

The development of a risk-based approach to managing the ecological impact of pollutants in highway runoff

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ABSTRACT

In the UK, the Highways Agency is responsible for the strategic road network. It is recognised that current design guidance to control pollutants in highway runoff is out of date. A research programme is in progress to develop a better understanding of pollutants in highway runoff and their ecological impact. The paper summarises the outcome of a study to: (1) monitor pollutants in highway runoff under different climate and traffic conditions at 24 sites; (2) develop standards to assess potential ecological risks; and (3) develop a model to predict pollutant concentrations in highway runoff.

Data collection and analysis of the resulting data have identified a link between pollutant concentrations and traffic density. A number of pollutants routinely present in highway runoff have been identified as posing the greatest ecological risk. Ecologically based standards for acute impacts have been derived for the soluble form of these pollutants. These standards will be used in conjunction with the model to indicate where runoff treatment may be required to mitigate ecological risk. The model and standards will be used to develop improved design guidance to protect receiving waters from pollutants in highway runoff by identifying where runoff treatment is required, and to what degree.

Key words | data collection, ecological impact, highway runoff, model development, pollution risk

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INTRODUCTION

In the UK, the Highways Agency is responsible for operating, maintaining and improving the strategic road network in England. The focus of the Highways Agency's ongoing research into the nature and impact of highway runoff is aimed at developing environmental assessment techniques that contribute towards sustainable development, whilst also being 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.* 2006). 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 & Montague 1994; Maltby *et al.* 1995; Bruen *et al.* 2006; Ellis & 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).

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, are largely derived from earlier guidance (HMSO 1998) and in some aspects based on data that may not be representative of the pollutants and concentrations currently found in highway runoff. The focus of the Highways Agency's ongoing research programme, undertaken in partnership with the Environment Agency, is to provide underpinning data and understanding of the nature and impacts of pollutants in highway runoff. The key objectives of this research programme are:

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.

This paper is focused on the outcome of 2 particular studies aimed at addressing objectives 1 and 2. Objective 3 is being investigated concurrently through a sister research project. In 2003, the Highways Agency commissioned a 3 year study to build on the results from an earlier study (Crabtree *et al.* 2006) to address objective 1. This study was based on a systematic approach to measuring pollutants in routine, non-urban highway runoff at 24 locations under a range of climate and highway conditions throughout England. The aim of the study was 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.

DATA COLLECTION PROGRAMME

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°C and cold < 3°C). 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 120,000 annual average daily traffic (AADT).

Site monitoring involved continuous rainfall and runoff flow monitoring (depth and velocity) and automatic or remote telemetry triggering of a 24 bottle auto-sampler when the flow in the highway drain reached a site defined threshold. 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 weather period (ADWP) of 24 hours. Samples were prepared from the individual auto-sampler bottle samples to produce a flow weighted event mean concentration (EMC) sample for subsequent analysis for a range of pollutants. This allowed for direct comparison with the results from the previous study (Crabtree *et al.* 2006) that had 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. Data collection was carried out in two Stages.

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.* 2006). Ten events were captured at each site for rainfall, runoff and event mean flow weighted (EMC) pollutant concentrations of 56 determinands, including total and dissolved metals and PAHs, MTBE, Cyanide, de-icing salt, Nitrate and Total Suspended Solids (TSS), plus particle size distribution of the TSS. The results from all four sites indicated higher pollutant concentrations than those found at lower traffic density sites in the previous study.

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 each of the 6 traffic band sites in all of the four climate regions. Ten events were captured at each of the 24 sites to give a total of 240 Stage 2 events. EMCs were collected from each event and analysed for 36 determinands, on the basis of those routinely detected in highway runoff in Stage 1 and at concentrations that may present an ecological risk (Crabtree *et al.* 2006).

SUMMARY OF RESULTS FOR POLLUTANTS IN HIGHWAY RUNOFF

A statistical analysis of all the runoff event data, plus data from the earlier Highways Agency study (Crabtree *et al.* 2006) study, was carried out on compatible data from a total of 340 events at 30 sites. Overall, the results, with the exception of total Lead, showed higher concentrations of pollutants than those identified in the previous and current Highways Agency design guidance (HMSO 1998; HMSO 2006), as shown in Table 1. The values for Total Lead are based on data from the 1980s, whereas the new data are

considerably lower and reflect the benefits of removing Lead based additives from petrol.

A number of determinands have been identified as significant pollutants to be included in the improved design procedure in relation to their potential risk of ecological impact. Table 2 identifies the summary statistics for these significant pollutants.

One of the original project objectives was to investigate and determine any relationships between individual contaminants found in highway runoff and to identify the existence of any substances that may be taken as indicative of a range of other pollutants. A linear regression analysis indicated that, with the exception of total PAH as an indicator of concentrations of other total PAHs, there was no evidence to support the use of one or more indicator substances, including Total Suspended Solids (TSS), as a surrogate for others. For example, Figure 1 shows that there was no relationship between total copper and TSS.

A further objective, to support the development of the predictive model, was to identify any relationships between pollutants in highway runoff and site and rainfall event

Table 1 | Comparison of current design guidance with monitoring data

Pollutant	HMSO 1998 median EMC* range	HMSO 2006 median EMC range*	All monitoring data median EMC* range
Total copper (ug/l)	10–50	13–87	13–242
Total zinc (ug/l)	35–85	40–317	34–903
Total lead (ug/l)	24–272	0.13–4.00	0.46–114
Total COD (mg/l)	28–85	41–149	48–411
Total suspended solids (mg/l)	12–135	27–201	40–612

*value exceeded by 10% and 90% of sites respectively.

Table 2 | Summary statistics for significant pollutants

Determinand	Units	LOD	Average EMC	Median EMC	Average event load/1000m ²	Runoff load units
Total Cu	ug/l	0.30	91.22	42.99	0.66	g
Dissolved Cu	ug/l	0.30	31.31	23.30	0.16	g
Total Zn	ug/l	0.60	352.63	140.00	2.44	g
Dissolved Zn	ug/l	0.60	111.09	58.27	0.50	g
Total Cd	ug/l	0.01	0.63	0.29	0.00	g
Total fluoranthene	ug/l	0.01	1.02	0.30	0.01	g
Total pyrene	ug/l	0.01	1.03	0.31	0.01	g
Total PAHs (Total)	ug/l	0.01	7.52	3.33	0.04	g
Total suspended solids (TSS)	mg/l	2.00	244.00	139.00	1.69	kg

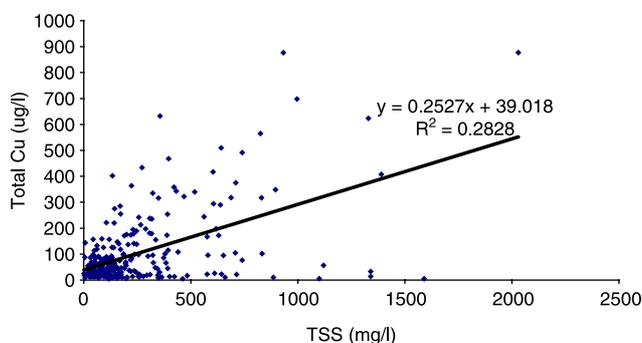


Figure 1 | Correlation between total copper and TSS.

characteristics. In summary, the results indicated that traffic flow (expressed as the two way annual average daily traffic flow (AADT) had the greatest influence on the concentrations of the significant pollutants. Figure 2 presents a 'box plot' illustrating the increase in dissolved copper concentrations with AADT. However, there was little evidence to indicate any regional climate effect except for PAHs, which while exhibiting a high variability, tended to be higher in the two colder climate regions in the north of England.

Investigation of the influence of event characteristics, including event rainfall, mean and peak rainfall intensity, antecedent dry weather period (ADWP); winter salting and seasonality showed:

- a decrease in pollutant concentrations with increasing event peak rainfall intensity;
- an increase in pollutant concentrations for metals with ADWP;

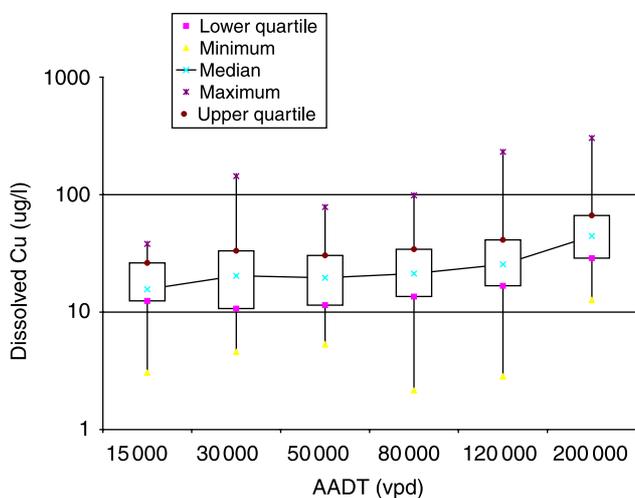


Figure 2 | Increasing dissolved copper concentrations with AADT.

- a seasonal effect with PAHs being lower in the summer and dissolved copper being higher; and,
- no consistent effect of winter salting on pollutant concentrations for metals and PAHs.

DEVELOPMENT OF RISK-BASED ECOLOGICAL STANDARDS FOR HIGHWAY RUNOFF

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 statistics for pollutant concentrations associated impacts from continuous discharges.

In early 2006, the study was extended to include Objective 2, the development of an assessment procedure to predict the potential ecological impact of soluble pollutants in highway runoff. Building on the results from an earlier study (Hurle *et al.* 2005), the aim was to identify receiving water runoff specific thresholds (RSTs), that will protect receiving water organisms from short-term exposure to soluble pollutants in highway runoff. 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 the soluble fraction of the significant pollutants found in highway runoff 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).

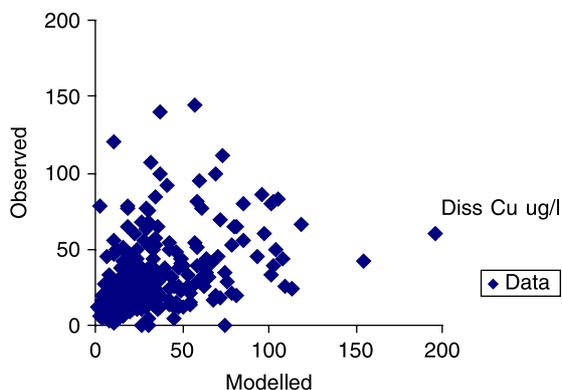
Table 3 | Exceedance of proposed soluble pollutant RSTs for all events

	Cadmium RST 40 ug/l	Copper RST 21 ug/l	Zinc RST 60 ug/l	Fluoranthene RST 13 ug/l	Pyrene RST 13 ug/l
Minimum EMC	0.01	0.3	0.6	0.01	0.01
Maximum EMC	5.4	304.0	1360	0.09	0.09
Number of EMCs exceeding the RST (% of total)	0	186 (54.5)	157 (46.0)	0	0

Table 3 shows the number of exceedances of the proposed RSTs in the full data set of 340 events. This comparison is, in effect, using the RSTs as discharge emission standards, rather than as receiving water standards when the dilution in the receiving water would be taken into account. The results demonstrate that copper and zinc showed exceedances of the proposed RSTs for around 50% of events, indicating that some degree of treatment or dilution in the receiving water would be required. However, there were no exceedances for cadmium, fluoranthene and pyrene.

CONCLUSIONS—INITIAL DEVELOPMENT OF A POLLUTION PREDICTION MODEL AND IMPROVED DESIGN GUIDANCE

The investigation of the effects of site and rainfall characteristics on pollutant concentrations suggests that there are no simple relationships and that individual event EMCs are a result of a combination of traffic density and a number of interacting variables related to rainfall event characteristics; for example, peak rainfall intensity, ADWP and seasonality.

**Figure 3** | Initial model results for dissolved copper.

The development of stochastic model driven by a long rainfall time series to predict event based concentrations for the significant pollutants is underway. Initial model development was focused on a deterministic approach and was based on representing the build up and wash off of pollutants from the highway surface. However, building on the initial data analysis, it became apparent that this approach would be unsuccessful. Therefore, model development has subsequently focused on a statistical approach using multiple linear regression analysis to assess the relative importance of the different potential explanatory factors and to provide regression equations to explain the variability observed in the data for each pollutant. An initial list of 28 potential factors influencing highway runoff pollutant concentrations were reduced to 5; including, AADT, ADWP, maximum hourly rainfall intensity, month and climate region. Different factors are more significant for each pollutant. Good results are being produced for copper and work is progressing to improve the model for zinc, cadmium and PAHs. Figure 3 compares the initial model predictions for dissolved copper compared to the observed data and shows that the model under predicts higher concentrations which only make up a small number of events.

Work on the development of a prototype design tool is also in progress and scheduled for completion in early 2008. In concept this will use the model to predict a 10 year sequence of results for concentrations and loads for the significant pollutants based on a 10 year rainfall time series and the site characteristics. The results will be assessed against the standards for the ecological impact.

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 goal 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 treatment of highway runoff at any given site. This will contribute to the sustainable management of the Highways Agency's road network.

ACKNOWLEDGEMENTS

This paper has been produced with the permission of the Directors of WRc and the Highways Agency. The views expressed in the paper are those of the authors and not necessarily of these organisations. The authors wish to acknowledge the data collection and data analysis support provided by colleagues from WRc and the Field Studies Council and, in particular, the contributions made by Frank Moy, Claire Brown, Andrew Turney and Janie Song.

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