Fig. 4.3).

The constructed wetland (Fig. 4.4) was designed as a surface flow system, i.e. the inflow passes through as free-surface (overland) flow (and/or at shallow depths) and above the supporting substrates. The wetland was planted with 500 *Phragmites australis* and 500 *Typha latifolia* in two separate compartments.

4.3.3 Results for Monasterevin

The West Monastervin Bypass (Site B) and the East Monasterevin Bypass (Site C) are within 4 km of each other; therefore the same rainfall regime applies to both sites. A total of 414.7 mm of rainfall were recorded during the 8-month monitoring period. In the period from March 2005 to October 2005, eight storm events at the filter drain and six storm events at the constructed wetland site were sampled for chemical analysis.

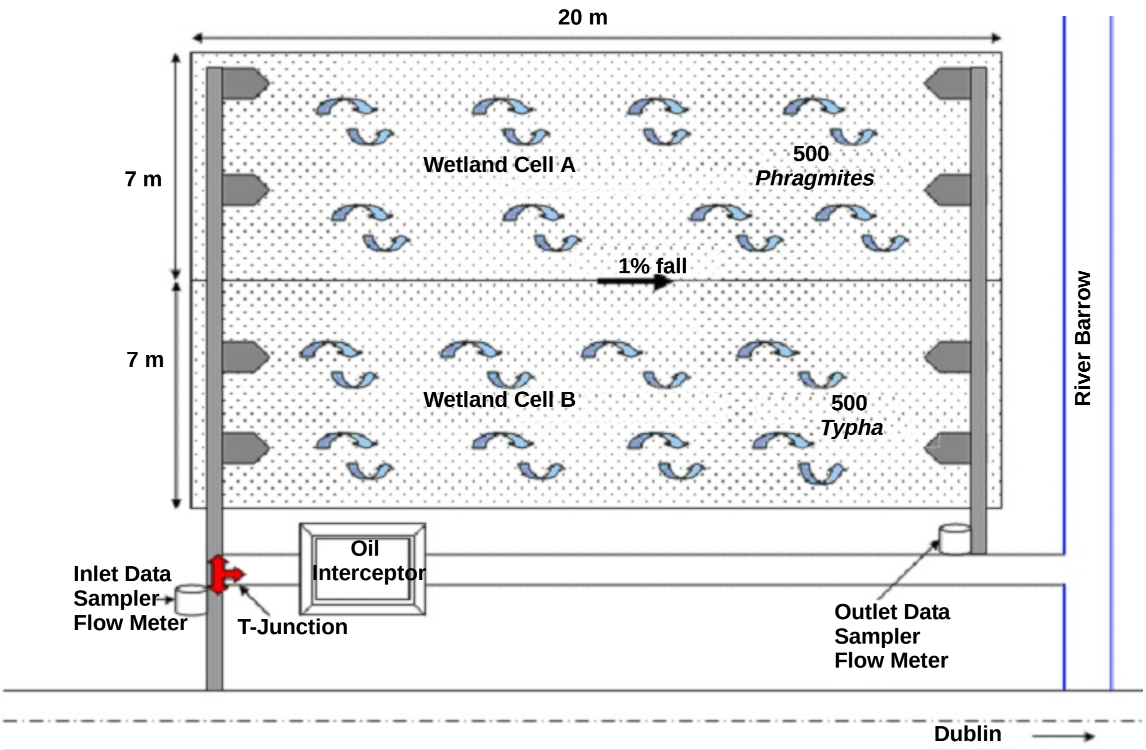


Figure 4.3. Diagram of wetland systems.

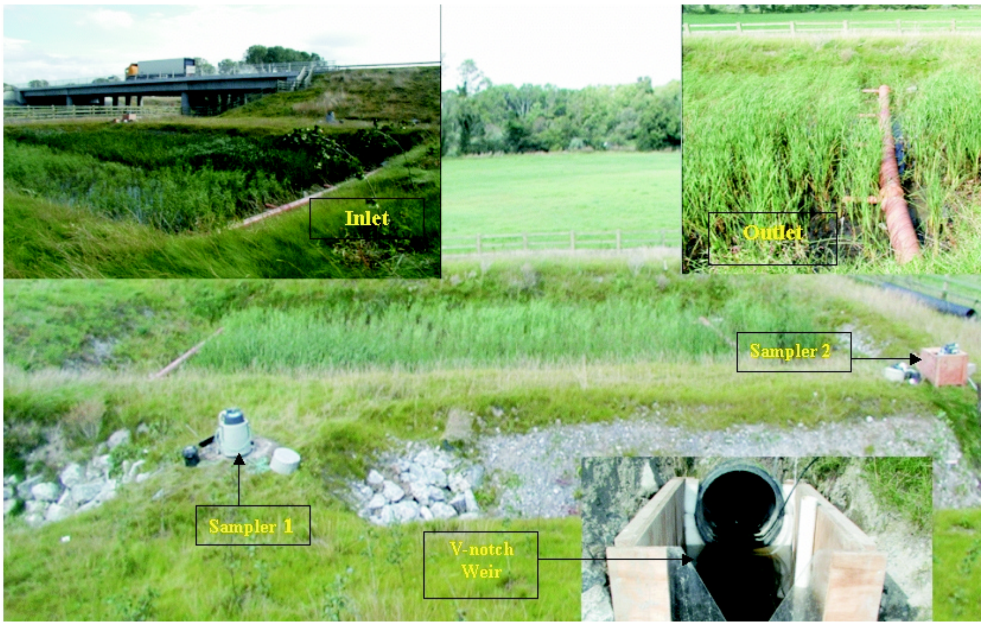


Figure 4.4. Wetland system with inlet and outlet.

4.3.4 Results for the kerbed site – wetland (Site B)

The mean run-off coefficient for the road was 0.82 which is a typical value for a 100% paved surface (Fig. 4.5). The peak flow is reduced, by as much as 96%, in some storm events by the wetland. The overall run-off volume flowing from the wetland is also greatly reduced by up to 94% of the total inflow. In the period from summer to autumn 2005, six rainfall events were sampled for chemical analysis. The temperature of the outflow increased by, on average, 1°C, suggesting that the wetland is acting as a heat sink and is discharging warmer water into the downstream waterbody. The average pH of the inflow was 7.2 and at the outflow was 8.4. Wetlands act as buffer zones and neutralise the acidic nature of the inflow. Dissolved oxygen ranged from 0 to 22 mg/l at the inflow of the wetland, but varied much less at the outlet, between 8 and 12 mg/l. The average specific conductivity was 10 µS/cm at the inflow and 125 µS/cm at the outflow.

The pollution removal performances are summarised in the bar charts of Fig. 4.6. and in Table 4.4. The removal efficiency of the constructed wetland for the total suspended solids was very high, ranging from 82 to 94%. Total phosphate removal efficiency ranged from 64 to 67%. The removal of zinc was high, ranging from 80 to 91%. The removal of cadmium ranged from 11 to 67%. The removal of lead ranged from 16 to 60%. This is quite varied and requires further investigation. The removal of copper ranged from 32 to 78%. Except for lead, all were comparable with the findings of Halcrow (1998), who reported ranges of 36–66% for the removal of copper. A noticeable observation from the results was an improvement in the pollutant removal efficiency of the constructed wetland as the plants established. This should be further investigated.

4.4 West Monasterevin Bypass Filter Drain (Site C)

The first section of this highway is immediately east of the New Inn roundabout. The drainage area is a straight 800-m length of two-lane east-bound carriageway with a total width of 11.6 m (including the filter drain). The road is surfaced with hot asphalt and the edge of the hard shoulder is continued with a filter drain of width 0.8 m. The total area from which run-off was collected was approximately 9,600 m^2. The drainage system is a filter drain. The surface run-off flows over and through the filter material and collects in a perforated pipe at the foot of the drain. This in turn discharges to a series of settlement ponds via an oil separator. The run-off is released into a tributary of the River Barrow.

The mean run-off coefficient is 0.19 (Fig. 4.7), which is a very low value for a filter drain system. It indicates that a large percentage of water is going elsewhere in the system possibly into the underlying groundwater. The mean concentrations of the contaminants during storm events are shown in Tables 4.5 and 4.6.

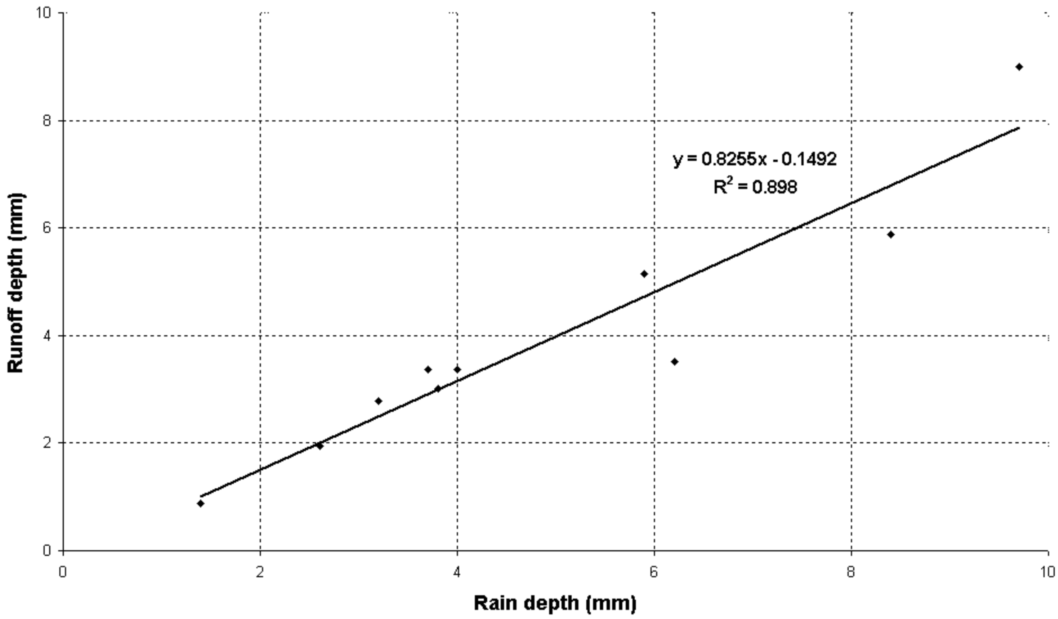


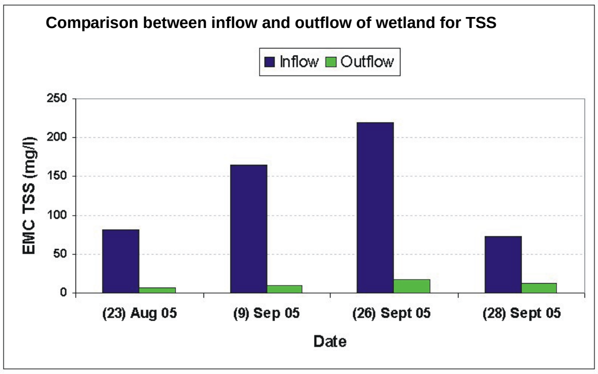
Figure 4.5. Determination of run-off coefficients for the kerbed Site B.

Table 4.4. Event mean concentrations of contaminants in the inflow and outflow of the wetland.

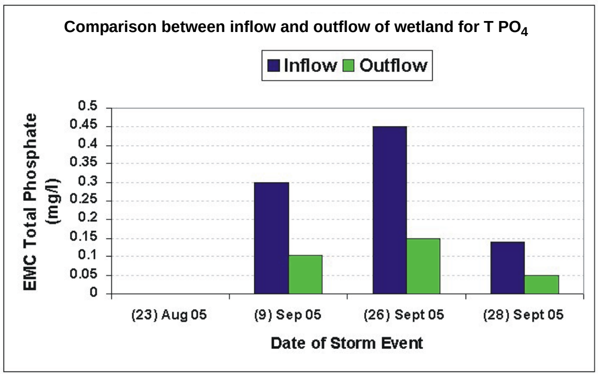
Substance	23 Aug 05		09 Sep 05		26 Sep 05		28 Sep 05	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Total suspended solids (mg/l)	81	7	164	10	220	18	73	13
Total organic carbon (mg/l)	–	–	12.3	12	–	–	–	–
Chloride (mg/l)	–	–	–	–	–	–	–	–
Total phosphate (mg/l)	–	–	0.3	0.105	0.45	0.148	0.14	0.05
Total copper (mg/l)	0.019	0.013	0.043	0.02	0.048	0.014	0.068	0.015
Total zinc (mg/l)	0.147	0.026	0.251	0.043	0.202	0.04	0.147	0.013
Total cadmium (mg/l)	0.0045	0.004	0.006	0.002	0.007	0.004	0.006	0.004
Total lead (mg/l)	0.05	0.042	0.08	0.032	0.09	0.045	0.068	0.028

Table 4.5. Flow-weighted mean concentration at Monasterevin Bypass (filter drain site).

Date	21 Mar 05	17 Apr 05	03 May 05	30 Jun 05	23 Jul 05	29 Jul 05	04 Aug 05
TSS (mg/l)	25	47	NA	NA	122	16	37
Total phosphate (mg/l)	0.09	NA	0.11	0.13	0.19	0.07	0.1
Cl^- (mg/l)	10.29	NA	NA	NA	NA	NA	NA
NPOC (mg/l)	2.31	4.58	2.12	11.09	21.64	3.63	NA
Total Cd (mg/l)	0.01	ND	ND	0.02	0.01	0.02	0.01
Total Cu (mg/l)	0.02	0.04	0.01	0.03	0.02	0.03	0.02
Total Pb (mg/l)	0.09	0.09	0.08	0.12	0.06	0.09	0.05
Total Zn (mg/l)	0.11	0.02	0.02	0.08	0.1	0.14	0.03
Filtered Cd (mg/l)	0.01	ND	NA	NA	ND	0.02	NA
Filtered Cu (mg/l)	0.01	0.01	NA	NA	0.03	0.02	NA
Filtered Pb (mg/l)	0.03	0.01	NA	NA	0.02	0	NA
Filtered Zn (mg/l)	0.11	0.01	NA	NA	0.07	0	NA



(a)



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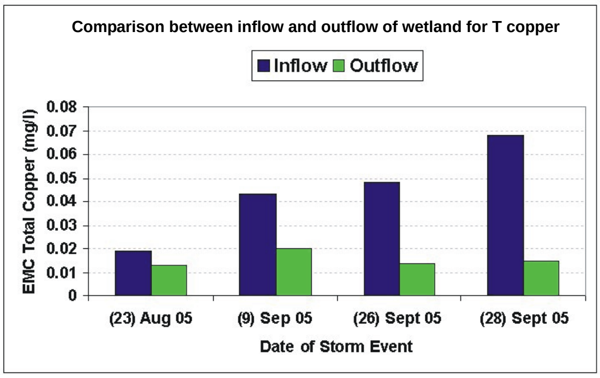

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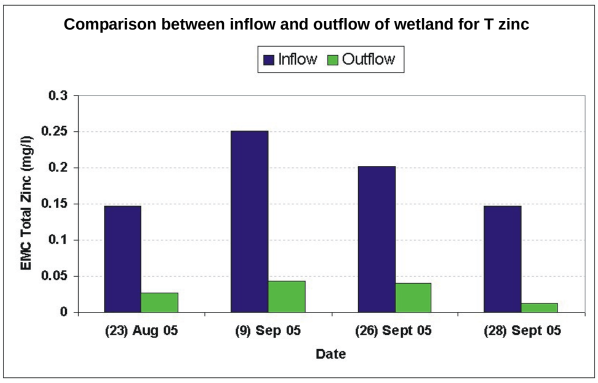

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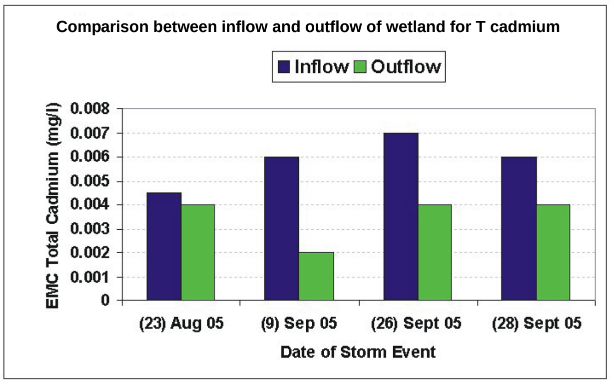

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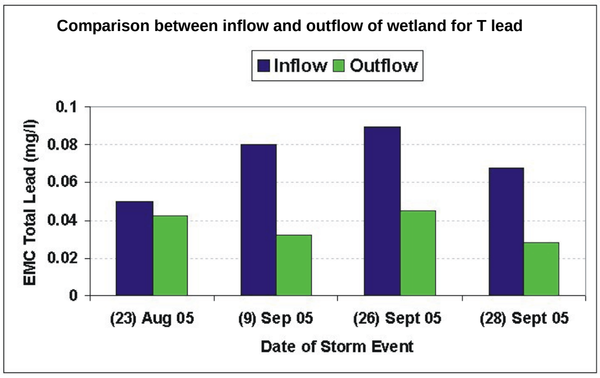

(f)

Figure 4.6. Bar charts showing the range of inflow and outflow concentrations for the wetland (EMC, event mean concentration).

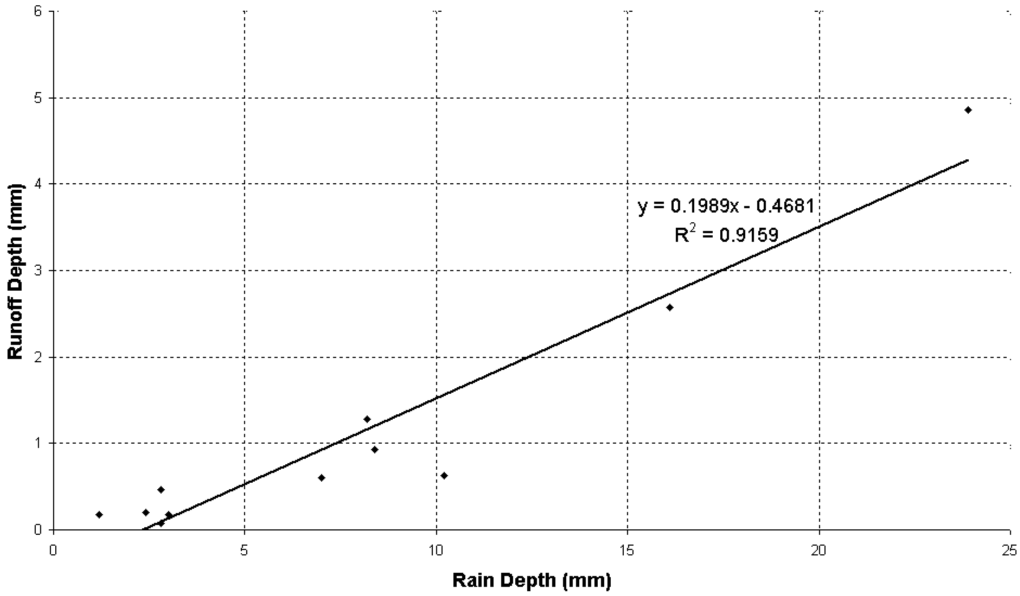

Figure 4.7. Determination of run-off coefficients for Filter Drain Site C.

Table 4.6. Filter drain output event mean concentrations.

Determinants	21 Mar 05	17 Apr 05	03 May 05	23 Jun 05
Total suspended solids (mg/l)	23	46	27	122
Total organic carbon (mg/l)	2.325	4.84	2.107	21.06
Chloride (mg/l)	10.6			
Total phosphate (mg/l)	0.08		0.1138	0.19
Total copper (mg/l)	0.024	0.044	0.0068	
Total zinc (mg/l)	0.104	0.023	0.023	
Total cadmium (mg/l)	0.01	0.004	0.0023	
Total lead (mg/l)	0.086	0.091	0.085	
Total PAH (µg/l)	1.681	<0.01		
Acenapthene (µg/l)	<0.01	<0.01		
Acenaphthylene (µg/l)	0.161	<0.01		
Anthracene (µg/l)	0.09067	<0.01		
Benzo(*a*)anthracene (µg/l)	0.119	<0.01		
Benzo(*b*)+(*k*)fluoranthene (µg/l)	0.05467	<0.01		
Benzo(*ghi*)perylene (µg/l)	0.04633	<0.01		
Benzo(*a*)pyrene (µg/l)	<0.01	<0.01		
Chrysene (µg/l)	0.345	<0.01		
Dibenzo(*ah*)anthracene (µg/l)	0.07433	<0.01		
Fluoranthene (µg/l)	0.078	<0.01		
Fluorene (µg/l)	<0.01	<0.01		
Indeno(*123cd*)pyrene (µg/l)	0.04133	<0.01		
Naphthalene (µg/l)	0.273	<0.01		
Phenanthrene (µg/l)	0.09	<0.01		
Pyrene (µg/l)	0.124	<0.01		

5 Water Quality of Storm Run-Off from Roads: Comparative Analysis

5.1 Comparison of Site Characteristics

The three sites selected for detailed analysis were all located on the same motorway, the M7, between Portlaoise and Dublin. Each of the sites has a typical mix of heavy goods vehicles and cars. Each site has also two traffic lanes with adequate travelling speed during non-rush hours. None of the sites encounter a build-up of rush-hour traffic; therefore there are no stop-and-go traffic conditions. The traffic counter on the Kildare Bypass section records a daily traffic of between 25,000 and 30,000 cars with a slight increase in the summer months. There is no recorded traffic count on the Monasterevin Bypass section as of yet, although as this is part of the same motorway the traffic numbers should be similar to those of the Kildare Bypass.

The percentage of pervious and impervious paving within a highway drainage area will affect the quantity and potential impacts of pollutants from highway storm water run-off. All the sites selected have completely impermeable surfaces. Other pavement characteristics that can affect the quality of the highway storm water run-off are the age of the pavement and the type of the pavement surface. All the pavements are rolled with hot asphalt. The Kildare Bypass site is 1 year older than the Monasterevin site. All three sites have very similar highway characteristics except that the drainage system differs at each site. The Kildare Site has a kerb and gully system whereas the Monasterevin sites are a filter drain and a kerb and gully leading into a wetland. All three sites met most of the requirements for suitable site selection (Table 5.1).

5.2 Comparison of Filter Drain and Kerbed Sites

A comparison was made between the direct highway run-off from the Kildare kerbed site and the highway run-off passing through the filter drain at the nearby Monasterevin site. Four storm events were selected for detailed analysis. The comparison details are shown in Table 5.2 and Fig. 5.1. The kerbed site consistently has much higher suspended solids, heavy metals and (when detected) PAHs. However, the filter drain occasionally has higher concentrations of TOC and Cl^{-}.

5.3 Comparison between the Sites

Comparing similar storm events between the Kildare site A and the filter drain site C suggests that the removal efficiency of the filter drain for the total suspended solids was very high, ranging from 89 to 98%. Removal

Table 5.1. Criteria for site comparisons.

Criteria	Location		
	Kildare	**East Monasterevin**	**West Monasterevin**
Type	Rural	Rural	Rural
AADT	25,000–30,000	25,000–30,000	25,000–30,000
Yearly precipitation (mm)	700–800	700–800	700–800
Surface pavement type	Rolled asphalt	Rolled asphalt	Rolled asphalt
Drainage area % paved	100	100	100
Highway surface area (m^2)	14,184	11,368	9,600
Number of lanes	2	2	2
Kerb/barrier in place	Yes	Yes	No
Section type	Elevated	Elevated	Elevated
Surrounding land use	Agricultural	Agricultural	Agricultural
Regular maintenance	Yes	Yes	Yes
Drainage surface type	Kerb and gully	C Wetland	Filter drain
Year highway opened	2003	2004	2004

Table 5.2. Comparison of filter drain site with kerb drainage site.

Substance	21 Mar 05		17 Apr 05		03 May 05		23 Jun 05	
	Filter drain	Kerbed site	Filter drain	Kerbed site	Filter drain	Kerbed site	Filter drain	Kerbed site
Total suspended solids (mg/l)	23	404.78	46	1847.61	27	1340	122	1117.97
Total organic carbon (mg/l)	2.325	2.101	4.84	10.47	2.107	1.958	21.06	8.785
Chloride (mg/l)	10.6	1.082						
Total phosphate (mg/l)	0.08	0.436		1.18	0.1138	0.982	0.19	0.848
Total copper (mg/l)	0.024	0.0957	0.044	0.27	0.0068	0.164		
Total zinc (mg/l)	0.104	0.556	0.023	1.59	0.023	1.026		
Total cadmium (mg/l)	0.01	0.0066	0.004	0.0125	0.0023	0.0096		
Total lead (mg/l)	0.086	0.1181	0.091	0.3325	0.085	0.2023		
Total PAH (µg/l)	1.681	6.496	<0.01	<0.01		<0.01		
Acenapthene (µg/l)	<0.01	0.304	<0.01	<0.01		<0.01		
Acenaphthylene (µg/l)	0.161	0.069	<0.01	<0.01		<0.01		
Anthracene (µg/l)	0.09067	0.472	<0.01	<0.01		<0.01		
Benzo(*a*)anthracene (µg/l)	0.119	0.206	<0.01	<0.01		<0.01		
Benzo(*b*)+(*k*)fluoranthene (µg/l)	0.05467	0.309	<0.01	<0.01		<0.01		
Benzo(*ghi*)perylene (µg/l)	0.04633	0.157	<0.01	<0.01		<0.01		
Benzo(*a*)pyrene (µg/l)	<0.01	0.217	<0.01	<0.01		<0.01		
Chrysene (µg/l)	0.345	0.542	<0.01	<0.01		<0.01		
Dibenzo(*ah*)anthracene (µg/l)	0.07433	0.219	<0.01	<0.01		<0.01		
Fluoranthene (µg/l)	0.078	0.892	<0.01	<0.01		<0.01		
Fluorene (µg/l)	<0.01	0.232	<0.01	<0.01		<0.01		
Indeno(*123cd*)pyrene (µg/l)	0.04133	0.119	<0.01	<0.01		<0.01		
Naphthalene (µg/l)	0.273	0.728	<0.01	<0.01		<0.01		
Phenanthrene (µg/l)	0.09	0.972	<0.01	<0.01		<0.01		
Pyrene (µg/l)	0.124	1.052	<0.01	<0.01		<0.01		

efficiencies for total organic carbon were very varied ranging from a negative removal (i.e. an increase) of –140 to 54%. The reasons should be investigated further. The removal efficiencies of total phosphate ranged from 78 to 88%. This is very high and is not well documented in the literature. The removal of zinc was high, ranging from 81 to 99% The removal of cadmium ranged from a negative value of –52 to 76%. This should be further investigated. The removal of lead ranged from 27 to 73%, which is lower than the 83% reported by Perry and McIntyre (1986). The removal of copper ranged from 41 to 83%. This will need further investigation.

5.4 Relationships between the Parameters Measured

A regression analysis indicated a strong linear relationship between TSS and many of the other parameters, particularly the heavy metals. To illustrate, Figure 5.2 shows one such correlation for the Kildare site. Similar strong correlations were found for the Maynooth filter drain site, but not for the Monasterevin (new filter drain) site. This may be because the latter has, in general, a lower suspended solids content in its run-off. The 'first flush' effect is clearly observed for suspended solids and other pollutants. The effect of the antecedent dry period (ADP) was also apparent in some of the parameters.

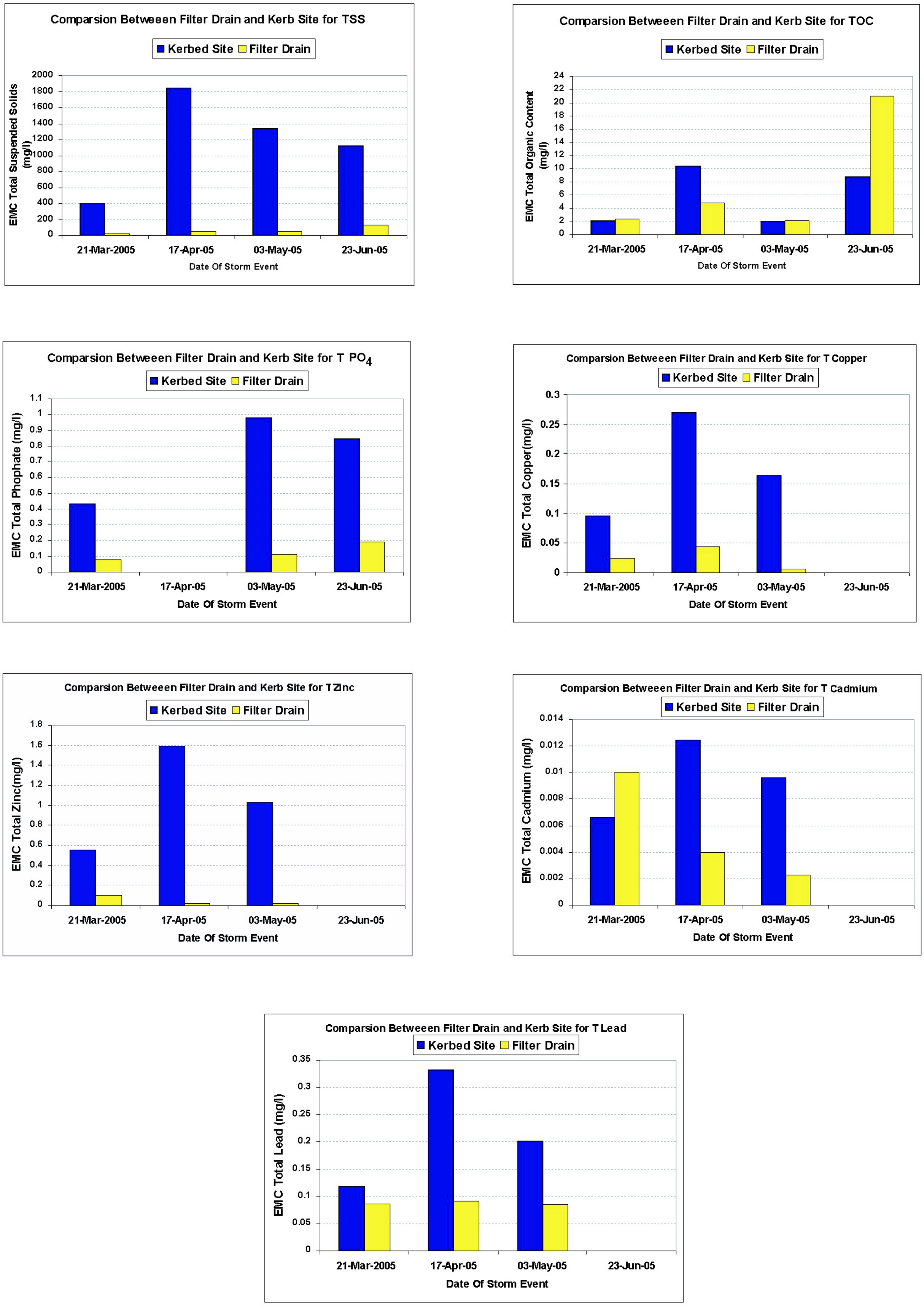

Figure 5.1. Comparison between kerb and filter drain sites (TSS, TOC, TP, Cu, Zn, Cd, Pb).

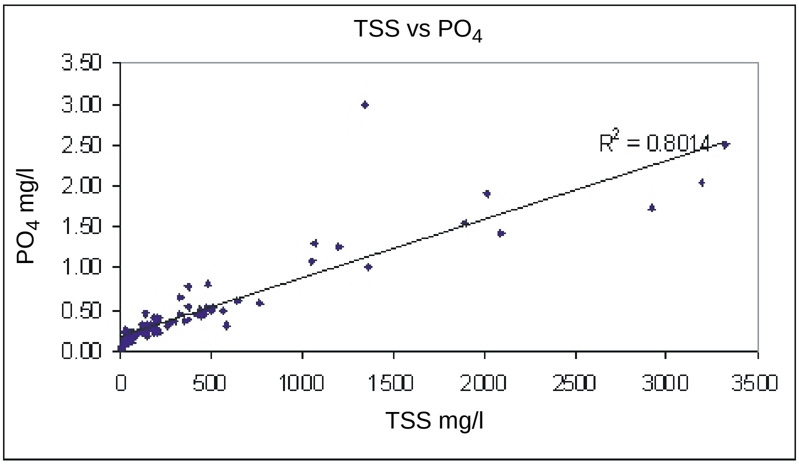

Figure 5.2. Relationship between total suspended solids and phosphate.

6 Assessment and Comparison of Treatment Options

6.1 Review of BMPs

Highway run-off BMPs are schedules of activities, prohibitions of practices, maintenance procedures, the use of pollution control devices and management procedures to prevent or reduce the amount of pollution introduced to receiving waters from highway run-off.

The most economical and effective time to address potential impacts of highways is during the initial planning and design stage. It is much more costly to correct any problems after the highway has been constructed. During the planning phase, the way to reduce a highway's impact is often as simple as choosing the route which avoids flood plain areas, environmentally sensitive areas, and minimises water crossings. During the design phase, after a highway's location and layout have been determined, the impact of highway run-off can be addressed and suitable BMPs can be integrated into the design. BMPs can be divided into two main groups:

1. Non-Structural BMPs – which deal with source management such as transportation and land-use planning.

2. Structural BMPs – which include the physical construction of a system such as a swale or a detention pond.

6.2 Non-Structural BMPs

The first consideration in BMP evaluation is whether non-structural BMPs (source controls) can be used effectively to prevent pollutants from entering highway run-off by eliminating the source of the pollution, or by preventing contact of pollutants with the rainfall and run-off (Washington State Department of Transportation, 1995). Non-structural BMPs are by far the most cost-effective means for reducing pollutant constituents in highway run-off; however, they seldom replace structural controls as an option. If they are properly deployed they can reduce the pollutant removal requirements for a structural BMP as well as provide some aesthetic appeal that may not be included in the selected structural BMP.

Non-structural BMPs are basically practical activities that can be carried out to reduce the source of the contaminants that are available to be carried in the highway run-off to nearby watercourses. They involve a good understanding of the highway and the pollutants that may be associated with it. A number of non-structural practices exist, including transport management, control of de-icing agents, and street and gully pot cleaning.

6.3 Structural BMPs

Many researchers, e.g. Barrett *et al.* (1995), have concluded that the most effective control measure will reduce the amount of particulates available for transport or will settle and/or filter the particulate matter in the run-off. Structural BMPs are used to treat the highway run-off either at the point of generation or at the point of discharge to receiving waters. The selection and successful design of selected structural BMPs for highway run-off is dependent on where it is to be sited and what is going to be treated. Structural BMPs can be grouped into five different categories each with similar and some different roles to play in treating highway run-off: (i) vegetated controls, (ii) ponds, (iii) wetlands, (iv) infiltration devices, and (v) water quality inlets.

6.4 International Approach to BMP Use

A wide number and variety of BMPs both structural and non-structural are used throughout highways in the UK. The most common structural practices found include filter drains, gully pots, oil interceptors, and detention and retention ponds. The most common non-structural practices include street cleaning and routine management practices.

Throughout other European countries swales and infiltration systems are frequently used. In France, constructed wetlands and porous paving with in-built reservoir structures are common. In colder climates, such as in Sweden and Denmark, retention ponds are frequently used to reduce peak flows and retain pollutants. In the more southern European countries, such as Spain, Portugal, Greece and Italy, current use of BMPs is limited but due to an increase in public awareness of environmental issues there is a growing interest in achieving their benefits.

7 Conclusions and Recommendations

7.1 Conclusions

7.1.1 Current situation

1. Highway drainage systems in Ireland are designed based on hydraulic considerations with little emphasis on the quality of the drainage water. The questionnaire survey showed that Local Authority road engineers expected that natural processes, such as sedimentation, filtration or biodegradation, would occur in drainage units and would remove some of the pollutants.

2. Filter drains are the most popular type of drainage system used on motorways and rural dual carriageways and were regarded by questionnaire survey respondents as effective in removing most of the pollutants.

3. The issue of road run-off is (and should be) considered in the Environmental Impact Statement (EIS) with other effects. Run-off treatment systems such as petrol interceptors, soakaways, ponds, etc., are installed in some places where the traffic volume is known to be high and where the drainage is directly into a receiving stream. However, many designers do not have information on which type(s) of treatment system(s) is (are) appropriate for a given outfall. There were no reported cases where impacts have been studied after a road scheme is completed nor the performance of these systems measured.

4. Survey respondents believed that national and EU legislation give sufficient coverage to the protection of surface and groundwater sources from pollution. However, none of this legislation specifically identified road run-off as a pollution source. Nevertheless, the groundwater protection strategy in Ireland has identified road run-off as a potential source of groundwater contamination.

5. There is no programmed inspection and maintenance programme in Ireland. Drainage systems are cleaned 'as required' due to blockage of pipes and flooding of road surface. Lack of personnel, resource and absence of dedicated funding have been blamed by Local Authorities for failing to carry out inspection and maintenance activities on a programmed basis.

6. Most of the Local Authorities understood the pollution risk of discharging untreated run-off into receiving waters. They would like to see some kind of treatment system to exclude sediment and hydrocarbons from the run-off using either an existing or a new system.

7.1.2 Contamination from road run-off

Traffic and road surfaces are significant sources of various types of contamination which form part of the run-off as it leaves the road pavement along highways in Ireland.

7.1.3 Contaminants

Analyses of the run-off waters showed that contaminants include suspended solids, heavy metals, hydrocarbons including PAHs, chlorides, nitrates and phosphorus. However, no MTBE was detected in the samples analysed.

7.1.4 Comparability

The nature and concentrations of contaminants measured were broadly comparable with those reported from similar site conditions in other European countries. Although contaminant concentrations show considerable variation, the common influencing factors are traffic flow, rainfall (amount, duration and antecedent conditions) and, possibly, the age of the fleet.

7.1.5 Traffic flow rates

Although our sites were on some of the busiest Irish roads, traffic flow rates were low (except for the M50) compared with major UK and European roads. In addition, the variation in traffic flow between our sites was small. For these reasons, we were not able to reliably establish the relationship between contamination levels and traffic flows.

7.1.6 Origin

Most of the contaminants detected are consistent with a road-traffic source. However, some, particularly nitrates and phosphorus, may have upstream sources in receiving waters or originate in soils or associated road infrastructure (e.g. embankments, median strips). Other potential water-related sources of contaminants associated with roads are airborne (e.g. aerosols, spray), which may fall on or beyond road margins, but these were not explicitly measured in this study.

7.1.7 Contaminant pathways

Drainage from most major roadway pavements in Ireland has surface water as the designated receptor. However, on the sites studied, significant proportions of the flow and the associated contaminant load from the road surface do not reach the intended receptor.

7.1.8 Run-off coefficients

Careful water balance calculations on four intensively investigated sites on the M4 and M7 suggest that there are alternative, undocumented pathways taken by part of the run-off. Run-off coefficients as low as 25% were recorded. Investigation indicated that there are subsurface pathways which bypass the designed drainage route to surface water. These bypass pathways have the potential to cause contamination of adjacent soils and subsurface waters.

7.1.9 Performance

Our study showed that constructed wetland performed well, removing up to 94% of the TSS, 67% of the total phosphate, 91% of total zinc, 67% of total cadmium, 60% of total lead and 78% of total copper. It is also clear from the Fig. 3.2 that these removal efficiencies seem to be increasing as the wetland establishes and matures. This requires further investigation. The peak flow and the total volume of run-off leaving the constructed wetland are substantially reduced. The peak flow at the inlet was reduced by as much as 96% at the outlet and the volume of water leaving the constructed wetland was reduced as much as 94% of the volume entering the constructed wetland. The constructed wetland has provided a habitat for many species of wildlife, including birds, frogs, snails, etc. The constructed wetland should be tested further to see if it performs as well in winter months and to establish its long-term performance and variability.

7.1.10 Surface water receptors: sediment

The contaminants as measured have been found in river sediments near road drainage outfalls. However, away from the outfalls, no consistent pattern of statistically significant changes between sediments upstream and downstream of the outfall was observed in most cases. However, in one location, the downstream concentrations of PAHs and heavy metals were significantly higher than upstream.

7.1.11 Surface water receptors: vegetation

Heavy metals have been found in the tissue of vegetation near road drainage outfalls. However, away from the outfalls, no consistent pattern of statistically significant changes between vegetation upstream and downstream of the outfall was observed.

7.1.12 Surface water receptors: macroinvertebrates

No adverse effects from the road drainage could be detected in the macroinvertebrate fauna. Where differences existed they were probably more related to limitations in the physical habitat or impacts from other sources.

7.1.13 Surface water receptors: fish

The analyses of the fish did not reveal a negative impact of road run-off on these biota. One of the major difficulties in the present study was that most sites were already impacted by upstream nutrient/organic pollution making it extremely difficult to isolate any possible effects of the road run-off from other pollution effects.

7.1.14 Surface water receptors: other contaminant sources

A large number of the rivers at the road crossing sites in eastern Ireland were already impaired from upstream sources. An extensive search of the region revealed very few unimpacted sites. More unimpacted sites were found in the west of Ireland.

7.1.15 Subsurface receptors: soil and groundwater

On sites where run-off was removed by French drain systems, there was a significant risk of the contamination in road run-off being trapped by adjacent soils. Investigation of 12-year-old sites on the M4 near Maynooth showed heavy contamination (PAHs and heavy metals) of soil adjacent to the road. Groundwater was not investigated directly as part of this study but the European experience (Transport Research Laboratory, 2002) showed that it is a potential receptor of significance in vulnerable conditions and requires further investigation.

7.1.16 Treatment options: French drains

French drains are commonly incorporated into Irish road drainage design to remove excess water from the road infrastructure. They are not expressly designed to perform a run-off treatment function, although they usually do play such a role. However, investigation showed that, as typically designed, their drainage functions appear to deteriorate relatively rapidly with age, mainly through clogging of surrounding soil and geotextiles. Frequent maintenance is required for efficient functioning as a drainage system. Moreover, this drainage system requires redesign if it is to perform a treatment role. At present, the deteriorating drainage function appears to enhance the treatment role.

7.1.17 Treatment options: constructed wetlands/ swales

A review of worldwide experience with alternative forms of treatment which can be incorporated into road drainage design showed that constructed wetlands would be the best all-round option for treatment, although it is clear that they should not be used alone. Combinations of systems to suit local conditions should be used. The combination of a swale and wetland showed promise for Irish conditions. A wetland was constructed adjacent to the M7 at Monasterevin and the treatment efficiencies so far measured and reported for the typical road run-off contaminants are uniformly high.

7.1.18 Treatment options: efficiency

No treatment options are maintenance free. The choice of treatment option should include maintenance as a factor, in terms of cost and efficiency, in the light of local conditions.

7.2 Recommendations

7.2.1 Design factors

1. The design of highway drainage systems, in addition to hydraulic considerations, should also take water quality considerations into account. Such considerations may require increasing the pot size of a kerb and gully system, improving the geometry of the road, reducing the catchment area contributing to an outfall, or facilitating conditions for over-the-edge drainage, etc.

2. Filter drains remove pollutants associated with suspended matter from the run-off. This function can however be impaired by blockage due to vehicular overrun and poor maintenance conditions. If the use of filter drain systems has to continue, the following problems have to be addressed:
   - The use of combined systems (filter drain and kerb and gully, filter drain and surface water channel and pipe system, and filter drain and over-the-edge drainage) has to be carefully examined to avoid the risk of groundwater contamination.
   - The use of a geotextile membrane to wrap the filter media facilitates blockage and creates maintenance problems. The top should be left open to avoid this problem.
   - In addition to the well-known problem of stone scatter with the filter drain system, compaction of the filter media is equally a serious problem in rural dual carriageways and motorways in Ireland. This also facilitates clogging. This problem has to be addressed by either increasing the frequency of cleaning, using a barrier or even allowing a wider hard shoulder.
   - Land drains connected to filter drains should be inspected carefully if they can introduce contaminants into the system.

3. Rainfall intensity and the antecedent dry period (ADP) have to be included in assessing the risk of pollution to receiving waters from road run-off in addition to traffic volume.

4. Although the effect of road run-off on water quality is included in the EIS, it is necessary to continue monitoring even after the road scheme is completed until the impacts are studied to a satisfactory level. This helps to prevent further damage to the environment from causes that might have been overlooked during the preparation of the EIS. The EPA has the legal right to make such monitoring continue.

5. Maintenance is a very important aspect of highway drainage that can improve the quality of the run-off and should be done on a programmed basis. If highway drainage systems are not properly and regularly maintained, they can act as sources of pollution. Blockage and ponding should not be the only reasons to initiate maintenance. Programmes should aim at improving the hydraulic efficiency of the system and the water quality of the drainage water.

6. Programmed inspection and maintenance activities reduce an unnecessarily high cost of maintenance after a problem has occurred. Minimum cleaning

frequency has to be established for the different types of systems even if there are no blockages or ponding. Problem sites should be identified and cleaning frequency should be increased for such sites.

7. Easy access for maintenance operations should always be ensured to avoid disruption of traffic.

8. Sufficient records of the maintenance work done should be kept to estimate costs of future work and comparison of methods.

9. Care must be exercised to avoid the introduction of pollutants into receiving waters during maintenance, road widening or the construction of new drainage or treatment systems.

10. The selection of a particular control option or a combination of systems for the management and treatment of highway run-off very much depends on the local and site characteristics.

11. When combining treatment systems, infiltration systems should be the last structures in the treatment train since they are adversely affected by high sediment loads.

12. Constructed wetlands alone should not be used in conjunction with infiltration devices, as wetlands have the potential to discharge large sediment loads and decaying matter which can clog infiltration systems. Barrett *et al.* (1995) conclude that wetlands are best positioned in the middle of treatment systems and should discharge to ponds or vegetated control structures.

13. A combination of run-off management and control measures is recommended whenever it is feasible (Burch *et al*., 1985).

14. Vegetative controls are the measures best suited to treat run-off as it is conveyed. Therefore, they are recommended wherever possible as collection and conveyance links between treatment systems (Burch *et al*., 1985). Under current EU legislation, the Water Framework Directive will dictate the likely measures to be employed so as to minimise risk to receiving waters under prevailing local conditions. Particular consideration for choice of treatment system in Ireland should relate to relatively high water tables and rainfall.

7.2.2 Surface water: sediments

As this study reflects the position in receiving surface waters at a particular point in time, the accumulation and distribution of sediments over time in the river and their potential long-term impacts on aquatic biota should be monitored. Longer-term evaluation would be worthwhile to substantiate current conclusions.

7.3 Groundwater

The unexplained losses of water from filter drain systems should be investigated further, with a view to determining if there are any implications for groundwater contamination.

7.3.1 Treatment options

The study has revealed the complexity of drainage and treatment pathways currently occurring in Irish road run-off drainage. At present, the lack of impact on surface water receptors may, in part, be due to the (inadvertent) trapping of contaminants along the pathway between the road pavement and the receiving water. A specific design protocol, for both drainage and treatment, should be developed for help in decision making on the best options for particular site conditions in Ireland. The options will depend on traffic densities, climate, hydrological and other site conditions. Under the EU Water Framework Directive, both surface water and groundwater receptors need consideration in any such protocol.

7.3.2 Monitoring of current treatment sites

To fully validate the treatment options of a constructed wetland and swale in Irish conditions, monitoring and evaluation should be continued on the sites constructed under this study.

7.3.3 Other treatment options

The role of oil interceptors was not examined in this study but the development of any protocol for the selection of treatment options should include the role of such devices. If the French drain is to continue in use, a re-design is required to improve its efficiency in terms of drainage as well as treatment if it is specifically to assume that role. In particular, it is recommended that the role of the geotextile be re-examined.

7.4 PAHs

A detailed examination of the various PAH species in stream sediments could be used to identify their origin.

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