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Development of a model based approach to predict concentrations of pollutants in highway runoff and the risk of adverse environmental impact

Développement d'une approche basée sur un modèle de prédiction des concentrations de polluants dans les ruissellements de chaussées et de l'impact éventuellement défavorable sur le mileu naturel

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RESUME

En 2003 la Highways Agency anglaise a engagé une étude sur trois ans à partir de l'approche systématique de la mesure des polluants dans les ruissellements des chaussées dans 24 emplacements de conditions diverses. Le but de l'étude est d'élaborer une approche basée sur un modèle de prédiction des concentrations de polluants dans les ruissellements des chaussées et des charges dans les sites en relation au climat régional, aux caractéristiques des chaussées et des évènements de pluie. Cette étude permettra à l'Highways Agency de se rapprocher de son but à long terme de pouvoir offrir de meilleurs conseils sur les circonstances dans lesquelles les ruissellements de chaussées peuvent avoir un impact important. Ce papier présente les résultats initiaux, une comparaison aux normes éventuelles d'évaluation des risques, et il décrit le développement d'un modèle d'évaluation des polluants dans les ruissellements des chaussées.

ABSTRACT

In 2003, the Highways Agency in England commissioned a 3 year study based on a systematic approach to measuring pollutants in highway runoff at 24 locations under a range of site conditions. The aim of the study is to develop a model based approach to predict highway runoff pollution concentrations and loads at a site in relation to regional climate, highway and rainfall event characteristics. The study will help to facilitate the Highways Agency's long term objective of being able to offer improved advice on the circumstances where, and when, highway runoff is likely to have a significant impact. This paper presents initial results from the data collection study; a preliminary comparison of monitoring results with potential standards derived for soluble pollutant impact risk assessment; and, describes the development of a risk assessment tool for pollutants in highway runoff.

KEYWORDS

Data collection, ecological impact, highway runoff, modelling, risk assessment.

1 INTRODUCTION

The Highways Agency is responsible for operating, maintaining and improving the strategic road network in England. Its aim is to provide safer roads, reliable journeys and informed travellers. One business performance indicator is to mitigate the potential adverse impacts of these roads on the environment. The focus of the Highways Agency's ongoing research into the nature and impact of highway runoff is aimed at contributing towards being socially and environmentally responsible and also ensuring that the Highways Agency will meet the requirements of the EU Water Framework Directive (EEC, 2000).

Highway surface runoff discharges may contain soluble and insoluble pollutants that have accumulated on the carriageway following periods of dry weather. In storm events, these pollutants may be transported via the highway surface water drainage system and discharged to receiving watercourses. Previous research has indicated that, in general, pollutant concentrations in highway runoff are low and often close to analytical limits of detection (Crabtree et al, 2004). However, under certain conditions it is possible that the pollutants in highway runoff may exert an acute and/or chronic impact on the chemical quality and ecological status of the receiving water (Luker and Montague, 1994; Maltby et al, 1995; Ellis and Mitchell, 2006). The results of previous research into pollutant levels and their causative relationships with rainfall event and highway characteristics have been inconclusive. However, traffic flow, climate and antecedent dry weather are considered to be potentially important factors, as are rainfall event intensity and duration (Crabtree et al, 2006).

In 1997, the Highways Agency, in association with the Environment Agency, commissioned a 5 year study to collect data to improve the understanding of the pollutants present in non urban highway runoff. This involved the instrumentation and monitoring of non urban highway surface water drainage and the receiving water at 6 motorway or major trunk route sites in the south of England. Highway runoff and associated sediment samples from 10 events at each site were analysed for 40 potential pollutants. The results from this study (Crabtree et al, 2004; Crabtree et al, 2006) identified a range of pollutants that were routinely present in highway runoff at concentrations that could, depending on the available dilution, adversely impact the ecology of receiving waters. The results also indicated that some of these pollutants were present at concentrations higher than those identified in the then current design guidelines for highway runoff pollution risk assessments (HMSO, 1998). However, concentrations of pollutants found were generally lower than those reported for runoff from urban highways (Strecker et al, 1990; Luker and Montague, 1994). Also, there was a positive relationship between metals, polyaromatic hydrocarbons (PAHs) and other pollutants.

The Water Framework Directive introduces more demanding environmental objectives than ever before, most notably the requirement for all inland waters to achieve good ecological status by 2015. Findings from the Highways Agency's own research programme (Crabtree et al 2006) has identified that some aspects of the recently updated methodology for assessing the impacts of highway runoff (HMSO, 2006), whilst representing the current best practice, is largely derived from data that may not be representative of the pollutants and concentrations currently found in highway runoff. Managing this risk is the focus of three research studies that have been implemented by the Highways Agency, in partnership with the Environment Agency, to provide the underpinning data and understanding of the nature and impacts of pollutants in highway runoff. The aim of this research is to support the development of more robust guidance coupled with an improved prediction methodology. These developments recognise the need to consider both the soluble and the insoluble components of highway runoff and, if deemed to be appropriate, take into consideration the influence of a 'first flush' of pollutants in highway runoff. The specific output objectives for each individual study can be summarised as:

1. to develop a model to predict pollutant concentrations in highway runoff ;
2. to develop ecologically based receiving water standards to control the impact of soluble pollutants in highway runoff; and,
3. to develop ecologically based receiving water standards to control the impact of insoluble pollutants in highway runoff.

To address objective 1, in 2003, the Highways Agency commissioned a 3 year study, to build on the results from the earlier study (Crabtree et al, 2004). The new study is based on a systematic approach to measuring pollutants in highway runoff at 24 locations under a range of climate and highway conditions throughout England. The aim of the study is to develop a model based approach to predict highway runoff pollution concentrations and loads at a site in relation to climate, highway and rainfall event characteristics. This paper presents initial results from the data collection study ; a preliminary comparison of monitoring results with potential standards derived for soluble pollutant impact risk assessments; and, model development to produce a predictive tool for pollutants in highway runoff.

2 HIGHWAY RUNOFF MONITORING PROGRAMME

The design of the monitoring programme was based on a 2 stage approach to monitor runoff from a total of 24 non-urban highway sites covering the range of climate and traffic conditions in England. Four climate regions were defined on the basis of annual average rainfall (wet >800 mm and dry <800 mm) and annual average winter temperature (warm >3^{o}C and cold <3^{o}C). These equate to the South West (warm/wet), the South East (warm/dry), the North West (cold/wet) and the North East (cold/dry) regions. Six sites were identified in each climate region to represent each of the 6 traffic flow bands defined by the Highways Agency, ranging from less than 15,000 to greater than 200,000 annual average daily traffic (AADT). Individual sites were selected on the basis of being able to monitor and sample untreated highway runoff from non-urban highway catchments with a minimum size of 1000 m^2 paved area. Site selection was also limited to sites with a hot rolled tarmac surface and, for safety reasons, where site access was off-highway. In practice, it was not possible to find suitable sites on the Highways Agency's network that met these criteria for all the traffic bands in each region, resulting in a duplication of sites for some traffic bands.

Site monitoring involved continuous rainfall and runoff flow monitoring (depth and velocity) and automatic or remote telemetry triggering of a 24 sample autosampler when the flow in the highway drain reached a site defined threshold. Sites were powered by 12 volt battery systems coupled to solar panels. The majority of sites incorporated a remote telemetry system to control equipment operation and to monitor operational performance and status. Rainfall event selection criteria aimed to capture runoff from events representing the full range of seasonal conditions for a range of rainfall intensities and totals. Event selection was based on a minimum antecedent dry period (ADP) of 24 hours. Flow weighted samples were prepared from the individual autosampler bottle samples to produce a flow weighted event mean concentration (emc) sample for subsequent analysis. This allowed for direct comparison with the results from the previous study (Crabtree et al, 2004).

Stage 1 monitoring was carried out between June 2004 and September 2005 at the 4 sites with the highest traffic band in each of the 4 climate regions. The aim of Stage 1 was to confirm the selection of key pollutants for the larger, subsequent Stage 2 monitoring programme and to obtain data from sites with higher traffic flows than those in the earlier study (Crabtree et al, 2004). Ten events were captured at each site for rainfall, runoff and pollutant concentrations of 56 determinands, including total and dissolved metals and PAHs, MTBE, Cyanide, deicing salt, Nitrate and Total Suspended Solids (TSS), plus particle size distribution of the TSS. Details of the Stage 1 monitoring sites are presented in Table 1.

Traffic region	Traffic Band	Site	Highway	Catchment Size m^2	Drainage Type	AADT	No. Lanes
Warm Wet	5	Bromsgrove	M5	2152	Gullies to Ditch	106000	3
Warm Dry	6	Luton	M1	43375	Concrete channel	146000	4
Cold Dry	5	Leeds	A1M	90220	Concrete channel	106000	8
Cold Wet	5	Lymm	M6	8675	Beany Blocks	135000	4

Table 1. Stage 1 Monitoring Sites

Stage 2 monitoring commenced in May 2005 and was originally scheduled for completion by August 2006 to allow the overall study to be completed by December 2006. However, the Stage 1 and Stage 2 monitoring period was characterised by the lowest observed rainfall in the south of England and, in particular, by two very dry winters. As a consequence, the Stage 2 data collection period was extended to December 2006, with overall study completion rescheduled to March 2007. The objective of the Stage 2 monitoring was to obtain a comprehensive data set for pollutants in highway runoff from 6 traffic band sites in each of the four regions. Ten events are to be captured at each of the 24 sites to give a total of 240 (plus 40 from Stage 1) events to support the development of the runoff pollution prediction model. In addition, there will be data from 20 events at each of the 4 highest AADT sites. An extra component of the Stage 2 monitoring is the collection of an additional 12 discrete samples from each event at the 4 Stage 1 sites. These samples are to investigate ‘first flush’ effects in highway runoff and their potential significance in terms of ecological risk. Over 200 Stage 2 emc samples and all 480 scheduled discrete samples had been collected by October 2006.

3 STAGE 1 RESULTS

The previous study (Crabtree et al, 2004; Crabtree et al, 2006) identified a number of key determinands found in highway runoff on the basis of their presence at concentrations more than 50% above the specified analytical limit of detection (LOD) in more than 50% of samples. An additional criteria was that observed concentrations could be at risk of breaching a range of potential, current water quality standards. While it is recognised that this is a conservative, precautionary approach, it provides a means of focusing data collection and modelling on pollutants in highway runoff that pose an ecological risk. The Stage 2 key determinand data from all 4 sites are summarised in Table 2 and compared to similar results from the previous study. Analysis of the Stage 1 results produced a revised list of key determinands for Stage 2 sample analysis with the addition of further individual PAHs. Dissolved Zinc, total and dissolved Cadmium and deicing salt (Na+Cl), while not meeting the selection criteria, were also added to support the development of ecological standards for highway runoff. In general, higher pollutant concentrations were found at the 4 Stage 1 sites than in the previous study. For the majority of key determinands, the average and maximum concentrations observed were greater than the results from the previous study. This may be a reflection of the comparatively higher traffic densities at the Group A sites, or other factors. The wider overall range of concentrations may be a reflection of site and event characteristics.

Three Stage 1 events produced total Zinc concentrations that were significantly higher than all other results. These results appear to be outliers in terms of routine runoff concentrations. The Stage 2 data will be used to clarify this issue.

Determinand	Units	LOD	Stage 1 Results		Previous Study*	
			Max	Average	Max	Average
Total Cu	ug/l	0.03	565.0	179.1	67.9	41.0
Filtered Cu	ug/l	0.03	304.0	63.3	33.6	20.6
Total Zn	ug/l	0.06	5730.0	799.5	221.5	140.3
Filtered Zn	ug/l	0.06	2600.0	298.3	536.0	50.9
Total Cd	ug/l	0.01	3.4	0.7	1.0	0.5
Filtered Cd	ug/l	0.01	1.2	0.3	ND	ND
Filtered Cr	ug/l	0.3	24.30	5.28	ND	ND
Total Pb	ug/l	0.1	310.0	74.6	51.4	23.1
Total Naphthalene	ug/l	0.01	0.9	0.3	0.5	0.1
Total Acenaphthylene	ug/l	0.01	0.3	0.1	0.1	0.0
Total Acenaphthene	ug/l	0.01	0.3	0.1	0.1	0.0
Total Fluorene	ug/l	0.01	1.0	0.2	0.1	0.0
Total Phenanthrene	ug/l	0.01	3.3	0.9	0.2	0.1
Total Anthracene	ug/l	0.01	0.8	0.2	0.1	0.1
Total Fluoranthene	ug/l	0.01	12.2	3.0	0.2	0.2
Total Pyrene	ug/l	0.01	12.5	3.4	0.2	0.2
Total Benzo[a]anthracene	ug/l	0.01	5.0	1.3	0.2	0.1
Total Chrysene	ug/l	0.01	7.4	2.2	0.2	0.1
Total Benzo[b]fluoranthene	ug/l	0.01	7.8	2.2	0.2	0.1
Total Benzo[k]fluoranthene	ug/l	0.01	3.5	0.9	0.2	0.1
Total Benzo[a]pyrene	ug/l	0.01	4.8	1.4	0.1	0.1
Total Indeno[1,2,3-c,d]pyrene	ug/l	0.01	4.9	1.3	0.1	0.0
Total Dibenzo[a,h]anthracene	ug/l	0.01	0.9	0.3	0.1	0.1
Total Benzo[g,h,I]perylene	ug/l	0.01	5.7	1.5	0.1	0.1
Total PAH (unfiltered)	ug/l	0.01	62.2	18.5	2.6	1.4
TSS	mg/l	2	1340.0	259.8	318.0	114.6
Deicing Salt (Na+Cl)	mg/l	0.2	6650.0	509.6	910.0	430.0

ND – no data * Crabtree et al, 2006

Table 2. Summary Stage 1 Results for Key Determinands Event Mean Concentrations

Relationships between key determinands were found to be poor and the data suggest that relationships between key determinands are not dependent on climate or site characteristics. The data showed no elevation of pollutant concentrations in winter, as shown in Figure 1, or following salt application, as illustrated in Figure 2. This may be a reflection of bias in the data due to the relatively small number of winter events in the data set. Furthermore, the data showed no relationships between pollutant concentrations and event characteristics.

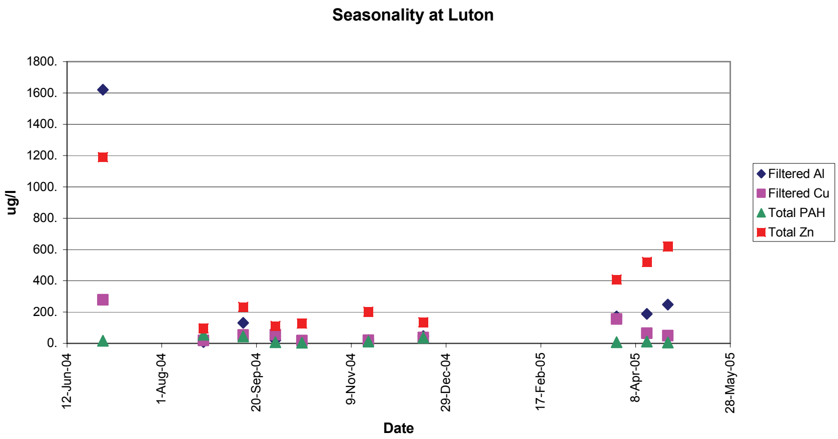

Figure 1. Seasonality in selected Key Determinand results at the Luton Stage 1 Site

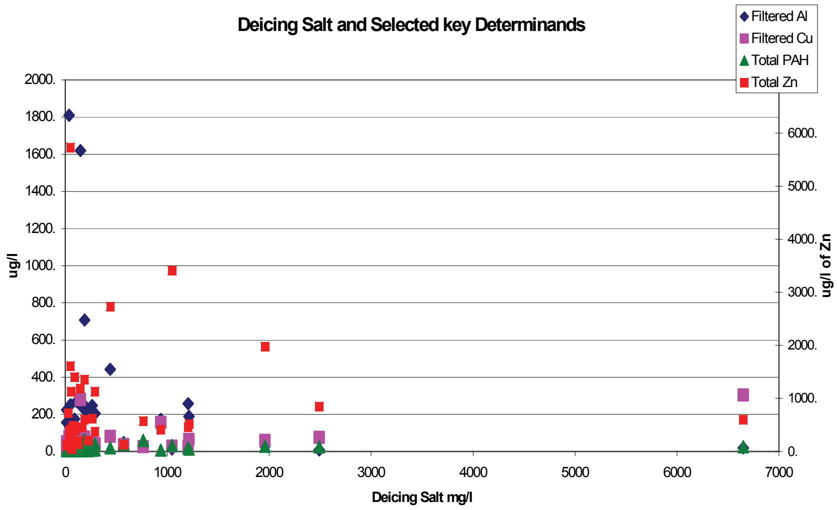

Figure 2. Comparison of Key Determinand Concentrations and De-icing Salt – all Stage 1 data

4 DEVELOPMENT OF AN ECOLOGICAL ASSESSMENT PROCEDURE

Intermittent wet weather discharges from highway runoff pose a risk of acute and chronic impact on the chemistry and ecology of the receiving watercourse. It is recognised that acute impacts are most likely to be caused by soluble pollutants. Insoluble, largely sediment attached, pollutants are more likely to cause a chronic impact over a longer time period. The risk of acute impact by soluble pollutants can be controlled by either an emission standard on the discharge or by receiving water impact standards. In each case, the episodic nature of the discharge and impact requires standards that recognise the combination of ecological risk factors associated with the concentration of the pollutant, the duration of the concentration and the return period of the impact event. This consideration precludes an approach based on annual mean and 90 or 95%ile exceedence statistics for pollutant concentrations associated impacts from continuous discharges. Intermittent discharge standards have been developed and applied successfully to control urban wastewater system wet weather discharges (Clifforde and Crabtree, 2002). In early 2006, the study was extended to include the development of an assessment procedure to predict the potential ecological impact of soluble pollutants in highway runoff. The aim is to identify runoff specific thresholds (RSTs) that will protect receiving water organisms from short-term exposure to soluble pollutants in highway runoff. Other Highways Agency studies, elsewhere, are underway to develop a risk assessment procedure for insoluble, sediment attached pollutants.

Potential RSTs have been developed, in part, from short-term (24 hour) toxicity data, generated from an earlier study carried out for the Highways Agency (Hurle et al, 2005). These RSTs have been prepared in a manner consistent with that used in the derivation of existing short-term and long-term environmental quality standards relevant for the implementation of the Water Framework Directive. For metals, it was recognised that the potential effects of hardness needed to be considered and this was achieved by deriving RSTs for different hardness ranges (<50, 50-200 and 200-250 mg CaCO3/l). Potential RSTs for soluble substances introduced into highway runoff by traffic have been derived for Cadmium (40 μg/l), Copper (21 μg/l) and Zinc (60 μg/l) for different hardness ranges, plus 2 PAHs - Fluoranthene (13.0 μg/l) and Pyrene (13.0 μg/l). The Stage 1 results indicate that the proposed RSTs for Copper and Zinc were exceeded by the emcs from many of the runoff events. The RSTs for Cadmium, Fluoranthene and Pyrene were not exceeded in any Stage 1 event.

A field validation exercise is being carried out at a Stage 2 monitoring site in the warm/wet region of the South West of England. In addition to the runoff monitoring, upstream and downstream river event monitoring is also being carried out. This includes continuous water quality monitoring, autosampling and in-situ bioassays based on upstream and downstream event deployment of caged Gammarus (Crane et al, 1996) as a relevant indicator organism. Initial results from 6 events showed that only 1 event had produced a downstream exceedence of the RST for Zinc, but without an increased Gammarus mortality at the downstream site. This indicates that the RSTs are precautionary in relation to the short duration of highway runoff events.

5 CONCLUSIONS – REQUIREMENTS FOR MODEL DEVELOPMENT

Stage 2 data collection and analysis will produce a more robust assessment of pollutant concentrations and their potential relationships with climate, site and event characteristics to support the development of a model based risk assessment procedure. This will be based on (1) an emission standard approach using the comparison of predicted event runoff emcs against RSTs for soluble and insoluble pollutants and, if exceeded, (2) an added risk, water quality standard approach by applying the RSTs to the downstream increase in pollutant concentration in the receiving water.

This modelling procedure will be developed in the final phase of the study as a prototype assessment tool. This will involve using pollutant build up and wash off relationships derived from the data and a monte-carlo mass balance approach to check resulting increased river concentrations. Model inputs will include site details for the highway discharge and receiving water course. It is envisaged that the model will run a continuous long-term simulation driven by a site related long rainfall time series; for example, 10-15 years, as used in addressing urban wastewater discharge impacts (Clifforde and Crabtree, 2002). Runoff event concentrations will then be compared to the RSTs and if appropriate, increased concentrations in the receiving water and associated potential ecological risk will also be assessed.

The outputs from this project will be used in conjunction with a parallel study investigating the toxicity of insoluble pollutants in highway runoff to develop new technical guidance on the assessment of water quality in the receiving environment in relation to highway projects. The Highways Agency's long term aspiration is to offer clear advice on the circumstances where, and when, highway runoff is likely to have a significant impact. In turn, this will inform improved decision making on the need for the provision of appropriate facilities for the treatment of highway runoff at a given site. This will contribute to the sustainable management of the Highways Agency's estate.

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