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Migration of Contaminants Associated with Pavement Construction

By

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Abbreviations

ASTM	American Society for Testing and Materials
BFS	blast furnace slag
BSE	bovine spongiform encephalopathy
C_i	initial concentration in water before 'partitioning'
C_f	final concentration in water after 'partitioning'
DOENI	Department of the Environment in Northern Ireland
DoRLaP	double ring laboratory permeameter
EA	Environment Agency
GCL	geosynthetic clay liner
k	coefficient of permeability
K_d	partition coefficient
MSW	municipal solid waste
RBCA	risk-based corrective action
RBSL	risk-based screening levels
SD	sustainable development
SEPA	Scottish Environmental Protection Agency
S_i	initial subgrade concentration before sorption by 'partitioning'
S_f	final subgrade concentration after sorption by 'partitioning'
S_{min}	minimum saturation
SSTL	site-specific target levels
SWM	solid waste material
WQS	Water Quality Standards
WMLR	Waste Management Licensing Regulations

Abstract

In order to achieve the goals of 'Sustainable Development', alternative (secondary) materials are being increasingly used as bulk-fill aggregate within pavement construction as substitutes for traditional aggregates. This finds an end-use for stockpiles of industrial by-products (and hence the allowing the land on which they stand to be reclaimed for other uses) and protects finite, natural resources which they replace from over-extraction.

Previously, there has been very little research concerned with the leaching of contaminants from alternative materials in pavement construction and the subsequent risks to water bodies from pavement drainage. It is this topic which is addressed here.

Two flow regimes within a pavement have been studied in order to predict contaminant movement: (1) vertical flow through the aggregate and pavement and then vertically through the natural subgrade to ground water below and (2) horizontal flow through the aggregate to be discharged through pavement sides drains. Using these analyses a generic user-friendly risk assessment guide by which contractors may assess an aggregate prior to use is presented. A case-study is provided to illustrate some of the issues of concern.

Guidelines in the risk assessment guide recommend the suitability of different physical parameters of a potential aggregate at a proposed pavement construction site for both water flow directions. If the subgrade at the site does not allow sorption by the soil to enable any contaminants in vertical flow to be below Water Quality Standards (WQS), the use of a geotextile clay liner to further increase sorption is recommended. If the concentrations of contaminants in water discharged from side drains is not below WQS for horizontal flow, guidelines determine whether the site rainfall and surface runoff allow sufficient dilution. In most situations alternative materials appear to be acceptable for use if pavement construction is on clay subgrades, with an exception of sites where the subgrades are shallower than those recommended or where they are close to areas of higher sensitivity, such as those in close proximity to protected groundwater.

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1 Introduction

1.1 Introduction

'Sustainable Development' (SD) is a key phrase in environmental debate today, with industry increasingly incorporating its principles into modern technology in order to meet set goals. Its roots trace back to the 1950s, with a growing awareness for the need to protect the environment. There was an increasing concern over the continual mining and quarrying of non-renewable natural resources. The subject of resource management to address environmental concern was brought into the political arena as a result of the publication of a report following a conference in 1984 of the 'World Commission on Environment and Development', chaired by the former Prime Minister of Norway, Gro Harlem Brundtland. This meeting consisted of 23 commissions from developed, less developed and communist countries. Out of this meeting, the report was published in 1987 called ‘Our Common Future’, which became known as ‘The Brundtland Report’. It was within this report that the term ‘Sustainable Development’ was officially introduced. SD was defined as "*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987).

In 1992 another major environmental conference was held in Rio de Janeiro, Brazil, called the ‘United Nations Conference on Environment and Development’ (McCormick, 1995). This conference became commonly known as the ‘Earth Summit’. It was attended by heads of state and official representatives from both developed and less developed countries, as well as a large number of non-governmental representatives. Many issues of concern were discussed and various pathways of action decided upon. One major pathway was ‘Agenda 21’. The basis of Agenda 21 was a plan of action to be implemented by the 21st century. The theme of SD was to be at the centre of any action. 'Local Agenda 21' was a plan of action to be carried out at a local level, making local authorities responsible for the management of natural resources within their areas (McCormick, 1995). More recently (August, 2002) a conference was held in Johannesburg, South Africa, referred to as the 'Earth Summit plus 10', being 10 years on from the Rio meeting. This meeting centred around world hunger, thirst, control of industrial emissions and third world debt, all issues encompassed under the larger umbrella term of SD.

A means by which industries are nowadays incorporating SD into work practices in order to address current concerns over the conservation of finite natural resources, is by the increasing use of alternative (secondary) materials as substitutes for primary aggregates within construction. Within the pavement industry the term 'alternative material' is given to a material that is a waste material/by-product of a previous use, sometimes having undergone an industrial process. The use of alternative materials has a two-fold benefit: firstly it enables industry to comply with the principles of SD and secondly it addresses the important issue of dealing with the constantly increasing quantities of industrial waste that are collecting throughout this country and overseas. Within pavement construction, alternative materials may be used as bulk fill and lower pavement layers below the pavement surface.

In order to be acceptable for use as aggregate in pavement construction, these alternative materials must meet the same criteria that have been set for the use of traditional aggregates. It would appear, however, that in the majority of cases these criteria are based on mechanical properties. This is usually sufficient for traditional aggregates that have been used over a long period of time. In most cases, either their lack of contamination potential is known, or any assessment to their suitability would be unlikely because they are so widely used, even if some contaminants may be shown to leach. In the case of alternative materials, however, it is essential to know their potential for causing environmental contamination prior to their use, but this requirement is rarely included within official regulations.

The Environment Agency (EA) is responsible for enforcing increasingly stringent regulations to control the disposal of waste into both surface and groundwater. This relates to waste disposed of directly into water bodies, as well as waste disposed of on land which can eventually seep through to the same water bodies. This latter method of disposing waste on land can be compared to the use of alternative materials in pavement construction, whereby any potential contaminants could 'leach' (seep) into water permeating through the pavement. The resultant drainage flow containing contaminants is known as 'leachate', and can eventually enter nearby water bodies.

Certain natural aggregates have been used in construction for many years and are deemed ‘inert’ (e.g. limestone and granite) and are considered, therefore, safe to dispose of into the water bodies. On analysis, however, even these materials may contain potentially toxic chemicals depending on their site of origin (e.g. limestone can contain high levels of organic residues). New groundwater regulations were introduced in 1999, (Part IIA of the Environmental Protection Act, 1990), strictly regulating the permitted levels of certain chemicals which can be disposed of into water bodies. If enforced ‘*per se*’, even some traditional materials would be banned from use in construction because of the chemicals within them. It is envisaged that some leniency may be shown to these well used aggregates. It is unlikely, however, that the same leniency will be shown towards alternative materials used as aggregates and, therefore, careful chemical analyses are essential during their assessment stages.

It was because of the increasing use of alternative materials within construction that the University of Nottingham commenced research into their use in pavement construction. Originally the main concern was whether these materials met physical specifications, but the growing concern over their potential to contaminate the environment has led to research into the area of contamination. The research described here deals with any possible 'risks' posed from contaminants which may result from the use of alternative materials. 'Risk' can have different definitions in different situations, but usually it is used to define the probability of the occurrence of an event. As described here, it is taken to mean the risk of contaminants leaching from pavement profiles entering water bodies at levels which exceed set regulatory limits. In this situation ‘risk’ can be defined as "*The likelihood of an adverse health effect due to an exposure to an environmental hazard*" (Stefanis and Pistikopoulos, 1997). The research described here leads on from a previous project (described in Chapter 2) assessing the leaching of potential contaminants from alternative materials used as bulk fill in pavement structures. Although chemical analyses of potential leachates from alternative materials in pavement construction has been undertaken both at the University of Nottingham and elsewhere, there appears to be little research data on the quantification of the risks of using such materials. One other project has been identified (Apul, 2001, 2003) assessing the risks from using recycled materials in pavement construction, but is being developed into a full risk assessment model, which is in contrast to the aim of the research described here. The aim of this research has been to quantify the risks from using alternative materials as aggregates in pavement construction in real-pavement scenarios. This has been undertaken in order to develop a generic (i.e. non site-specific) 'risk assessment guide' for use by industry prior to using these materials and is presented in the form of a short document. This risk assessment guide may be used by contractors with no prior knowledge of risk assessments, providing potential sequences of sites under review are assessed (e.g. subgrade permeability, subgrade depth and regional rainfall). This will allow alternative materials to be safely used within pavement construction, which will in turn protect natural resources from excessive extraction. It will also find an end-use for stockpiles of waste materials. Importantly, it will prevent industry having to implement costly clean-up procedures after the materials have been inappropriately used.

1.2 Background

There is a ten-year history of research at the University of Nottingham into alternative materials in pavement construction. This commenced with a small project on the mechanical properties of power station furnace bottom ash for the Central Electricity Generating Board and continued with a project on the use of industrial residues in pavement bases with Scott Wilson Kirkpatrick Pavement Engineering. This led to a major research project linked to the Transport Research Laboratory on the mechanical properties of alternative materials when used alone and when stabilised with binders. The environmental issues associated with the use of such materials then became apparent and CIRIA produced a report in 1997 (Baldwin, et al., 1997), in association with AEA Technology, Transport Research Laboratory and Green Land Reclamation, on leaching from such materials. A previous project at the University of Nottingham followed on from the CIRIA work to look in more detail at that issue and investigate the use of binders to control contamination (Hill, et al., 2001). That project is described more fully in Chapter 2. This in turn has led on to the research described here (funded by an Engineering and Physical Science Research Council grant) looking into the risks of using these materials.

Early in the life of the research, Britpave (the British In-situ Concrete Paving Association) became a financial contributor. That link is described further in Chapter

6. It became evident through discussions with Britpave members, that a generic risk assessment guide against which pavement construction aggregates could be assessed prior to use was lacking and would be considered a valuable contribution to the industry. This would provide a guide to assess a potential construction aggregate at a site without major expense and would help prevent costly clean-ups should a construction aggregate be inappropriately used.

1.3 Aims and Objectives

Overall Aim

The principle aim of the research described here has been to develop and assess a methodology for quantifying risk when using alternative materials in pavement construction. In the context of the research, the definition of risk (Stefanis and Pistikopoulos, 1997) previously quoted, can be adapted to mean "*the likelihood of an adverse health effect due to an exposure to a contaminant from alternative materials in pavement construction*".

The detailed **objectives** of the research have been:

- To assess the 'pathways' of possible contaminants from 'source' to 'receptor'.
- To adapt reasonable models of the movement of water through pavements.
- To quantify contaminant movement within pavements by predicting their carriage and deposition.
- To formulate a risk assessment methodology drawing on the studies undertaken to meet the previous objectives.
- To summarise the approach developed as a user-friendly generic 'risk assessment guide'.

The activities required to fully achieve the objectives presented above would have been beyond the timescale allocated to the research. It has been necessary, therefore, to select key elements which have been considered representative of a large proportion of pavement scenarios. By selecting key elements and eliminating other ones, it is understood that the research has been based upon broad assumptions in many circumstances. Due to the fact that the final risk assessment guide has been developed as a generic guide rather than a site-specific one, this method has been considered justifiable. This is because a generic guide is suitable for use in many construction scenarios, whereas a site-specific one would only be suitable for the one for which it was designed. Thus the key elements assessed within the research are given as follows:

Defining 'source-pathway-receptor' scenarios for selected potential contaminants: the 'source-pathway-receptor' scenarios which have been selected for use within this research are described further on. They cover the 'source' aggregates and 'receptor' water bodies selected and considered appropriate for the research requirements. The 'pathway' selection is also described, where two key elements (vertical and horizontal flows) have been selected from several potential ones, because they have been deemed most appropriate for use. It has been necessary to select a range of potential contaminants on which to base the calculations, because to assess every potential contaminant would have been outside the scope and timescale of this research. Calculations have been based upon data from Hill, et al. (2001). The data extracted are based upon lysimeter tests, details of which are given in Chapter 2. It was decided that calculations described here would be based upon the same contaminants and aggregates as those assessed within the lysimeters, because of readily available data.

Performing risk assessments for 'source-pathway-receptor' movements of selected potential contaminants: there are three main approaches used to undertake risk assessments: (1) qualitative, (2) quantitative, and (3) semi-quantitative, all of which are described further in Chapter 2. Qualitative risk assessments usually present risk in the format of 'low', 'medium' or 'high', whereas quantitative risk assessments usually present risk in a numbered format, where for example, '1' may equal low risk and '10' may equal high risk. Semi-quantitative approaches may be a combination of both qualitative and quantitative approaches. Due to the stringent enforcement of water quality standards (WQS) by the EA (described later) it was decided that the risk assessment guide would determine whether a potential aggregate being considered for use at a particular construction site was either acceptable or unacceptable for use. Rather than the user obtaining results in a quantitative manner and deciding whether the resultant degree of risk is acceptable or not, the guide has been developed as a result of quantitative calculations, but presented in a qualitative/semi-quantitative manner, with the resultant risk being either acceptable or not.

Taking into account geographic, engineering and environmental factors: there are many external factors which influence an assessment of a potential aggregate at a site under review. These include:

(1) geographic locations (e.g. valleys, water meadows, highland areas and hill slopes),

(2) engineering factors (e.g. subgrade material, depth of subgrade to water table, frost penetration and proposed construction sequence such as embankments, cuttings or ground level), and

(3) environmental factors (e.g. stability of water table and rainfall events).

It has been necessary to make a selection of factors considered most important in the development of the risk assessment guide within the timescale of the research, which would allow an overall generic site assessment to be undertaken. Three main factors have been selected: (i) site rainfall, (ii) subgrade material, and (iii) depth of subgrade as those being the most important. Other factors such as the influence of micro-climates, hill slope and frost penetration have not been incorporated as they would have been more relevant for site-specific assessments.

Developing a computer model (in the form of spreadsheets) to aid the risk assessment procedure: the development of a computer model to fully simulate all the contributory factors was outside the scope of the research, but spreadsheets have been designed to estimate the movement of water and contaminants within a pavement (described fully in Chapters 3 and 5). The spreadsheets may be used to determine the movement of water in the two 'pathways' assessed, to quantify the retardation rate of contaminants onto the subgrade through which vertical flows move, to quantify the hourly rate of water and mass of contaminant discharged through pavement side drains in horizontal flow and to quantify the amount of water required to dilute contaminants to WQS in horizontal flow. Calculations within the spreadsheets reflect site sensitivity and variations in local rainfall.

Producing a generic user-friendly guide to allow a risk assessment to be carried out on alternative (and traditional) materials to be used as bulk fill aggregates: the user-friendly risk assessment guide is a proactive rather than reactive document. This means that the risk assessment guide will be available against which materials can be assessed *prior* to their use, rather than as a component of a clean-up procedure afterwards. It is because the guide is generic rather than site-specific that the assumptions made have been considered to be justifiable. If the guide had been designed to be site-specific, more site-specific factors would have been included.

1.4 Project Description

All primary or alternative (secondary) construction aggregates have the potential to pose some harm due to their chemical composition. 'Harm' is defined by the EA as "*harm to the health of living organisms and their ecological systems and in the case of humans, harm also to his property*" (Spedding, 1999). In order to assess the magnitude of the harm, risk assessments can be undertaken. Within a risk assessment the risk of such harm can be presented either qualitatively (descriptively such as low/medium/high) or quantifiably (probability such as 'one in x chance'). The basis of the research described here has been to determine the risks from the use of alternative materials in pavement construction.

Risk is often presented within a 'source-pathway-receptor' scenario, where:

Source:	is the original material, contaminant or hazard.
Pathway:	is the route taken by the contaminant from the source.
Receptor:	is the human, flora or fauna which suffers harm as a result of the source.

An example of the 'source-pathway-receptor' scenario could be the case of a human drinking contaminated water. The 'source' would be the source of the chemical (such as a leaking petroleum tank), the 'pathway' would be the route the chemical takes to the water abstraction site (the ground through which it seeps) and the 'receptor' would be the groundwater into which it flows. It follows that a human drinking the contaminated water would be a secondary 'receptor'. This may also be presented in a different manner, whereby the groundwater into which the chemical seeps may be taken to represent part of the 'pathway' and a human drinking the water then becomes the primary 'receptor'. A real example could be the Bovine Spongiform Encephalopathy (BSE) crisis, where the remains of sheep with an illness called 'scrapie' were fed to cattle, which subsequently developed BSE, also known as 'mad cow disease'. In this case the sheep were the 'source' of the contamination, the actual feeding of the remains to the cattle was the 'pathway' and the cattle were the 'receptors'. It follows that humans eating the beef became secondary 'receptors'. This again may be presented differently, whereby the cattle which were fed the remains may be taken to represent part of the 'pathway', and the humans eating the beef then became the primary 'receptors'.

In pavement construction there are various 'pathways' by which the 'source' contaminants move towards the 'receptors'. The 'pathways' are dependent on:

(1) water entering the pavement profile ('ingress') and being available into which the contaminants may leach and by which they are transported, and

(2) water leaving the pavement profile ('egress'), which facilitates the leachate reaching the 'receptors'.

Different components of 'ingress' and 'egress' are listed below where, for the reasons presented, some have been eliminated. This has been done as it has been considered that within pavement profiles either their individual contribution of water compared with total volume of water, or the limited circumstances when they would occur are sufficiently low, in relation to the ones selected for assessment. Their elimination, therefore, has been considered to be justifiable.

In order to illustrate the components of 'ingress' and 'egress' presented below in relation to the 'pathways' selected within 'source-pathway-receptor' scenarios in pavements, a schematic of a typical pavement construction scenario may be seen in Fig. 1.1, which is followed by a brief description.

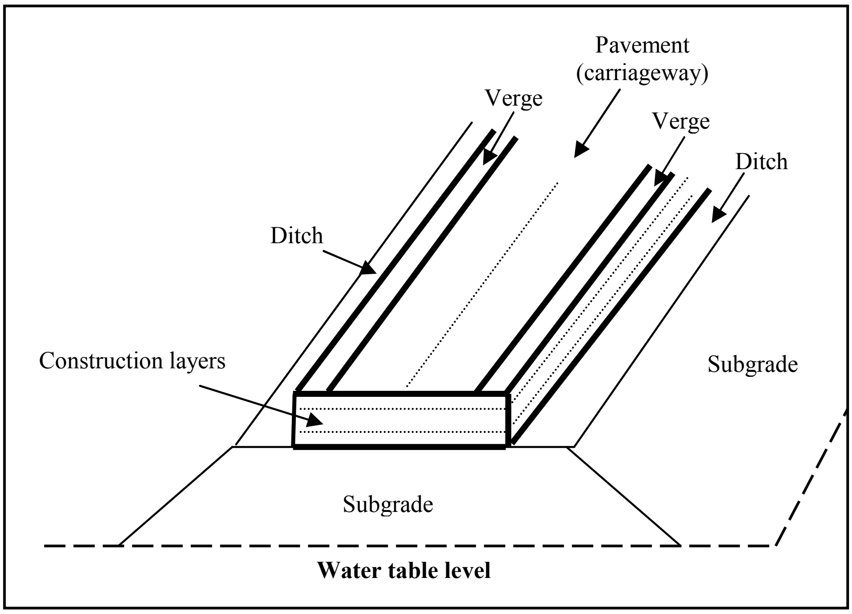


Fig. 1.1 Schematic cut-away view of pavement construction scenario

From Fig. 1.1 it may be seen that a pavement is constructed in various layers between the surface in contact with vehicle tyres, and the ground (subgrade) over which the pavement is built. Each of the layers in the pavement has a specific role and its properties need to relate to that role. These layers range from simple unsurfaced, compacted aggregate pavements for haul roads or low volume roads in developing countries to the thick, multi-layer bituminous or concrete roads used for heavily trafficked routes in developed countries (Hunter, 2000). This project has been undertaken based upon a typical pavement structure found in the UK, where details of the roles of each layer are presented further in Chapter 2.

The appropriate selection of 'pathways' from 'ingress' and 'egress' is as follows (Dawson and Hill, 1998):

Ingress:

- Pavement surface
  - construction joints : (considered under 'surface cracking' and *assessed within the research*).

  - cracks resulting from shrinkage during/after construction : (considered under 'surface cracking' and *assessed within the research*).
  - cracks resulting from distress due to loading : (considered under 'surface cracking' and *assessed within the research*).
  - diffusion through intact materials : (low contribution to total volume of water entering pavement and *excluded from the research*).
- Subgrade
  - artesian flow : (will only be applicable in a few limited circumstances and *excluded from the research*).
  - pumping action under traffic loading : (will only be applicable in a few limited circumstances and *excluded from the research*).
  - capillary action of lowest pavement layers : (low contribution to total volume of water entering pavement and *excluded from the research*).
- Pavement margins
  - reverse gradient of permeable layers above formation level : (will only be relevant in a few limited circumstances and *excluded from the research*).
  - lateral or median drain surcharging : (will only be relevant if drainage maintenance is neglected and *excluded from the research*).
  - capillary action of pavement layers : (low contribution to volume of water entering pavement and *excluded from the research*).
- Other sources
  - pavement or ground runoff via unsealed shoulder : (will only be relevant in a few limited circumstances and *excluded from the research*).
  - leaking pipes and gulleys in pavement : (will only be relevant if drainage maintenance is neglected and *excluded from the research*).
  - direct rainfall on pavement during construction : (not considered to be a long-term route of 'ingress' and *excluded from the research*).

Egress:

- Pavement surface
  - pumping through cracks/joints existing as described in Ingress above : (although relevant in very badly cracked surfaces, the quantification has been outside the scope of this research, and *excluded from the research*).

  - capillary rise and evaporation through cracks : (low contribution to total volume of water leaving pavement and *excluded from the research*).
  - diffusion/evaporation through intact material : (low contribution to total volume of water entering pavement and *excluded from the research*).
- Subgrade
  - soakaway to permeable, low water table subgrade : (considered under 'vertical flow' and *assessed within the research*).
  - capillary action of subgrade : (considered under 'vertical flow' and *assessed within the research*).
- Pavement margins
  - gravitational flow in aggregate to lateral or median drain : (considered under 'horizontal flow' and *assessed within the research*).
  - vertical flow in aggregate to open-graded drainage layer below : (pavements assessed within this research are not constructed with underdrains and *excluded from the research*).

The 'source-pathway-receptor' scenarios in pavement construction assessed can be identified in the following way, where the 'pathways' selected for assessment from the factors above are summarised below:

Source:	the potential contaminants within construction aggregates (primary or alternative).
Pathway:	this commences with the infiltration of rain through cracks in bituminous surfaces. It then comprises of the routes taken by the water containing contaminants in the form of leachate arising from the source. This is either: (1) vertically below the pavement through the subgrade towards the groundwater below, or (2) horizontally through the aggregate towards the side drain, from which it is discharged and will subsequently drain into a water body.
Receptor:	the water body into which the leachate from the source drains via the pathway.

Within 'source-pathway-receptor' scenarios, it is possible to take the receptor as being the water body, with humans, flora or fauna which come into contact with the contaminants as being secondary receptors. Alternatively, the water body may become part of the pathway, and the humans, flora or fauna then become the primary receptors. Following discussions with industry (discussions of this research with Britpave has previously been described), it became evident that contractors are mainly concerned as to whether concentrations of potential contaminants discharged into water bodies are below WQS. These WQS are set through legislation and are maximum contaminant concentrations that may be discharged into water bodies. These contaminants may be within materials being directly discharged into water bodies, or in the form of leachates draining from materials, seeping through the ground and eventually being discharged into water bodies. The EA stringently enforces the WQS and it has been considered, therefore, that the water bodies into which contaminants may leach would be regarded as the receptors. It should be noted, however, that there is a 'grey' area regarding WQS. It appears that in some circumstances WQS are enforced '*per se*', whilst in others site-specific levels are in force. It is advisable, therefore, that contractors liase with local EA officials in order to ascertain relevant WQS for any site under review.

It is the study of the pathways within pavement profiles through which potential contaminants from source aggregates will drain and hence enter receptor water bodies, on which this thesis is based. Computations have been developed in order to simulate the movement of the contaminants towards the receptors by simulating vertical and horizontal flows. This has been done in order to obtain data allowing an assessment to be undertaken as to whether concentrations of contaminants reaching the receptors are below WQS. If concentrations of contaminants exceed the WQS, hence making them unacceptable, a method has been developed in order to reduce such concentrations to levels below WQS. As previously described, an assessment of the source aggregates was undertaken by Hill, et al. (2001), and although resultant data has been used within calculations described here, no assessment of the aggregates has been undertaken.

In order to simulate the vertical and horizontal flows of drainage within pavement profiles, contributory factors controlling drainage have been identified. These factors are given below:

Paved surfaces: as well as being a surface on which traffic can drive, a paved surface offers the first mechanism by which to interrupt the pathway from source to receptor. This is achieved by preventing the infiltration of rainfall, which becomes the basis of the water flow within pavements. Surface cracking allows infiltration of water, data for which have been obtained through infiltration testing using apparatus designed and used within this research. Details of the infiltration testing can be found in Chapter 3.

Local rainfall events: it is important to determine the effects that the variability in rainfall events have on pavements. It is the rainfall infiltrating through the pavement surface cracks (outlined in 'Paved surfaces' above) that forms the flows which permeate through the aggregates, into which contaminants enter as leachates, and subsequently drain through pavement profiles.

***Composition of subgrade*:** it can be seen in Chapter 3 that computations have been developed to simulate the vertical flow of drainage from the pavement through the subgrade towards groundwater below. Flow rates are dependent upon the composition of the subgrade, which is reflected in the coefficient of permeability (k) value. Subgrades have the ability to adsorb contaminants (by sorption) providing the residence time of flows is sufficient. Clay subgrades have a range of k values where $k \leq 10^{-7}$ m/s, and calculations show that these clay subgrades with very low permeability are sufficiently low for sorption to reach equilibrium. Due to this, clays are the subgrades on which most calculations have been based. This matches with the fact that 80% of UK pavements are constructed on clay subgrades (Dawson, 1998). If pavements are constructed on subgrades of granular materials with larger k values, methods by which to counteract the consequently low residence times have been suggested (outlined in 'Geosynthetic Clay Liners' below).

Depth of subgrade: in this research the depth of the subgrade is taken to be the depth of the natural soil below the base of the pavement down to the level of the water table.

The depth of the subgrade, therefore, influences the flow times for drainage to reach the water table (in combination with 'Composition of subgrade' above).

Geosynthetic Clay Liners (GCLs): in pavements constructed on subgrades other than clay or on clay subgrades with k values too large for sorption to equilibrium, additional GCLs offer a further area of clay on which sorption of the contaminants may occur. These GCLs are designed with k values as low as $k=10^{-14}$ m/s (CETCO, 2000).

Chemical reactions: chemical reactions such as changes in mobility, precipitation, toxicology and synergistic effects from contaminants released from the aggregates within the pavement may produce either enhanced or inhibitory effects. These may occur due to changes in pH which in turn will effect the mobility and reactions of the chemicals. A study of the chemistry of potential contaminants within the alternative aggregates has been outside the realms of this research. It has been decided, however, that as calculations have been based upon data obtained from leachate analyses in Hill, et al. (2001), it would be assumed that any likely chemical reactions would have already occurred prior to the analyses. This makes the lack of study of the chemistry of the potential contaminants acceptable.

1.5 Thesis Content

This thesis has been laid-out in the following chapters, in order to allow the reader to gain a full understanding of the background to, and approach taken, by the author:

Chapter 2 – Previous Work: the aim of the chapter has been to review both past and current research relating to the use of alternative materials in pavement construction. There is an emphasis on assessing potential environmental risks that arise from their use. This has been undertaken in order to compare the research described here with other research in a similar field, in order to determine whether this research offers new knowledge to the field of science and can, therefore, be deemed original.

There are three main themes reviewed in Chapter 2, which are:

(1) a description of the previous leaching project undertaken at the University of Nottingham (Hill, et al., 2001). A brief introduction to the leaching tests carried out is given with information on data selected for use here,

(2) the use of aggregates in construction - it reviews the history of research into aggregates in construction and particularly pavement construction, and introduces the principles of recycling construction aggregates. It then looks at the use of alternative materials, and assesses research into their use in the UK and overseas. The fact that there appears to be a bias towards assessing the mechanical properties of alternative materials over their potential to contaminate water bodies is introduced, and

(3) risk assessments - it reviews risk definitions, the perception and communication of risk assessments and legislation controlling their application. Examples of different methods available to assess risks are given and their roles within the use of alternative materials in pavement construction is examined.

Chapter 3 – Flow Regimes: this chapter addresses the numerical input to this research. Most of the numerical input deals with the pathways and flow regimes by which contaminants from source materials are transported towards receptor water bodies. The pathways commence with infiltration of rain through cracked pavement surfaces. Due to the lack of published data on infiltration rates, infiltration testing using apparatus designed for use here is described, along with an analysis of generated data. Computations have been designed to simulate flow paths within pavement profiles, which relate to the transportation and deposition of contaminants from source materials to receptors. The equations upon which the computations have been based (some of which have been extracted from literature) are presented and example calculations are given illustrating the methods behind the computations.

Chapter 4 – Cumbria – A Case Study: over 25 years ago, blast furnace slag (BFS) was used as bulk fill during the construction of the A66 in Cumbria. There was a big incident at the time where local river systems were contaminated due to contaminants in the slag leaching into drainage from the new construction. Data relating to the incident were forwarded to the University of Nottingham at an early stage of this research, and it was considered that the problems would present a good case study. The presentation of both original and new data (generated within field work) is given. The case study has also presented this research with real data by which to assess the risk assessment guide.

Chapter 5 – Computations, Results and Discussion: this chapter fully describes computations designed within this research to simulate water flows through pavements. A method has been developed to quantify the transportation of contaminants within the pavement aggregate and their deposition within subgrades or man-made settling pools. If contaminant concentrations in water exceed WQS, a method by which the use of CGLs may reduce the levels to WQS is described. In some circumstances dilution of raised contaminant levels by surface runoff may be acceptable and calculations to quantify this are given. Results from the computations with their implication in pavement construction are presented.

Chapter 6 – Risk Assessment Guide: this guide has been designed based upon computations developed in order to assess construction aggregates (both alternative and traditional) prior to construction. Descriptions are given as to the adaptation of the data into the actual guide. The user assesses the aggregate and site under review against the guide for compliance. This is undertaken for vertical and horizontal flow paths. If the combination of aggregate and site is unsuitable, the user is advised that recommendations for use cannot be given. Construction sequences present within the A66 in Cumbria (the case study) are assessed in accordance with the risk assessment guide. An example using the risk assessment guide is given and the full risk assessment guide is presented as an appendix.

Chapter 7 – Conclusions and Future Work: conclusions from the research are presented. This is undertaken by re-visiting the original objectives in order to assess whether the main aim has been addressed. Full conclusions are then given. Certain factors limiting the research have become apparent and these are presented along with recommendations for further research in order to better accommodate these areas.

Appendix: Full data sets relevant to the research are given. These consist of relevant data from Hill, et. al. (2001) on which calculations have been based. The applicable WQS are presented, against which results from calculations within some of the spreadsheets as well as the risk assessment guide have been assessed. The case study of the A66 in Cumbria has been undertaken by comparing current data with those obtained early in the life of the road. Data sets from both the original and new studies are given, as well as grid references for sample site locations. The risk assessment guide is presented as a complete document in Appendix 6.

2 Previous Work

2.1 Introduction

In Chapter 1 the overall aim and objectives of the research are presented. It has been argued that a growing concern for environmental and finite resource protection in the 1950s led to industry (both general and pavement construction) looking towards the substitution of traditional primary aggregates with alternative secondary ones. This is particularly the case within pavement construction, where alternative materials may be used as bulk fill in base and sub-base layers. It would appear, however, that the main criteria against which natural aggregates are assessed prior to use are their mechanical properties. Unfortunately, when alternative materials are assessed these mechanical criteria are not sufficient. This is because in some cases there may be risks to human and environmental health from potential contaminants in leachates entering water flowing through these materials. It also appears that in cases where the alternative materials are assessed for environmental contamination, tests are not appropriate for pavement construction but are based on contaminated land scenarios.

The following review discusses past and current research into the testing and consequences of using alternative materials in pavement construction and different approaches to the concept of risk assessments. It commences with a review of research at the University of Nottingham undertaken by Hill, et al. (2001). This is followed by the main literature review, where the areas that have been investigated are divided into two main sections:

(1) 'Aggregates in Construction' with sub-sections on the pavement industry, alternative materials, alternative materials at an international level, guidelines to the use of alternative materials, mechanical properties vs. contamination potential and legislation controlling the use of alternative materials, and

(2) 'Risk Assessments' with sub-sections on risk definitions, the perception and communication of risk assessments, how to include legislation within risk

assessments, methods available to assess risks and risk assessments associated with alternative materials in pavement construction.

Within each of the main sections there is an outline of research early in the life of the topic under review and this continues to current-day research.

2.2 Leaching Project at the University of Nottingham

The leaching project was undertaken at the University of Nottingham prior to the research described here (Hill, et al., 2001). The principal aims of the leaching project were:

- To determine an appropriate testing strategy (based on existing methods) for assessing the leaching potential of primary and alternative aggregate materials.
- To propose, where required, suitable binder treatment methods that will reduce the leaching potential to a level beneath that required by regulatory authorities.

In order to undertake the project, fourteen aggregate materials were selected for inclusion, and consisted of air-cooled BFS, asphalt planings, basic oxygen steel slag, china clay sand, crumbed rubber, foundry sand, furnace bottom ash, granite, limestone, minestone, municipal solid waste (MSW) incinerator ash (old and new incinerators), pulverised fuel ash and sewage sludge incinerator ash. Out of those materials, granite and limestone were selected to represent primary aggregates. In addition, six binders were also selected and consisted of bitumen, cement, cement kiln dust, flue-gas desulphurisation gypsum, granulated BFS and quicklime.

All the selected materials have proven mechanical performance criteria and are available in substantial quantities, making them suitable for use in pavement construction and bulk fill. A leaching test was selected with the view that initially when assessing an aggregate, rapid bench-top tests would be undertaken (CEN, 1996). If a material fails the criteria then further testing would be performed. Two further types of laboratory tests were undertaken:

(1) permeameter tests using apparatus known as Double Ring Laboratory Permeameter (DoRLaP)(Birtwhistle, 1997). The principal behind the DoRLaP is to separate water flows through the specimen from flows between the specimen and the equipment, so that the permeability of the specimen may be correctly assessed. In this test there is a small amount of solid to large on-going quantities of water; and

(2) tank tests utilise one quantity of water into which the specimen is submerged and water samples are taken at regular time intervals, the principle of which is to see the variations in contaminant input over periods of time from diffusive leaching.

To verify that the performance obtained in the laboratory testing was representative of large scale or in-situ conditions, outdoor lysimeter trials were undertaken (Hill and Dawson, 2000). Lysimeters are outdoor testing cells representative of real-pavement conditions. Nine test cells containing different aggregates or mixtures at realistic gradings and degrees of compaction were established with a surface area of 1 m^2 and an overall depth of approximately 0.6 m (Fig. 2.1). The completed cells had a gravel drainage layer in the base upon which a 0.35 m layer of test material was placed. The completed cells were topped with single-size coarse gravel. The lysimeters were designed to replicate conditions during construction (before asphalt paving) which is seen as a worst-case scenario. The cells were exposed to the natural environment for nine months and the leachates which resulted from rainfall precipitating through the aggregates were sampled, and periodically analysed. There were no factors, therefore, limiting the flow of rain through the aggregates other than the inherent properties of the aggregates themselves.

It is the data obtained from those analyses that have been used within the research described here. The relevant data can be seen in Chapters 3 and 5, whilst fuller data sets are presented in Appendix 1. Due to the fact that the computations have been based upon data obtained within Hill, et al. (2001), the aggregates and binders used within each lysimeter are presented below (Table 2.1), followed by a brief description of the aggregates and their source origins:

Table 2.1 Aggregates in lysimeters as used within the leaching project

Lysimeter 1	China clay sand + cement* + cement kiln dust*
Lysimeter 2	Foundry sand
Lysimeter 3	Crumbed rubber (2-8mm)
Lysimeter 4	BFS + granulated BFS + lime*
Lysimeter 5	MSW incinerator ash + bitumen*
Lysimeter 6	Lean mix (limestone + cement*)
Lysimeter 7	Limestone (Type 1)
Lysimeter 8	BFS
Lysimeter 9	MSW incinerator ash
*= binder	

China clay sand: china clay (kaolin) is used in the paper and ceramic industries. In the UK it is produced in SW England, with Britain being the largest producer, and is extracted from kaolinized granite. The waste material is composed of:

- overburden.
- waste rock.
- coarse sand waste.
- micaceous residue.

(Sherwood, 1995a)

***Foundry sand**:* foundry sand is a by-product of the metal casting industry. It consists primarily of clean, uniformly sized, high-quality silica sand or lake sand that is bonded to form moulds for ferrous (iron and steel) and non-ferrous (copper, aluminium, brass) metal castings. The most common casting process used in the foundry industry is the sand cast system. Virtually all sand cast moulds for ferrous castings are of the green sand type. Green sand consists of high-quality silica sand and approximately 10% bentonite clay (as the binder), 2% to 5% water and approximately 5% sea coal (a carbonaceous mould additive to improve casting finish). The type of metal being cast determines which additives and what gradation of sand is used. The green sand used in the process constitutes upwards of 90% of the moulding materials used (American Foundrymen's Society, Undated).

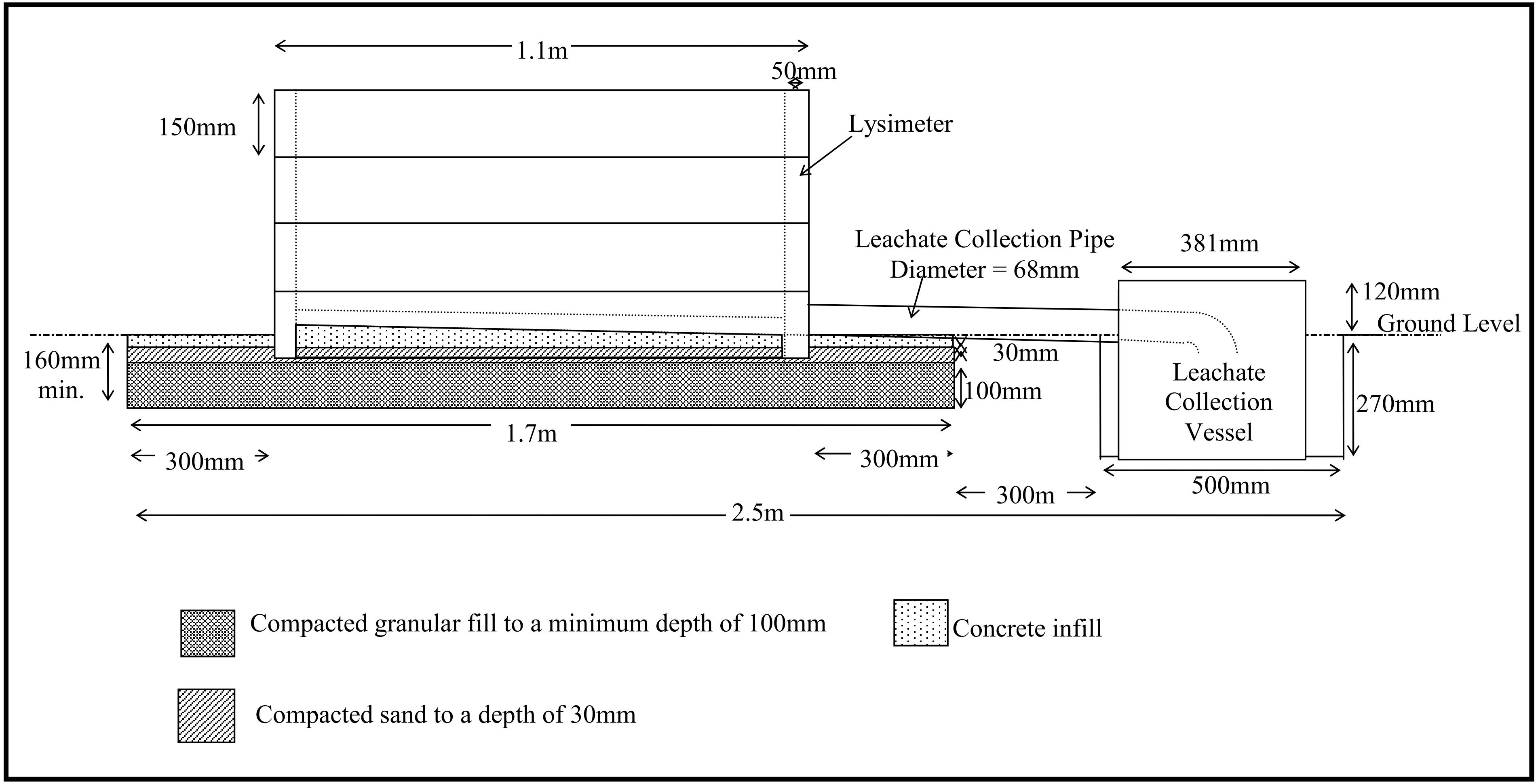


Fig. 2.1 End view of lysimeter (Hill, 2002)

Crumbed rubber (2-8 mm): in the UK 25 million car and 3 million truck tyres are discarded each year, of which 67% are stockpiled, landfilled or illegally dumped (Al-Tabbaa, 1998). Tyre crumb, which currently constitutes a fairly small arising, is attracting attention as a possible additive to construction materials. There have been number of trials in the US examining the use of shredded tyres and rubber crumb in roads and embankments (Ahmed, 1993).

BFS: BFS is a by-product from the manufacture of pig-iron and is formed by the combination of the earthy constituents of iron ore with limestone flux. Iron ore is a mixture of oxides of iron, while the silica and alumina compounds combine with the calcium of the fluxing stone (limestone and dolomite) to form the slag (Sherwood, 1995a).

MSW incinerator ash: about 2 million tonnes of the total annual arising of UK MSW is currently incinerated at modern mass-burn plants. About one-third (by weight) of the materials burnt are deposited as ash from the furnace (termed bottom ash). A much smaller volume of ash is recovered from the exhaust gases either through electrostatic precipitators, cyclones or in filters. Furnace bottom ash forms between 80% and 90% of the total ash production (Coventry, et al., 1999). Incinerator wastes takes up less space compared with untreated household wastes and are, therefore, more environmentally preferable to tipping the unburnt waste into a landfill site (Sherwood, 1995a). In addition, untreated household wastes have the potential to cause contamination through the migration of leachates and formation of landfill gases, whereas ash is inert and remains so without further degradation.

Limestone: limestone is a traditional aggregate commonly used as bulk fill in pavement construction and obtained through quarrying. Although a commonly used aggregate, it was decided to review its properties to see whether it is indeed chemically inert or whether there are any raised contaminant levels which have never been identified. This is due to the fact that because it has been used for a long time, analysis is not usually undertaken.

2.2.1 Data

Data was collected throughout the life of the lysimeters in order to determine the cumulative leaching properties of the aggregates in relation to quantities of rainfall and time. Total rainfall and volumes of leachate collected from each lysimeter are illustrated in Table 2.2.

Table 2.2 Total rainfall and volumes of leachate collected from lysimeters during the test period 8/9/99-26/9/00 (Hill, 2000)

Total No. of Days of Test Period	Total Rain During Test Period (l)	Lysimeter	Total Volume of Leachate Collected for Each Lysimeter (l)
384.00	641.40	1	421.58
		2	528.46
		3	543.80
		4	519.54
		5	551.22
		6	566.84
		7	535.37
		8	539.94
		9	575.59

It can be seen from Table 2.2 that volumes of leachate collected varied for each lysimeter, reflecting the different permeabilities of the aggregates. Lysimeter 1 consisted of china clay sand with additional cement and cement kiln dust used as binders, and was the lysimeter from which the least quantity of leachate was collected.

Chemical analyses of the leachate were undertaken by the British Geological Survey periodically during the project. The determinants for which analyses were undertaken which are relevant to the research described here were as follows: chloride, sulphate, nitrate, barium, manganese, iron, aluminium, nickel, copper, zinc, chromium, cadmium, lead and arsenic.

Although not included in the list above, sodium has been selected as an example to illustrate the type of data obtained from sampling taken on nine occasions (Table 2.3).

Table 2.3 Sodium as an example to illustrate concentrations for the dates when chemical analyses were undertaken (Hill, 2000)

	Sodium Concentrations (mg/l)								
	Lysimeters								
Date	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
21/10/99	110	1011	6	111	41	173	6	147	1892
01/11/99	54	901	3	308	43	150	19	93	3175
24/11/99	82	785	6	397	40	206	18	65	3440
19/01/00	68	296	6	243	59	158	10	17	1863
07/02/00	198	239	7	233	49	212	11	21	2247
28/02/00	49	86	3	73	14	38	3	10	471
24/03/00	112	125	4	54	34	101	3	11	799
10/04/00	90	103	6	129	45	109	7	11	1528
26/09/00	13	18	1	9	22	10	0.3	5	157
Mean	86	396	5	173	39	129	8	42	1730

Curves on log scales were generated for cumulative release (mg/kg) of contaminant against cumulative L/S (l/kg). Within the research described here gradients of these graphs have been determined. The resultant gradients are the cumulative concentrations of contaminants which is the format required within this research. This is illustrated in Fig. 2.2 which again uses sodium release from Lysimeter 1 as an example:

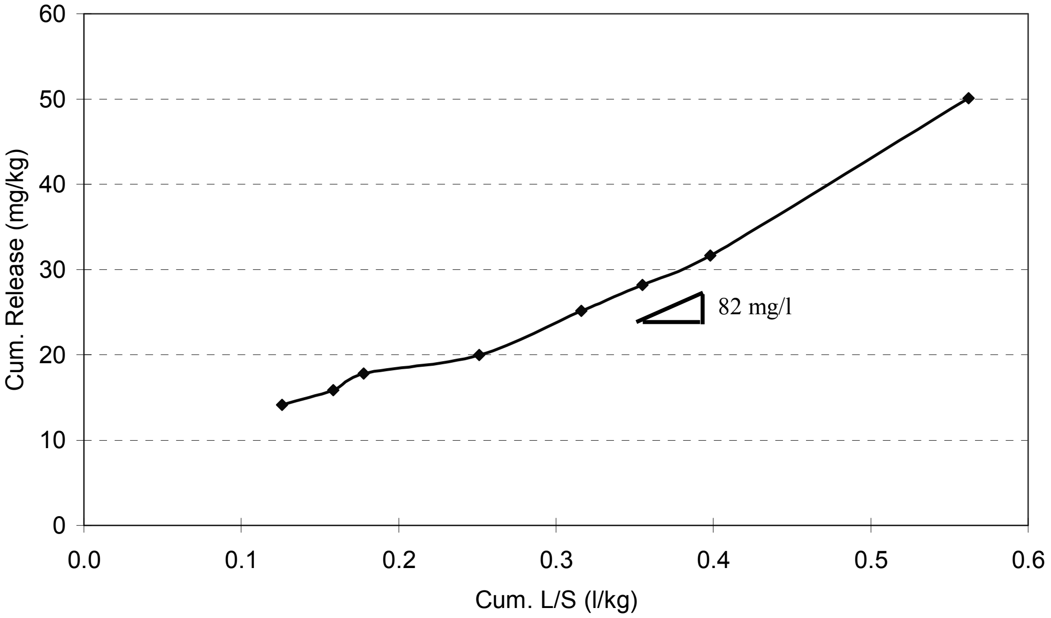


Fig. 2.2 Gradient obtained from sodium release plotted as cumulative release (mg/kg) against cumulative L/S (l/kg) for Lysimeter 1 (from Hill, 2000)

In Fig. 2.2 the 'x' axis represents total water as a ratio of solid, whilst the 'y' axis represents cumulative release of solid. The gradient of the line (i.e. contaminant release) is 82 mg/l. It can be seen in Table 2.3 that the mean sodium concentration obtained from sampling is 86 mg/l, which is very similar to that calculated for cumulative release (mg/kg) against cumulative L/S (l/kg). This implies that using the data for concentrations obtained through analysis is very similar to obtaining gradients of lines for cumulative release against cumulative L/S values. This consequently means that data determined from chemical analyses by Hill (2000) has been used within calculations rather than through determining gradients of cumulative release.

Within permeameter tests the ratio of solid to quantity of water was small, and curves of cumulative release (mg/kg) against cumulative L/S (l/kg) reflect this. In tank tests only one quantity of water was used and, therefore, a vertical line is present, with higher cumulative releases (mg/kg) of contaminants than in the other two types of tests. The highest cumulative release from tank tests appears to be very similar to where the curve for the cumulative release from lysimeter tests level off, showing a relationship between release from both of these tests. Results from the tank test inferred that in order for flows of water through the specimen to reach maximum equilibrium between the water and contaminants, the flows must remain in contact with the aggregates for 4 days for uncompacted and 16 days for compacted specimens (Hill, 2000). Because of the similarity between tank test and lysimeter results it was assumed, therefore, that if rain flowing through aggregates in the lysimeters were also there for the same timescale, maximum equilibrium values between the water and contaminants could be reached. The implications of those results in relation to real pavement scenarios are as follows: within the unsurfaced lysimeters rain flows had the potential to be in contact with the aggregates for sufficient time for any contaminants and the water to reach equilibrium. In surfaced pavements, where rain infiltration rates are determined by surface cracking, infiltration of water will take longer. This means that flow rates within the aggregate will be lower (less water within the pavement profile at any one time) and this will result in the flow of water in surfaced pavements having the potential to remain in contact with the aggregates for longer periods of time than within the lysimeters. These flows would, therefore, allow contaminants to reach equilibrium providing residence times were of a sufficient magnitude.

LaGrega, et al. (1994) state that the same factors control desorption (from solid to liquid phase) as control sorption (from liquid to solid phase) and are dependent on the physical and chemical properties of the contaminant and the medium into which the chemicals are entering. Desorption can take an extremely long time, thus giving the plume shape a 'long tail of decreasing contamination' (EPA, 1988). This is also termed 'hysteresis', whereby the process of desorption does not occur at the same rate as sorption, the reverse process (LaGrega, et al., 1994). Due to the long tail resulting from desorption, it may be accepted that it takes a longer period of time than the process of sorption. For the purposes of this research it has been accepted, therefore, that the 16 days residence time given by Hill (2000) for which water must be in contact with compacted aggregate to achieve equilibrium is also sufficient for most sorption processes to also reach equilibrium, although some may reach it much more rapidly.

The resultant contaminant concentrations obtained within the leaching project, multiplied by flow rates determined in this research, gives quantities of contaminants flowing through the pavement profile per unit time. The results of computations based upon the latter rate are given in Chapter 5.

2.3 Aggregates in Construction

2.3.1 History

Natural aggregates are naturally occurring rocks that have developed through geological processes over thousands of years and are often used as construction materials. The main aggregates used in construction are limestone, sandstone, granite, sand and gravel. These materials are usually removed from their natural sites by mining or quarrying.

Concern over environmental impacts of aggregate extraction in the UK has increased sharply since 1960. Aggregate extraction represents the loss of two finite resources: the aggregates themselves and the unspoilt countryside from which they are extracted. The environmental impacts of these extractions are loss of natural countryside, visual intrusion, heavy lorry traffic on unsuitable roads, noise, dust and blasting vibration (Sherwood, 1995b). Civil engineering is an industry that requires large quantities of aggregate and, therefore, is a major contributor to the ever increasing extraction demand.

Raw natural materials for civil engineering construction have to be obtained by open-cast methods, resulting in large amounts of derelict land (e.g. old quarries). Derelict land can be defined as "*land so damaged by industrial or other development as to be incapable of beneficial use without treatment*" (EA, 2004). Mining results in large amounts of mineral wastes and by-products being produced for which there is little demand, and are usually stockpiled in spoil tips (Sherwood, 1995b). Due to this, Great Britain has derelict land of over 20,000 hectares. There is approximately a further 40,000 hectares of previously developed land which could be redeveloped (National Land Use Database, 2003).

Productions of natural aggregate for the period of 1965-1997 may be seen in Fig. 2.3. It can be seen that production peaked in the late 1980s and reduced to a lower level in the 1990s. Crushed rock has generally been extracted in larger quantities than sand and gravel.

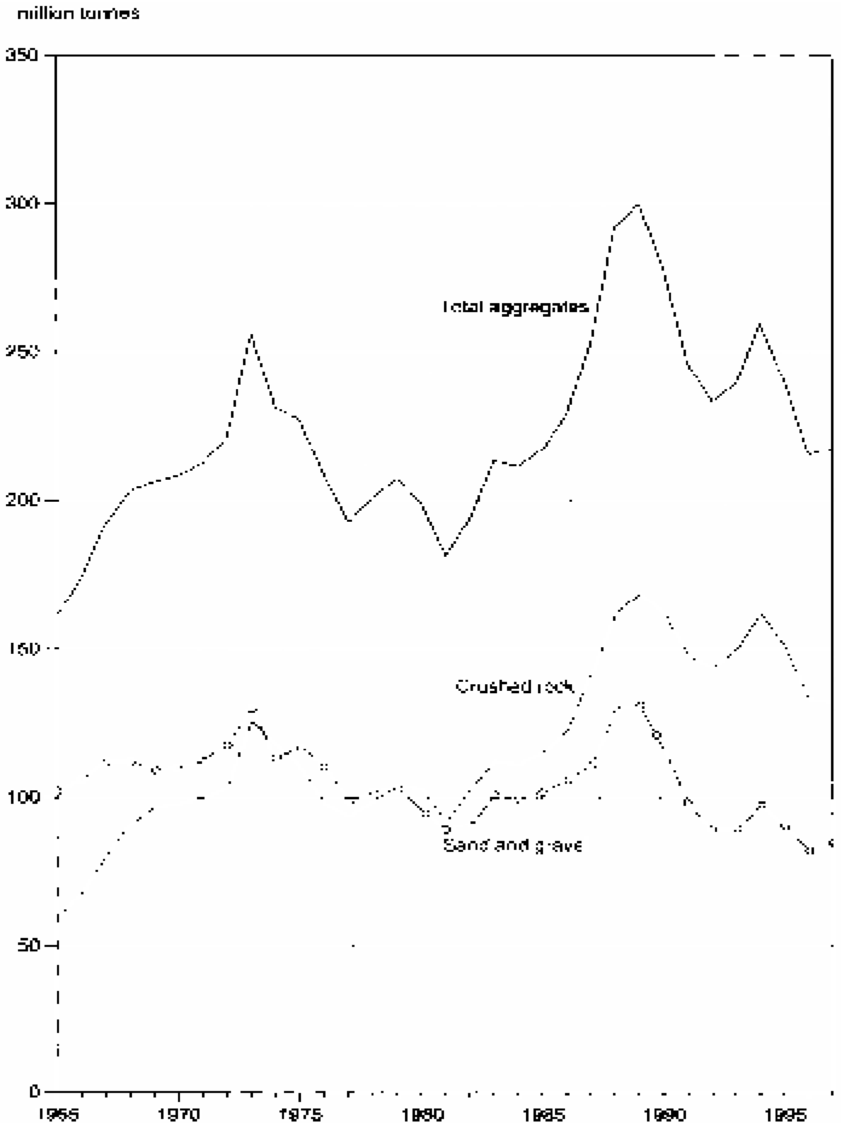


Fig. 2.3 UK productions of natural aggregate from 1965-1997 (Hillier and Highley, 1998)

2.3.2 Pavement Industry

2.3.2.1 Pavement Structure

It is appropriate at this point to discuss the structures that make up a pavement profile, an area introduced in Chapter 1, where a cross-section of a typical pavement construction scenario may be seen (Fig. 1.1). A pavement is made up of a number of layers called 'pavement layers' (of which Figs. 2.4a and b give typical examples). Other forms of pavement such as composite and rigid composite (DOT, 1991) are also built from time to time and their use is much less frequent than the fully flexible pavement used as examples in Figs. 2.4a and b. For the majority of pavements the material quality, in terms of durability and bearing capacity, increases from the bottom upwards so that the specification requirements for any given layer are higher than those of the layer immediately beneath it. Building in layers generally means that costs are reduced and a wide range of construction materials can be used, particularly for fill and capping materials which are used in the lower layers.

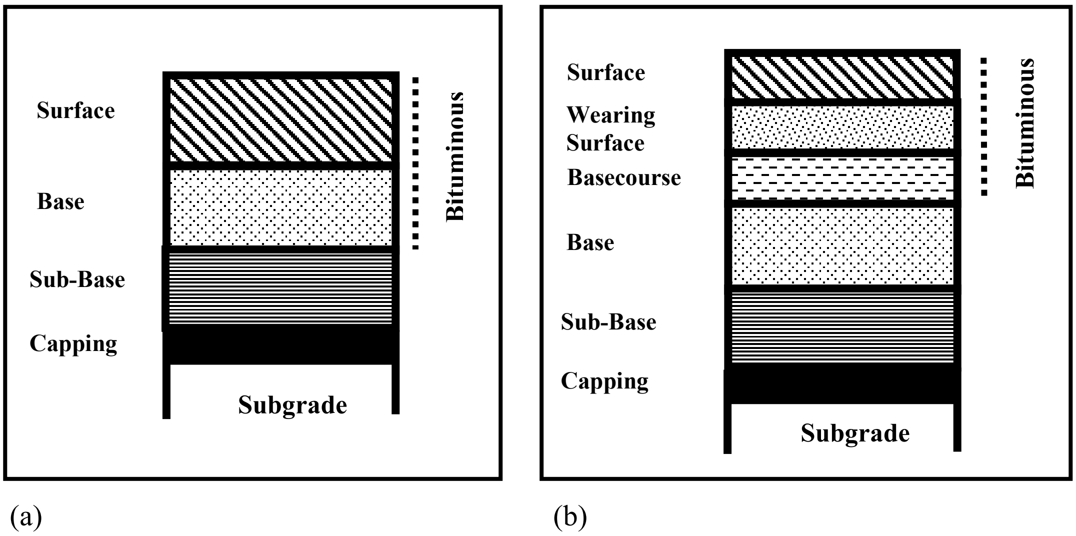


Fig. 2.4 (a) Basic road structure and (b) Heavy duty road structure (adapted from Hunter, 2000; Sherwood, 1994b)

In the UK, the requirements given in the Specification for Highway Works (Highways Agency, 1998) are mandatory for all pavement construction which is funded by central Government. This is a national specification because, although usually referred to as the DOT Specification, it is issued jointly by the Department of Transport, the Scottish Office, the Welsh Office and the Department of the Environment for Northern Ireland.

The evaluation of a material for any particular application in pavement construction is, therefore, most readily done by comparing its properties with those of materials known to be satisfactory, as described in the national specification. Research is in progress to define more closely the requirements of the individual pavement layers. This is so that 'end-product' specifications may be used that would permit the use of any material meeting the design requirements of a particular layer. Until the results of the research are incorporated into new specifications, however, there are none currently regarding the use of alternative materials. There is no solution at present other than to accept that if alternative materials are to be used they must be shown to meet the existing specifications (Sherwood, 1995a). Details regarding the specific layers are given below:

Wearing course: this is made of the surface and wearing surface (when the latter is present) and has to provide resistance to the effects of repeated loading by tyres and to the effects of the environment. Additionally, it must offer adequate skid resistance in wet weather as well as a comfortable vehicle ride. It must be resistant to cracking and should be impermeable, except in the case of porous asphalt, which is designed to allow water to permeate through the surface where it is directed into collection areas below. Wearing courses represent only small proportions of the total depths of construction, but they account for fairly high proportions of total costs of pavements. More stringent requirements are imposed than for lower layers of pavements (Hunter, 2000; Sherwood, 1995a).

Basecourse and base: these layers provide the main structural layers in the pavement. The pavement basecourse and bases are normally the thickest elements of flexible pavements on which the surfacing rests. They are the most important layers of flexible pavements. They are expected to bear the burden of distributing the applied surface loads so that the bearing capacities of subgrades are not exceeded. The essential requirements are that the material/materials selected offers/offer the following properties:

- High elastic stiffness.
- High fatigue strength.
- High resistance to permanent deformation.

(Hunter, 2000; Sherwood, 1995a).

Foundation: this is specified as the sub-base and capping and is usually constructed of granular materials. Granular materials consist of crushed rock or gravel and are assessed by particle sizes. Specific functions of sub-base and capping and the requirements from aggregate used within these layers are given below:

Sub-base:

- To provide working platforms on which paving materials can be transported and compacted.
- To be structural layers which assist in spreading the wheel loads so that subgrades are not over-stressed.
- To be insulating layers against freezing where subgrades consist of materials likely to be weakened by frost action (to fulfil this function sub-bases must themselves be frost-resistant).

Capping:

- To protect subgrades from adverse effects of wet weather.
- To provide working platforms on which sub-base construction can proceed.
- To allow full load-spreading capabilities of sub-bases to be realised, which would not be possible if laid directly on weak subgrades.

The thicknesses of sub-bases are not related to traffic intensity, and only to a slight extent on the bearing capacities of subgrades. Deficiencies in this are compensated for by requiring greater thicknesses of capping layers. Both unbound and cement-bound aggregates can be used. The Department of Transport (DOT, 1991) has encouraged the stabilisation of in-situ subgrade materials for the construction of capping layers. The alternative to stabilisation of in-situ subgrades is either to use unbound granular materials or to stabilise with cement-bound imported granular materials, which would be unsuitable for use in unbound forms. The specifications cover various granular materials for capping (Hunter, 2000; Sherwood, 1995a).

Aggregate used in foundations: the aim of a foundation design is to select an aggregate that is appropriate for the strength of the underlying subgrade and the anticipated loads which will be imposed by construction traffic.

The physical requirements for aggregates used as bulk fill materials are fairly easy to meet, but there are some restrictions to the use of certain materials, because of set criteria which must be met:

- Materials must not be in frozen conditions.

- Materials must not be susceptible to spontaneous combustion, except unburned colliery spoil compacted in accordance with methods specified.
- Materials must not show hazardous chemical or physical properties.
- Frost-susceptible materials must not be used within 450 mm of the pavement surface (with bulk fill, however, materials are usually used at greater depths than this).
- Materials must not have high soluble sulphate content if used within 500 mm of concrete, cement-bound or other cementitious materials.

Through a correct aggregate selection, foundations should show the following mechanical properties:

- To have sufficiently high stiffness to limit the transmission of stress to underlying weaker material.
- To contribute to the overall stiffness of the completed foundation to resist cracking to asphalt layers under traffic loads.
- To have sufficient strength and deformation resistance to perform without itself suffering excessive deterioration.

(Hunter, 2000; Sherwood, 1994).

2.3.2.2 Aggregate Recycling

Initially, concerns over the extraction of large quantities of natural aggregates in the pavement industry led to these natural aggregates being recycled. This was before their substitution with alternative ones was considered. In 1980 the Transportation Research Board initiated NCHRP Project 1-17 in the US (Epps, et al., 1980) in order to provide early guidelines for recycling pavement materials. Test findings led to the followings structural conclusions:

- Hot recycled asphaltic concrete is generally structurally comparable to conventional asphaltic concrete.
- Hot recycled asphaltic concrete used as a base course is potentially very effective in either maintaining or increasing the structural capability of a pavement section.

- Hot recycled asphaltic concrete surfaces are slightly stiffer than conventional asphaltic concrete surfaces. As a consequence their fatigue characteristics require careful study.
- In-place, recycled asphaltic concrete materials used as base courses have successfully employed stabilisers including asphalt cement, emulsified asphalt, lime and cement.

Resultant guidelines were intended to provide the following information:

- To point out the potential advantages of recycling.
- To assist both in making a preliminary analysis of recycling as a pavement rehabilitation alternative and in identifying a suitable methodology.
- To provide guidance and criteria for making a detailed analysis of cost, energy, material design, structural design, construction specifications, and quality control.

It may be concluded, therefore, that concern over the extraction of large amounts of traditional aggregates for pavement construction resulted in the development of guidelines towards the recycling of existing pavement materials, for reconstruction and rehabilitation of existing pavements. Major benefits of this recycling were said to be the conservation of aggregates, binders and energy as well as the preservation of the environments from where these aggregates were extracted (Epps, et al., 1980). Despite recycling pavement aggregates for reconstruction and rehabilitation works, vast quantities of natural aggregates were still being extracted, and this led to their substitution by alternative ones.

2.3.3 Alternative Materials

Alternative materials are materials (aggregates) which are the by-product of a previous use and originate from mining, quarrying, industrial processes or from household waste (Table 2.4).

Table 2.4 Examples of alternative materials

Alternative Materials	
Construction/demolition waste	Mine residues
MSW incinerator ash	– tailings
Steel slag	– minestone (coal)
BFS	– slate waste
– power station waste	– spent oil shale
– pulverised fuel ash	– china clay sand
– furnace bottom ash	Black top planings
– fuel gas	Crumbed rubber
– desulphurisation gypsum	Cement kiln dust
Foundry sands	Sewage sludge ash

The availability and use of some alternative materials are illustrated in Table 2.5.

Table 2.5 Availability and use of alternative materials (Baldwin, et al., 1997)

Material	Proportion of Annual Production Reused (%)	Estimated Stockpile (million tonnes)
Blacktop planings	100	n/k
Cement kiln dust	0	small
China clay sand	<1	350
Construction/demolition waste	46	n/k
BFS	100	0
Minestone spoil	8	3600
MSW incinerator ash	n/k	n/k
Pulverised fuel ash	45	n/k
Crumbed rubber	n/k	≈25 million tyres/yr
Sewage sludge incinerator ash	n/k	n/k
Slate quarry residues	<5	440
Spent oil shale	0	100
n/k=not known		

The vast quantities of both waste materials being produced and natural aggregates being extracted, led to research into uses of the former as substitutes for the latter in the form of alternative aggregates. If materials can be used as alternatives to some civil engineering materials, their use will have a three-fold benefit by:

(1) conserving natural resources,

(2) disposing of the waste materials which are often unsightly, and

(3) clearing valuable land for other uses (Sherwood, 1995b; Hammond, 1988).

This was recognised in a report in 1992 at Governmental level that stated: "*to reduce the environmental effects of quarrying new materials the Government is keen to encourage the greatest possible use of waste and recycled materials in accordance with the principles of sustainable development*" (DOE and DOT, 1992).

Some waste materials that may be used as alternative materials in pavement construction are already in use, whilst others are of potential value (Table 2.6)

Table 2.6 Potential uses of waste materials and by-products in road construction in the UK (Sherwood, 1995a)

Material	**Bulk Fill**	**Unbound Capping Layer**	**Unbound Sub-Base**	**Cement-Bound Material**	**Concrete Aggregate or Additive**	**Bitumen-Bound Material**	**Surface Dressing Aggregate**
Crushed concrete	High*	High	High	High	High	Some	None
Asphalt planings	High*	High	High	Low	None	High	None
Demolition wastes	High	Some	Some	Low	Low	Low	None
BFS	High*	High	High	High	High	High	High
Steel slag	Low	Low	Low	Low	Low	Some	High
Burnt colliery spoil	High	High	Some	High	Low	Low	None
Unburned colliery spoil	High	Low	None	Some	None	None	None
Spent oil shale	High	High	Some	High	Low	Low	None
Pulverised fuel ash	High	Low	Low	High	High	None**	None
Furnace bottom ash	High	Some	Some	High	Some	Low	None
China clay sand	High	High	Some	High	High	Some	Low
Slate waste	High	High	High	Some	Some	Low**	None
Incinerator ash	High	Some	Some	None	None	None	None

*   Suitable but inappropriate (wasteful)
**   Pulverised fuel ash and slate dust can be used as a filler

Mining and quarrying wastes (particularly colliery spoil) show both the largest production rate and stockpiles out of all the waste materials studied. Coarse mining and quarrying wastes are dumped on lands as close to the mines as possible (Hammond, 1988). Pavement construction uses large volumes of mining and quarrying wastes directly as materials for embankments, fill and improved subgrades. They have also been used as aggregates for foundation, base and surface courses, fillers, binders and stabilising agents. In the developing world the construction of infrastructure has led to local depletion of naturally available materials in some cases, and mining and quarrying wastes could well satisfy some of this demand (Hammond, 1988).

The concern over the depletion of natural aggregates, which has previously been discussed, along with concern over the increasing quantities of waste materials being accumulated, is exemplified in Chini, et al. (1996), where reasons for recycling old concrete and reusing it as aggregate were given as being two-fold: (1) reducing the extraction of natural raw materials and (2) stimulating the re-use of waste materials. In urban areas where landfill space is scarce and dumping concrete is difficult and costly, reusing it as aggregate is cost-effective and eliminates disposal problems, although recycled concrete is not a concern within this research. Chini, et al. (1996) illustrate concerns over the depletion of natural resources and the need to utilise waste materials as substitutes.

2.3.4 Alternative Materials at an International Level

Similarly to the UK, early international research into the use of alternative materials in pavement construction also dates back to the 1970s, with research and assessment of waste materials and industrial by-products in the US, Africa, Asia and Europe (Hammond, 1988). International bodies such as the Organisation for Economic Co-Operation and Development (OECD), the International Union of Testing and Research Laboratories for Materials and Structures (RILEM), the International Council for Building Research Studies and Documentation (CIB) and the American Society for Testing and Materials (ASTM) all undertook research on different aspects of waste materials during this early period (OECD, 1977; Gutt and Nixon, 1979).

An example of the early international research was in 1979 when Blunk discussed uses of iron and steelmaking slags in pavement construction in the Federal Republic of Germany. Dense BFSs were used in top layer road bases and in surface seals. This application decreased over time as a result of changes in blast furnace technology, when by 1979 crystalline BFSs were combined with granulated slag in unconsolidated surface layers (Blunk, 1979).

In present times, over 20 years after Blunk (1979) described the uses of iron and steelmaking slags, the use of alternative materials in pavement construction is gaining ever-wider acceptability internationally. As with the concerns over the growing production of industrial waste in the UK, similar concerns could be seen in the US, where 4,500 million tonnes of waste per year were produced in 1998 and could be classified into four major groups:

- Domestic (200 million tonnes).
- Industrial (400 million tonnes).
- Mineral (1,800 million tonnes).
- Agricultural (2,100 million tonnes).

(Shelburne and Degroot, 1998).

In 1998 reasons given by officials in Massachusetts, US to increase recycling and composting were:

- The conservation of natural resources and energy.
- The protection of water and air quality by reducing the amount of waste landfilled or burned.
- To helps drive economic development by stimulating manufacturing industries capable of using the recyclable materials as raw material.

(Shelburne and Degroot, 1998).

Clearly it was considered to be both economically and environmentally advantageous if alternative uses could be found for these large amounts of waste.

It appears appropriate to compare the scope of recycled materials available for use as alternative materials in pavement construction for a European country (the UK) with the US. This is because both countries are increasingly introducing recycled materials into pavement construction to provide an end use for the materials themselves and to prevent the over-extraction of natural aggregates. The contents in Table 2.6, which describes potential uses of waste materials and by-products in the UK, can be compared with those presented in Table 2.7, which describes current and potential uses for waste and recycled materials in highway construction in Massachusetts, US. Whilst some of the applications in Table 2.7 have long been used as common practice, others are still considered experimental. Some may eventually be shown to be inappropriate for this use (Shelburne and Degroot, 1998).

The significant difference between the UK and Massachusetts' uses for these materials which can be seen when comparing Table 2.6 with Table 2.7, is that in Massachusetts the use of household waste (plastics, glass, compost and tyres) has been included in the list of materials under review, whereas in the UK they have not. In the Massachusetts article, however, the research was carried out 3 years after the UK research was undertaken, by which time these waste and recycled materials were becoming more widely acceptable for use as alternative aggregates. Another important differentiating factor is that in the Massachusetts data the research investigated all highway uses including landscaping, whereas in the UK's data it only centred around pavement layers. Due to the wide ranging types of recycled materials being assessed for potential use in Massachusetts, along with ones currently been used in highway construction, the transportation industry has particularly been identified as a market in which to develop a sustainable use for waste and recycled materials in the future. Specific issues of concern in the proposed investigations include physical and chemical properties, constructability, quality control, field performance, long-term physical and chemical stability and environmental impact (Shelburne and Degroot, 1998).

New Zealand is another country in which the production of large quantities of waste materials has led to an increasing desire to find alternative uses for these materials. Estimates suggest that 2.5 million tyres are being sent to scrap each year, including 1.2 million from the Auckland region alone. The tyres that are not re-treaded are commonly disposed of in landfill, causing problems with compaction. The Ministry of the Environment has indicated that restrictions on landfill disposal of tyres could be introduced, making the potential for using crumbed tyres in pavement construction highly significant. Other materials under consideration include construction and demolition wastes, glass, BFS, steel slag and plastic (Boyle and Khati, 1998).

Table 2.7 Current and potential uses for waste and recycled materials in highway construction in Massachusetts, US (adapted from Shelburne and Degroot, 1998).

Material	Current and Potential Application
Recycled asphalt cement concrete	Asphalt cement concrete aggregate; Portland cement concrete aggregate; aggregate for base and subbase; Embankment fill
Recycled Portland cement concrete	Asphalt cement concrete aggregate; Portland cement concrete aggregate; aggregate for base and subbase embankment fill; rip-rap
Coal combustion fly ash	Asphalt cement concrete; Portland cement concrete aggregate; sandblasting; embankment fill; deicer
Scrap tyres (crumb rubber)	Asphalt cement binder; crack sealant; stress absorbing membrane interlayer; railroad crossing mats; Portland cement concrete aggregate
Scrap tyres (shredded)	Base course insulator; embankment fill; retaining wall backfill; blasting mats; noise walls; retaining wall blocks
Plastics	Asphalt cement concrete aggregate; Portland cement concrete aggregate; drain pipes; delineator posts; cones; fences; barrels; noise walls; miscellaneous construction items; guardrail offset blocks; speed bumps; sign blanks; car stops; plastic lumber; geotextiles
Glass	Asphalt cement concrete aggregate; Portland cement concrete aggregate; base course aggregate; drainage aggregate; embankment fill; traffic paint
Compost	Topsoil upgrading; turf establishment; landscaping; weed control; erosion control; siltation control
BFS	Asphalt cement concrete aggregate; Portland cement concrete aggregate; base course aggregate; deicer; embankment fill
Steel slag	Asphalt cement concrete aggregate; Portland cement concrete aggregate; base course aggregate; friction aggregate; blasting grit; embankment fill
Foundry sand	Asphalt cement concrete aggregate; Portland cement concrete aggregate; flowable fill; deicer; embankment fill
Shingles	Asphalt cement concrete; cold patch

Works Central Laboratory in New Zealand has undertaken research funded by Transit New Zealand, examining the use of crumb rubber in bituminous binders (Anon., 1993; Boyle and Khati, 1998). Research finds that asphalt pavements incorporating crumb rubber has a higher resistance to rutting and thermal cracking due to the elastic and adhesion properties of rubber. This type of pavement has a higher resistance to reflection cracking which reduces oxidation, ageing and stripping (Boyle and Khati, 1998). This appears similar to research in the UK into the use of shredded tyres in pavement aggregate (Al-Tabbaa, 1998), looking at the mechanical properties of tyres when used in varying quantities.

Works Central Laboratory are also investigating the use of waste oil, of which at present only 20% of the 30 million litre waste which is annually generated in New Zealand is refined and recycled. Additionally, 2-3 thousand tonnes of waste oil distillation bottom are produced annually from refined waste oil. A use for it in pavement construction could be as an extender for bitumen (Boyle and Khati, 1998).

Other recycled waste and materials being tested in New Zealand for possible use in roading and paving work include:

- Aggregates made from iron slag.
- Aggregates made from steel making slag.
- Rubber.
- Plastics.

Their main applications being:

- Stabilisation of roads.
- Patch Repairs (hot or cold application).
- Waterproofing (hot or cold application).
- Slurry seals (hot or cold application).
- Hot asphalt mix, mainly incorporating plastic.

(Boyle and Khati, 1998).

2.3.5 Guidelines to the Use of Alternative Materials

Due to the fact that there are limited guidelines on the use of alternative materials in pavement construction, under the direction of the Road Engineering Standards Committee, in 1985 the British Standard Institution (BSI) published its guide 'Use of Industrial By-Products and Waste Materials in Building and Civil Engineering' (BSI, 1985). BFS, pulverised fuel ash and colliery spoil were the alternative materials with the greatest proportions being used. BFSs were being extensively used in pavement construction, both as aggregate and when granulated, as cementitious binding agents. They may also be processed to provide dense or light-weight aggregate for concrete. Pulverised fuel ash can be used in pavement construction and may also be processed to form light-weight aggregates. There are British Standard (BS) specifications for these BFSs and pulverised fuel ash, BS 1047 and BS 3892.

In 1985 when the Standards were developed, the view of the Department of the Environment (DOE) was that *"waste materials and by-products are unlikely to make a major contribution to augment the supply of natural aggregates in present market conditions. However, in some regions significant quantities are used so there may be potential for the increased use of such materials and this should be encouraged wherever possible"* (BSI, 1985). This indicates that although there was sufficient interest in alternative materials to warrant the development of specification standards, the views of the Institution were sceptical as to any widespread use of these materials. Since their development in 1985, however, the BSs have not been widely used.

In 1995 the DOE published further specifications for waste and recycled materials as aggregates (Collins and Sherwood, 1995). This covered permitted uses of waste materials in pavements and related constructions and also other potential outlets for these materials. The materials covered by the specifications included colliery spoil, spent oil shale, china clay sand and slate waste, pulverised fuel ash, slags and construction and demolition wastes.

It appears, therefore, apart from the BSI guide published in 1985 and the DOE Standards and Specifications published in 1995, there are very limited guidelines controlling the use and requirements of alternative materials in construction.

2.3.6 Mechanical Properties vs. Contamination Potential

The fact that research into the suitability of alternative materials as substitutes for natural aggregates predominantly centres around the mechanical properties of the materials, rather than on any potential risk of contamination to receiving water bodies, has previously been mentioned and will now be discussed further.

Three papers presented at a symposium in 1979 on the utilisation of steelplant slags as construction aggregates can be considered as examples of the emphasis of mechanical bias in assessing alternative materials early in the life of these alternative materials being used in pavement construction. The use of steel furnace slag as aggregate in asphaltic concrete was addressed by Heaton (1979) who looked at skid resistance, resistance to abrasion and affinity for bitumen. Minty (1979) addressed BFS as base material and looked at size distribution, plastic index and maximum dry compressive strength. Finally, Walter, et al. (1979) addressed BFS as an aggregate on road surfacing by looking at skid resistance. All these papers have a similar mechanical emphasis, with no environmental factors being considered. This is not surprising, however, as the research was undertaken in the 1970s, which was early in the history of environmental concern over the use of alternative materials in pavement construction.

More recently, the BSI report (1985) which has previously been discussed, recommended that the following analyses must be carried out: sampling (with interpretation of results), compaction (to aid assessment of transport costs and plastic limit), moisture content control (often carried out by visual inspection), California Bearing Ratio (CBR) testing (to determine required thickness) and frost susceptibility (only a problem if the fill is less than 450 mm from the surface). Other special considerations applied to colliery spoil, pulverised fuel ash and metallurgical slags. Detailed analysis was given as to the possible uses of alternative materials in pavement construction. Conclusions indicated that many of the materials could be used as fill for base and sub-base layers, but only BFSs and steel slags were suitable for use as aggregate in bituminous surfacing (BSI, 1985). In this case the physical properties of the alternative aggregates compared with traditional ones were considered, whereas no similar comparison for potential environmental contamination had been undertaken. This concludes that in the report of 1985, although guidelines controlling the mechanical performances required from alternative materials were present, there were no such guidelines for the assessment or quantification of environmental contamination which could result from the use of alternative materials in pavement construction. This confirms the apparent bias of mechanical properties over contaminant potential within the Standard.

This mechanical bias in research was similarly exemplified in 1990 by Mulheron and O'Mahony, who discussed the physical and mechanical properties of recycled aggregates. The object of their research was to produce draft specifications and standards for the use of recycled aggregates obtained from demolition debris. The research was carried out to:

(1) assess the ability of recycled aggregates, currently in production, to meet existing specifications and standards for Type 1 and Type 2 granular sub-base materials, and

(2) monitor the performance of recycling plants in operation in the UK and investigate the sources of any variation in the recycled aggregates produced.

Surprisingly, although 20 years after the early research into the use of alternative materials in the 1970s, again no mention was made by Mulheron and O'Mahony (1990) of the possibility of materials tested to offer any potential for contaminating water.

By the mid 1990s research began to acknowledge the need for attention to be paid to the properties of alternative materials from an environmental/human health perspective. The previously mentioned DOE publication of standards and specification for waste and recycled materials as aggregates (Collins and Sherwood, 1995), covered permitted uses of waste materials in pavement and related construction. The evaluation of materials was undertaken for physical and chemical properties. As well as commenting on the uses and potential uses for alternative materials, the report noted that in some circumstances it was considered safer to use alternative materials in pavement construction rather than in building work, where some materials were considered a high risk for people within buildings (Collins and Sherwood, 1995). Although the report commented on potential risks to people within buildings constructed from alternative materials, there was no quantifiable assessment of how this concern could be addressed. The bias in this report, as has been the case with other reports documented previously within this chapter, was on mechanical properties over contaminant potentials.

Alternative materials used in road construction were discussed in Sherwood (1995a, b). In Sherwood (1995b) research addressed the suitability of alternative materials for various construction scenarios. However, similarly to Mulheron and O'Mahony (1990) and Collins and Sherwood (1995), the main criteria used for this assessment were mechanical ones, mainly assessing as to whether they complied with various BSI and DoT regulations with regards to strength. Reference was made regarding other factors including costs of using alternative materials, the environmental benefits to be gained and any pollution problems that may arise must also be considered. It was said, however, that such issues were outside the scope of the research (Sherwood, 1995b). It would appear, therefore, that although the author acknowledged the need for environmental assessments, they were outside the scope of the research.

Sherwood (1995a) offered greater environmental concern than Sherwood (1995b), with Health and Safety and pollution of ground water being considered. According to Sherwood (1995a), other authors assumed that any chemicals within naturally occurring materials (such as china clay and slate wastes) that may be soluble and pose risks by polluting water, would have been identified long ago and their use discontinued, whilst other materials which are by-products of industrial processes may still have the potential to pollute. However, in Sherwood (1995a) there were no results of leaching tests and no indications how these concerns could be addressed.

To assess the mechanical bias over environmental concern within research into the use of alternative materials, the following paper from the US has also been reviewed, the research for which was undertaken in the form of two questionnaires:

Paper: "*Utilization of Waste Materials in Highway Industry – A Literature Review*" (Amirkhanian, 1997).

Q1: This related to the use of Solid Waste Materials (SWM) in flexible and rigid pavements in the US.

The objective of these survey was to determine the extent of use of SWM in pavements. The problems encountered by the states which replied (49 states/98%) related to mechanical problems encountered, with no mention of environmental matters. Future research specified by 40 highway agencies as being particularly necessary did include recycling and environmental impacts amongst a list of various areas of concern.

The results can be classed as being purely qualitative – with no comparisons from State to State. Out of the list of items requiring further research, environmental impacts were listed, but were only one of many proposed research areas. There were no indications as to whether any environmental monitoring had already been undertaken at all, and if not, how this could actually be approached in the future. It appears from this questionnaire that within the study there was a mechanical rather than environmental bias.

Q2: This related to health issues associated with the use of SWM in flexible and rigid pavements.

A questionnaire was sent out to all State health departments regarding the health issues associated with the use of SWM in highway construction. The objectives of the study were to determine: (1) the amount and scope of SWM, (2) if current legislation dealt with health issues, and (3) the health-related issues that States may be interested in studying in the future.

Out of the 50 questionnaires sent out only 27 (54%) replied. Two States had legislation that deals with health issues. Two other States have performed research in this area. Eighteen States had an interest in future research regarding health issues. The two environmental concerns mentioned most were surface and groundwater contamination. and material toxicity and immobilisation.

There was even less information regarding the actual questions asked within Questionnaire 2 than Questionnaire 1, with no indication as to the issues asked. Again without any precise data, questionnaires like these remain purely qualitative, offering the reader no quantifiable knowledge. The implications were, however, that health issues associating with contaminant toxicity and water body contamination were issues to be dealt with in the future, but at the time the paper was written were widely lacking in State research.

A literature review in the above paper was undertaken on 13 alternative materials: bottom ash, compost, construction debris, fly ash, glass, incinerator residue, phosphogypsum, plastics, reclaimed asphalt paving, shingle scraps, slag, sludge and tyres. In all cases the end-uses of these materials were documented, whilst only compost, incinerator residue, sludge and tyres were noted as sources of potential contaminants. In the case of incinerator residue, there was concern over leaching of heavy metals, but due to research both in the private and public sectors these problems were expected to be overcome. There was no indication as to what the research comprised of and what could be done to address the contamination potential posed by the other materials causing concern. It appears from this second questionnaire that within the study there was also a mechanical rather than environmental bias to the research.

From the previous sections it appears that the proposed bias towards mechanical properties over environmental concern within research into the suitability of substituting primary aggregates in pavement construction with alternative ones was evident in the early life of their use. This was exemplified in the 1970s (Heaton, 1979; Minty, 1979; Walter, et al., 1979). In more recent research through the 1990s (Mulheron and O'Mahony, 1990; DOE, 1995; Sherwood, 1995b) this bias towards mechanical properties over environmental concern was still evident. Conclusions can be drawn that research into the suitability of using alternative materials often centres around the physical/mechanical properties of the materials rather than on their environmental impact. Although Sherwood (1995a) stated that there was a possibility of contaminants leaching from alternative materials, there were no indications as to how this concern may be addressed.

This lack of environmental consideration may have been expected in research dating back to the 1970s, early in the life of alternative materials being used within pavement construction. In the 1990s, however, when a much stronger environmental movement was in existence, with regulations controlling industrial discharges in both the UK and overseas, it would be expected that the area of environmental impact would have been higher on industrial agendas. This would have led to an increase in relevant research.

2.3.7 Legislation Controlling the Use of Alternative Materials

In the UK environmental protection is partly controlled through legislation which is enforced by the EA (England and Wales), the Scottish Environmental Protection Agency (SEPA) (Scotland) and the Department of the Environment in Northern Ireland (DOENI). The main areas within the legislative system that act to control the use of alternative materials in pavement construction can be divided into two sections: (1) waste management licensing, and (2) water quality. In the UK earlier legislation has been upgraded to comply with EC Directives. Under EC law, a Directive is not legally binding on individuals and organisations, but Member States must ensure that their national legislation enables Directives to be implemented (Baldwin, et al., 1997) and it is that legislation which is binding.

Legislation in the environmental field changes very rapidly. Therefore this brief review will inevitably be somewhat dated by the time it is read. The following discussion should, therefore be reviewed as indicative rather than normative.

2.3.7.1 Waste Management Licensing

In the UK the main acts controlling the disposal of waste which have specific implications for pavement construction were summarised in 1997 by Baldwin et al. and are reproduced in Table 2.8.

Table 2.8 Legislation controlling the use of waste materials in road construction (Baldwin, et al., 1997)

Act	Outline of Control
• The Environmental Protection Act 1990 updated to: • The Environment Act 1995. • Joint Circular 11/94 (Environment Protection Act 1990: • Part II Framework Directive on Waste) 1994. • Part IIA Environmental Protection Act 1990	**Controlled Waste** *(household, industrial, and commercial waste - excludes waste from mines and quarries).*
• The Waste Management Licensing Regulations (WMLR) 1994 including: • Council Directive 75/442/EEC and • Schedule 3.	**Directive Waste** *(any substance or object which the producer or person in possession of it discards, or intends or is required to discard).*

Implications: if not 'used', Directive Waste materials are considered to be waste and are subject to Waste Management Licensing Regulations (WMLR) and require a licence for disposal, or while remaining waste (stockpiled), will be exempt from this requirement. This will apply to stockpiled materials which offer the potential to be used as alternative aggregates. N.B: not all Directive Waste is Controlled Waste (Baldwin, et al., 1997).

Directive Waste that is not also Controlled Waste is not subject to the Environmental Protection Act (1990) and mine or quarry waste is, therefore, excluded. The Council Directive sets limits on this exclusion from the WMLR and only mineral wastes are excluded. Therefore, mineral mining and quarrying waste will not be classed as controlled wastes. This means that materials such as minestone spoil, slate quarry residues, china clay sand and spent oil shale will remain outside the scope of the Environmental Protection Act (1990) control and may be used in pavement construction without a licence (Baldwin, et al., 1997).

The exemption of a Waste Management Licence under Schedule 3 of the WMLR includes certain recovery activities of some materials destined for specific processing or reuse. This includes ash, slag and gypsum which are three waste materials which can be used within pavement construction. Certain waste materials (e.g. ferrous slag, sewage sludge, incinerator ash, pulverised fuel ash and MSW incinerator ash) are exempt from licensing if they are to be used in *relevant* work for which they are deemed *suitable*. These regulations mean, therefore, that in many cases certain waste materials which can be used within pavement construction are exempt from licensing if they are proven to be suitable for such use. Temporary storage of waste on the site where it is produced, prior to its collection, is also exempt from licensing. Exemption from licensing must be registered with the EA (England and Wales) and the SEPA (Scotland) (Baldwin, et al., 1997).

Schedule 3 also relates to the storage of waste. Waste must be stored at the place where the activity is to be carried out. The maximum volume that can be stored is 20,000 tonnes. Schedule 3 is relevant to the storage and use of certain types of waste which may be used in pavement construction including ash, slag and gypsum. In the case of a waste that is not produced on site, its storage is not permitted for longer than 3 months before use. There is no constraint on the period of storage of a waste produced on site (Baldwin, et al., 1997).

Part IIA of the Environmental Protection Act (1990) was introduced in 1999 and enforced as from April 2000. This act has the potential to offer the most stringent control over the use of alternative aggregates yet. This is because the use of any material containing potential contaminants which may leach into groundwater which are listed as 'banned' are strictly prohibited from use. The implications of Part IIA are addressed below.

2.3.7.2 Water Quality

In the UK the main acts protecting water quality which have specific implications for pavement construction were summarised in 1997 by Baldwin et al. and are reproduced in Table 2.9.

Table 2.9 Legislation protecting water quality when using alternative materials in pavement construction (Baldwin, et al., 1997)

Act	**Outline of Control**
The Environmental Protection Act 1990	Environmental protection. 'Red' List.
The Water Resources Act 1991	River quality regulations and groundwater protection.
The Water Act 1998	Enforcing a system of discharge consents, monitoring and sampling procedures.
Directive 76/464/EEC	*"Pollution caused by certain dangerous substances discharged into the aquatic environment of the Community".*
Directive 80/68/EEC	*"Protection of groundwater against pollution by dangerous substances".*
Daughter' Directives	List I – ('Black List') substances. List II – ('Grey List') Substances.
Part IIA of the Environmental Protection Act 1990 (enforced from April 2000)	Offers the strictest control yet over waste, especially with List 1 and 2 substances.
Water Framework Directive Directive 2000/60/EC	Will update existing water legislation and introduce an integrated approach to water management.

Implications: by law the UK is committed to control the discharge of a range of dangerous substances into the aquatic environment. The first EC legislation to control discharges to water was Directive 76/454/EEC which was later updated by Directive 80/68/EEC. Further 'Daughter' Directives set European standard for what are known as 'List I' (or 'Black List') substances (dangerous substances characterised by being toxic, persistent and bioaccumulative) and 'List II' (or 'Grey List') (less toxic) substances (Appendix 2) (Baldwin, et al., 1997). The most recent act protecting groundwater which was introduced in 1999, and enforced as from April 2000, was

Part IIA of the Environmental Protection Act 1990 (see below), offering the strictest control yet over these substances. These regulations will have the effect of controlling the use of alternative materials in pavement construction if there is a chance that they contain any substances from Lists I or II which may leach into the local water system.

Until the introduction of the Part IIA regulations, two methods of control for limiting the discharge of List I substances into water systems were in place:

- Limit Values were set consisting of uniform fixed emission limits to be complied with, irrespective of the source of the discharge or the nature of the receiving water.
- Quality Objectives, similar to the UK WQS, were introduced where set concentration limits were not to be exceeded in the receiving water. These limits did not vary according to the use of the water, but may have varied between marine and fresh water for example.

In the UK the latter method was favoured, whereas the other Member States preferred the former one. Limits to the discharge of List II substances into water systems was controlled by Member States having to develop programmes that included appropriate water quality objectives.

In the UK prior to the Part IIA regulations, the WQS were based upon the use to which a particular stretch of water was to be put (e.g. abstraction for drinking water or agricultural purposes, or the type of aquatic life to be protected). This is in slight contrast to the Quality Objectives where the limits did not reflect the use of the water (Baldwin, et al., 1997).

Prior authorisation by the authorities in each Member State was required before discharging any substances in List I or II. This was via the EA (England and Wales) and the SEPA (Scotland).

In 1988 the DoE identified a list of the most dangerous substances from List I into a 'Red List' and later incorporated them into the Environmental Protection Act (1990). In 1991 the Government issued a consultation document for substances on the 'Red

List' List for which Quality Objectives had not yet been set at EC level (Baldwin, et al., 1997).

The introduction of the important new groundwater regulations described above now offer stricter control than previous regulations. They also complete the implementation of the Groundwater Directive 80/68/EEC. These regulations help prevent pollution of groundwater by controlling discharges of dangerous substances where they are not already covered by existing legislation (EA, 1998).

The new Water Framework Directive is a long-term management strategy set at European level and to be transposed into legislation country-by-country. In December 2003 the UK Government put the framework into legislation and has a timetable for the implementation of the full framework, which gives up to 2027 to achieve the main objectives. Areas covered under the framework include river basin characterisation, river basin planning, environmental monitoring, classification and reporting, priority and other specific polluting substances, programme of measures and groundwater daughter directive along with others.

2.3.7.3 Drinking Water Standards

In the UK the main acts protecting drinking water quality which have specific implications for pavement construction were summarised in 1997 by Baldwin et al. and are reproduced in Table 2.10.

Table 2.10 Legislation controlling drinking water quality which will apply to the use of alternative materials in pavement construction (Spedding, 1999).

Act	**Outline of Control**
Directive 75/440/EEC	*"Quality required of surface water intended for the abstraction of drinking water".*
Directive 79/869/EEC	*"Methods of measurement and frequencies of sampling and analysis of surface water intended for the abstraction of drinking water"*
Directive 80/778/EEC	*"Quality of water intended for human consumption".*

Implications: the Drinking Water Directives within Table 2.10 set stringent standards for the quality of drinking water. Member states monitor drinking water and take the necessary steps to ensure compliance with mandatory standards.

Both the EA and the World Health Organisation set safe maximum limits for chemicals within drinking water which are deemed safe for human consumption. The limits are based on allowable parts per million (mg/l) or parts per billion (μg/l) of the chemical in water, above which levels would be harmful to human health. This has implications on alternative materials used in pavement construction, because if they contain chemicals which may leach into groundwater with levels above the safe limits, they are banned from use.

2.3.7.4 Implications of Part IIA of the Environmental Protection Act (1990)

It is important to discuss the implications of the new regulations on the use of alternative materials in pavement construction in comparison with their implications on the use of primary materials. As previously described, some traditional materials may contain toxic chemicals at higher levels than in alternative materials. In one instance limestone was found to contain higher levels of phenol than those found in BFS (York, 1999).

It is expected, however, that the EA may show some leniency towards the use of traditional materials even if analysis shows higher levels of some substances than regulations permit. It would be difficult to prevent the use of traditional materials (such as limestone) from construction after they have been used for many years. It is unlikely, however, that the same leniency will be shown towards alternative materials containing chemicals in List I.

After the enforcement of the Part IIA act, anyone who disposes of listed substances (including materials which contain these substances) onto or into land must apply for authorisation, if they want to continue with this disposal. Under the new regulations virtually no substances on List I are to be allowed into groundwater at all. Any construction material that may leach substances from List I are banned completely from use, or from List II, will be carefully monitored (EA, 1998).

The importance of the research described here is great when considered in relation to these new regulations. By banning the use of any alternative material containing substances on List I, the regulations allow no quantifiable assessment to determine at what levels the substances constitute a 'risk'. By carrying out a risk assessment for alternative materials, quantifiable levels of risk may be determined, below which it may be safe to use the materials and above which the risks may be too great. A blanket regulation of 'no use' of List I substances does not allow for any areas proven to be of low risk, in which the use of the alternative materials would carry no health or harm implications.

As already stated, if any risk assessments are currently undertaken for the use of alternative materials in pavement construction, they tend to be inadequate for the material and scenario required. Environmental testing is often carried out using inappropriate tests which are not designed for real-pavement construction scenarios. Levels of contaminants in the leachates from alternative materials determined from inappropriate testing may not necessarily represent the true levels of contaminants leaching in pavement drainage which actually discharge into groundwater. Computations have been undertaken to evaluate vertical and horizontal drainage of contaminants within and from a pavement. In some instances it has become evident that as long as there is a sufficient depth of clay subgrade present at a construction site, any initial levels of contaminants from List I which may be within the initial leachate draining from an aggregate will be adsorbed onto the clay. This consequently illustrates that subsequent drainage discharging from the subgrade into groundwater is free from contamination. This indicates that the method designed within this research for assessing the risks from using alternative materials in pavement construction may thus be deemed an important tool when assessing the suitability of different alternative materials for pavement construction.

2.4 Risk Assessments

2.4.1 Risk Definitions

In 2001, Rudland, et al. defined ‘risk assessment’ as the “*identification, estimation and evaluation of risks*”, which reflects their definition of ‘risk’ as the “*probability that due to a hazard an adverse effect will occur under defined conditions*”. This reflected their definition of ‘harm’ as “*harm to the health of living organisms or other interference with the ecological systems of which they form part*” (based on Section 78A of the Environmental Protection Act, 1990).

At first sight Oregon DEQ (2003) seemed to define risk as the "*product of a chemical’s toxicity and the amount of exposure that <u>someone</u> receives from that specific chemical*". However, in making a risk assessment, risk is evaluated at an environmental, not human, level. Oregon DEQ (2003) suggest that to quantify risk at a contaminated site you must at least have the following information:

- The nature of the release.
- The magnitude of the release.
- The extent of the contamination.
- The toxicity of the identified contaminants.
- The possible ways that exposure might occur.

In order to review these recent definitions of risk assessment, they were compared with earlier definitions within the 1990s.

In 1993 DeSesso expressed the view that the paradigm for conducting risk assessments, as articulated by the National Research Council (US), was geared primarily towards the assessment of potentially adverse health in humans. Lovell (1993) understood risks to be related to human health and defined ‘risk’ as “*the chance that a particular adverse effect actually occurs in a particular time period*”. In that definition ‘risk’ is presented in terms of ‘chance’, which is also another way of expressing 'probability'. Some risk events are known to be quantifiable, with risk tables available showing the probability of an event happening. An example of this is the probability of being struck by lightning, an event which is commonly quoted.

The view that risk assessments initially centred around human health problems and were concerned with the estimation of the damage to human health by hazardous pollutants, was later echoed by Stefanis and Pistikopoulos (1997) who felt that risk assessments were traditionally defined as *"The likelihood of an adverse health effect such as a carcinogenic death, due to an exposure to an environmental hazard"*. They felt that more recently risk assessments were taken to include risks posed to the environment. By taking into account both the scheduled and unscheduled events which could lead to the degradation of air, water and soil, Stefanis and Pistikopoulos (1997) interpreted environmental risks to represent the "*probability of environmental damage due to undesired events multiplied by the severity of the degradation*".

From the views expressed by Stefanis and Pistikopoulos (1997) (documented above) and later endorsed by Smrchek and Zeeman (1998), it is evident that in the early 1990s risk assessments were undertaken to address issues regarding harm to human health, but by the mid 1990s they began to incorporate issues concerned with degradation of environmental systems too. The logic appears to be: prevent significant environmental degradation and human health will automatically be ensured.

Smrchek and Zeeman (1998) expressed the opinion that the assessment of 'risks' posed by chemicals to ecosystems and landscapes or drainage basins is an important goal for studying widespread pollution problems. It follows, therefore, that as the different definitions for quantifying risk reflect whether the receptor of the contamination is either human health alone or is extended to include natural environments too, so the actual input parameters will vary accordingly.

Different risk assessment approaches are presented later in this chapter and the three main ones assessed within this research take the form of qualitative, semi-quantitative and quantitative, depending on the information available and whether they are generic or site-specific. The risk assessment process developed within this research is primarily concerned with the risk to water bodies through the use of alternative materials. If water bodies are contaminated by chemicals leaching out of the alternative materials, however, a risk to human health would probably follow (e.g. if the water body was close to a drinking water abstraction point). This means that although risk assessments may primarily be aimed at environmental conditions, it is likely that risks will consequently be posed to humans as well. In Chapter 6 the risk assessment approach adopted within this research is compared with the three main approaches in order to consider its place within current risk assessment procedures.

2.4.2 The Perception and Communication of Risk Assessments

The issue of risk assessment is widely discussed in articles within Hester and Harrison (1998), where they state that it is considered by many to be a scientific tool, being influenced by the broader ethical, social, political, economic and institutional issues which characterise risk management. Gerrard and Petts (1998) agree with this and feel that risk management encompasses disciplines from the natural, engineering, political, economic and social sciences. According to them, an important issue is to identify and address the public's understanding of risk as a major part of risk management and to ensure that the public understands the fundamental differences in quantitative rather than qualitative assessments and must be reassured over unbiased results.

Gerrard and Petts (1998) consider that one of the key issues highlighted by the multidisciplinary nature of risk management is whether risk assessment as a scientific process can and should be separated from risk management. In general, the basis of the arguments for and against separation are rooted in fundamental views of the role of science and society. It is recognised that risk assessment is clearly a part of the process of managing risks, and is noted that there are many different risk assessment approaches in different decision-making contexts. Quantitative risk assessment relates to an activity or substance and attempts to quantify the probability of adverse effects due to exposure. By carrying out quantitative risk assessments, numerical values are given for particular risks. The risk management cycle identifies the different issues that need consideration as seen by Gerrard and Petts (1998) (Fig. 2.5).

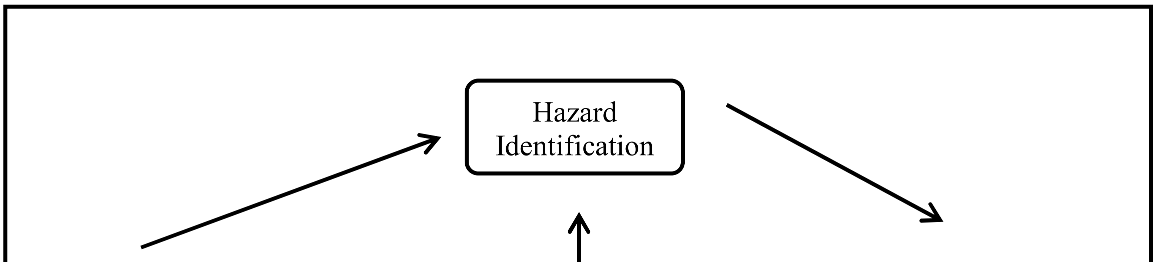


Fig. 2.5 The risk management cycle (adapted from Gerrard and Petts, 1998)

The risk management cycle shown in Fig. 2.5 assumes that with correct feedback the cycle will encompass all areas of the management of risk, with risk assessment being an equal parameter within the 'Risk Perception and Communication' goal. This cycle appears too simplistic, however, because it fails to clearly identify at what stage action should be taken to prevent contamination or remediation undertaken to clean up contaminated land. In many situations policy development and implementation are not always sufficient for the prevention of contamination problems. This is particularly the case with the present-day emphasis on the re-use of land (sometimes already contaminated), often known as 'brownfield' sites.

In the beginning of the 1980s in the US the scientific aspects of risk assessment were being corrupted by social policies (Gerrard and Petts, 1998). The rise of risk assessment as a tool for decision makers was criticised both from industry and from environmental groups. Those in industry argued that it was too conservative and created public fear and unnecessary financial hardship. Environmental and community groups saw the tool as being too simplistic and narrow to deal with the complex reality of risk issues.

These views held by Gerrard and Petts (1998) are similar to those of Tal (1997), who feels that the US environmental movement’s opposition to quantitative risk assessments has been fairly consistent since the 1980s. The strength of the movement has undermined federal and state credibility, including the effectiveness of risk communication efforts. Environmentalists generally do not believe quantitative risk assessment methods sufficiently characterise the danger of environmental hazards to humans and ecological systems. They widely agree that too much effort goes into quantifying risks, and too little is done to reduce or eliminate them. Many environmentalists feel that risk assessments consist of too much excessive uncertainty (Tal, 1997).

In the UK since the 1980s, there have also been similar problems arising from insufficient risk communication within the risk management framework (Petts, 1994; LaGrega, et al., 1994). Early discussions of risk communication place much emphasis upon the need to learn how to convey risk estimates to the public. It was thought that if the information in risk assessments could be communicated more effectively, the ‘irrational’ resistance of the public to technological risk would be dispelled. Greater effort to understand the basis of public concern, to accept concerns as legitimate and to involve local communities and the public in decision-making is now generally accepted as the way forward (Petts, 1994; LaGrega, et al., 1994).

According to Gerrard and Petts (1998) a similar discomfort to that felt by scientists in the US was felt by some scientists in the UK concerned with the gradual incursion into their domain of social and political dimensions. This was illustrated in the preface to The Royal Society's second risk management volume, published in 1992 (TRS, 1992), which followed the first volume published in 1986 (TRS, 1986). The preface to the second volume contained the explanation that the contents should not be read as a report of the Society's, but of the chapter authors' views.

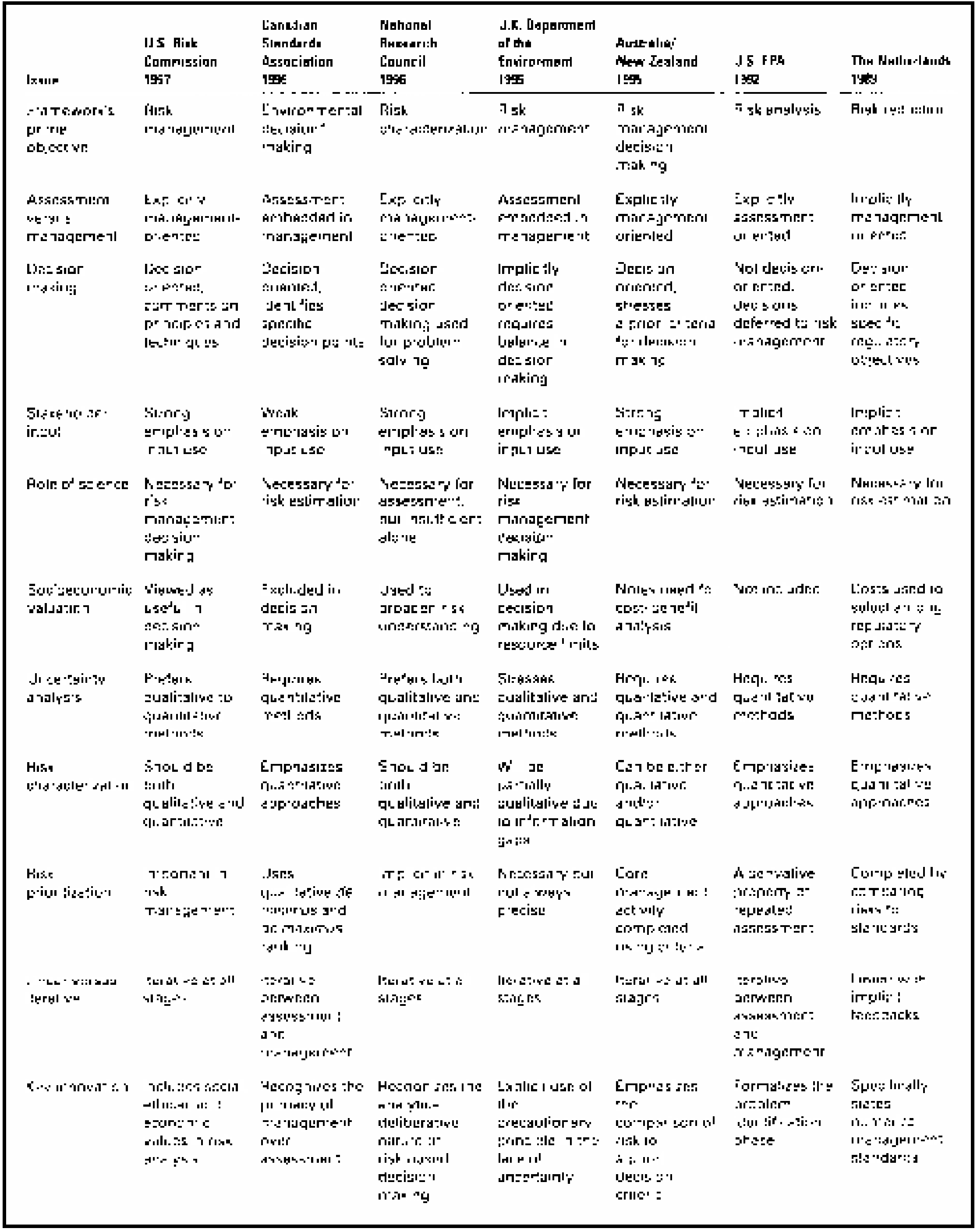
2.4.3 How to Include Legislation Within Risk Assessments

It would appear that before legislation can be implemented to enforce risk assessment procedures, society must decide which environmental criteria are most important (McCarty and Power, 1997). It is important that an appropriate framework for environmental decision-making exists. Unfortunately, the debate concerning the development of a decision-making framework, so that science-based policies can be developed, is far from complete (McCarty and Power, 1997). Although environmental impact is now included in many project design objectives, it would appear that, traditionally, environmental risk assessments have centred around qualitative guidelines. The new framework must incorporate the quantitative (science-based) assessments of both routine and non-routine releases in order to obtain a methodology (Stefanis and Pistikopoulos, 1997).

Although countries vary considerably in their commitment and input to risk assessment issues, most countries do have a growing framework on which policies are developed. A comparison can be made between the frameworks on which seven authorities base their risk assessment/management roles (Table 2.11) (Power and McCarty, 1998). It can be seen in Table 2.11 that in spite of differing objectives, ages, nations of origin and sponsoring agencies, a number of critical themes are common to all frameworks. For example, in the assessment versus management issue, all parties except the US Environment Protection Agency preferred a management oriented direction and all without exception agreed that it was necessary for science to play a part in both risk assessment and management issues.

Published literature suggests that the subject of risk assessment has traditionally been aimed at assessing specific problems usually after an event occurs, such as a site with a history of contamination, as may be the case with a 'brownfield' site, or for a one-off incident such a clean-up procedure after a BSE contamination problem, through the improper disposal of animal carcasses (Gerrard and Petts, 1998). There is a lack of availability of pro-active tools for the assessment of sites or conditions before any contamination problems occur. It would appear, however, that risk assessment documents and computer models are now beginning to reflect current legislation such as WQS, where the framework is set at a European level but the WQS are legislated at a UK level by the EA, SEPA and DOENI. This is instead of older risk assessments which have been based upon more traditional permissible limits. A review of current risk assessments is undertaken below. All approaches are for land contamination scenarios, most of which take into account the potential for human ingestion of contaminants, and allow for the potential of natural attenuation (such as dilution by water bodies). Although acceptable for sites with a history of contamination, they are not suitable when assessing a potential contaminant prior to use, as would be the situation for which the risk assessment guide presented in this thesis has been developed.

Table 2.11 A comparison between the different frameworks used by seven different parties when addressing their risk assessment and management processes (Power and McCarty, 1998)



Issue	U.S. Risk Commission 1997	Canadian Standards Association 1997	National Research Council 1996	U.K. Department of the Environment 1995	Australia/ New Zealand 1995	U.S. EPA 1992	The Netherlands 1989
Framework's prime objective	Risk management	Environmental decision making	Risk characterization	Risk management	Risk management decision making	Risk analysis	Risk reduction
Assessment versus management	Explicitly management-oriented	Assessment embedded in management	Explicitly management-oriented	Assessment embedded in management	Explicitly management oriented	Explicitly assessment oriented	Implicitly management oriented
Decision making	Decision oriented, comments on principles and techniques	Decision oriented, identifies specific decision points	Decision oriented decision making used for problem solving	Implicitly decision oriented requires balance in decision making	Decision oriented, stresses a priori criteria for decision making	Not decision oriented, decisions deferred to risk management	Decision oriented includes specific regulatory objectives
Stakeholder input	Strong emphasis on input use	Weak emphasis on input use	Strong emphasis on input use	Implicit emphasis on input use	Strong emphasis on input use	Implied emphasis on input use	Implicit emphasis on input use
Role of science	Necessary for risk management decision making	Necessary for risk estimation	Necessary for assessment, but insufficient alone	Necessary for risk management decision making	Necessary for risk estimation	Necessary for risk estimation	Necessary for risk estimation
Socioeconomic valuation	Viewed as useful in decision making	Excluded in decision making	Used to broaden risk understanding	Used in decision making due to resource limits	Notes need for cost-benefit analysis	Not included	Costs used to select among regulatory options
Uncertainty analysis	Prefers qualitative to quantitative methods	Requires quantitative methods	Prefers both qualitative and quantitative methods	Stresses qualitative and quantitative methods	Requires qualitative and quantitative methods	Requires quantitative methods	Requires quantitative methods
Risk characterization	Should be both qualitative and quantitative	Emphasizes quantitative approaches	Should be both qualitative and quantitative	Will be partially qualitative due to information gaps	Can be either qualitative and/or quantitative	Emphasizes quantitative approaches	Emphasizes quantitative approaches
Risk prioritization	Important in risk management	Uses qualitative definitions and dominance ranking	Implicit in risk management	Necessary but not always precise	Core management activity completed using criteria	A derivative property of repeated assessment	Completed by comparing risks to standards
Linear versus iterative	Iterative at all stages	Iterative between assessment and management	Iterative at all stages	Iterative at all stages	Iterative at all stages	Iterative between assessment and management	Linear with implicit feedbacks
Key innovation	Includes social, ethical, and economic values in risk analysis	Recognizes the primacy of management over assessment	Recognizes the analytic-deliberative nature of risk-based decision making	Explicit use of the precautionary principle in the face of uncertainty	Emphasizes the comparison of risk to a priori decision criteria	Formalizes the problem identification phase	Specifically states numerical management standards

2.4.4 Methods Available to Assess Risk

2.4.4.1 Risk Assessment Approaches

There are three main approaches used when undertaking a risk assessment and these are as follows:

2.4.4.1.1 Qualitative

This is an assessment which uses generic guidelines and/or standards to make judgements about the significance of the risk information held about a site. Although a great deal of quantitative information in the form primarily of site investigation data will underpin this assessment, only a descriptive or narrative statement about the risk to sensitive receptors is made. Generic guidelines or standards indicate nationally, or sometimes regionally, acceptable levels of risk to certain receptors assuming defined (often worst-case) exposure scenarios. These guideline values are used directly in relation to the site and receptor of concern. No site-specific estimate of risk is calculated. The assumptions inherent in the generic guidelines are used as a surrogate for the conditions relevant, or potentially relevant, to the site of concern. Qualitative risk assessments require a detailed understanding of the basis of the generic values and the assumptions inherent within them, if robust decisions are to be made. They form the most numerous and common assessments made about sites (Cairney, 1995; Petts, et al., 1997).

Conclusions from a qualitative assessment may include the following:

(1) the database is insufficient for a firm judgement to be made, although no concentrations exceed the relevant guideline value, and/or there is so little data that the investigation was a waste of time and money,

(2) the database is sufficient for decisions to be made,

(3) although guideline values are exceeded for a number of samples, it is judged that this does not matter,

(4) action values are exceeded – remediation is required, and

(5) a site-specific quantified risk assessment should be carried out (Cairney, 1995; Petts, et al., 1997).

Results from qualitative risk assessment are often presented in categories such as 'low', 'medium' or 'high'. This allows a simplistic assessment of a site to be undertaken at a relatively lower cost compared to site-specific ones (Cairney, 1995; Petts, et al., 1997).

2.4.4.1.2 Semi-Quantitative

This approach can be relevant when considering the risks from either a single site, or for comparing a large number of sites. It is for the latter that most systems have been produced. Most use a numerical approach and put all information and situations onto a common scale by assigning scores or sub-scores to risk factors relevant to the 'source-pathway-receptor' scenario of concern. Once each risk factor is scored, the sub-scores are combined into a final score which provides a semi-quantitative assessment of the risks related to a site or group of sites. At the most simplistic, the scores are descriptive ('high', 'medium' or 'low' as in the qualitative approach). Semi-quantitative approaches provide an indicator, rather than an estimate, of risk. An important part of it allows the screening out of insignificant potential risks so as to help focus a full risk assessment either qualitatively or quantitatively. This method, therefore, offers the rigour of the quantified approach whilst still retaining the flexibility needed to overcome scientific information deficiencies (Cairney, 1995; Petts, et al., 1997).

The terminology used in different countries in relation to different tools varies. Some countries refer to 'hazard ranking', others to 'preliminary risk assessment' and other to simply 'qualitative risk assessment'. Some systems require no site-specific measurements to be made and require only the same information as would result from a desk study. Other systems use measured concentration of contaminants and translates the information available from the detailed site investigation and the comparison with generic guidelines, into a set of scores to provide a common basis for comparison of potential risks across a number of sites. Semi-quantitative systems are frequently derived for use by non-experts to allow decisions to be made as an expert would in a robust and consistent manner (Cairney, 1995; Petts, et al., 1997).

2.4.4.1.3 Quantitative

This is a site-specific approach and will usually follow some form of qualitative or semi-quantitative assessment. It is not a cost-effective approach to be used in all situations, as it can be expensive, time consuming and problematic. It is likely to be required, however, where:

(1) generic guidelines do not cover the contaminant(s) of concern and/or are insufficiently protective relative to the receptor(s) of concern in terms of their sensitivity and activity patterns,

(2) generic guidelines would be overly protective as a result of conservative assumptions used in their derivation,

(3) observed concentrations of contaminants exceed the generic guidelines to an extent which indicates the potential for risk to be realised,

(4) local background levels are high compared to the generic guidelines, and

(5) a site is causing considerable public concern and there is demand for a fuller understanding of the risk presented by the site (Cairney, 1995; Petts, et al., 1997).

In quantified risk assessments there are two statistical methods used to obtain risk values – probabilistic and deterministic. In the former, a series of simulation using different input values, drawn from a probability distribution to reflect uncertainty are computed and distributions of risk reflecting uncertainty and/or variability are produced. This method is known as the 'Monte Carlo' method and is computationally more complex than the deterministic method. The latter computes a single value for the level of risk, which may contain an inherent uncertainty in the value determined.

Various methods are available in order to undertake quantified risk assessments. One approach regularly used is a 'tiered' system and the principles behind it are presented below. This is followed by a simple equation approach, in order to illustrate the fact that sophisticated risk assessment methods are not always necessary, although detailed input parameters are.

Tiered-System Approaches:

The use of tiered risk assessment systems is an approach used to undertake risk assessment widely documented amongst literature, and can be adapted and presented in the form of a computer or hard-copy model. Descriptions of two tiered systems are given below, followed by examples of computer and hard-copy models.

An example of a two-tiered system used for the assessment of contaminated sediment is described in Dillon (1994). Tier 1 is used to determine whether there is 'Direct sediment bioaccumulation in contaminated sediments', whilst at Tier 2 'Indirect exposure via trophic transfer' is determined. The Tier 2 evaluation is initiated only if direct sediment bioaccumulation is demonstrated at the Tier 1 evaluation stage. The principle behind this tiered system can be summarised by stating that at Tier 1 the issue is whether or not there is a risk, the answer to which is 'Yes' or 'No'. If the answer is 'Yes', then at Tier 2 an evaluation must be undertaken to determine the magnitude of the risk.

Another available tiered system frequently referred to within the literature is a three-tiered system developed by the American Society for Testing and Materials (ASTM), called Risk-Based Corrective Action (RBCA) (Fig. 2.6) (ASTM, 1995). The system was developed for use at petroleum release sites, but is adaptable for circumstances other than just those for which it was developed. The RBCA system commences with an initial site assessment and classification with an initial response initiated, such as interim remediation if appropriate. The Tier 1 evaluation commences with the identification of potential sources, transport pathways and exposure pathways. Tier 1 risk-based screening levels (RBSL) obtained from look-up tables are compared with site conditions. If the RBSLs are exceeded by chemicals, and remediation back to Tier 1 RBSL is not possible, further interim remedial action is appropriate, and Tier 2 evaluation is initiated. At the Tier 2 evaluation additional site data is collected. Site conditions are compared with Tier 2 site-specific target levels (SSTL). If the Tier 2 SSTL are exceeded by chemicals and remediation back to Tier 2 SSTL is not possible, further interim remedial action is appropriate, and Tier 3 evaluation is initiated. At the Tier 3 evaluation, addition site data is collected. Site conditions are compared with Tier 3 SSTL, and if chemicals of concern exceed Tier 3 SSTL, a remedial action program is initiated, and this may require continued monitoring. If continued monitoring is unnecessary, no further action is required.

Within any tiered-system, at each higher tier a more detailed and sensitive site risk assessment is undertaken. It follows, therefore, that a system consisting of 3 tiers as developed and described in ASTM (1995) will offer a more sensitive site assessment than one with only two tiers, as developed and described in Dillon (1994).

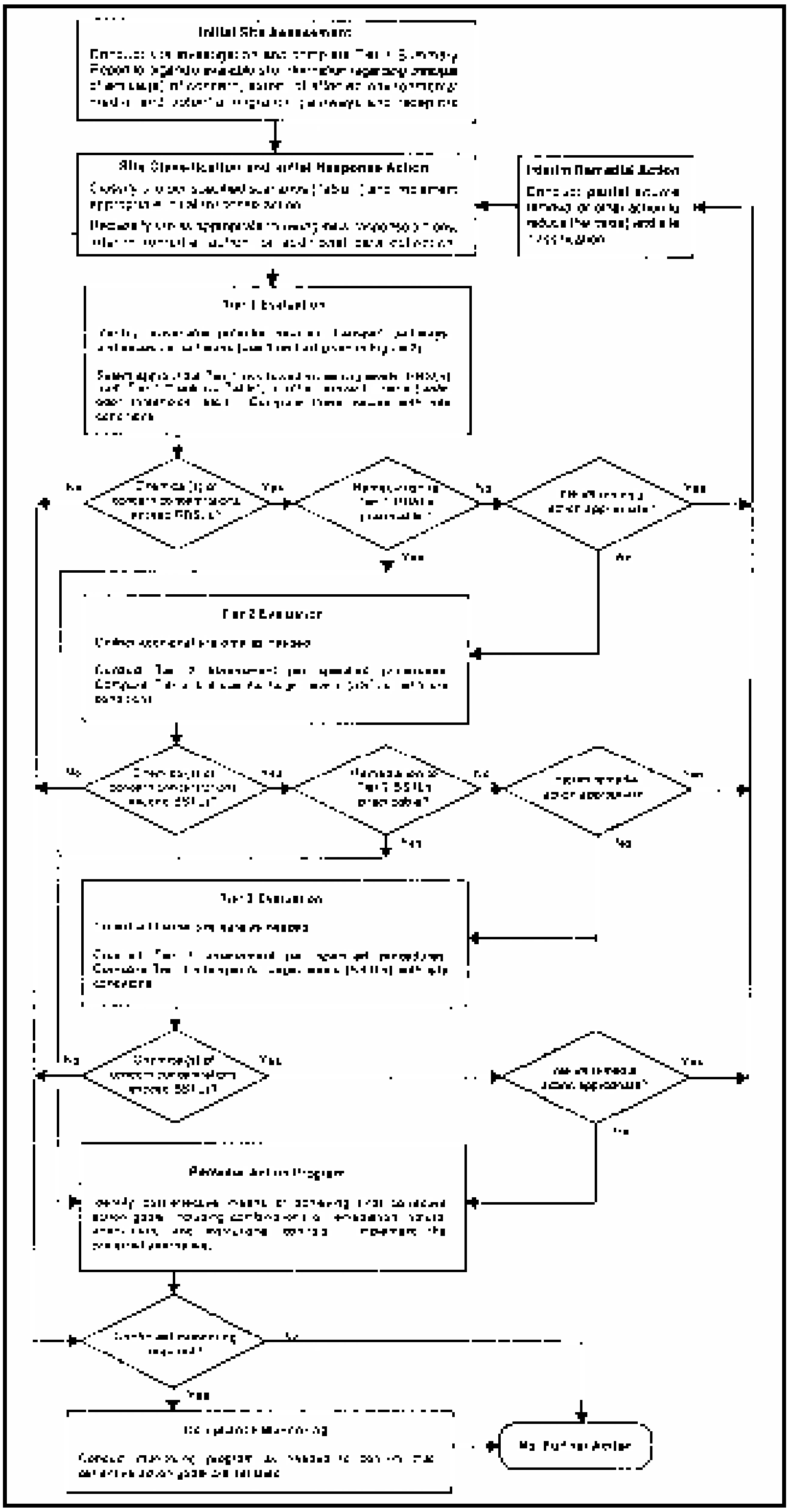


Fig. 2.6 Risk-Based Corrective Action process flowchart (ASTM, 1995)

Computer Models: RISC-HUMAN (Van Hall Instituut, 1998) is a tiered model dealing with soil contamination. Different exposure pathways that can be addressed at different tiers including water evaporation, drinking water, showers, cooking, vegetables, direct contact, meat milk and eggs, fruit, surface water.

The model requires at least one (measured) soil, sediment or ground water concentration and can calculate the distribution over the soil phases, the transport to the contact media and the exposure. Due to the fact that within this model the pathways by which contamination can occur are clearly identified, it is possible to implement protective measures, in the aim of interrupting some/all of the pathways, and consequently reduce the risks.

Golder Associates (1998) have developed ConSim, a tiered-system type of model based on a four-tiered approach, although within the model the tiers are called 'levels'. It is based upon contaminant source and transportation systems and includes numerical groundwater flow and contaminant transport modelling, should it be appropriate. Level 1 relates to contaminant source assessment, Level 2 to unsaturated zone transport and aquifer dilution, Level 3 to saturated zone transport and Level 4 to a final analysis.

Hard-Copy Model: guidelines for Environmental Risk Assessment and Management (DETR, et al., 2000) were developed in a tiered-format as a shift in emphasis within risk assessment. This change in emphasis reflects the use of risk assessment at the outset of an assessment for making decisions about environmental management (risk management) rather than just as a means by which to remediate contaminated land. Although these guidelines assist with risk management as a whole, the approach is still in contrast to that of the risk assessment guide described here. The risk assessment guide has been developed to allow an assessment of the potential risks from the use of alternative materials in different construction scenarios *prior* to construction, whereas the guidelines are still used *after* contamination has occurred.

Similar to the RBCA approach previously described (ASTM, 1995), the guidelines in DETR, et al. (2000) are presented as a three-tiered approach. Within the guidelines of the latter, Tier 1 describes risk screening, Tier 2 describes non-detailed quantitative risk assessments and Tier 3 describes detailed quantitative risk assessments. Similar again to the tiered systems previously described, the attention to detail of this approach increases as each tier is ascended.

It follows that the third-tier of these three-tiered systems will be more sensitive than the second tier of a two-tiered system (Dillon, 1994). It appears that ConSim, the computer model with the facility for a four-tiered assessment, has the potential to be the most site-sensitive of the available facilities reviewed here.

Risk Equation:

Due to the fact that the risk assessment requirements will vary from site to site, sophisticated models are not always necessary in order to assess the potential risks. In some circumstances a simple equation approach may be sufficient for determining required information, an example of which is outlined below from which human intake quantities from a known source [Eqn. 2.1] can be determined. In order to assess the 'pathways' from 'source' to 'receptor' the following factors must be assessed:

- Source (e.g. a lagoon).
- Chemical release mechanism (e.g. leaching).
- Transport mechanisms (e.g. ground water flow).
- Transfer mechanisms (e.g. sorption).
- Transformation mechanisms (e.g. biodegradation).
- Exposure point (e.g. residential well).
- Receptors (e.g. residential consumers of drinking water).
- Exposure route (e.g. ingestion).

(LaGrega, et al., 1994):

An evaluation of these factors is necessary to allow the different parameters to be obtained. In order to determine receptor doses, the key factors influencing the uptake of contaminants by the body can be simplified as follows:

Ingestion:	contaminant concentration in the ingested media. amount of ingested material. bioavailability to the gastro-intestinal system.

Inhalation: concentration in air and dust.
particle size distribution.
bioavailability to the pulmonary system.
Rate of respiration.

Dermal contact: concentration in soil and dust.
rate of deposition of dust from air.
direct contact with soil.
bioavailability.
amount of skin exposed.
(LaGrega, et al., 1994)

These factors (when known) can be entered into Eqn. [2.1]:

$$I = \frac{(C \times CR \times EF \times ED)}{(BW \times AT)} \tag{2.1}$$

where:

I: intake (mg/kg of body weight/day)
C: concentration at exposure point (mg/l in water or mg/m^3 in air)
CR: contact rate (l/day or m^3/day)
EF: frequency (day/year)
ED: exposure duration (yr)
BW: body weight (kg)
AT: averaging time (days)
(LaGrega, et al., 1994).

The known intake quantities may be sufficient to determine the risks posed from particular contamination sources, or may then be used as input parameters in other risk assessment systems.

2.4.5 Risk Assessments Associated With Alternative Materials in Pavement Construction

The search into research on risk assessments has produced a wide-range of literature, either based on the historic (risk assessment) or modern (risk management) concepts. Various new models are becoming available which have been developed to comply with current legislation. An example of this is the recent launch of CLEA (Contaminated Land Exposure Assessment) (CLEA, 2002) which, in conjunction with the development of new Soil Guideline Values, offers a means to assess risks posed to human health caused by exposure to soil contamination resulting from land use. The new Soil Guideline Values have been developed to comply with the formal requirements of Part IIA of the Environmental Protection Act (1990), and supersede ICRCL (Interdepartmental Committee on the Redevelopment of Contaminated Land) values previously used in many risk assessment systems.

Only one other research project similar to the one on which this thesis is based has been identified (Apul, 2001, 2003). The similarity between the two is that both are based upon producing pro-active models in order to assess potential aggregates *prior* to construction, rather than as clean-up tools after contamination may have occurred. Although both are concerned with assessing risks posed from the use of alternative materials in pavement construction, the principle aims of both projects are different. Apul (2001, 2003) is developing a computerised risk assessment model, against which to fully assess recycled pavement materials on a site-specific basis, whereas the aim of the research described here has been to develop a short, user-friendly document in the form of a generic (i.e. non site-specific, but site-sensitive) risk assessment guide. This guide may be used by road contractors (with no prior knowledge of risk assessments) to rapidly and reliably assess alternative materials prior to construction at the assessment stage of an aggregate, taking into account various site parameters. This guide has not, as yet, been developed into a full risk assessment model.

It appears, therefore, that no previous research has been undertaken similar to this, in order to produce a similar pro-active risk assessment guide document. As a result the research described here can be deemed original.

3 Flow Regimes

3.1 Introduction

Pathways provide the link and mechanism by which contaminants released from source materials actually reach receptors and are the areas on which this research has concentrated. This chapter describes the flow regimes which facilitate the movement of contaminants from source to receptor, which have been simulated through computations. These have been based upon published literature considered appropriate for describing the mechanisms by which water flows through pavements and by which contaminants are transported and deposited. The actual output data from the simulations are presented in Chapter 5, and it is upon those data that the development of the risk assessment guide has been based.

3.2 Flow Paths

As previously described in Chapter 1, two main flow regimes have been identified as the most appropriate pathways on which to assess the movement of contaminants from source aggregate to receptor water bodies. Both commence with 'infiltration', whereby rain enters pavements through cracks in bituminous surfaces and flows into the aggregate layers, at which point contaminants may leach into the water. The two main flow regimes consist of:

(1) vertical seepage of water through aggregates in pavements and then vertically through subgrades towards groundwater below, and

(2) horizontal seepage of water through aggregates in pavements towards side drains, from where they are discharged either directly into water bodies or into standing areas such as natural or man-made settling pools.

The methods by which these flows have been simulated and numbers generated, are given further on.

3.2.1 Infiltration

3.2.1.1 Introduction

Apart from rain entering pavements during construction, the main route through which it is assumed that it enters is by infiltration through cracks and pores in bituminous surfaces. This is important as it facilitates the leaching and subsequent transportation and deposition of contaminants.

There is limited previous and/or current research into infiltration rates with little data available. Because of this, infiltration testing was undertaken on different sites on the University of Nottingham campus. This was undertaken using apparatus developed within this research, full details of which are given below. The main aims of the testing were to:

- Design suitable apparatus by which to undertake infiltration testing on bituminous pavement surfaces.
- Generate a database suitable for use in the project calculations.
- To use the mean infiltration rate as a maximum infiltration rate possible through cracked pavement surfaces.

Despite the data being from a small sample size (seven sites), it was important for the data to be of a realistic magnitude and this was determined through a comparison with data generated away from the University of Nottingham, details of which are also presented below.

3.2.1.2 Infiltration Testing

3.2.1.2.1 Apparatus

The apparatus was a form of dual-ring infiltrometer and consisted of:

- *An inner frame:* this was constructed from a section of pre-formed 6 mm Perspex tubing.
- *An outer frame:* this was initially constructed using 6 mm sheet Perspex, which

was rolled into a circular tube with a diameter of 700 mm. The Perspex, however, fractured close to the adhesion site soon after construction. It was considered that it would be less stressful to the Perspex to construct a square frame from four pieces rather than a tubular one. The square frame was constructed using 10 mm Perspex.

- *A tank of water:* this formed the feeder tank and was based upon the design of a Mariott bottle, a bottle designed to measure water flow under constant head conditions.

(the above apparatus are illustrated in Fig. 3.1.)

- *A further tank of water:* this contained an additional supply of water.

3.2.1.2.2 Experimentation

The principle behind the infiltration testing was to maintain a constant head in the inner frame, into which water from the feeder tank entered. The feeder tank consisted of a unit with a sealed bung in the top into which a tube was inserted. The tube was set to reach a level near the bottom of the feeder tank. The feeder tank was set at a height so that the lower end of the tube was level with the height within the inner frame at which the constant head was to be maintained. A tap in the feeder tank was attached to piping which led into the inner frame. The feeder tank was filled to a required height of water, which was observed against a calibrated line. Initially the air at the top of the tank was of atmospheric pressure. As water left the tank through the piping, the air pressure in the tank tended to reduce, due to the sealed bung allowing no air to enter around the bung. Air was sucked in through the tube to take the place of the water leaving the tank. The air pressure on the tube which went through the bung was normal atmospheric pressure. The water level in the inner frame fell as infiltration occurred through surface cracks, and water entered the inner frame through the piping from the feeder tank. The atmospheric pressure on the tube through the bung in the feeder tank formed a balance with the atmospheric pressure on the surface of the water in the inner frame. The effect of this was to maintain equal levels between the bottom of the tube in the feeder tank and the water level in the inner frame. As the feeder tank level fell, readings were taken from the calibrated line at regular time intervals for data analysis, where the fall in water level within the feeder tank equalled the rate of infiltration from the inner frame. The constant head in the inner frame was maintained until the water in the feeder tank fell *below* the level of the bottom of the tube, at which point the experiment ended. The head level used varied somewhat from test to test and was approximately 140 mm above pavement level.

It was important that the water flowing from the inner frame moved vertically through the pavement surface as infiltration occurred and did not spread laterally below the immediate surface. This was achieved with the use of the outer frame. The outer frame was filled with water and a flow was maintained through the pavement surface cracks, in a similarly manner to that from the inner frame, using water from the additional tank. The principle behind the use of the outer frame was that despite a percentage of water spreading laterally below the immediate surface, it was assumed that some of the flow would move vertically through the pavement surface. The vertical flow from the outer frame created a wall of water around the flow from the inner frame. This consequently prevented the flow from the inner frame from spreading laterally.

3.2.1.2.3 Adhesion of Frames

The first stage of the infiltration testing was to establish a tight seal between the inner and outer frames and the pavement surfaces, to prevent water seeping through the surface aggregate particles before infiltration could occur. This was done by applying a sealant to the pavement surface to bind the surface aggregates in order to fill the voids between them, in the areas on which the frames were to be adhered. A ready-made bituminous sealant allowed water to permeate through. Rings of 200 PEN hot bitumen did not stiffen, whilst 50 PEN bitumen offered sufficient stiffness and dryness to create a sealed aggregate surface, but could not be removed from the apparatus after use. Evo-Stik ‘Impact Adhesive' provided an excellent surface aggregate seal and was easy to clean.

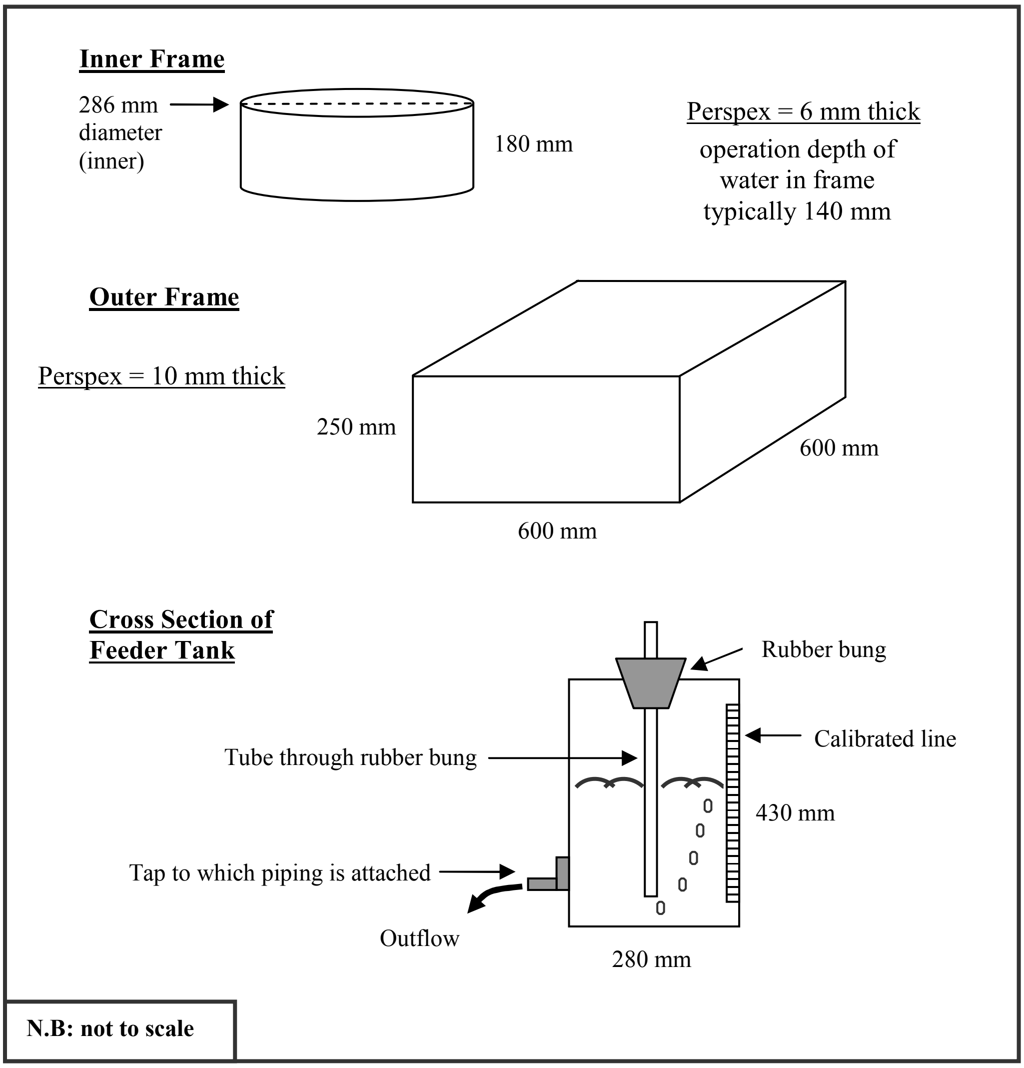


Fig. 3.1 Infiltration apparatus

The Evo-Stik 'Impact Adhesive' was applied to outlines of the two frames on the pavement surface and allowed to dry (approximately 1-2 hours). Once dry, the frames were adhered to the adhesive layers with Evo-Stik 'All Weather Sealant' (a further 1-2 hour to dry). This provided a good seal between the frames and the adhesive layers. The apparatus in situ is illustrated in Plate 3.1.

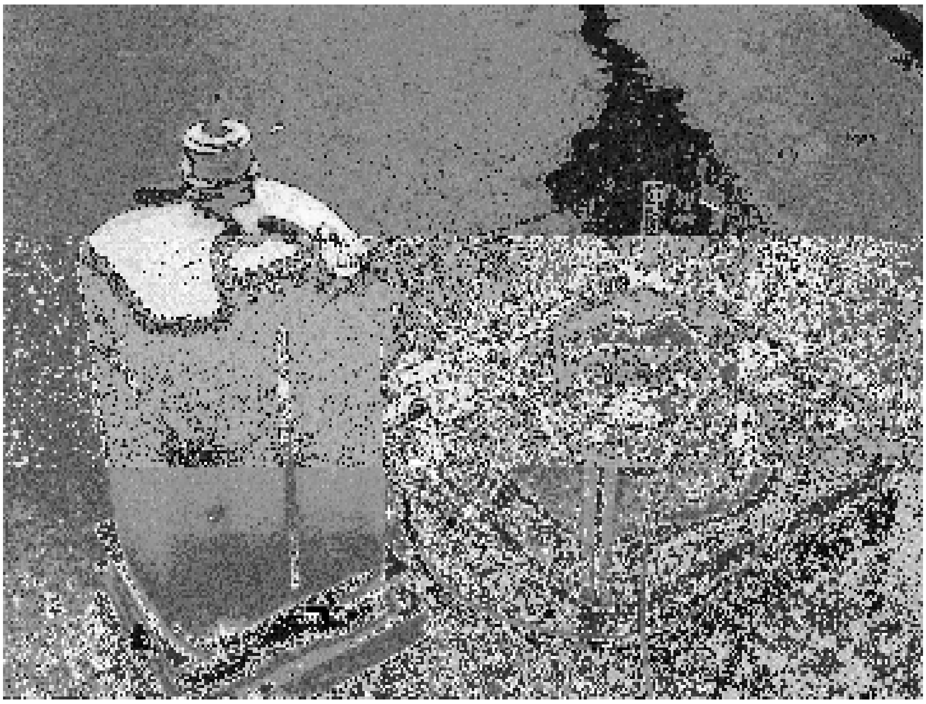


Plate 3.1 Infiltration apparatus in the field

3.2.1.3 Data

3.2.1.3.1 Project Infiltration Data

Seven sites were selected for infiltration testing, and 6 of these consisted of two types of surface distress:

(1) area distress covering at least 600 m^2, including 'alligator-type' and fatigue cracking and surface ravelling, and

(2) linear cracking consisting of lengths of longitudinal cracks, either on the normal road surface or on the edge of a patch repair over a service trench. The cracking types are both distress-types as classified in SHRP (1993). One site, with no cracking but situated on a patch over a service trench, was also selected. The differences between the two types of cracking are illustrated in Plates 3.2 and 3.3.

Plate 3.2 Area or 'alligator-type' cracking (Site 6)

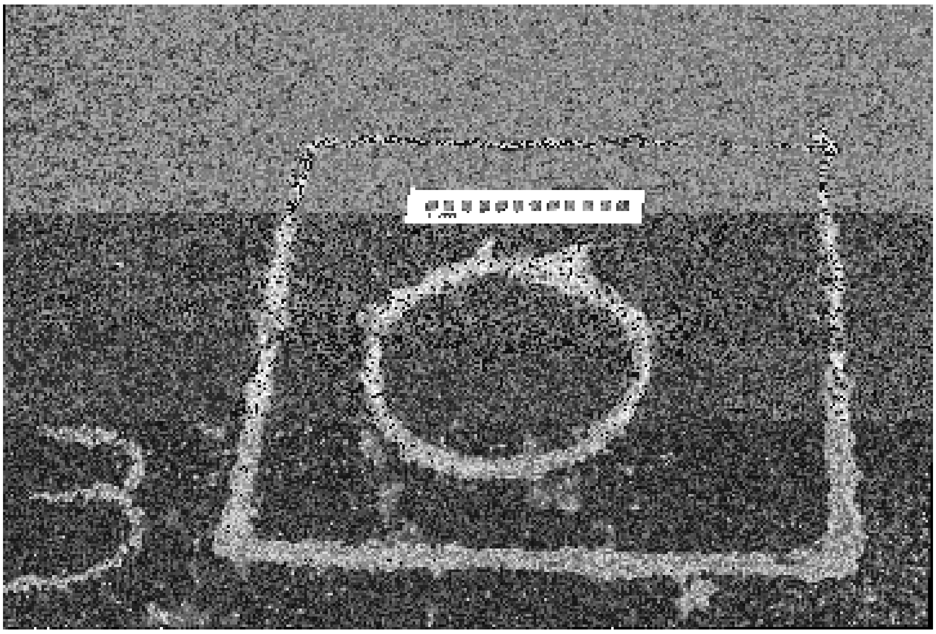


Plate 3.3 Linear (longitudinal) cracking represented by the junction of a patch over a service trench and the normal road surface (Site 3)

Site information and resultant data are illustrated in Table 3.1. Although data have been presented for both (1) alligator-type area cracking, and (2) linear (longitudinal) cracking in the same format (l/h/m^2) within Table 3.1, the actual means by which these values were calculated varied. It was assumed that for area cracking, the distressed areas were representative of the immediate square metre areas surrounding them and, therefore, infiltration rates within the testing for the inner ring were directly extrapolated up from l/h/apparatus area (0.0641 m^2) to l/h/m^2. This was undertaken by using the following equation:

$$\mathrm{IR} = \frac{1}{\mathrm{a}}(\mathrm{i}) \qquad [3.1a]$$

where:

IR: infiltration rates (l/h/m^2)
a: area of inner frame
i: mean infiltration of inner frame (l/h)

For linear (longitudinal) cracking, the actual cracks were selected as isolated cracks on otherwise intact surfaces. In that case, simple extrapolation from l/hr/cm length of cracking to l/h/m^2 would have resulted in a higher infiltration rate, by assuming similar cracking to the entire square metre within which the cracks were situated. To overcome this, a similar approach to that of Baldwin, et al. (1997) was adopted. In their approach, crack lengths were extrapolated to the point where maintenance of distressed pavement surfaces is undertaken. Baldwin, et al. (1997) thought this represents a point when 10% of the surface is cracked and equals 0.002 cm of crack/cm^2. This represents a worst-case value for infiltration through cracks if they exist in the same magnitude across a pavement surface. In order to extrapolate data determined in this project to maintenance levels as determined by Baldwin, et al. (1997), the following equation was used:

$$\mathrm{IR} = \frac{0.002(\mathrm{i_c})10000}{1000} \qquad [3.1b]$$

where:

IR: infiltration rates (l/h/m^2)
$\mathrm{i_c}$: mean infiltration of inner frame (cm^3/h/cm crack)

Table 3.1 Site Information and infiltration rates generated by project infiltration testing

Site	**Weather**	**Distress Classification***	**Distress Severity Level***	**Infiltration (l/hr/m^2) ('alligator-type' area cracking)**	**Mean Infiltration at Maintenance Level (l/h/m^2) (linear longitudinal cracking)**
Site 1 (a)	Dry, sunny	Fatigue cracking	Medium		
		(alligator-type)			
Mean (l/hr)				0	n/a
Site 1 (b)	Dry, sunny	Fatigue cracking	Medium		
Mean (l/hr)		(alligator-type)		0	n/a
Site 2	Dry, sunny	Longitudinal cracking	Medium		
	(wet previous two days)				
Mean (l/hr)				n/a	2.70
Site 3	Dry, breeze, some cloud	Longitudinal cracking	Patch is o.k		
	(rain previous eve./night)	Edge of Patch	Seal is gone		
		(over service trench)			
Mean (l/hr)				n/a	0.22
Site 4	Drizzle, breeze	Patch (over service trench)	Low		
	(sunny previous 24 h)	Sight ravelling			
Mean (l/hr)				8.78	n/a
Site 5	Dry, warm	Patch (over service trench)	None		
		No ravelling			
Mean (l/hr)				4.88	n/a
Site 6 (a)	Dry, sunny, v. windy,	Fatigue Cracking	Medium		
	v. cold	(alligator-type)			
		Some ravelling			
Mean (l/hr)				8.70	n/a
Site 6 (b)	Drizzle, warm, rain p.m.	Fatigue Cracking	Medium		
	(rain previous night)	(alligator-type)			
		Some ravelling			
Mean (l/hr)				3.52	n/a
Site 7 (a)	Dry, sunny, v. windy,	Fatigue Cracking	Medium		
	v. cold	(alligator-type)			
		Some ravelling			
Mean (l/hr)				2.04	n/a
Site 7 (b)	Drizzle, warm, rain p.m.	Fatigue Cracking	Medium		
	(rain previous night)	(alligator-type)			
		Some ravelling			
Mean (l/hr)				2.50	n/a
Mean infiltration rate obtained from both alligator-type area and linear longitudinal cracking ……………. 3.33 l/h/m^2					
n/a = not applicable					
*** Types of classification taken from SHRP (1993)**					

3.2.1.3.2 Data From Other Sources

In 1976 Ridgeway reported similar testing on bituminous surfaces in the US in order to determine infiltration rates. In that report, Ridgeway suggested four factors which influence infiltration rates: (1) the water-carrying capacity of the crack or joint, (2) the amount of cracking present, (3) the area that drains to each crack, and (4) the intensity and duration of the rainfall. The method by which the research was undertaken was by placing a bottomless wooden box, sealed with clay around its edges, on an area of pavement. The crack length was measured. Sufficient water was added to the box to maintain a thin layer over the enclosed pavement. The data collected from this test were the quantities of water infiltrating the pavement structure per unit length of crack. The mean infiltration rate generated by Ridgeway (1976) was approximately 100 cm^3/h/cm of crack. Site crack lengths and infiltration rates are illustrated in Table 3.2.

Table 3.2 Site crack lengths and infiltration rate generated by Ridgeway (1976)

Sites	**Crack Length (cm)**	**Infiltration Rate (cm^3/h/cm of crack)**	
		Summer 1974	**Fall 1974**
1	**160**	9	28
2	**107**	620	230
3	**183**	100	56
4	**241**	56	37
5	**152**	2	2
6	**208**	37	n/a
7	**147**	19	84
Approx. mean infiltration rate (cm^3/h/cm of crack)			**100**
n/a= not available			

By entering the mean value of 100 cm^3/h/cm as determined by Ridgeway (1976) into Eqn. [3.1a], an infiltration rate of 2 $l/h/m^2$ is determined. This represents infiltration rates at maintenance level. That value is a similar magnitude to the mean infiltration rate of 3.33 l/h/m^2 generated within this research, and so giving confidence to its accuracy.

3.2.1.4 Summary of Infiltration Testing

There were two aims for undertaking infiltration testing within this research, and they were to:

(1) produce infiltration rate data for use within computations, and

(2) use the mean infiltration rate determined through the testing as a maximum infiltration rate possible through cracked pavement surfaces.

This was done through designing infiltration apparatus which was used on seven sites within the University of Nottingham campus. Data generated were of similar magnitudes to those generated by Ridgeway (1976). Several factors became evident, however, due to limitations of the testing regime. In order to gain good data from any form of experimentation, testing requires a larger number of samples than was the case within the infiltration testing, which was limited to seven. This was due to a time constraint within the research. Many pavement sites within the University campus are of similar ages and their construction sequences are very likely to be the same. A range of construction scenarios reflecting different cracking regimes would give a more accurate range of infiltration rates. This is because although surface distress may appear similar, distress at deeper base and sub-base levels in older pavements may well facilitate greater infiltration rates than in newer pavements. It was not possible to obtain cores of the sites in which the testing was undertaken and hence construction materials are unknown. Without this knowledge the influence that the base has on infiltration rates cannot be determined. An example of this would be if bituminous layers were placed above old concrete pavement surfaces, infiltration rates would be greatly retarded. Testing was carried out on a limited number of occasions, whereas all site testing should, theoretically, be repeated in order to compare seasonal differences. In extremely cold weather surface freezing will prevent any infiltration, whereas in times of extremely heavy rainfall aggregate below the immediate surface may become fully saturated and will prevent further infiltration.

A range of infiltration rates from between 2.04 $l/h/m^2$ and 8.78 $l/h/m^2$ were determined. It was decided that the mean value of 3.33 $l/h/m^2$ would be used within this research as the maximum infiltration rate in a pavement surface reaching maintenance level. This has been considered justifiable because infiltration at the larger infiltration rates obtained through the infiltration testing may not be possible in many pavement surfaces, despite surface cracking. Consequently, all rainfall below that value has been taken to be capable of infiltrating through surface cracks when the surface is distressed to maintenance level, and has been taken to represent a worst-case scenario. The mean infiltration rate used in this context is reflected within computations and the risk assessment guide.

3.2.1.5 Rainfall Data

In order to determine the percentage of rainfall which has the potential to infiltrate through cracked pavement surfaces at maintenance levels, comparisons have been undertaken between rainfall data over a five-year period and the mean infiltration rate generated from the testing (being 3.33 $l/h/m^2$, which is equivalent to 3.33 mm $rain/h/m^2$). Theoretically, all rainfall below the mean value should have the potential to infiltrate through surface cracks which have reached maintenance levels. This is assuming that rainfall is evenly distributed throughout a time period (e.g. an hour). In reality if rain falls with a high intensity for a short period of time, even the mean infiltration rate for pavement surfaces at maintenance levels may be exceeded and puddles will form. For the purposes of calculations, however, rainfall data have been used as if evenly distributed throughout the time period for which they were quoted.

Rainfall data for a five-year period from 1993-1997 (inclusive) have been obtained from the Institute of Hydrology (Inst. of Hydrology, 1993-1997). The data covers the

England, Scotland, Wales and N. Ireland. Data for these areas were selected because they represent the British Isles as a whole, in order to compare regional differences. The maximum regional rainfalls for each month which fell over the 5 years are illustrated in Fig. 3.2, where the actual year in which the maximum rain fell has been omitted.

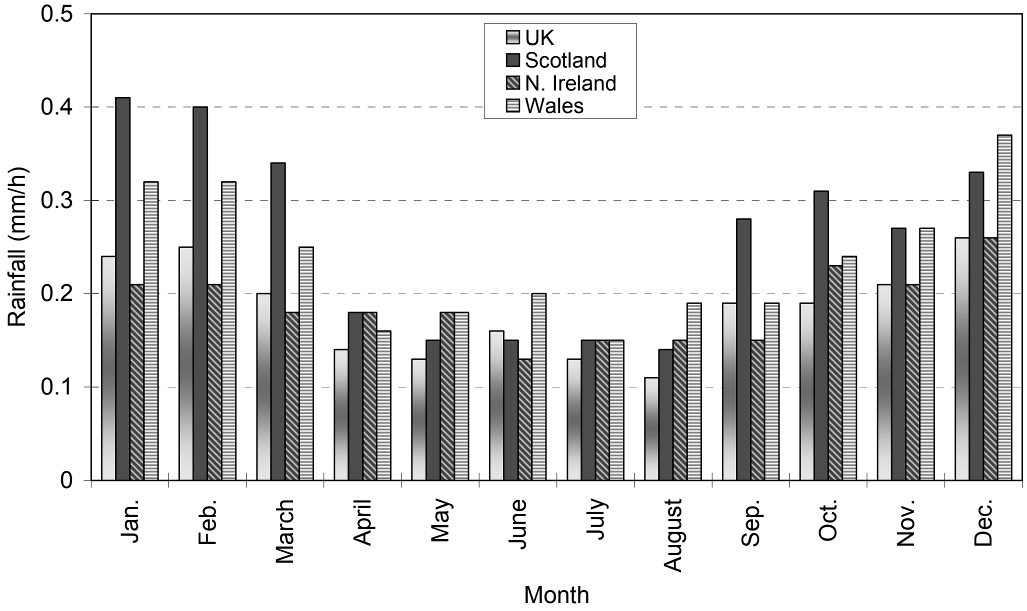


Fig. 3.2 Illustration of five-year monthly maximum rainfalls for UK, Scotland, N. Ireland and Wales (Inst. of Hydrology, 1993-1997)

From Fig. 3.2 it is evident that the highest rainfall during the five-year study was in a January in Scotland when 0.41 mm/h rain fell (equivalent to 0.41 l/h/m^2). This value is still well below the mean infiltration rate generated within this research.

Hourly rainfall rates over a twenty-four-hour period for Aberdeen and London (Fig. 3.3) for a typically wet day have been used to further illustrate the fact that rainfall rates are usually below the maximum infiltration rate generated within this research. These data have been selected as a comparison of two geographically remote areas.

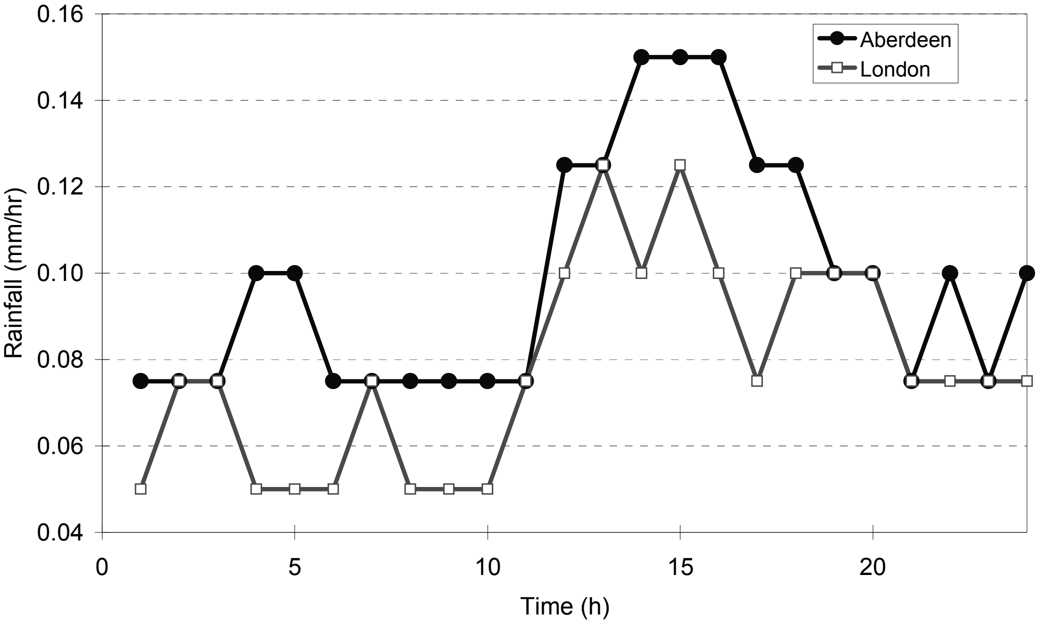


Fig. 3.3 Illustration of mean rainfall over a 24-hour period (Ward, 1975)

3.2.1.6 Darcy's Law

Following the generation of infiltration rates obtained within this research, calculations have been undertaken using Darcy's law in order to obtain credible flow rates so as to allow a comparison between the two to be carried out:

$q=Aki$ [3.2a]

where:

q: flow volume per unit time (m^3/s)
A: cross-sectional area of soil corresponding to the flow area (m^2)
k: coefficient of permeability (specific for the material under review - m/s)
i: hydraulic gradient

given that:

i: $\Delta H/l$
where:

ΔH: head loss (m)
l: length of flow path (m)

According to Baldwin, et al. (1997) a hydraulic gradient of $i=0.025$ is the minimum hydraulic gradient likely to be encountered in practice, and it is the value which has been taken to represent the hydraulic gradient during horizontal flows when flows are saturated. Maximum horizontal gradients are not likely to be much greater than this except in the unlikely event of flooded pavements but unflooded drains. A vertical hydraulic gradient of $i=1$ has been taken to represent vertical flows when flows are saturated. By taking $i=1$ to be the vertical hydraulic gradient, an assumption is made that the flow is unsurcharged, i.e. there is no head of water above the flow exerting pressure. If the flow was surcharged, i.e. there was a head of water above the flow, a vertical hydraulic gradient of $i>1$ would be present.

Flows according to Darcy's Law are said to be saturated. Calculations have been carried out to see whether water available from infiltration is great enough to enable these saturated flows within pavements to actually exist. Values for hydraulic gradients of $i=0.025$ for horizontal flows and $i=1$ for vertical flows have been inserted into Eqn. [3.2a], using BFS aggregate as an example. BFS has been selected as it is an alternative aggregate that has been assessed within this research:

Vertical flow:

$$q=7 \times 0.22 \times 1 \text{ m}^3/\text{s} \qquad [3.2b]$$

$$=5{,}544 \text{ m}^3/\text{h}$$

where:

A: 7 m^2 (assuming a typical pavement half-width of 7 m and length of 1 m)
k: 0.22 m/s (coefficient of permeability of BFS during vertical flow, from Baldwin, et al., 1997)
i: 1 (hydraulic gradient during vertical flow)

Horizontal flow:

q=1 x 0.29 x 0.025 m^3/s [3.2c]

=26.1 m^3/h

where:

A: 1 m^2 (assuming a width and depth of 1 m)
k: 0.29 m/s (coefficient of permeability of BFS during horizontal flow, from Baldwin, et al., 1997)
i: 0.025 (hydraulic gradient during horizontal flow, from Baldwin, et al., 1997)

From the above two equations it can be seen that when saturated, flows through BFS as great as 5,544 m^3/h vertically [Eqn. 3.2b] and 26.1 m^3/h horizontally [Eqn. 3.2c], could exist. The infiltration testing, however, gave a mean value of only 3.33 $l/h/m^2$, which is equivalent to 0.00333 m^3/h. This, therefore, illustrates the fact that unsaturated water flows should be expected, because water available through surface infiltration is far below the requirements necessary for saturated flows to exist.

In order to further illustrate the fact that water required for saturated flows through aggregates will not be met by infiltration, further calculations based upon Eqn. [3.2a] with varying k and i values for vertical and horizontal flows may be seen in Tables 3.3 and 3.4 below. In addition, the flow of water through a clay subgrade is also presented in Table 3.3 as a comparison.

Table 3.3 Flow volumes due to variations in k and i values for vertical flow (('adaptation to) "Baldwin, et al., 1997)

q (m^3h)	**A (m^2)**	**k (m/s)**	**i**
Aggregate Flow			
55,440	7	'2.2	1
554.4	7	'0.022	1
5,765.76	7	"0.22	*1.04
Subgrade Flow			
0.055	7	**$2.2x10^{-9}$	1
*=assume head of water of 0.02 m and aggregate depth of 0.5 m			
**=typical clay subgrade			

Table 3.4 Flow volumes due to variations in k and i values for horizontal flow (('adaptation to) "Baldwin, et al., 1997)

q (m^3/h)	A (m^2)	'k (m/s)	i
Aggregate Flow			
261	1	'2.9	"0.025
104.4	1	'0.029	"0.025
261	1	"0.29	'0.25

It is evident from Tables 3.3 and 3.4 that despite variations in k and i values, quantities of water required to enable saturated flows through aggregates to exist will not be provided by infiltration through surface cracks. The relationship of unsaturated horizontal flows to calculations described here is addressed later.

For vertical flows permeabilities are usually lower for some subgrades, particularly clays, than for pavement aggregates. Due to the low flow volumes existing in vertical clay subgrades, it is likely that these flows will be saturated. This is because the water at the aggregate/subgrade border will enable the saturation of the clay to be maintained. It is also evident that the low vertical flow volumes through clay subgrades compared with higher horizontal flow volumes through aggregates will determine the preferential horizontal flow direction towards the side drains. Examples of subgrade permabilities are given in Fig. 3.4.

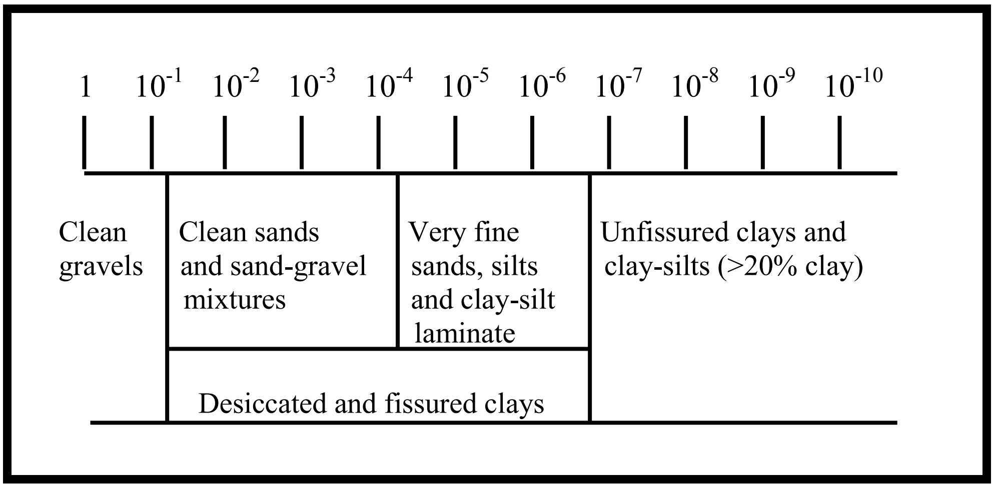


Fig. 3.4 Values for permeability (m/s) (BSI, 1986)

3.2.2 Pavement Flows

As previously discussed, for the purposes of calculations when rain infiltrates into pavements it is assumed that the water divides between vertical and horizontal flows. Due to the difficulty in determining the percentage of total flow divided between the two, computations have been undertaken for both flows as if they were the only route. In each case the flows along with the transportation and deposition of contaminants have been considered as maximum. Consequentially these may be taken to represent worst-case scenarios because in reality, vertical and horizontal flows occur simultaneously. An illustration of infiltration with vertical and horizontal flow paths can be seen in Fig. 3.5.

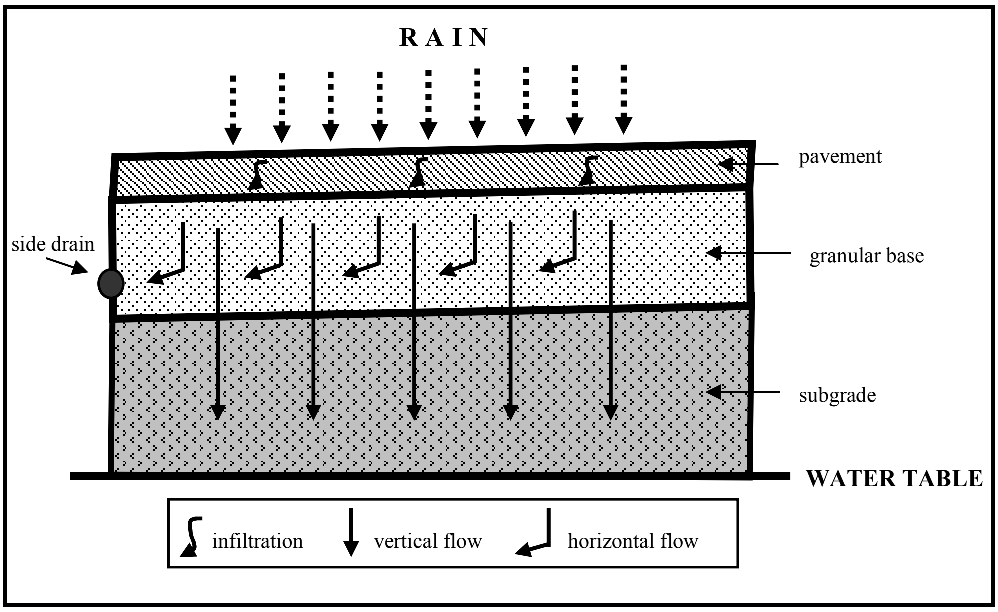


Fig. 3.5 Illustration of infiltration with vertical and horizontal flow paths

By knowing contaminant concentrations from Hill (2000), the actual rate of contaminant movement in and from the pavement may be calculated, if rates of water flows in which the contaminants are transported can be determined. Otherwise, although the presence of contaminated water may be assumed, it is not known whether contaminants are actually transported away from the pavement. The equations on which the simulations for vertical and horizontal flows have been based, and the methods by which they were used, are described below.

3.2.2.1 Vertical Flow

3.2.2.1.1 Sorption Model Development

Within porous pavement layers water may move vertically through the aggregates towards the subgrades below. As described in Chapter 2, it became evident from Hill (2000) that 16 days is sufficient contact time for desorption in compacted aggregate to reach equilibrium.

The process of sorption may be assessed based upon the principle of 'partitioning'. Partitioning is a process whereby contaminated water enters a medium (in the case of this research the medium is the natural subgrade below a pavement) and contaminants migrate from the water onto the surfaces of the subgrade particles. The process of partitioning can be described using 'partition coefficients' (sometimes called 'distribution coefficients') (K_d). Ames and Rai (1978) assert that all operating retention mechanisms are combined into one K_d value. The K_d model assumes that the liquid and solid phases are at equilibrium and that there is a linear relationship between solute concentration in the solid and liquid phases (Sheppard and Thibault, 1990). The process of partitioning provides a simple means of describing ion sorption and provides the basis for nearly all of the reactive transport models that have been applied to environmental problems worldwide, according to Bethke and Brady (2000).

Because of the worldwide acceptance of this method by which to calculate the process of sorption, it was selected as the method upon which to design the computations now reported. It is important, however, that the residence time of contaminated water draining through subgrades is adequate for sorption between the subgrades and water to reach equilibrium. Computations have been designed based upon a required 16 days where, in reality, this would be the maximum time.

Within the research the subgrade has been divided conceptually into thin, finite horizontal layers. Different rates of contaminant loss will occur in each layer, with rates dependent on subgrade material. Rates of contaminant loss will be greater in materials with lower k values, because loss rates are dependent on the residence times of water within each layer, details of which may be seen below. The process of partitioning is based upon the following equation:

$$K_d=S/C \qquad [3.3a]$$

where:

K_d: partition coefficient, specific for the sorbent (soil) and contaminant (l/kg)
S: mass of contaminant sorbed per mass of sorbent (mg/kg)
C: concentration of contaminant in water at equilibrium (mg/l)

(LaGrega, et al., 1994)

At equilibrium, Eqn. [3.3a] can be rewritten as:

$$K_d=S_f/C_f \qquad [3.3b]$$

where:

S_f: final concentration in soil after partitioning (mg/kg)
C_f: final concentration in water after partitioning (mg/l)

For conservation of mass it follows that contaminants lost from water flows are taken up by subgrades. In order to further verify this, the following equation applies:

$$(C_i - C_f)Bv = (S_f - S_i)M \qquad [3.3c]$$

where:

C_i: initial water concentration before partitioning (mg/l)
S_i: initial soil concentration before partitioning (mg/kg)
Bv: bed volume (l) (in this case = V_v is saturated)
M: mass of dry solids in soil (kg)
V_v: volume voids (l)

Rearranging 3.3c and substituting from 3.3b gives:

$$C_f=\frac{C_iBv+S_iM}{Bv+K_dM} \qquad [3.3d]$$

A calculation is presented below using Eqn. [3.3d] based upon an example pavement section with an area of 1 m^2, a depth of 0.01 m and a specific gravity of 2.7 Mg/m^3 (required to allow the mass and volume based concentrations to be related), assuming the following example parameters are known before partitioning:

C_i:	5 mg/l
S_i:	0 mg/kg
Bv:	2.3 l
M:	21 kg
K_d:	2 l/kg
V:	$0.01m^3$

After partitioning the following values are determined:

C_f:	0.2596 mg/l
S_f:	0.5192 mg/kg

K_d values are chemical and subgrade-dependent and are determined by laboratory testing. Although published literature giving K_d values exist, there are limited accurate published data due to the difficulty in obtaining exact results. This is confirmed by the Environmental Protection Agency (EPA, 1999), who state that K_d values are a direct measure of partitioning of a contaminant between the aqueous and solid phases, and the process attempts to account for various chemical and physical retardation mechanisms that are influenced by a myriad of variables. Using uranium as an example, they state that K_d values may vary over six orders of magnitude depending on the composition of the aqueous and solid phase chemistry. In 1990, Sheppard and Thibault (1990) compiled a compendium of K_d values for clay subgrades, which are presented in Table 3.5, in which the large ranges may be seen. This is similarly exemplified in the risk assessment model ConSim (Golder Associates, 1998) which is also presented in Table 3.5. It may be seen that in some instances there are large ranges of K_d values for each contaminant and in other instances there are no data at all. Ranges of values for loam subgrades used in ConSim are also given in Table 3.5, because consisting of some clay, they are closer to clay subgrades than those for other subgrade-types also in their lists.

Table 3.5 Ranges of K_d values ([1]Sheppard and Thibault, 1990) and K_d values for loam subgrades for contaminants available within ConSim ([2]Golder Associates, 1998)

	[1]K_d Ranges for Clay Subgrades (averages in brackets) (l/kg)	**[2]K_d Ranges for Subgrades (l/kg)**	**[2]K_d Ranges for Loam Subgrades (l/kg)**
Cl	n/a	n/a	n/a
SO_4	n/a	n/a	n/a
NO_3	n/a	n/a	n/a
Ba	n/a	1.4	n/a
Mn	23.6 to $4.9x10^4$ (180)	3 to $1.3x10^5$	41 to $1.3x10^5$
Fe	15 to 2,121 (165)	1.2 to $4x10^4$	200 to 3,300
Al	n/a	n/a	n/a
Ni	305 to 2,467 (650)	20 to 8,100	20 to 8,100
Cu	n/a	$1x10^4$	n/a
Zn	200 to $1x10^5$ (2400)	1.1 to $1.6x10^5$	11 to $1.6x10^5$
Cr	(1500)	0.091 to $4.4x10^4$	0.091 to 999
Cd	112 to 2,450 (560)	1.6 to 1,500	1.6 to 990
Pb	(550)	27 to $2.7x10^5$	990 to $2.7x10^5$
As	n/a	29	n/a
n/a=not available			

Given the enormous range of possible K_d values quoted in Table 3.5, illustrative values of K_d have been used in computations now reported. These values are K_d=0.05, K_d=0.5, K_d=10 and K_d=100 l/kg, which cover some of the range.

In order to evaluate partitioning within subgrades, the method used within this research has been to divide subgrades (irrespective of subgrade material or depth), into 100 layers (Fig. 3.6) (which represents the 'pathway' for contaminant movement). The depth of subgrade has been taken as the in-situ natural ground below the pavement, down to the water table below. The 100th layer, therefore, represents the bottom of the subgrade, which is in effect the water table (the 'receptor'). A spreadsheet has been designed where rows represent Layers 1-100 and columns represent input time intervals. In doing so, it is possible to determine how partitioning occurs in individual layers as well as within subgrades as a whole. It follows, therefore, that when the extent of partitioning within different layers is known, it is possible to calculate the contaminant concentrations within water at specific layers as the water drains through the subgrade from Layer 1 to 100.

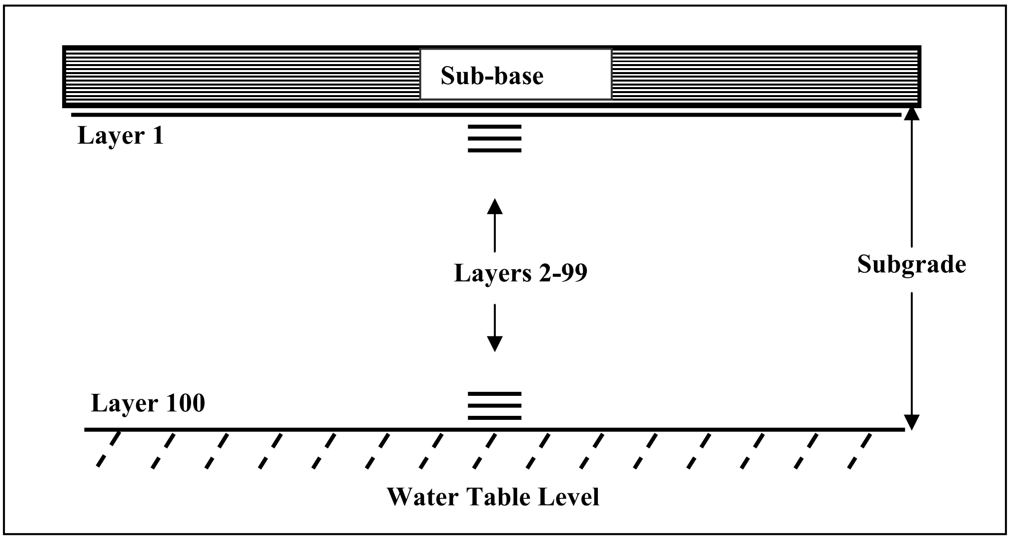


Fig. 3.6 Conceptual subgrade 100 layer system used within computations

The time that it takes for water to flow from one layer to the next has been called a 'time interval', because with this method 'real' times are not obtained. The process of converting time intervals to real time is addressed below. In real environmental conditions, the input of water is usually a continuous process. In order to undertake the computations, input has been taken to be in separate steps (Fig. 3.7). The time between each input of water has been called an 'input time', and is dependent on the time it takes for the water to flow from one layer to the next. This makes it equivalent to a time interval.

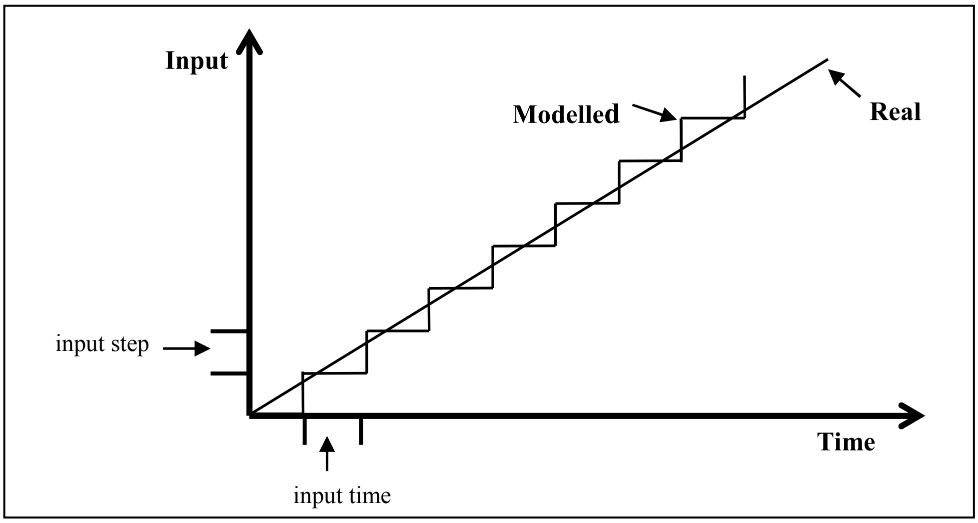


Fig. 3.7 Modelled vs. real water input concept used within computations

Initially, the subgrade will be assumed to have no contaminants within it (S_i). In the 1st input time, contaminated input water (C_i) will flow through the 1st layer and partitioning will occur. The output water from the 1st layer (C_f) will have a lower concentration of contaminants in it compared with that of the input water. The subgrade in the 1st layer will then have raised levels of contaminants within it (S_f), compared with being contaminant-free as was the case before the water flowed through. After partitioning occurs, the water leaves the 1st layer and another input of water will enter (2nd input time). At the start of the 2nd input time, the subgrade in the 1st layer will already have a certain concentration of contaminants within it. This is due to partitioning having occurred during the flow of water from the 1st input time. Partitioning will again occur, this time with a fresh contaminated water input, but as the subgrade already has a concentration of contaminants within it, the amount partitioned from the water to the solid phase will be less than with the water from the 1st input time. As a result, the output water from the 2nd input time will be of a higher contaminant concentration to that of the output water from the 1st input time. Now considering the second layer, the water initially within the 1st layer from the 1st input time will flow through to the 2nd layer. The concentration in the input water to the 2nd layer will be less than that to the 1st layer, because partitioning has already occurred in the 1st layer.

As a result of these processes occurring as ongoing events, the concentration of the contaminant in the output water from the 1st layer will gradually increase over time, as the amount partitioned reduces. This is due to the loading of the subgrade in the 1st layer with contaminants from each previous input time. In contrast, the concentration of contaminants in the advancing 'front' of contaminated water as it passes each successive layer (from Layers 1-100) will be reduced. This is because each input water will have a lower contaminant concentration than it did for the previous layer, due to the partitioning that occurs in each layer. As the water from the 1st input time flows vertically through the subgrade, each layer it consequently enters will have an initial subgrade concentration of 0. As subsequent input time waters reach the same layers, concentrations of output waters will increase due to the then presence of contaminants already in the subgrade from the previous input time. This reduces the amount partitioned from each 'step' of water.

This process continues until the subgrade is fully saturated with contaminants and has no further sites for the contaminants to be sorbed onto, and no further partitioning may occur, or until the limitations of the computational model are reached, where the maximum number of input times are 954. This results in a maximum number of time intervals of 1053, which occurs when the water of the 954th input time flows through to the 100th layer.

In order to evaluate the accuracy of the conceptual approach adopted in the development of the model, an analysis of the model is undertaken later in this chapter. Within it, data from the 100 layer model are compared with those from a similar model with a lesser number of layers and a comparison is also undertaken between the model and the more traditional transport mechanisms.

3.2.2.1.2 Using the Model

In order to demonstrate the process of partitioning, computations have been undertaken to determine the concentrations of contaminants in output water from the 1st layer where the input concentration is 0.05 mg/l, for K_d values of K_d=0.05, K_d=0.5 and K_d=10 l/kg (Fig. 3.8).

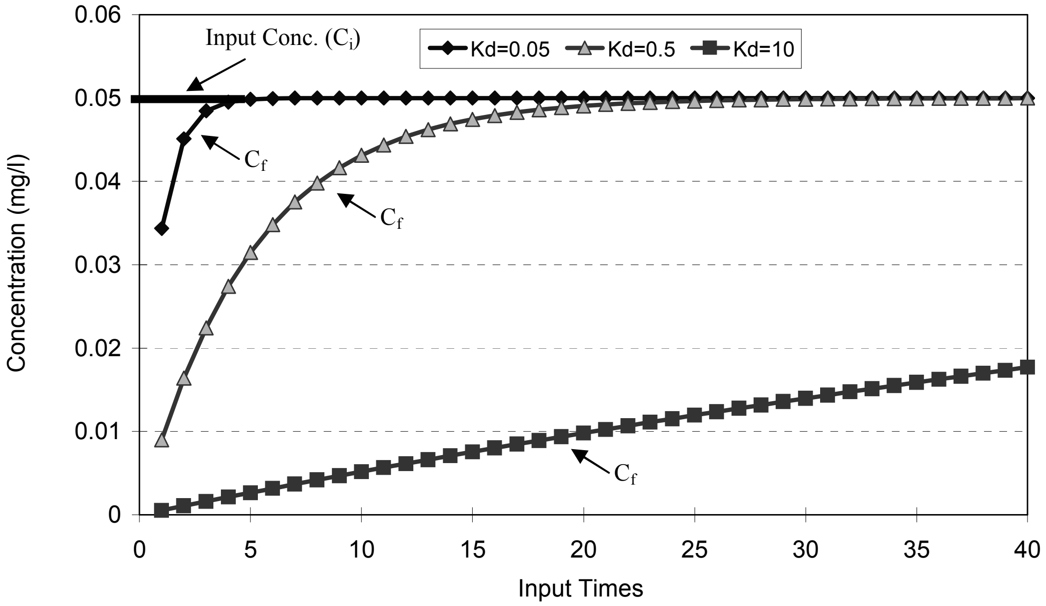


Fig. 3.8 Illustration of breakthrough concentrations at different input times using a range of K_d values (l/kg) in the 1st layer for input conc. 0.05 mg/l (C_i=initial water conc., C_f=final water conc.)

It can be see in Fig. 3.8 that the lower the K_d value, the faster the computed partitioning. This results in a greater concentration of contaminants in the outflow water from the 1st layer and a lesser computed breakthrough time. Given the nature of the model, the number of input times necessary for the output concentration of the water flow to equal the input concentration in the 1st layer is infinite. It follows, therefore, that after 1053 time intervals in the 100th layer (equivalent to the maximum 954 input times) the contaminant concentration in the output water for K_d=10 l/kg will be of a very low magnitude.

Computations assessing contaminant concentrations in output water have been undertaken for the 100th layer, which is equivalent to the bottom of the subgrade, after both 100 and 299 time intervals (equivalent to 1 and 200 input inflows arriving at the base of the model), based upon K_d values of K_d=0.05, K_d=0.5, K_d=10 and K_d=100 l/kg. The results are illustrated in Figs. 3.9 and 3.10, in which output concentrations are normalised by dividing them by the input concentrations and are presented as factors of input concentrations. A value of 1, therefore, means the concentration in the output water is equal to that in the input water and the contaminant can be said to have completely broken through the subgrade layers

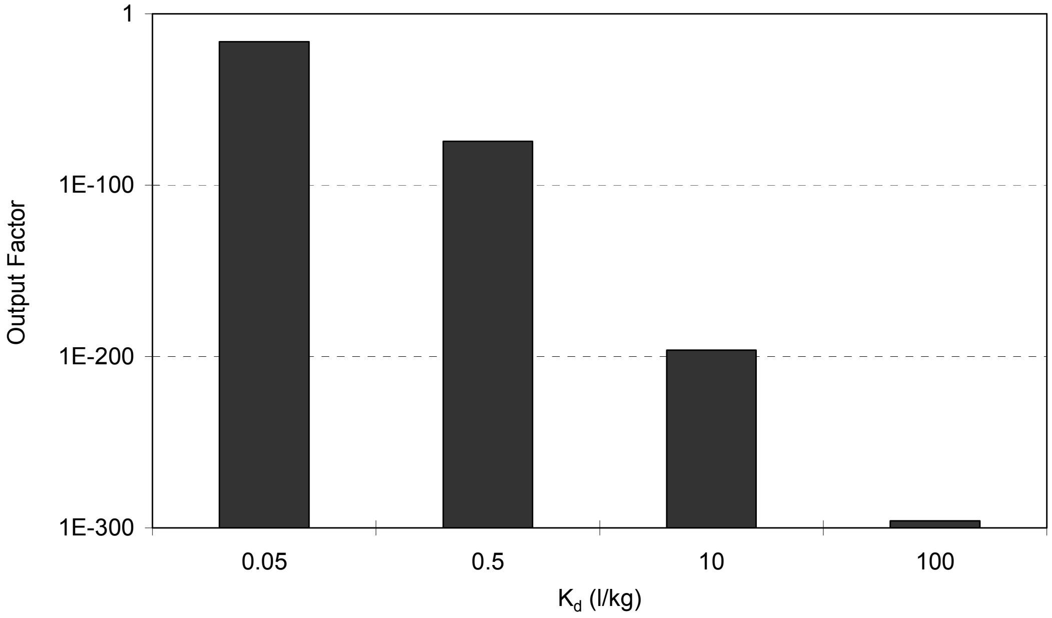


Fig. 3.9 C_f/C_i (=output factor) after 100 layers (100 time intervals) presented as factors of input conc. where an absolute correlation is designated a factor of 1

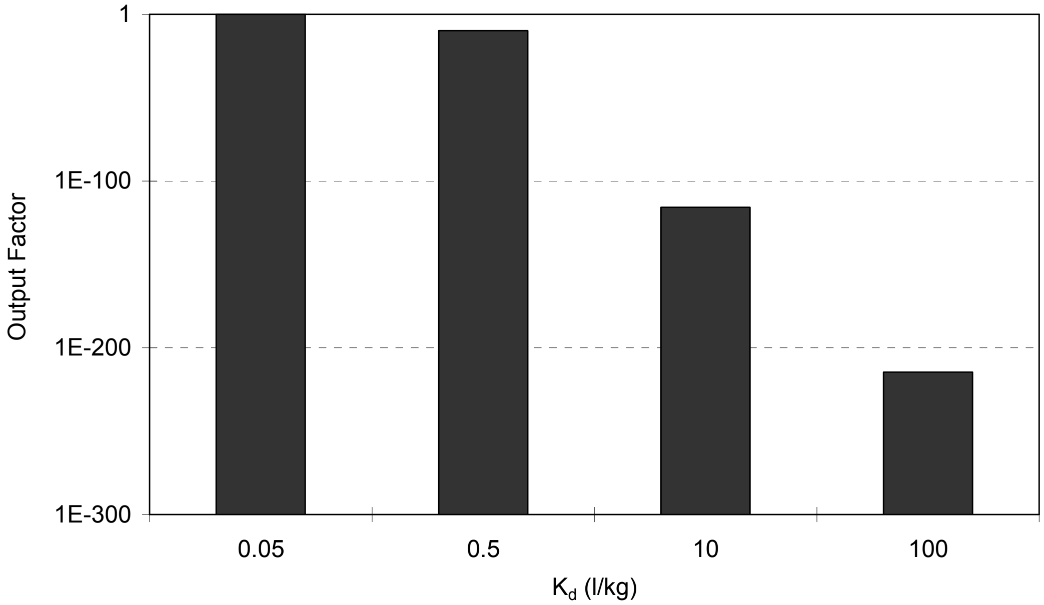


Fig. 3.10 C_f/C_i (=output factor) after 100 layers (299 time intervals) presented as factors of input conc. where an absolute correlation is designated a factor of 1

Contaminant concentration in output water as a factor of input concentration is K_d-dependent rather than input concentration-dependent, because the partitioning computations are linear. This means that calculations undertaken for individual input concentrations as factors, are representative of other concentrations. The efficiency of partitioning based upon K_d values is also particularly evident, where the extremely low factors of output concentrations in relation to input concentrations for K_d values of K_d=10 and K_d=100 l/kg can be seen. By comparing Fig. 3.9 with Fig. 3.10 it is also evident that the concentrations of contaminants in the output water from the 100th layer are larger after 299 time intervals than after 100 time intervals.

Due to these very low concentrations of contaminants in output water when using K_d=10 and K_d=100 l/kg, further computations have been undertaken for K_d=0.05 and

K_d=0.5 l/kg alone. Although initial guidelines have been developed based upon these lower K_d values, also in the risk assessment guide (see Chapter 6) breakthrough time predictions have been made for conditions where contaminants have high K_d values.

A graph has been plotted for every 10th layer from Layers 10 to 100 for K_d=0.05 and K_d=0.5 l/kg, to show the number of time intervals necessary for output concentrations to equal 10% of input concentration, and is illustrated in Fig. 3.11. This percentage has specifically been selected for two reasons and is the percentage upon which the risk assessment guide (Chapter 6) has been based. Firstly, due to model limitations, for many percentages greater than 10% it is not possible to calculate the number of time intervals necessary for output concentration to reach that proportion of the input concentration at some particular layer, but at 10% it is possible at all layers, thus making it a value whereby results may readily be determined and made available for comparison; and secondly at 10% of input concentration, most contaminants fall within WQS, thus providing a basis for design. This is explained further in Chapters 5 and 6 while an analysis of the model approach is undertaken further in this chapter.

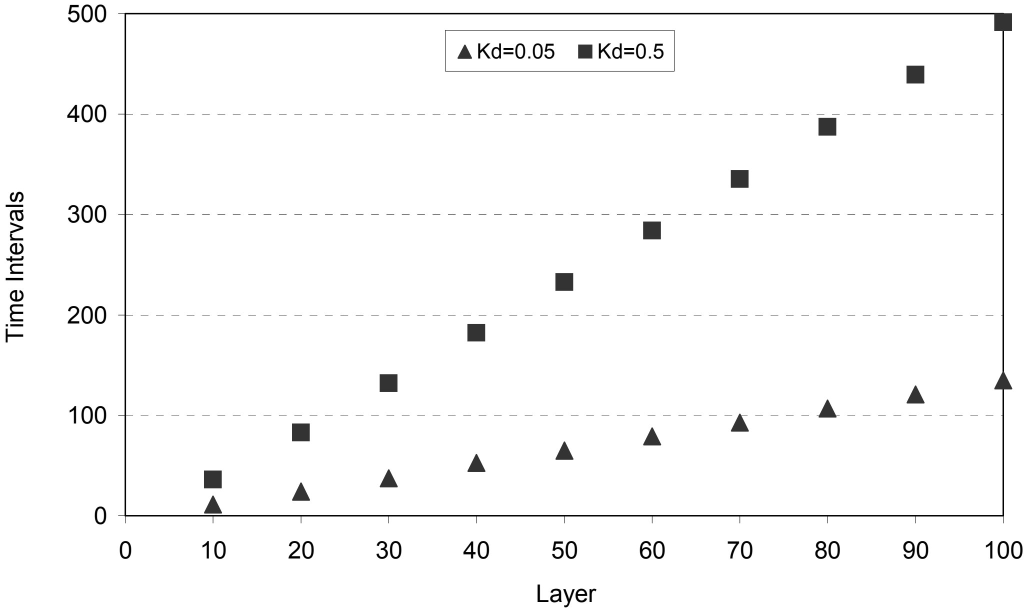


Fig. 3.11 Time intervals necessary for output conc. to equal 10% of input conc. for K_d=0.05 and K_d=0.5 for every 10th layer from Layers 10-100

Three main assumptions have been made in the above computations:

(1) the rate of release of contaminants from the source materials is constant and water flowing through the subgrade is of an initial constant contaminant concentration, whereas in reality after the initial release of contaminants in water flow, the rate of release will be reduced. This means that the final concentration of contaminants in flows that reach water table levels will in reality be less than the computations show,

(2) initially the soil is contaminant-free, whereas in reality over the years the soil will have adsorbed contaminants from other water flows and the rate of partitioning may be less than computations show, and

(3) soil is homogenous in structure and partitioning occurs at a constant rate throughout, whereas in reality voids in soil or compacted areas known as 'clods' will alter the rate at that point.

Despite the differences between assumptions made and reality, computations give an idea of the process of partitioning. Therefore, despite final contaminant concentrations in water reaching water table levels being inevitably inaccurate to some extent, the magnitude of the variations in final concentrations resulting from changes in K_d and initial water input concentrations becomes evident.

3.2.2.1.3 Transport Mechanisms

Depending on conditions, three main transport mechanisms determine the rate of flow of a solid (in this case a contaminant) in a liquid medium as follows:

(1) *advection:* contaminants will be transported by the liquid medium they are in, and the flow rate will be the same as the flow rate of the medium,

(2) *diffusion:* contaminants will move regardless of the motion of the medium they are in, by moving down the concentration gradient, from a more concentrated to a less concentrated state, and

(3) *dispersion:* contaminant will be transported by the liquid medium but the course they take will depend on the solid they are moving through. Thus, if moving through soil, the contaminants will be transported around particles and through pore spaces arriving at the end of the route at different times dependent on the route they have taken.

The computations described here are based upon advection as a transport mechanism, meaning that they represent contaminants being transported by moving water through the subgrade.

3.2.2.1.4 Residence Times

Another factor which is important when assessing vertical flows within pavements is that adequate residence times of the water draining through the subgrade must be present. This is to ensure that sorption by partitioning reaches equilibrium. In order to relate real times with time intervals within vertical flows, it is important to calculate the times that the flows remain within each layer of the 100 computational layers, in order to see if they are of sufficient magnitude for partitioning to reach equilibrium (16 days).

Coefficient of permeability, k values, which allow for exactly 16 days residence time per computational layer can be seen in Fig. 3.12. In Chapter 5, examples of contaminant transportation using both advection and dispersion are given in order to compare results to see whether this approach is a fair representation.

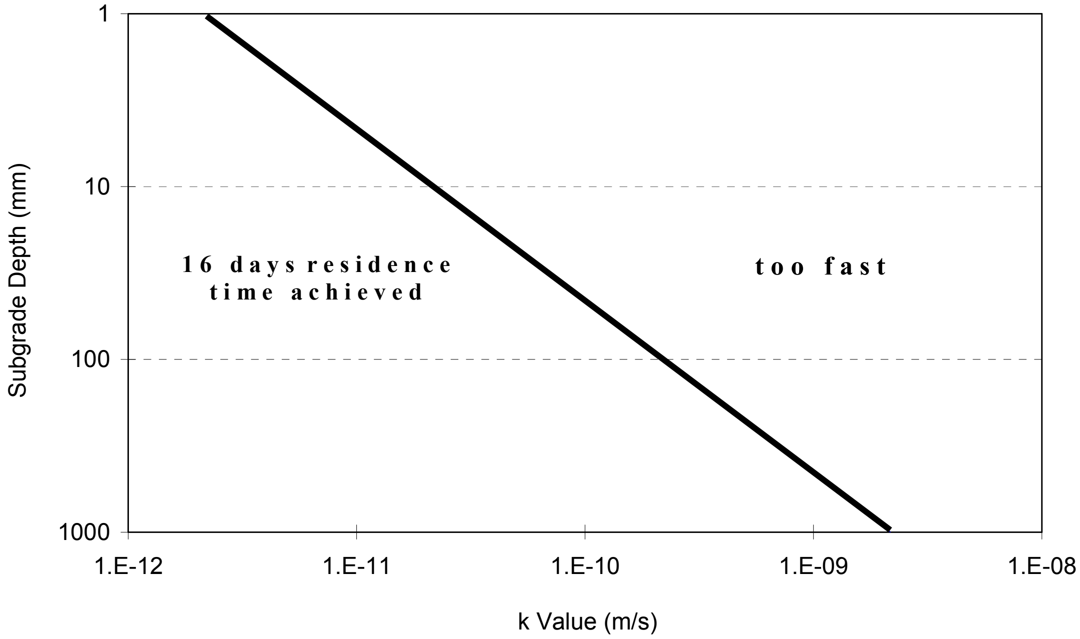


Fig. 3.12 Corresponding subgrade depths and k values to achieve 16 days residence time per computational layer assuming 100 layers in model in each case

A part of the research has been to compare the relationship between subgrade depths, coefficient of permeability (k) values and residence times. The approach used, has been to compare layer residence times for different total subgrade depths using the same k values with different factors of magnitude (rather than determining k values that give exactly 16 days residence times per subgrade depth as illustrated above), and computations have been undertaken through the following equations:

$$R = \frac{d}{v_s} \qquad [3.4a]$$

where:

R: residence time per layer (s)
d: depth of each computational layer (m)
v_S: pore velocity (m/s)

and:

$$v_s = \frac{v}{n} \qquad [3.4b]$$

where:

v: Darcy's flow velocity (m/s)
n: porosity

and:

$$v = ki \qquad [3.4.c]$$

where:

k: coefficient of permeability (m/s)
i: hydraulic gradient

Eqn [3.4a] may thus be re-written as follows, which is the formulation used in the modelling:

$$R = \frac{nd}{v} \qquad [3.4d]$$

The approach used, herein, when describing subgrades above the water table has been to describe them as having a total 'depth'. When describing GCLs, being manufactured products, the approach has been to describe them as having a total 'thickness'. For the computations, when either a subgrade or GCL is divided into the conceptual 100 sub-layers, each individual layer has been described as having a 'depth'. The individual layer depth for both a subgrade and a GCL will, therefore, vary according to either the total subgrade depth or the total CGL thickness (being 100th of the total depth/thickness). This will be the case for both the tables and text in the following work.

Layer residence times for 600 mm and 3 mm subgrades depths have been determined for a range of k values from $k=3x10^{-1}$ m/s to $k=3x10^{-13}$ m/s. These depth have been selected because 600 mm represents a typical subgrade depth and 3 mm represents a contrast for use as a comparison. Results can be seen in Table 3.6.

Table 3.6 Residence times (days) for 2 subgrade depths determined through computations at different k values

*Subgrade Type	k (m/s)	Depth of Subgrade (mm)	
		600	3
		Depth of Each Layer (mm)	
		6	0.03
		Residence Times per Layer (days)	
Clay	$3x10^{-13}$	70000	300
Clay	$3x10^{-12}$	7000	30
Clay	$3x10^{-11}$	700	3
Clay	$3x10^{-10}$	70	0.3
Clay	$3x10^{-9}$	7	0.03
Clay	$3x10^{-8}$	0.7	0.003
Clay	$3x10^{-7}$	0.07	0.0003
Sand/Silt/Clay-Silt	$3x10^{-6}$	0.007	0.00003
Sand	$3x10^{-5}$	0.0007	0.000003
Gravel	$3x10^{-1}$	0.00000007	0.0000000003

n.b: Highlighted cells represent k values for the subgrade depths where residence times <16 days (*BS 8004, 1986)

It can be seen from Table 3.6 that in order to achieve 16 days residence time per layer a k value of $k \leq 3x10^{-10}$ m/s for a subgrade depth of 600 mm and a k value of $k \leq 3x10^{-12}$ m/ for a subgrade depth of 3 mm are required. Although this approach does not give a k value at which an exact residence time of 16 day is achieved, it is a method by which residence times for the same k value at different factors of magnitude may be compared. Clearly, this is a linear relationship between k value, subgrade depth and residence time. An important fact that is evident is that only clay subgrades (and fairly impermeable clay subgrades at that) allow 16 days residence times per layer. Due to the fact that 80% of UK roads are constructed on clay subgrades (Dawson, 1998), it follows that for 80% of UK roads the required 16 days residence times per layer *may* be achieved, thus allowing sorption to reach equilibrium. This will not occur for more permeable clay subgrades.

The same approach used has been to calculate residence times for different subgrade depths, using a range of k values of $k=3x10^{-8}$ to $k=3x10^{-13}$ m/s, in order to obtain residence times of at least 16 days.

Table 3.7 Residence times for a range of k values for different total subgrade depths

k Values (m/s)	Depth of Subgrade (mm)				
	1000	600	200	100	50
	Depth of Each Layer (mm)				
	10	6	2	1	0.5
	Residence Times per Layer (days)				
$3x10^{-13}$	120000	70000	23000	12000	6000
$3x10^{-12}$	12000	7000	2300	1200	600
$3x10^{-11}$	1200	700	230	120	60
$3x10^{-10}$	120	70	23	12	6
$3x10^{-9}$	12	7	2	1	0.6
$3x10^{-8}$	1.2	0.7	0.2	0.1	0.06

n.b: Highlighted cells represent k values for different subgrade depths where residence times <16 days

Two contrasting results that can be seen in Table 3.7 are that to achieve at least 16 days residence time for a total subgrade depth of 1000 mm a k value of $k=10^{-10}$ m/s is necessary, whereas for a total subgrade depth of 50 mm a k value of $k=10^{-11}$ m/s is necessary.

A reciprocal relationship exists between residence time and permeability, while a linear relationship exists between residence time and subgrade depth. This relationship means that a decrease in a k value by a factor of 10 gives a residence time increase by the same factor. It also means that a decrease in subgrade depth by a factor of 10 gives a decrease in residence time also by the same factor.

Breakthrough times for contaminants in water flowing through subgrades resulting from computations can be found in Chapter 5.

3.2.2.1.5 Geotextile Clay Liners

In some construction scenarios, the subgrade at a site under assessment may consist of a material other than clay. As already determined, k values of subgrade materials other than clay are too great to allow sorption of contaminants by partitioning to reach equilibrium. In some scenarios the subgrade may be more permeable clay and its properties may again not comply with the required parameters of subgrade k value and depth to water table to achieve the minimum 16 days residence time per computational layer.

In circumstances where subgrades do not allow sorption of contaminants by partitioning to reach equilibrium, a method by which to compensate for this is to use a GCL below the pavement and above the subgrade. When GCLs are used, the clay lining allows sorption by partitioning to occur, similarly to subgrades. To simulate GCLs, computations have been undertaken for a range of clay thicknesses from 5 mm to 1 mm, using k values of $k=3x10^{-11}$ to $k=3x10^{-13}$ m/s. These k values have been selected because they represent some typical GCL values (CETCO, 2000). Residence times per computational layer can be seen in Table 3.8.

Table 3.8 Residence times for a range of k values for different GCL thicknesses

k Value (m/s)	**Thickness of GCL (mm)**				
	5	**4**	**3**	**2**	**1**
	Depth of each Layer (mm)				
	0.05	**0.04**	**0.03**	**0.02**	**0.01**
	Residence Times per Layer (days)				
$3x10^{-13}$	580	460	350	230	120
$3x10^{-12}$	58	46	35	23	12
$3x10^{-11}$	5.8	4.6	3.5	2.3	1.2

n.b: Highlighted cells represent GCL thicknesses for different k values where residence times <16 days

Data in Table 3.8 should be interpreted with a different emphasis to those resulting from natural clay subgrades. For natural clay subgrades the depths of subgrades and their k values are site-determined, and computations will verify whether they comply with the necessary 16 days residence time per computational layer. When using manufactured GCLs, the k value will be as low as the manufacturer is able to produce, and the corresponding thickness may be adjusted to achieve the 16 days residence time per computational layer. Within the computations undertaken for a k value of $k=3x10^{-11}$, a GCL thickness of 14 mm would be required in order to achieve the 16

day residence time. In reality the production of a GCL of this thickness would be too costly.
Breakthrough times for contaminants in water flowing through GCLs resulting from computations can be found in Chapter 5.

3.2.2.1.6 Summary

The three sections 'Sorption Model Development', 'Using the Model' and 'Residence Times', demonstrate the theory, and the method adopted here, for determining:

(1) time intervals necessary for flows to reach different depths (computational sub-layers) within subgrades and GCLs, and

(2) permeability values and corresponding subgrade and GCL layer depths necessary to achieve 16 days minimum residence times per sub-layer.

The main implication is that by combining the two points listed above it is possible to allocate real times to time intervals. It is possible, therefore, to determine the actual breakthrough times for different percentages of input concentrations of contaminants to reach different depths. This may be done by multiplying the number of time intervals it takes for different percentages of input concentration to reach a particular layer, by the residence time per layer. Consequently, this allows times for the movement of contaminated flows through subgrades as a whole to be calculated.

3.2.2.1.7 Analysis of the Model Approach

The approach used within the modelling described here is presented above. In order to assess the accuracy of the model designed to simulate vertical flow and to ascertain the part played by discretisation inherent to the model itself, the following analysis has been undertaken.

Freeze and Cherry (1970) have described a method by which to determine the breakthrough time for output concentration to equal 50 percent of input concentration

(T_{50}), using K_d values, which they term the 'retardation factor'. This is an empirical value originally developed by Vermeulen and Hiester (1952). Freeze and Cherry's method is represented by Eqn. [3.5a].

Retardation Factor: $$\frac{v_s}{v_c} = 1 + \frac{\rho_b}{n} \cdot K_d \qquad [3.5a]$$

thus:

$$T_{50} = \frac{Nd}{v_c} = \frac{Nd}{v_s}\left(1 + \frac{\rho_b . K_d}{n}\right) \qquad [3.5b]$$

where:

v_s:	average linear velocity of the water in the pores
v_c:	velocity of the $C/C_o = 0.5$ contour
ρ_b:	bulk density
n:	porosity
K_d:	partition coefficient
d:	depth of one layer across which water flows
N:	number of layers

and:

ρ_b: $\rho_d + n\rho_w$

where for the saturated conditions being considered:

ρ_d:	dry density
ρ_w:	density of water = 1 kg/l

Calculations based upon the same example site parameters using both the research model method and retardation factor method as seen in Eqn. [3.5a] (Freeze and Cherry, 1970) have been undertaken to confirm the accuracy of the former, where site and model parameters used are:

Total depth of subgrade (mm):	600
Depth of each layer (d) (mm):	6
No. of layers (N):	100
K_d (l/kg):	0.05
ρ_d (kg/l):	2.1
n:	0.3

- Research model with 100 layers

  Breakthrough time for T_{50}:

  Time intervals per layer: 144.68
  Residence time per layer (days): 694.44
  Actual time (days): 100472

- Freeze and Cherry (1970) using Retardation Factor

  Breakthrough time for T_{50} for the same case as above:

  Actual time (days): 97222

Calculations have also been undertaken using the research model method, but based upon fewer (but commensurately thicker) layers, viz 10, 30, 50, 70 and 90 layers, and results can be seen in Table 3.9.

Table 3.9 Comparison of T_{50} as determined through research model with Freeze and Cherry (1970)

Breakthrough Time (T_{50})	**No. of Layers in Research Model**					
	10	**30**	**50**	**70**	**90**	**100**
Time Intervals for T_{50}	14	43	72	101	130	145
Residence Time per Layer (days)	6944	2315	1389	992	772	694
Actual Time for T_{50} (days)	95385	99148	99905	100230	100411	100472
Percentage Difference to Freeze and Cherry	-1.9	2.0	2.8	3.1	3.3	3.3

From Table 3.9 the similarity in breakthrough times at T_{50} using the research model for different numbers of layers (between 95385 and 100472 days) to those determined by Freeze and Cherry (1970) (97222 days) is evident. Thus we can be confident that the research model is realistic in its prediction of breakthrough times.

Although the percentage difference between breakthrough times using the research model to those determined by Freeze and Cherry (1970) is less in models with lesser numbers of layers, it is evident that the research model's prediction of breakthrough is only sensitive to the number of layers used when that number is small (perhaps <70).

An important fact is that the method described by Freeze and Cherry (1970) is based upon an empirical measurement, as an error of only a few percent in the original measurements would allow total agreement with the approach adopted here.

An important difference between the research model and the method described by Freeze and Cherry (1970) is that in the research model an allowance for 16 days residence time per computational layer is built-in, whereas Freeze and Cherry effectively assume that the process of partitioning is instantaneous. Thus they predict an advancing contaminant front which instantaneously changes from clean to full contamination as it passes (so called 'plug-flow'). In order to investigate the effect of this instantaneous equilibration compared to a more realistic one, a number of assumptions have been investigated. Assuming a subgrade with a total depth of 60 mm is divided into 10, 20, 40, 70 and 100 layers, Fig. 3.13 illustrates the breakthrough concentrations to T_{50} and Fig. 3.14 illustrates breakthrough concentrations to T_{90} for this model. Sufficient time for full equilibration is assumed throughout.

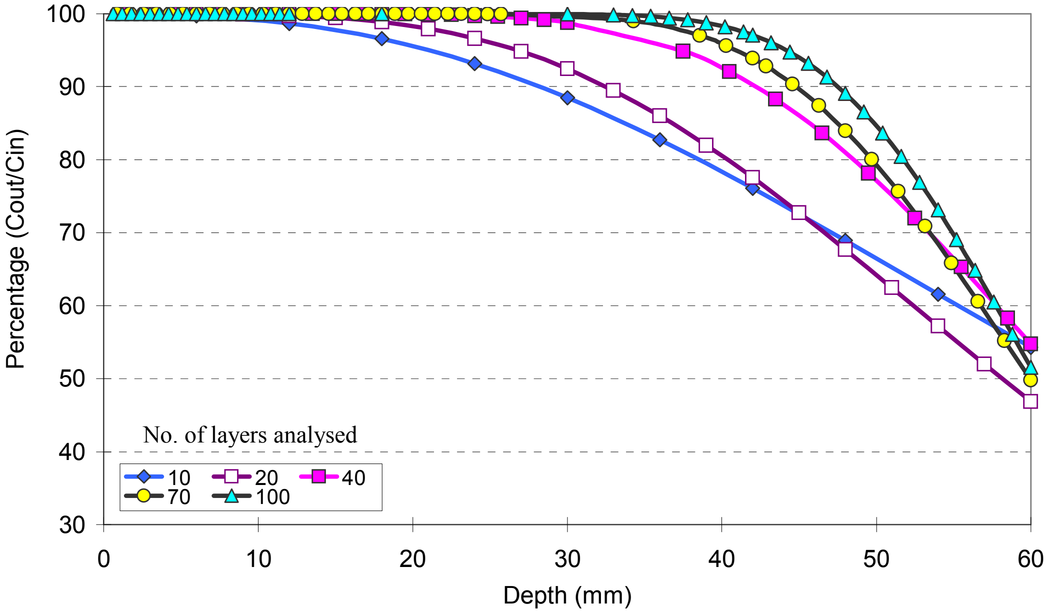


Fig. 3.13 Illustration of T_{50} for research model with full equilibration based upon different

numbers of layers (result 'snapshot' given when C/C_o is the closest to 50%)

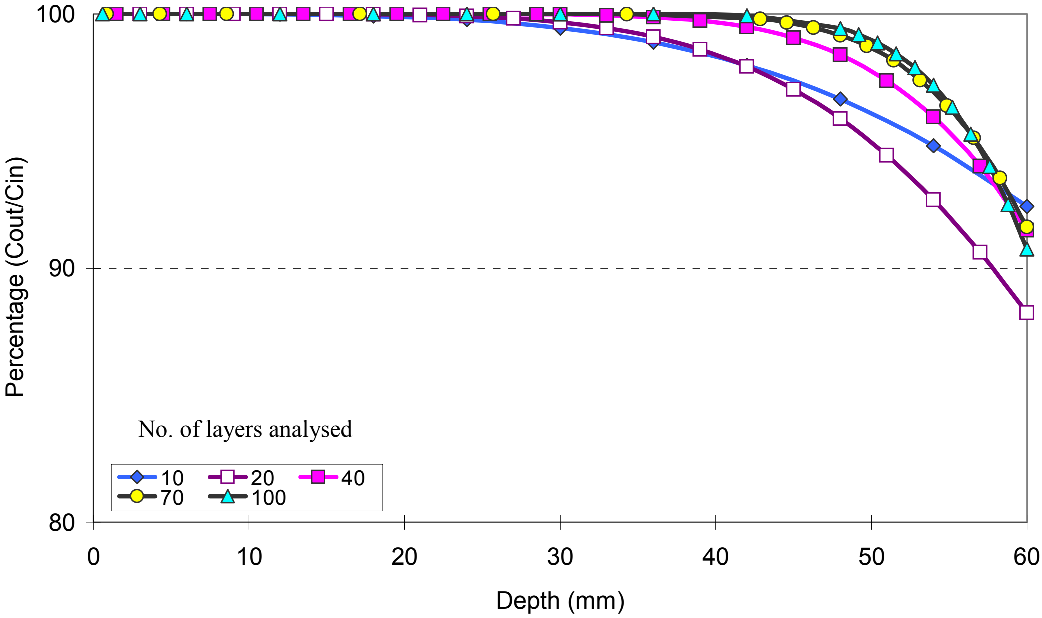


Fig. 3.14 Illustration of T_{90} for research model with full equilibration based upon different numbers of layers (result 'snapshot' given when C/C_o is the closest to 90%)

For both T_{50} and T_{90}, the time interval at which the output concentration is as close to 50% (or 90%) as possible has been extracted from the spreadsheet, to allow concentrations at lesser depths (lesser number of layers) to be determined.

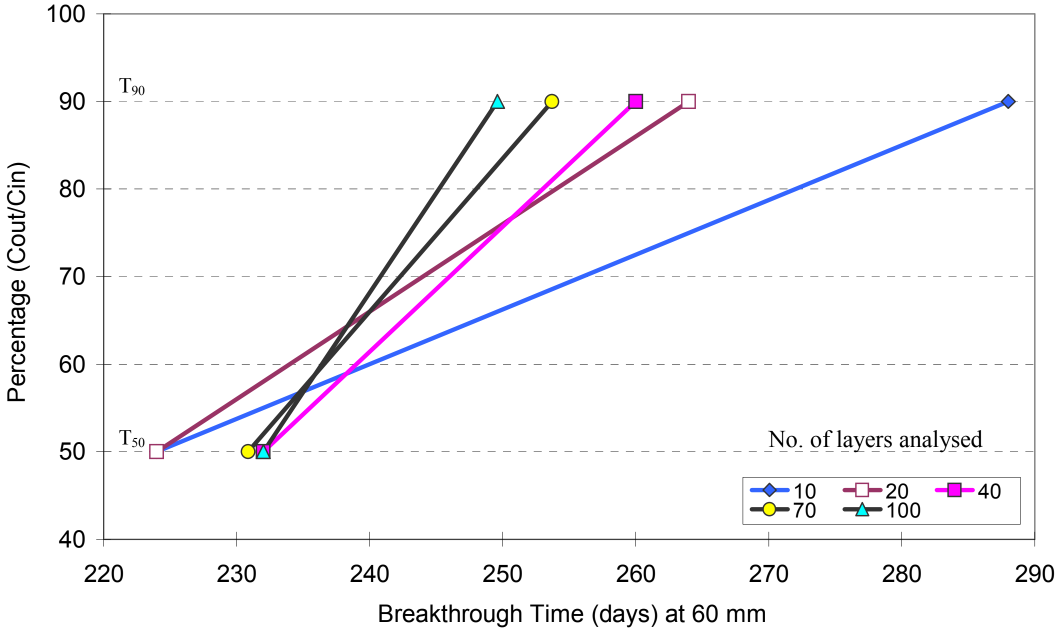


Fig. 3.15 Breakthrough times for T_{50} and T_{90} at 60 mm depth

In Fig. 3.15 it can be seen that the times for T_{50} at 60 mm range from 224 days for a 10 layer model to 232 for a 100 layer model (a difference of 8 days), whilst the times for T_{90} at 60 mm range from 288 days for a 10 layer model to 250 days for a 100 layer model (a difference of 38 days). It is also evident that it takes a much greater time for T_{50} to increase to T_{90} at 60 mm for a 10 layer model (64 days difference) as opposed to the time for T_{50} to increase to T_{90} for a 100 layer model (18 days difference). This shows that with an increase in the number of layers in a model, the differences in breakthrough times to T_{90} decrease from T_{50} to T_{90}. This tends to confirm that the reason 'plug-flow' is not seen is an artefact of the discretisation of the computational approach.

A further method that can be used to compare the accuracy of 100 layers in the research model with the method described by Freeze and Cherry (1970) is by assessing the differences in the curves of the graph produced using the research model for different numbers of layers (Fig. 3.16) with the plug-flow vertical curve obtained through Freeze and Cherry (1970). Fig. 3.16 has been produced by taking T_{50} for each analysis with the different numbers of layers and subsequently plotting breakthrough concentrations for four layers either side of the notional breakthrough depth (except for the 100 layer model, where 100 is the maximum computable number of layers available, so only data on the upstream side is shown). A small adjustment is made to ensure that all the lines plot exactly through the layer 0, T_{50} point. This shows that the apparent diffusion seen in Fig. 3.13 is not simply a linear function of the fineness of the discretisation (otherwise the results in Fig. 3.16 would be co-linear).

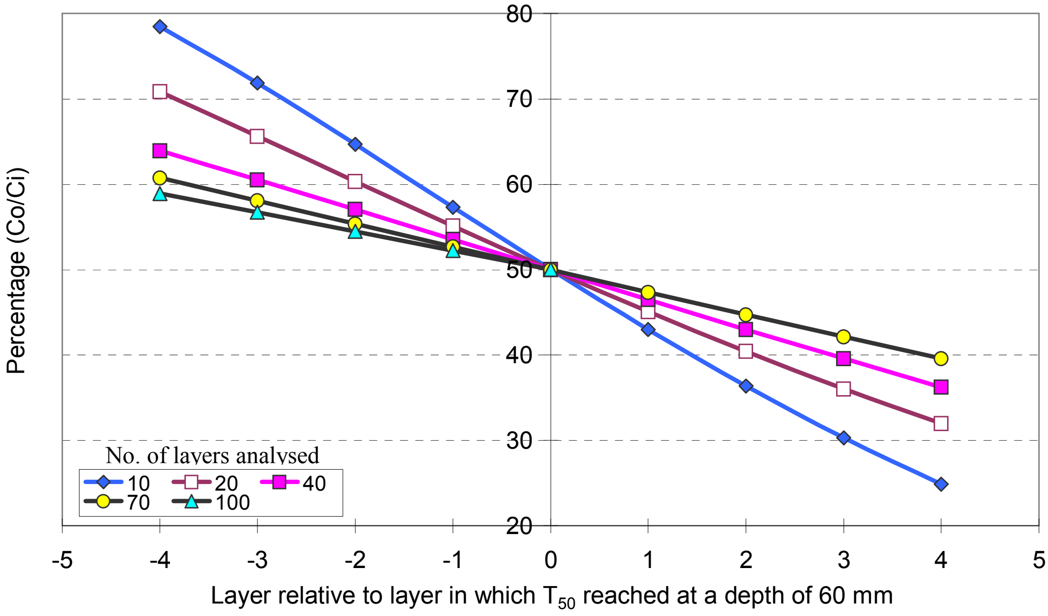


Fig. 3.16 Illustration of gradients in curves for different numbers of layers

The calculations for the different number of layers in the model presented above have assumed a 16 day residence time for full equilibrium and, consequently, full partitioning to occur. A further analysis of the research model has been undertaken for the same number of layers in the model, but based upon a state where partitioning does not reach equilibrium. The method used for this has been to assume that the 10 layer model does allow for a 16 day residence time (and full equilibrium), but that a finer discretisation and, hence, shorter residence time in any one layer, means there must be a non-equilibrium condition pertaining. To simulate non-equilibrium, an arbitrary equation has been used, which although may not be representative, is taken to give an illustration of possible values. The equation used may be seen in Eqn. [3.5c].

$$K_{d\ \mathrm{adjusted}} = \left(1-\left(\frac{16-t}{16}\right)^2\right) \text{ x } K_{d\ \mathrm{original}} \qquad [3.5c]$$

where:

t: adjusted residence time in one layer of the model (in days)
$K_{d\ original}$: 0.05 l/kg

On this basis, the adjusted residence times and $K_{d\ adjusted}$ (Eqn [3.5c]) may be seen in Table 3.10.

Table 3.10 Determining K_d adjusted values for inclusion in model

No. of Layers in Research Model	**10**	**20**	**40**	**70**	**100**
Adjusted Residence Time per Layer (days)	16	8	4	2.29	1.6
$K_{d\ adjusted}$ (Eqn. [3.1c]) (l/kg)	0.05	0.0375	0.0219	0.0133	0.0095

Breakthrough concentrations and times for T_{50} and T_{90} have been determined as before, but with $K_{d\ adjusted}$ replacing K_d (see Figs. 3.17 and 3.18).

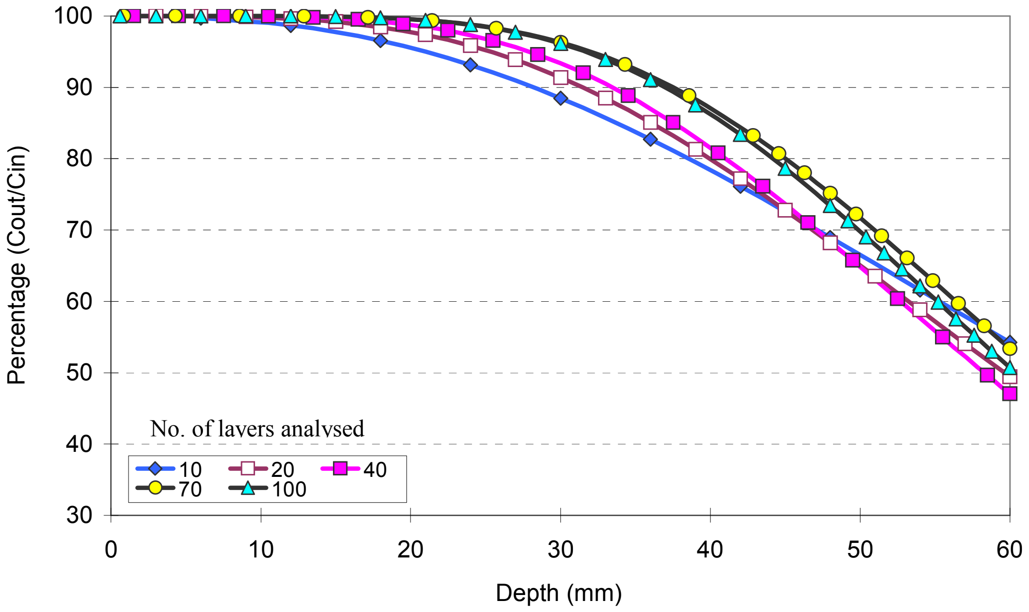


Fig. 3.17 Illustration of T_{50} for research model based upon different numbers of layers where the curves for 20-100 layers are at non-equilibrium

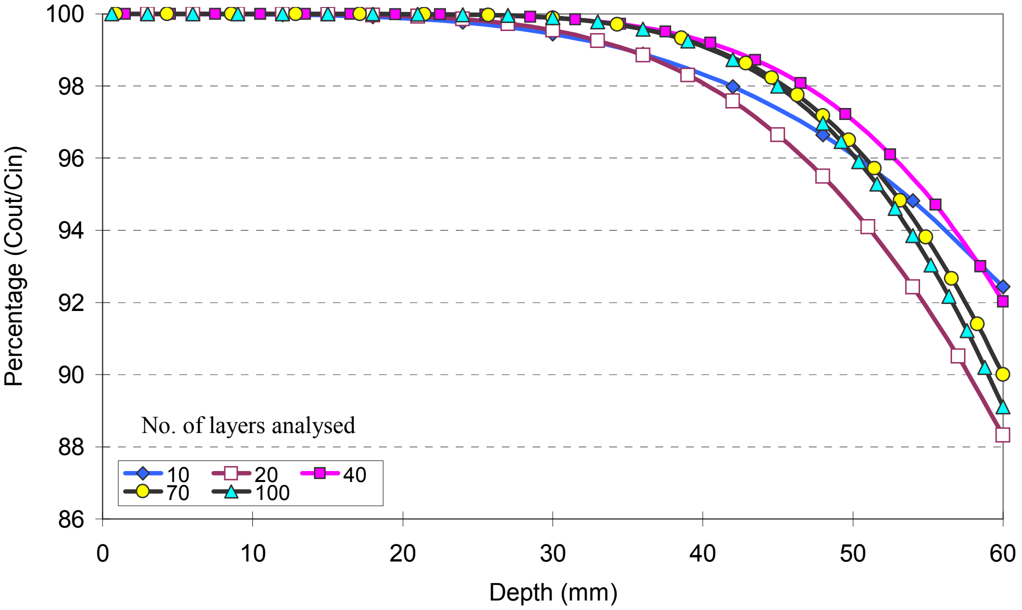


Fig. 3.18 Illustration of T_{90} for research model based upon different numbers of layers where the curves for 20-100 layers are at non-equilibrium

It is immediately apparent that there is now far less difference between the coarse and fine models (except for the 10 layer model) (c.f. Figs. 3.13 and 3.14 with Figs. 3.17 and 3.18) and that the response is less like 'plug-flow' (c.f. Figs. 3.13 and 3.17). Therefore the effect of better discretisation which brings the numerical results closer to the plug-flow predictions of Freeze and Cherry (1970) are offset by the effects of inadequate residence time which make the results diverse from a 'plug-flow' form. Hence values of T_{10} and T_{90} predicted by the research model may be given more credence than direct comparison with Freeze and Cherry at first suggests.

When comparing Fig. 3.19 with Fig. 3.15 it can be seen that breakthrough times occur more quickly at non-equilibrium (see Fig. 3.19), when less partitioning occurs. By transposing this to a 'real' pavement scenario, it means that a higher concentration will arrive at the bottom of the subgrade under consideration in a given time.

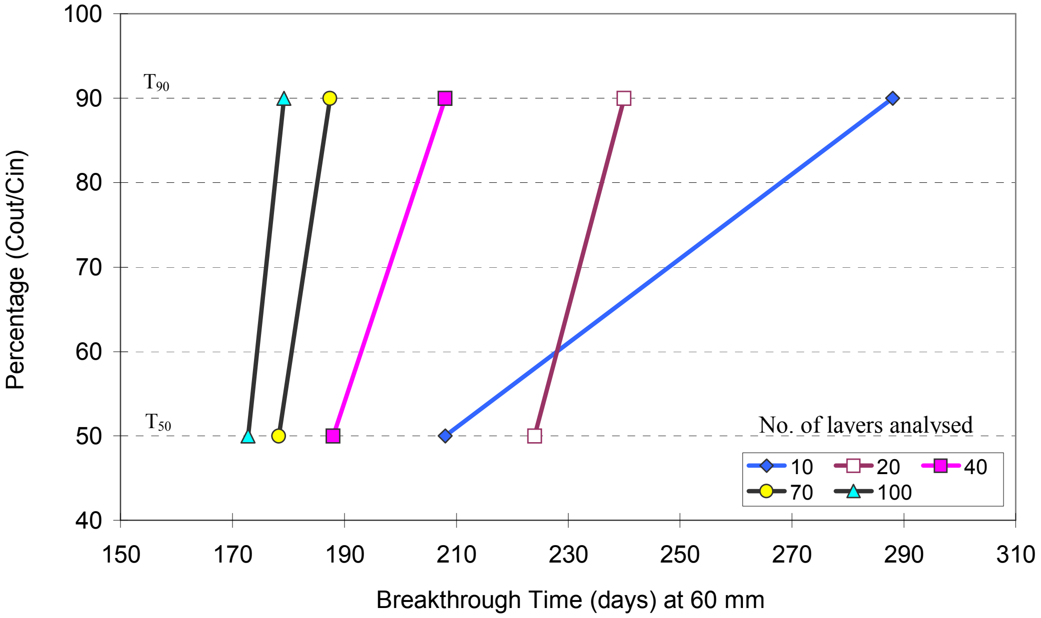


Fig. 3.19 Breakthrough times for T_{50} and T_{90} where the curves for 20-100 layers are at non-equilibrium

It has not been possible in the time available to further study the degree to which plug-flow is or is not a plausible model of reality but the need for sufficient time to ensure equilibrium at least suggests that a model of contaminant arrival which shows some apparent diffusion may not be unreasonable. A validated non-equilibrium model to replace Eqn. [3.5c] and a theoretical development might be able to ascertain the answer to this question, but they are beyond the present thesis's scope. The clear match between predicted T_{50} values of the present model and that of Freeze and Cherry (1970) has been demonstrated.

A further analysis is undertaken in Chapter 5 in order to assess the accuracy of the 10% of input concentration values in respect to the 'Analysis of Model Approach' undertaken above.

It is important to emphasise the fact that the breakthrough times determined and presented here are those predicted by the model and may not be exactly what happens in reality. From the analysis of the model it would appear that:

- If infinite numbers of layers could be used, in effect, the partitioning would cause an advancing plug-flow front through the soil.
- Apparent dispersion is seen which is, thus, a function of the model.
- A finer and finer discretistion would be needed to ensure that an advancing plug-flow is still approximated as K_d gets larger.
- Residence time requirements for full equilibration, as indicated by a K_d partitioning approach, are not met for finely discretised subgrades. It is likely that the reduction in apparent dispersion seen with finer and finer model discretisation is offset by increased true dispersion due to non-equilibrium conditions.

The model described here may be classed as a 'Mixing Cell Model'. That described by Bajracharya and Barry (1993), incorporates a transport model which, similarly, introduces a numerical dispersion coefficient into the simulations.

3.2.2.2 Horizontal Flow

Flow within an aggregate layer may move horizontally towards the side drains. Two main approaches have been selected upon which to base calculations in the spreadsheet simulations in order to determine these horizontal flow rates:

(1) 'Minimum Saturation' describes the minimum level of saturation which will remain within an aggregate after maximum drainage occurs (McEnroe, 1994). At this point the soil is said to be at 'field capacity' (Fitzpatrick, 1974), and

(2) 'T_f Drainage' describes the time that it takes for a particular percentage of the drainable quantity of water to drain from an aggregate (McEnroe, 1994). Equations illustrating above two approaches are given below. Following that, further equations which have been developed in order to calculate drainage rates in the format required

for this research are also presented.

Earlier in this chapter it became evident that during flows through most pavement aggregates, saturated conditions will not exist. The following two methods that have been used to determine drainage rates during horizontal flows are derived from approaches that reflect the flow regimes in pavements, according to their authors. They assume that saturated conditions are present below the phreatic surface (Fig. 3.20), and that unsaturated conditions are present above it. A fully saturated soil is two-phase, being composed of solid soil particles and pore water. A partially saturated soil is three-phase, being composed of solid soil particles, pore water and pore air (Craig, 1993). Although the two approaches are based upon both saturated and unsaturated conditions, there is no indication as to how accurately the calculations based upon the unsaturated conditions reflect the pore air that will be present. In reality as the water drains from the saturated zone, air will replace the water in the pore space. The air in the pore space will have the effect of reducing the water movement, and may result in drainage rates being lower than those estimated.

Minimum Saturation (S_{min}) (McEnroe, 1994):

This represents the minimum degree of saturation which remains within an aggregate under normal air pressure. It is specific for a particular pavement scenario, and is related to the k value (intrinsic for the aggregate under review) and the geometry of the pavement, as illustrated in Fig. 3.20.

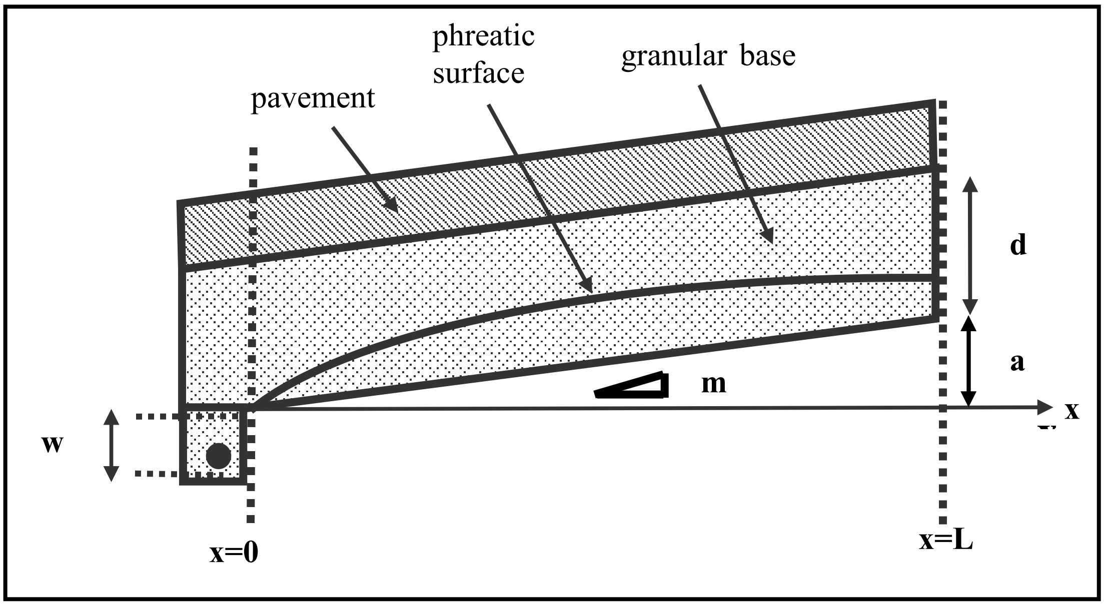


Fig. 3.20 Illustration to show cross section of a typical pavement (McEnroe, 1994)

According to McEnroe (1994) S_{min} can be determined through the application of Eqn. [3.6a], where symbols are defined for the pavement cross-section illustrated above:

$$S_{min} = S_r + (1 - S_r)\left\{\frac{x_1}{L} + \frac{(\psi_a - w)(x_2 - x_1)}{dL} - \frac{m(x_2^2 - x_1^2)}{2dL} - \frac{\psi_a^{\lambda}}{mdL(1-\lambda)(2-\lambda)} \cdot \right. \tag{3.6a}$$

$$\left. \left[(w + d + mL)^{2-\lambda} - (w + d + mx_1)^{2-\lambda} - (w + mL)^{2-\lambda} + (w + mx_2)^{2-\lambda}\right] - \frac{\psi_a(x_2 - x_1)}{dL(1-\lambda)}\right\}$$

where:

S_r: residual saturation
x_1: distance from edge drain (m)
x_2: distance from edge drain (m)
Ψ_a: air entry head (m)
w: bottom of drain pipe from bottom of granular base (m)
d: depth of base (m)
L: length (half-pavement width) (m)
m: gradient of pavement (m/m)
λ: pore size distribution index
given that:

Ψ_a: $[k^{-0.5}]4.543\text{x}10^{-3}$

and:

k: coefficient of permeability (m/s)

and x_1 and x_2 are related by:

$$x_1 = \begin{cases} 0 & \frac{\psi_a - w - d}{m} < 0 \\ \frac{\psi_a - w - d}{m} & 0 \le \frac{\psi_a - w - d}{m} < L \\ L & \frac{\psi_a - w - d}{m} > L \end{cases} \qquad x_2 = \begin{cases} 0 & \frac{\psi_a - w}{m} < 0 \\ \frac{\psi_a - w}{m} & 0 \le \frac{\psi_a - w}{m} < L \\ L & \frac{\psi_a - w}{m} > L \end{cases} \tag{3.6b}$$

The relationship between k and S_{min} taken from Eqn. [3.6a] has been plotted in Fig. 3.21, based upon typical pavement values of the parameters listed above, where:

S_r:	0.1
w:	0.6 m
d:	0.225 m
L:	4.65 m
m:	0.025 m/m
λ:	4
k:	3 to 3×10^{-8} m/s

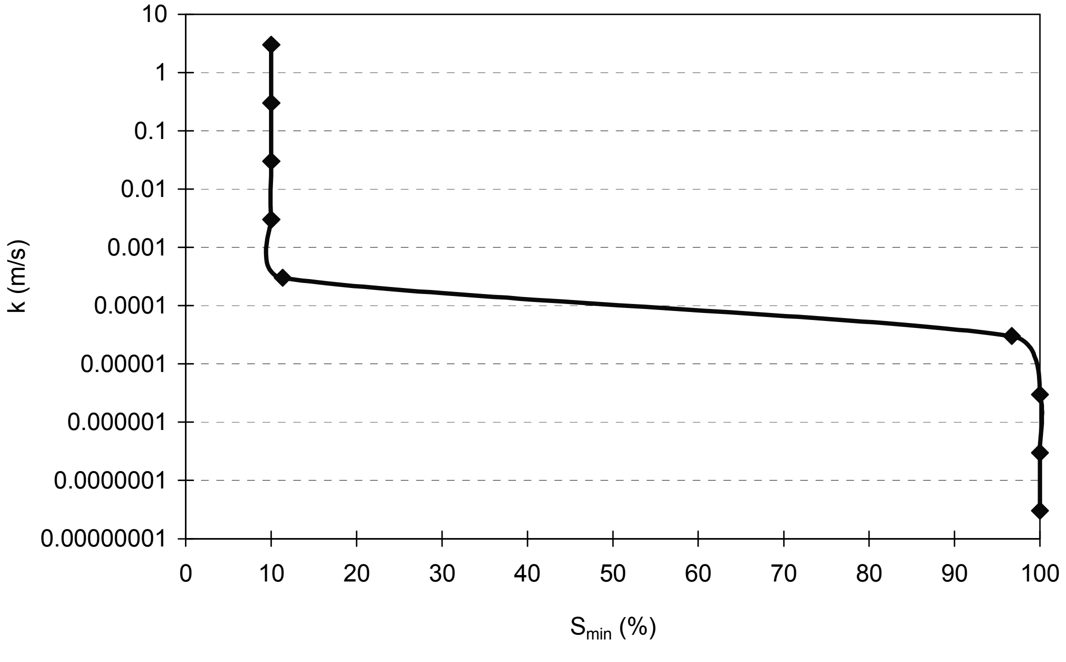


Fig. 3.21 Relationship between k and S_{min} values

It can be seen from Fig. 3.21 that the minimum S_{min} value obtainable is 10%, after which no further drainage may occur, regardless of increases in k values. 100% (maximum) saturation is reached when k $\leq 3\times10^{-6}$ m/s.

T_f Drainage (McEnroe, 1994; Moulton, 1980):

T_f describes the time that it takes for a particular percentage ($_f$) of the drainable quantity of water to drain from an aggregate and is expressed non-dimensionally (McEnroe, 1994; Moulton, 1980). The drainable quantity of water is equivalent to 100% saturation minus the minimum saturation. For example, if minimum saturation is 10% as illustrated in Fig. 3.21, then the drainable quantity of water is 90%. Therefore T_{50} is the time taken to drain 50% of the drainable volume, which is equivalent to 45% of the pore space.

Both McEnroe (1994) and Moulton (1980) describe methods for determining T_{50} which are given here as Eqns. [3.7a] and [3.8a] respectively. McEnroe's equation is specific for 50% drainage, whilst Moulton's allows any proportion to be examined.

(1) T_f (McEnroe, 1994):

$$t = \frac{T_{50} L n_d}{km} \qquad [3.7a]$$

which is equal to:

$$t = \frac{T_{50} L^2 n_d}{ka} \qquad [3.7b]$$

where:

m: a/L

$$T_{50} = \left(1.225 - 0.4D^{-\frac{1}{3}}\right)\left(1 - D \ln \frac{D+1}{D}\right) \qquad [3.7c]$$

and:

t: actual time (s)
n_d: drainable porosity = $n(1-S_{min})$
n: porosity
k: coefficient of permeability (m/s)
D: d/mL

(2) T_f (Moulton, 1980):

$$t = \frac{T_f \, n_d \, L^2}{kd} \qquad [3.8a]$$

where:

T_f: obtained from S_1 graph for known S_1 value. Obtained from dimensionless drainage lines which are plotted on a published graph of dimensionless time factor against required degree of drainage (T_f).

when:

$$S_i = \frac{Lm}{d} \qquad [3.8b]$$

The difference between Eqns. [3.7b] and [3.8a] is that the former bases calculations on L/a whilst the latter on L/d (Fig. 3.20). The difference in value between 'a' and 'd' will determine the relationship of one from the other. In effect they are two methods using differing approaches. In practice, however, they prove to be very similar.

T_{50} calculations were undertaken for both sets of equations, using the same parameters for 'depth of base', 'length', 'gradient', and 'drainable porosity' as in Eqn. [3.6a] using a variety of magnitudes of k, where the closeness between the resultant times are presented in Fig. 3.22.

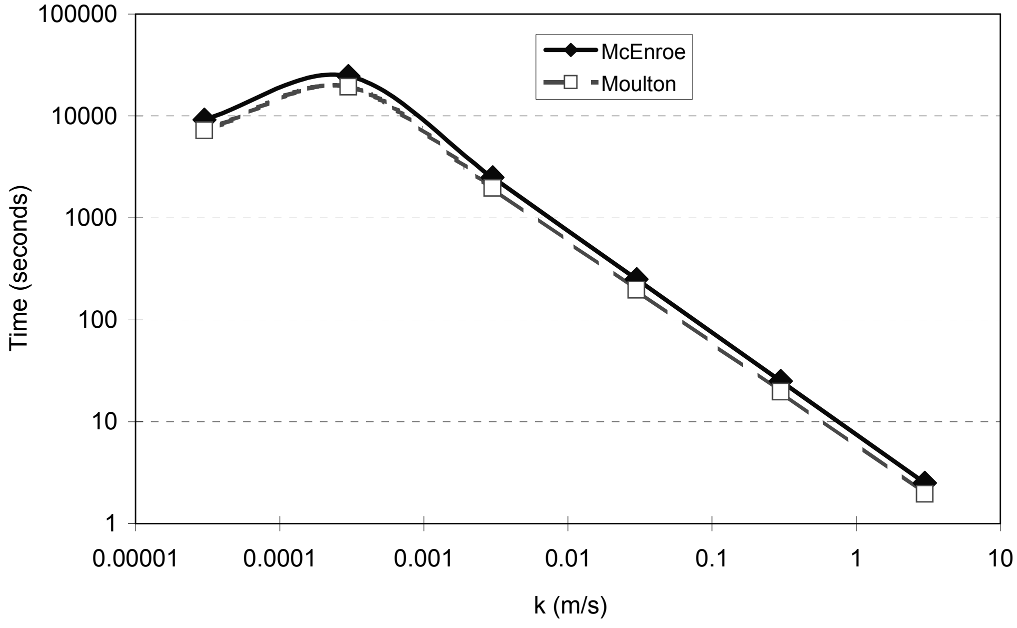


Fig. 3.22 Times for T_{50} drainage using equations by McEnroe (1994) and Moulton (1980)

Due to the high correlation between both data sets, it was assumed that thereafter the accuracy of obtaining the times for other percentile drainage times ($T_{10\text{-}90}$) from Moulton (1980) alone could be accepted as reliable, and resultant data are presented in Fig. 3.23, for a range of T_f values.

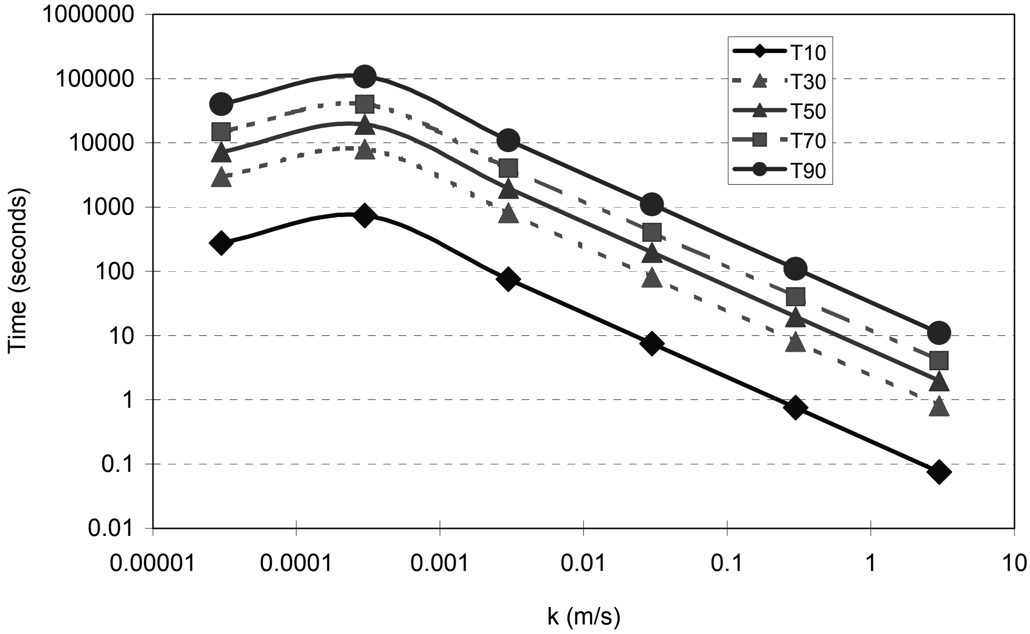


Fig. 3.23 Times for a range of T_f drainages using the equation by Moulton (1980)

In Fig. 3.23 it is evident that the initial 10% of drainage takes disproportionally less time than subsequent drainage times. It can be seen from Figs. 3.22 and 3.23 that initially drainage times increase as k decreases. This means that drainage times increase as the k values reduce to $k=3x10^{-4}$ m/s. As k values continue to reduce after that point, drainage times reduce slightly until $k=3x10^{-5}$ m/s, after which point no further drainage occurs.

From the above section it is evident that drainage quantities (up to the corresponding S_{min} value) and drainage times to any percentage (defined by T_f) can be calculated.

The format required within this research has been drainage rates per hour, in order to determine the quantity of contaminants being transported within water flows in the pavement per hour. To calculate that it was necessary to know the rates of water entering (infiltration of rainfall) and water out (drainage) per hour. Rainfall data are usually presented as hourly rates, and drainage rates per hour have been determined through equations derived from Eqns. [3.8a] and [3.8b], which are presented in the following section.

Due to the fact that for some k values not all input water drains within 1 hour, Eqns. [3.8a] and [3.8b] have been used to calculate drainage times for T_{10} to T_{90}, which have been used to plot graphs in Figs. 3.22 and 3.23. A final end time for T_{99} (where it is assumed that 99% of drainable water is the point after which, in effect, no further drainage will occur) has been calculated by initially plotting drainable saturation (where drainable saturation = saturation-S_{min}) against time. In order to achieve a curve which can be readily fitted to a simple exponential form, Fig. 3.24 has been derived, but with the x axis plotted as T_x-T_{99}, where T_x is established by using different values for T_{99} until the highest correlation coefficient (R^2) for an exponential trend line is achieved (Fig. 3.24).

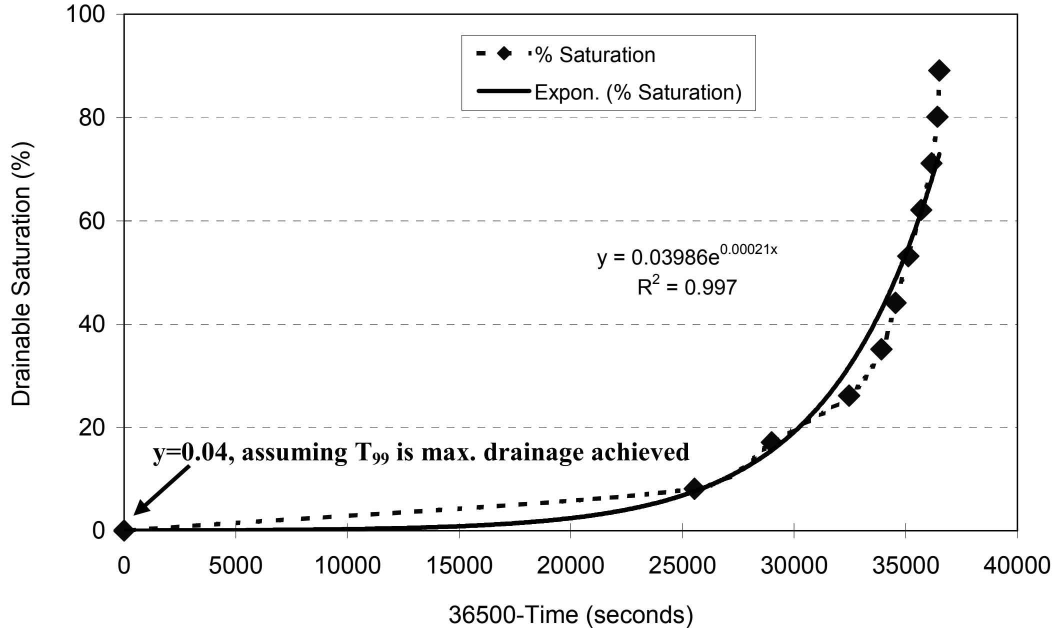


Fig. 3.24 Drainable saturation plotted against time (T_0-T_{99}) for example n and k values,

where n=0.2 and k=0.003 m/s (allowing for S_{min}=10%). These n and k values have been selected because they represent typical values in pavement construction

It can be seen in Fig. 3.24 that for T_{99} that for this example the end time of 36500 seconds gives an R^2 value of 0.997, and represents the fitted relationship where:

$$\text{drainable saturation} = 0.03986e^{0.0002(36500-t)} \qquad [3.9a]$$

The end time of 36500 has been used to plot the graph in Fig. 3.25, which shows saturation against time, and allows for a residual saturation of 10.04% (S_{min}) assuming that T_{99} is maximum drainage achieved.

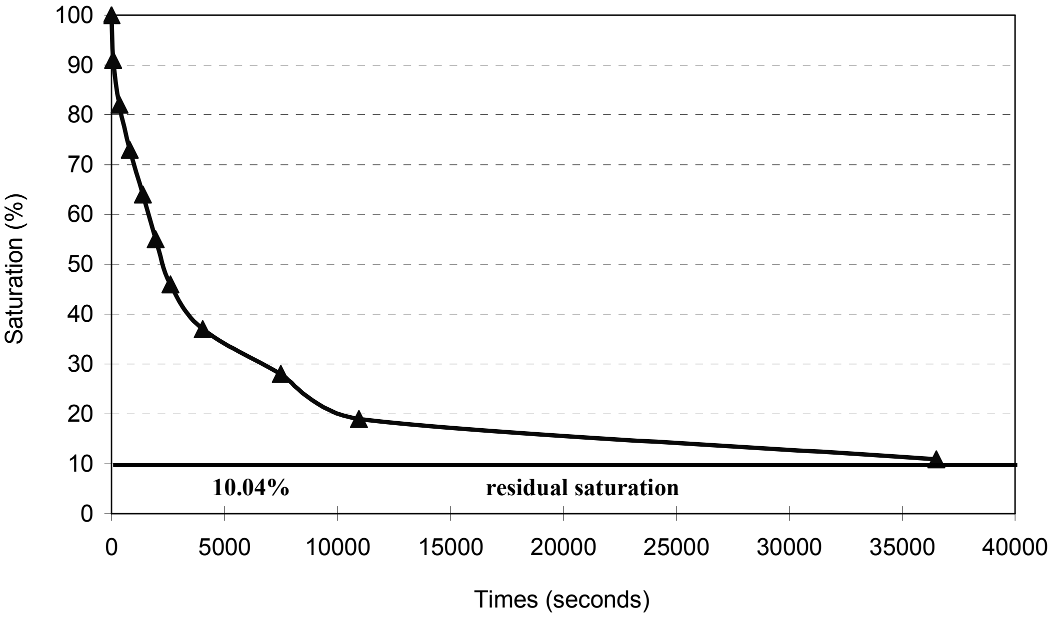


Fig. 3.25 Saturation plotted against time (T_0-T_{99}), where T_{99} (end time) is taken to be 36500 seconds for n=0.02, k=0.003 m/s

An exponentially decaying drainage rate has been assumed (Fig. 3.24) and this decay has been mathematically fitted, where drainable saturation and time are related as:

$$\text{\% drainable saturation achieved} = Ae^{B(c-t)} \qquad [3.9b]$$

where:

t: time since drainage started when fully saturated
A, B: model coefficients
c: time notionally needed for completion of drainage

The change in saturation in any particular hour can then be calculated using Eqn. [3.9b].

A prediction of saturation at any particular time may be made using Eqn. [3.9c]:

$$\left[\Delta S_d\right]_t^{t+1hr} \qquad [3.9c]$$

where:

S_d: drainable saturation

Using Eqn. [3.9c] based upon examples in Figs. 3.24 and 3.25, the following equation to predict saturation is developed:

$$0.04 \times (e^{0.0002(36500-t)}) - (e^{0.0002(36500-(t+3600))}) \qquad [3.9d]$$

The numeric constants change for other material and pavement arrangements.

Predicted saturation as shown in Eqn. [3.9d] has been used to calculate hourly rates of water draining horizontally through pavement aggregates into the side drains. Rainfall over a twelve-hour period has been extracted from Ward (1975) previously presented as a twenty-four-hour rainfall event (Table 3.11).

Table 3.11 Example of a 12-hour rainfall event for Aberdeen (Ward, 1975)

Time Interval End	**12-Hour Rainfall Event (l)**
1	0.08
2	0.08
3	0.08
4	0.08
5	0.08
6	0.13
7	0.13
8	0.15
9	0.15
10	0.15
11	0.13
12	0.13

A graph of calculations of a pavement drainage regime based upon the twelve-hour rainfall event is illustrated in Fig. 3.26.

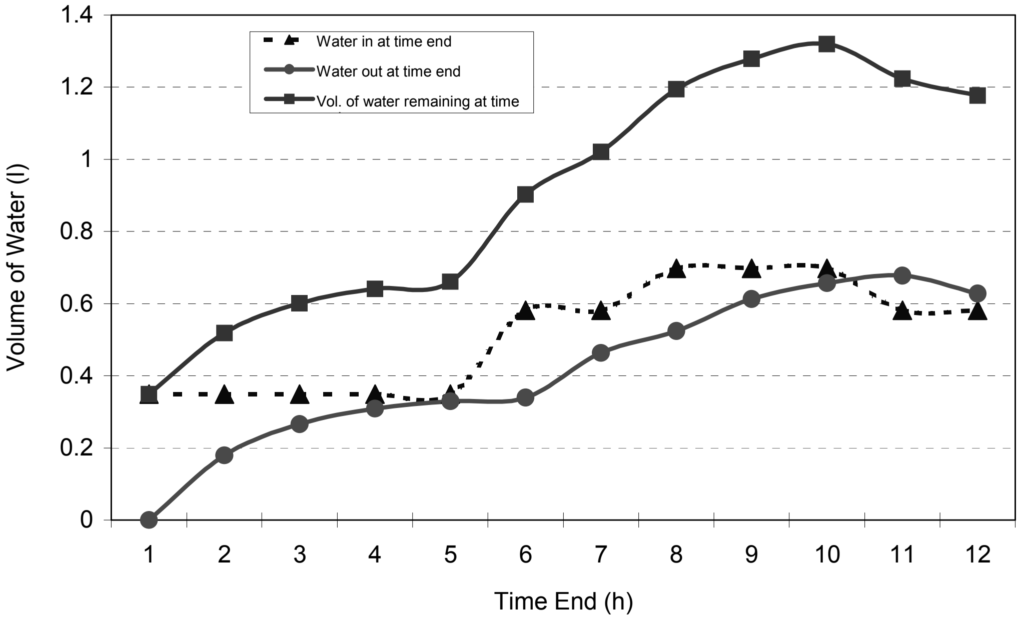


Fig. 3.26 Drainage levels for 12-hr rainfall event

From Fig. 3.26 it can be seen that because there is no water present at the start, the water remaining equals that entering at the first time end. No water drains out during that hour. At each subsequent time end, the volume of water remaining equals the water in during that time end minus the water out plus the volume of water remaining from the previous time end. Over the twelve-hour rainfall event there is an increase in water in and a subsequent increase in both water remaining and water out. At the end of the rainfall event the water entering closely equals the water out, with a subsequent reduction in water remaining.

From the equations illustrated above, the rate of contaminant deposition into side drains per hour may be calculated. Calculations based upon this twelve-hour rainfall and three additional rainfall events and a discussion on the implications of the equations illustrated within this chapter within pavement construction are presented in Chapter 5.

4 Cumbria – A Case Study

4.1 Introduction

This Case Study was based around a section of the A66 in Cumbria, the general location of which can be seen in Fig. 4.1. The A66 trunk road from Keswick to Workington, Cumbria was constructed around 1975, using BFS as bulk fill. The road was built over an acidic bog, marshy material was removed and the area was back-filled with approximately 300,000 tonnes of BFS. At some sites the road was constructed at ground level, the material was removed and the site constructed in the form of trenches, with the same amount of slag put into the road as the material removed. At other sites, however, where embankments were constructed much larger amounts of slag were introduced than material removed. The slag was used below the water table. The BFS used within the construction of the A66 was obtained from works in Workington and a chemical analysis of slag can be seen in Table 4.1.

Table 4.1 Comparison of solid analysis of Workington BFS with typical BFS (Law, 1999)

Plant	Ore Used	CaO	MgO	SiO_2	Al_2O_3	MnO	BaO	S_2^{2-}	Other
Workington	Hematite	44.5	2.4	35.3	10	0.7	3.2	2.5	1.4
Workington	Fe/Mn	38.3	3.7	24.8	15.4	11.1	1.4	3	2.3
Typical BF	Basic Fe	39	7	36	15	0.7	<0.5	1.5	0.3

Contamination problems relating to sulphide released from BFS began to be detected, and an overview to this problem is outlined below and forms what has been termed the 'Original Study' within this thesis. Ian Law (Environmental Protection Officer for the EA) was the River Inspector for the National River Authority at the time when the road was constructed and his knowledge of the past events and current interest form the basis of the historical information given here. The following account of events has been extracted from information forwarded by Law (1999, 2001) which was the result of various reports and letters written during the time of the original study. In order to retain the anonymity of the authors of these reports, some were presented for

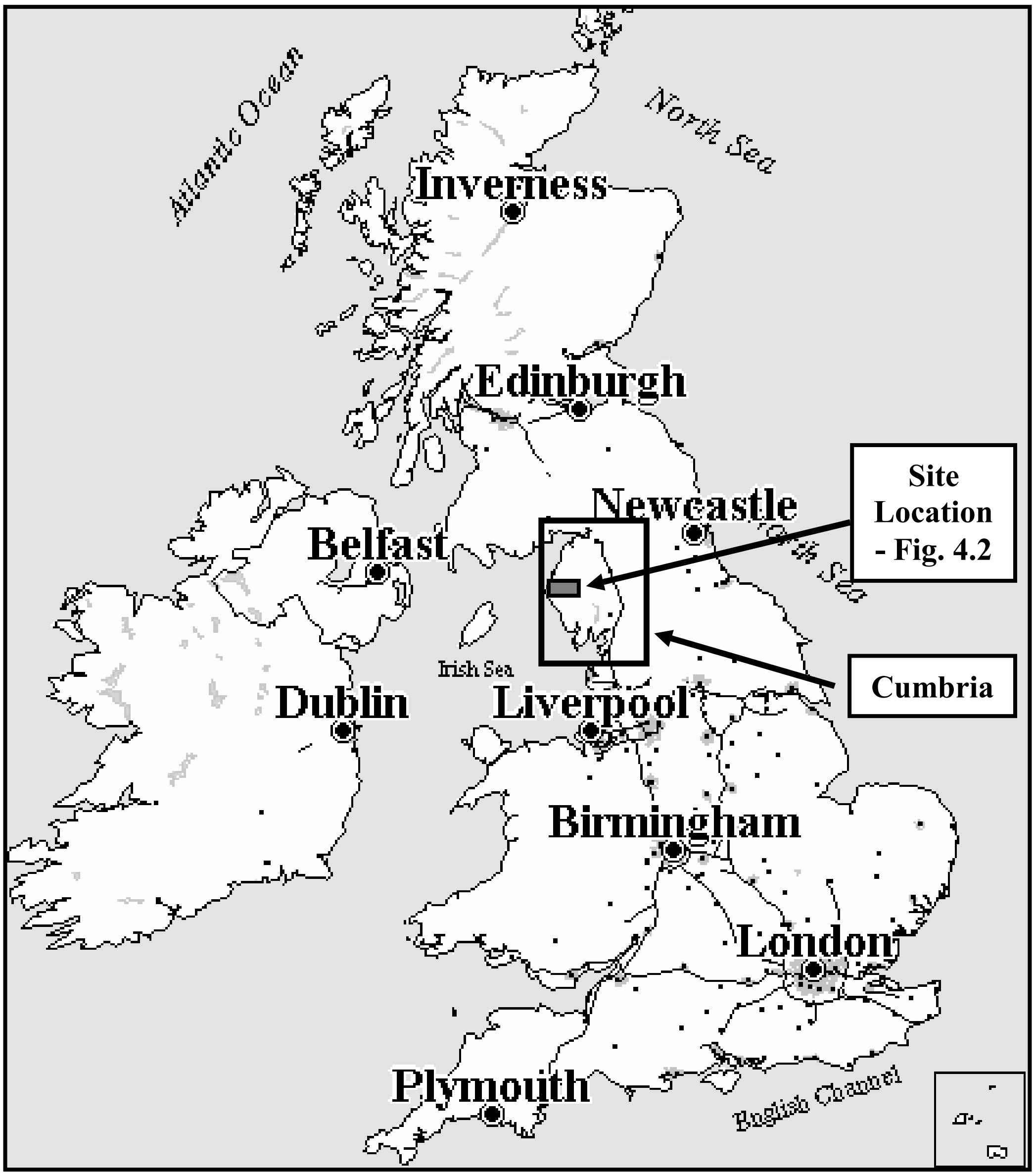


Fig. 4.1 Map of the UK showing Cumbria

Source: Microsoft AutoRoute Express

use within this research in an anonymous format, and consequently none have been referenced within this chapter. This also is the case with the data presented within tables, which were forwarded to the University of Nottingham as data analyses reports, which again have not been referenced.

Overview to the sulphide contamination: problems began to occur as a result of sulphide gas and associated sulphide-liking bacteria. In winter the problem was not so severe since there would be plenty of water in the local receiving streams to enable dilution to occur. However, as groundwater continued to flow into the receiving streams whose flow rates had decreased during the summer months, along with temperature increases, excessive algal blooms occurred.

At the time there was concern that permanent damage had been done to the small streams bordering the A66, Dubwath Beck and Tom Rudd Beck, both being important spawning streams for salmon and sea trout. There was some evidence of 'avoidance' and reduced spawning for a number of years. Farmers complained that stock would not water from the streams.

Law stated in 1999 that he had recently revisited some of the original sites and there was only one that could be described as 'active'. There was still evidence of black deposits on beds of the streams and adjacent vegetation.

The following sections in the 'Original Study' summarise events and data collected over a five-year period approximately 25 years ago when signs of the contamination first became evident. All of the sections outlining the engineering works, sulphide contamination and biological observations as well as the presentation and analysis of the original data have been produced and written within this research and are a result of analysing and interpreting the reports and letters forwarded to the University. The format used is considered to follow the sequence of events as fully as the available information would allow.

4.2 Original Study

4.2.1 Engineering Works

The A66 runs from Scotch Corner (approximately 4 miles NE of Richmond, Yorkshire) to Workington, Cumbria on the west coast, by-passing Penrith, Keswick and Cockermouth. Its course through the northern part of the Lake District involves several crossings over some prime fishing rivers. The anglers and visitors are very sensitive to the least discoloration of any watercourse. The actual section of the A66 which was studied within the original and new studies (information regarding the new study can be found further on in this chapter) covers the area between Bassenthwaite Lake and Great Clifton (Fig. 4.2).

The contract for the construction work was undertaken by Tarmac Limited supervised by Cumbria County Council, who acted as agents for the Department of the Environment.

During May, June and July 1975 numerous complaints were made by anglers and fishing interests on the River Derwent and the River Cocker of discoloration of both rivers as a result of construction works associated with the new A66 trunk road. Virtually all the complaints of discoloration of the River Derwent were in regard to the river downstream of the Cocker-Derwent confluence at Cockermouth and in particular downstream of the Broughton area. On the Cocker, the complaints were limited to the river downstream of the Simonscales Lane bridge site on the outskirts of Cockermouth, the only point were road works cross the main river. The complaints were of discoloration severe enough to limit or completely stop angling in the rivers, but there were no reports and no evidence was found of any associated fish mortalities.

On River Cocker, discoloration was the result of works in or very close to the river and was associated with the construction of a bridge over the river. The discoloration was caused by the presence of plant working actually in the river, crossing the river or by the wash-off of silt and fine solids from the surrounding roadways during periods of heavy rain. There were in some instances actual pumping of heavily contaminated water from excavations adjacent to the river. Severe discoloration of River Cocker had effects upon the Derwent for some distance downstream of the confluence at Cockermouth. In addition there were also works carried out on the river bank. This necessitated the building of bunds in the main river, causing marked contamination of the river. Water from these sites was also pumped to the river.

Following complaints, meetings were held with Cumbria County Council, Tarmac Limited and North West Water Authority. Following further complaints, a meeting was held in July 1975 between Cumbria County Council (Project Manager), the resident Tarmac Engineer, the Regional Fisheries Officer and the Principal Fisheries Assistant who represented both the fisheries and water quality interests. It was agreed that the rivers Cocker and Derwent would be inspected daily by Cumbria County Council and Tarmac and, if necessary, samples would be taken. Any reports of discoloration sufficient to stop fishing would be investigated and any future claims for compensation would be considered once the works were completed. Works scheduled to be carried out on the banks of the River Derwent below Broughton Cross were delayed until after the end of the fishing season (31st October).

After November 1975, the anonymous reports indicate that samples of water discharging from drains from the roadway were found to be 'contaminated' (to an unspecified level) with sulphides and hydrogen sulphide (but actual values were not found within the reports presented to this research). This was thought to result from BFS used for road foundations. Biological and fisheries investigations showed that there was a marked impact on the invertebrate fauna and fish populations in the two streams receiving the drainage from the new road - Dubwath Beck and Tom Rudd Beck.

Another meeting was held in April 1976 with Cumbria County Council, the Department of the Environment and representatives of the Rivers Division, and it was agreed that this section of the water course would be regularly monitored.

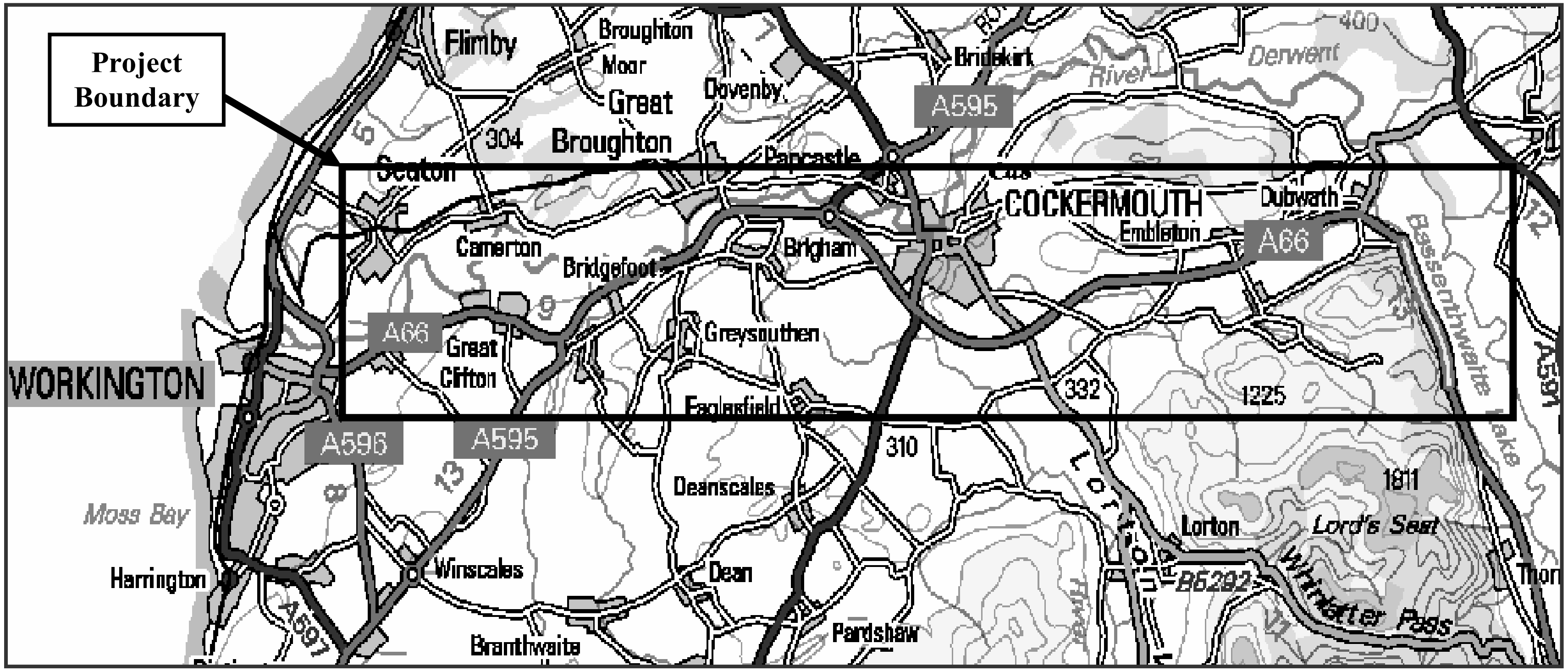


Fig. 4.2 Map to illustrate project boundary

Source: Microsoft AutoRoute Expres

At that point in time, no mention was made of the sulphide contamination to any angling interests, associations or related organisations, to allay unnecessary concern and premature reaction from these outside bodies until a full investigation had been carried out.

4.2.2 Investigations into the Sulphide Contamination

Towards the end of 1975, following a complain of sulphurous smells in Dubwath Beck, subsequent inspections and analysis of water discharging from a number of road drains from the A66 between Bassenthwaite and Cockermouth indicated the existence of sulphide contamination of water discharging from many points on the length of this road. Sampling of drains discharging to Dubwath Beck and Tom Rudd Beck produced sulphide levels sufficiently high to warrant concern on the polluting effects on these two receiving watercourses and the effect upon the natural invertebrate and fish populations in the streams.

The slag used for the road foundations contained large quantities of sulphide compounds, particularly calcium sulphide. Also, due to the pumice-like nature of BFS, hydrogen sulphide is present, trapped within gas pockets in the hard matrix. This gas is naturally released to the atmosphere on fracture of the slag. It is possible that chemical and/or biological attack and degradation of the material may take place.

The level of the total sulphides in the water discharging from a number of road drains or gulleys varied when random samples were taken. Levels of between 0.19 mg/l and 17.8 mg/l were obtained in March, 1976, for example (Law, 1999). The smell of the water indicated that in addition to sulphide ions, hydrogen sulphide was also present.

Marked changes were detected both in the invertebrate and fish populations in Tom Rudd Beck below the point where discharge from the A66 enters the stream. Similar changes in the invertebrate fauna were found in Dubwath Beck, although due to major land drainage works fish population surveys were not carried out.

The reports presented to this research stated that hydrogen sulphide has been shown to be toxic to fish life in concentrations as low as 0.004 mg/l. Sulphide levels of 0.53 mg/l and 0.42 mg/l were found in Dubwath Beck and Tom Rudd Beck respectively (Law, 1999). In both streams extensive growths of the filamentous sulphur-liking bacteria Thiothrix were also found and identified. This bacteria is dependent upon the presence of hydrogen sulphide for its growth.

In addition to the direct toxic effect of hydrogen sulphide on fish, they also exhibited an 'avoidance reaction' at these sub-lethal concentrations. The limited survey that was carried out on Tom Rudd Beck demonstrated that the population of brown trout and other salmonids upstream to any contamination was approximately 0.4 fish per sq. meter, whilst downstream of the discharges this figure dropped to zero fish per sq. meter, with 0.1 fish/sq. meter in a stretch receiving an intermediate volume of discharge.

4.2.3 Biological Observations from the Sulphide Contamination

The Biological Section of the National River Authority (now the EA) first became involved in mid February, 1976 when Law, the River Inspector for the area, asked for a sample of filamentous bacterial growth to be identified. It was thought to be associated with suspected sulphide pollution of Dubwath Beck and Tom Rudd Beck. From its morphology and growth conditions it was initially identified as a colourless filamentous hydrogen sulphide oxidising organism. Following this, an invertebrate sampling programme was undertaken towards the end of February and in March live samples of the bacterial growth were taken to the Freshwater Biological Association Windermere Laboratory for identification.

Invertebrate groups: the Dubwath Beck was walked from the point of its discharge to Bassenthwaite Lake for 1500 m upstream, and a significant polluting discharge noted on the left bank, which was receiving drainage from the new road drain system. It was slightly coloured and had a visual impact on Dubwath Beck, a downstream 'plume' of greyish white sulphur bacterial growth on the bottom gravel spreading across the beck as the water from the drain progressively mixed with the beck water.

There were no signs of sulphur bacterial growth upstream of the discharge, apart from in a roadside drainage structure upstream of the ditch.

Samples were taken at six sites, two upstream and four downstream of the ditch. In addition to the invertebrate samples, stones were collected for observations on algal communities and specimens of the bacterial growths were taken.

Results showed that fauna upstream were characteristic of a small, clean stream. The fauna downstream appeared significantly restricted. Sensitive stonefly and Ecdyonurid mayfly nymphs were absent and the common mayfly *Baetis rhodani*, which was numerically dominant upstream, was reduced in numbers, such that Tubificids were then dominant. Flatworm Polycelis was absent from all downstream sites. The total number of species found had declined from eighteen to twelve. Each site had varying quantities of invertebrates, which correlated with proximities to road discharge areas. One site showed a grey green tinge and a strong smell of hydrogen sulphide, and this site received direct runoff from an adjacent bridge.

Tom Rudd Beck was similarly sampled at three sites, one being upstream and two downstream of the road discharge point. The upstream site showed a typical clean stream fauna, with broadly similar stream characteristics to those at the upper sites on Dubwath Beck. The fauna was in fact, more diverse and rich in sensitive groups than at the clean Dubwath Sites. At one site, 100 m downstream of the discharge, the number of species recorded rose with no loss of sensitive groups. At another site, however, there was a massive change. Conspicuous whitish tufty growths of sulphur bacteria covered the stones and there was a strong smell of hydrogen sulphide and the water was a milky-green colour. It is highly likely that additional pollution occurred upstream between the previous site and this site. The Plecoptera, Ephemeroptera, Trichoptera and Coleoptera had been eliminated, but Chironomids were abundant, associated with the bacterial growths and Tubificids were present.

Bacterial growth: one bacterial grown sample was taken from each site downstream of the discharges in both rivers. Samples consisted of cultures of the hydrogen sulphide oxidising bacterium Thiothrix. Thiothrix is dependent on the presence of 0_2,

CO_2 and H_2S for its development. It obtains its energy by the oxidation of hydrogen sulphide, producing colloidal sulphur which is deposited within the organism.

Thiothrix occurs naturally in small numbers within a stream in small habitats in which anaerobic hydrogen sulphide production has occurred. It may be concluded that it had been promoted to a dominant status in both Dubwath Beck and Tom Rudd Beck by the sulphide pollution of the originally aerobic habitat. The milky, greenish white colouration of the beck waters noted at some sites could have been due to colloidal sulphur, resulting from Thiothrix going into suspension. Regarding the nuisance value of Thiothrix growths, it seemed better to regard them as a symptom of the more serious basic problem of sulphide pollution (toxicity effects and oxygen depletion) rather than as a potential problem in their own right. Cold temperatures appear to favour their growths. In a sense, the growth though aesthetically undesirable in streams, has the beneficial effect of converting toxic hydrogen sulphide into colloidal sulphur.

4.2.4 Summary

Whilst the polluting effects of the discharges were related to sulphide concentrations, it was thought appropriate at the time for the study to also include the input values for sulphate and calcium carbonate. BFS is composed of metal ore and calcium compounds, with calcium sulphate and calcium carbonate often present as soluble components, and entrapped in vacuoles, gaseous hydrogen sulphide. Although the precise process of sulphide leaching and/or release was unknown, it was thought likely that whatever the process, there was a breakdown, either chemically or bacterially, of the calcium sulphate/carbonate matrix with the release of sulphate and calcium together with sulphides and hydrogen sulphide.

Water samples were taken (information regarding the method of obtaining the samples was not available for inclusion within this report) to compare flow rates (l/s) with daily masses (kg/d) of sulphide (measured as S), sulphate (measured as SO_4^{2-}) and calcium (measured as $CaCO_3$) during five periods, denoted as Periods A-E. The timescale (but not sampling days), weather conditions, mean flow rates and concentrations are given below (Table 4.2). The daily input of sulphate and calcium into the two streams increased as the flow increased. This was similar for sulphide input to Dubwath Beck, with a much less well defined trend for sulphide into Tom Rudd Beck. This lack of relationship for sulphide may have been due to the complexities of the sulphide-hydrogen sulphide reaction and the fact that hydrogen sulphide is lost to the atmosphere particularly at the higher flows when more turbulent water conditions prevail. This aspect may well explain the low levels of sulphide found in Tom Rudd Beck at the downstream sampling point 2 km below the lowest point of contamination, as compared with the sampling point on Dubwath Beck which was only 0.5 km below the lowest point of contamination. The result of that was that there was less opportunity for hydrogen sulphide to dissipate to the atmosphere from Dubwath Beck compared with Tom Rudd Beck. Additionally, Tom Rudd Beck had a faster more turbulent flow that Dubwath Beck, hence increasing the atmospheric dissipation.

Table 4.2 Results of testing carried out during original study

Period	**A**	**B**	**C**	**D**	**E**
Dates	**22.6.7-9.9.76**	**23.9.76-31.1.77**	**22.3.7-24.5.77**	**30.5.77-8.8.77 and 23.5.78-25.7.78**	**6.9.77-14.2.78**
Weather Type	**1976 Drought**	**Autumn/Winter - Wet Period**	**Spring - Wet Period**	**Summer - Dry Periods**	**Autumn/Winter - Wet Period**
Dubwath Beck					
Flow Rates (l/s)	35	359	205	56	318
S_2^{2-} (kg/day)	0.35	5.6	4.02	0.48	1.85
SO_4^{2-} (kg/day)	64.2	679	316	115	347
$CaCO_3$ (kg/day)	197	1129	476	206	552
Tom Rudd Beck					
Flow Rates (l/s)	14.8	231	118	35.6	398
S_2^{2-} (kg/day)	0.09	0.9	0.015	0.002	0.04
SO_4^{2-} (kg/day)	40	48	120	127	212
$CaCO_3$ (kg/day)	59.5	99	273	511	738

With the increase in the mass input of the sulphate and calcium carbonate to the two streams, there was undoubtedly a substantial increase in the release of these two chemicals from the road works generally, and it was suggested that the great majority came from the slag. This was either as a result of increased percolation of rainwater through the slag mass, surface runoff from the A66 flowing through the embankments or the flow of groundwater in the debogged areas. Since the problem only arose in areas associated with the debogging, it was most likely that the increased flow of groundwater through the slag mass in times of wet weather resulted in the increased contaminant discharge, a hypothesis put forward during the investigation.

During the drought of 1976, there was a gradual decrease in the amount of material entering the streams. However, at the end of the drought and with the onset of rain there was a sharp increase and the mass remained high over Autumn/Winter and fell slowly during the following Spring. Levels again fell during the Summer of 1977, though not as low as those encountered in 1976. A further increase occurred again during the Autumn, Winter and early Spring of 1977/78 and gradually fell to low levels during the late Spring of 1978. The three chemicals studied (sulphide, sulphate and calcium) were higher for Dubwath Beck than for Tom Rudd Beck. A likely cause is that 150,000 tonnes of slag were used in the debogging operations in the catchment area of Dubwath Beck, compared with 65,000 tonnes on similar construction work in Tom Rudd Beck area.

The cyclic changes confirmed the theory that most of the contamination arose from the discharges of heavily contaminated water from the debogged areas. Basically, the debogging entailed the removal of a considerable depth of peat along the line of the proposed roadway and the filling in of the resultant trench with slag to form a solid foundation. It was argued that the trench containing slag then filled with groundwater to the level of the normal water table. In dry weather there was little inflow or outflow and the concentration of calcium, sulphate and sulphide rose due to chemical and/or biological action. With the onset of wet weather, groundwater rose as was apparently detected through limited borehole monitoring. It was shown that the water table alongside the A66 varied by approximately 1 m between Winter and Summer levels. An influx of water into the trench caused overspill into drains and watercourses crossed by the road and consequently a discharge of the contaminated groundwater to the two principal streams.

Initially the concentration of resultant contaminants rose, the extent of this and the time for which it continued depended upon the rate of flow of the groundwater and/or surface water through the trench. If the initial flow rate was high and it continued for an extended period (late Autumn through to Spring) the trench was flushed out and the concentration of contaminants then fell considerably. With the onset of the next dry period, flows into the trench decreased and there would then have been an increase in the degree of contamination of water within the trench. The start of the next wet period again saw the discharge being heavily contaminated.

It was concluded at the end of the study that the problem of contamination of the two streams could be expected to continue for as long as the main bulk of the slag mass remained in these two locations, which was expected to be for a considerable length of time. No actual timescale for this was given, but one can assume it was expected to be for the life of the road.

The greatest effect of the contamination was on the fish stocks. Both streams carried stocks of resident brown trout and the upper reaches of both streams were used as spawning grounds for salmon and migratory sea-trout. It appeared that following the onset of the contamination few, if any, salmon or sea-trout used either stream for spawning, even when seasonal variations in water flow resulted in lower levels of contamination. Fish show a marked avoidance reaction to water containing hydrogen sulphide at levels as low as 0.004 mg/l. It was probable that the lack of migratory fish spawning in these two streams was due to avoidance rather than direct toxicity to fish once they had entered them. This lack of spawning would consequently have an impact on the fish progeny approximately 5 years later.

4.2.5 Presentation of Original Data

During the original study of the water systems around the A66, periodic water sampling was undertaken from eighteen water sampling sites (numbers 1 to 17 and A). The water sampling sites may be seen in Fig. 4.18. Grid locations and full data sets for these sample sites can be seen in Appendices 4 and 5. In addition, four boreholes were used, but the data were not recorded in sufficient detail to be presented within this thesis. Data from sites 1, 9, 10, 14, 15, 16 and 17 were selected for presentation here, because they were the only sites from which water samples were in most cases consistently obtained and from which, therefore, trends in contaminant levels can be seen. It should be noted, however, that in some cases data previously cited within this chapter have not be presented in the tables of data either here or in

Appendix 4, because some were extracted from written documents but not presented in tables forwarded to the University of Nottingham.

Data extracted for presentation here can be seen in Tables 4.3 to 4.6. These data are also presented graphically in Figs. 4.3 to 4.6. It should be noted that gaps in the graphs reflect absence of data. pH values for the sites determined during the study are presented in Table 4.7 and Fig. 4.7.

An important point to mention is that data presented here were forwarded to the University of Nottingham as complete data sets, with no information as to analytic techniques used or standard deviation included within results. This makes comparisons of data presented within the original study with data presented within the new study (presented further on) slightly inconclusive. This is because analytic techniques between both data sets may have been very different with different margins of error. For full comparisons to be undertaken, analytic techniques and margins of error would need to be identical. However, trends in both data sets do reflect contaminant concentrations at the time of sampling (regardless of analytic techniques), and sites with raised concentrations may be taken to be major contributors of contaminants within the two river systems.

Table 4.3 Calcium levels during original test period (mg/l)

Site	Date																
	4/5/76	**8/6/76**	**16/06/76**	**29/07/76**	**02/08/76**	**31/07/77**	**28/03/78**	**01/02/79**	**17/04/79**	**18/12/79**	**14/04/80**	**21/07/80**	**30/07/81**	**21/12/81**	**15/09/82**	**20/12/82**	**19/12/83**	**19/12/85**
1	n/a	36	24	29	25	21	n/a	22	15	7.6	8.4	6.1	6	n/a	5.2	n/a	6.0	5.9
9	n/a	54	68	118	106	52	43	46	46	16	21.6	15.1	19	n/a	16	n/a	14.0	13.4
10	n/a	18	20	30	252	20	19	19	17	15.2	14.0	6.8	10	n/a	8.2	n/a	9.6	10.1
14	n/a	n/a	60	110	120	53	49	43	50	20.4	22.2	15.4	19	n/a	15	n/a	18.0	17.3
15	n/a	148	160	130	136	80	73	93	63	31.2	36.4	75.5	51	n/a	4.6	n/a	25.0	22.7
16	n/a	300	320	292	284	226	197	276	286	39.6	113.6	117.4	108	n/a	103	n/a	110.0	13.6
17	n/a	n/a	n/a	1300	1270	194	214	202	210	86	88.0	81.5	75	n/a	86	n/a	79.0	74.0

n/a=not available

Table 4.4 Magnesium levels during original test period (mg/l)

Site	Date																
	4/5/76	**8/6/76**	**16/06/76**	**29/07/76**	**02/08/76**	**31/07/77**	**28/03/78**	**01/02/79**	**17/04/79**	**18/12/79**	**14/04/80**	**21/07/80**	**30/07/81**	**21/12/81**	**15/09/82**	**20/12/82**	**19/12/83**	**19/12/85**
1	18	4	18	n/a	n/a	n/a	n/a	n/a	n/a	2.4	2.7	1.9	2	n/a	2	n/a	1.9	1.8
9	10	26	14	n/a	n/a	n/a	n/a	n/a	n/a	7.3	3.7	2.8	3.3	n/a	3.5	n/a	2.9	2.8
10	6	10	8	n/a	n/a	n/a	n/a	n/a	n/a	3.6	3.9	1.7	2.3	n/a	2	n/a	2.1	2.1
14	8	n/a	26	n/a	n/a	n/a	n/a	n/a	n/a	4.6	6.4	2.4	3.2	n/a	3.1	n/a	3.0	2.8
15	10	32	22	n/a	n/a	n/a	n/a	n/a	n/a	6.3	5.1	4.8	4.3	n/a	2.6	n/a	5.6	3.9
16	n/a	20	30	n/a	n/a	n/a	n/a	n/a	n/a	3.2	6.3	6	6.1	n/a	5.4	n/a	5.2	1.6
17	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6.1	6.3	5.8	5.8	n/a	6.3	n/a	5.2	5.6

n/a=not available

Table 4.5 Sulphide levels during original test period (mg/l)

Site	Date																
	4/5/76	**8/6/76**	**16/06/76**	**29/07/76**	**02/08/76**	**31/07/77**	**28/03/78**	**01/02/79**	**17/04/79**	**18/12/79**	**14/04/80**	**21/07/80**	**30/07/81**	**21/12/81**	**15/09/82**	**20/12/82**	**19/12/83**	**19/12/85**
1	n/a	<0.006	<0.006	<0.006	<0.006	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.003	n/a	<0.005	<0.005	0.01	0.0	<0.003
9	n/a	0.083	0.1	0.025	0.118	0.11	0.02	<0.01	0.05	0.07	0.07	0.005	n/a	0.05	<0.005	n/a	0.0	0.03
10	n/a	0.014	<0.006	0.018	0.017	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	n/a	n/a	<0.005	<0.005	0.02	0.0	<0.003
14	n/a	1.56	0.016	0.067	<0.006	<0.01	0.02	<0.01	<0.01	0.09	<0.01	0.003	n/a	<0.005	<0.005	<0.01	0.0	<0.003
15	n/a	0.006	0.7	1.58	1.47	1.27	0.26	0.53	0.28	0.26	0.28	0.350	n/a	0.12	1.6	0.56	0.5	0.45
16	n/a	0.048	0.028	0.007	<0.006	1.1	0.28	0.07	0.12	0.16	<0.01	0.003	n/a	0.08	<0.005	0.1	<0.01	<0.003
17	n/a	0.117	n/a	0.145	3.9	<0.01	0.12	0.06	0.15	<0.01	0.12	<0.003	n/a	<0.005	<0.005	<0.01	0.0	<0.003

n/a=not available

Table 4.6 Sulphate levels during original test period (mg/l)

Site	Date																
	4/5/76	**8/6/76**	**16/06/76**	**29/07/76**	**02/08/76**	**31/07/77**	**28/03/78**	**01/02/79**	**17/04/79**	**18/12/79**	**14/04/80**	**21/07/80**	**30/07/81**	**21/12/81**	**15/09/82**	**20/12/82**	**19/12/83**	**19/12/85**
1	11	9	18	17	13	7	13	10	10	11.0	12	25	<5	16	n/a	<0.2	10	20
9	47	3.3	62	72	62	18	31	22	24	31	174	21	52	29	n/a	45	24	18
10	18	9	22	19	15	84	7	10	n/a	16.0	18	17	14	41	n/a	22	0.5	14
14	44	n/a	62	74	69	36	24	17	6	21.0	26	26	32	23	n/a	25	20	19
15	279	125	206	62	81	69	39	49	32	37.0	41	n/a	86	20	n/a	36	n/a	26
16	n/a	254	200	106	91	176	160	100	105	42.0	76	73	82	107	n/a	25	80	19
17	n/a	n/a	n/a	1805	1730	48	62	57	48	159.0	46	163	60	44	n/a	58	50	48

n/a=not available

Table 4.7 pH levels during original test period

Site	Date																
	4/5/76	8/6/76	16/06/76	29/07/76	02/08/76	31/07/77	28/03/78	01/02/79	17/04/79	18/12/79	14/04/80	21/07/80	30/07/81	21/12/81	15/09/82	20/12/82	19/12/83	19/12/85
1	7.2	8.1	7.7	7.3	7.4	6.8	8.0	8.6	8.1	7.0	6.5	7.2	7.3	7.0	7.3	7.8	7.7	7.1
9	8.2	8.4	8.0	9.2	9.2	7.1	6.1	6.6	6.5	6.2	6.7	7.2	6.9	6.8	7.0	7.1	7.3	7.1
10	7.4	9.0	7.2	8.1	8.3	8.2	7.2	7.8	7.5	7.0	7.4	7.0	7.3	7.0	7.3	7.1	7.6	7.4
14	8.2	8.0	7.3	7.2	7.6	7.3	7.4	7.8	7.6	7.1	7.2	7.2	7.5	7.3	7.3	7.0	7.8	7.4
15	9.2	7.6	7.3	7.4	7.4	8.3	7.6	7.7	7.5	7.2	7.0	7.1	7.3	7.3	8.9	7.5	7.7	7.5
16	n/a	7.4	7.4	7.7	7.6	7.5	7.3	7.6	7.4	7.1	7.1	7.3	7.5	7.3	7.5	7.2	7.5	7.5
17	n/a	n/a	n/a	7.1	7.0	7.4	7.5	7.8	7.6	7.0	7.2	7.3	7.5	7.2	7.5	7.2	7.5	7.3

n/a=not available

Table 4.8 Sites, dates and contaminant levels corresponding with higher pH values

Determinant (mg/l) and pH	Site and Date																
	1			10				9					14		15		
	28/03/78	01/02/79	17/04/79	08/06/76	29/07/76	02/08/76	31/07/77	04/05/76	08/06/76	16/06/76	29/07/76	02/08/76	04/05/76	08/06/76	04/05/76	31/07/77	15/09/82
Ca	n/a	22	15	18	30	252	20	na	54	68	118	106	n/a	n/a	n/a	80	4.6
Mg	n/a	n/a	n/a	10	n/a	n/a	n/a	10	26	14	n/a	n/a	8	na	10	n/a	2.6
S_2^{2-}	<0.01	<0.02	<0.03	0.014	0.018	0.017	<0.01	n/a	0.083	0.1	0.025	0.118	n/a	1.56	n/a	1.27	1.6
SO_4^{2-}	13	10	10	9	19	15	84	47	3.3	62	72	62	44	n/a	279	69	n/a
pH	8	8.6	8.1	9	8.1	8.3	8.2	8.2	8.4	8	9.2	9.2	8.2	8	9.2	8.3	8.9

n/a=not available

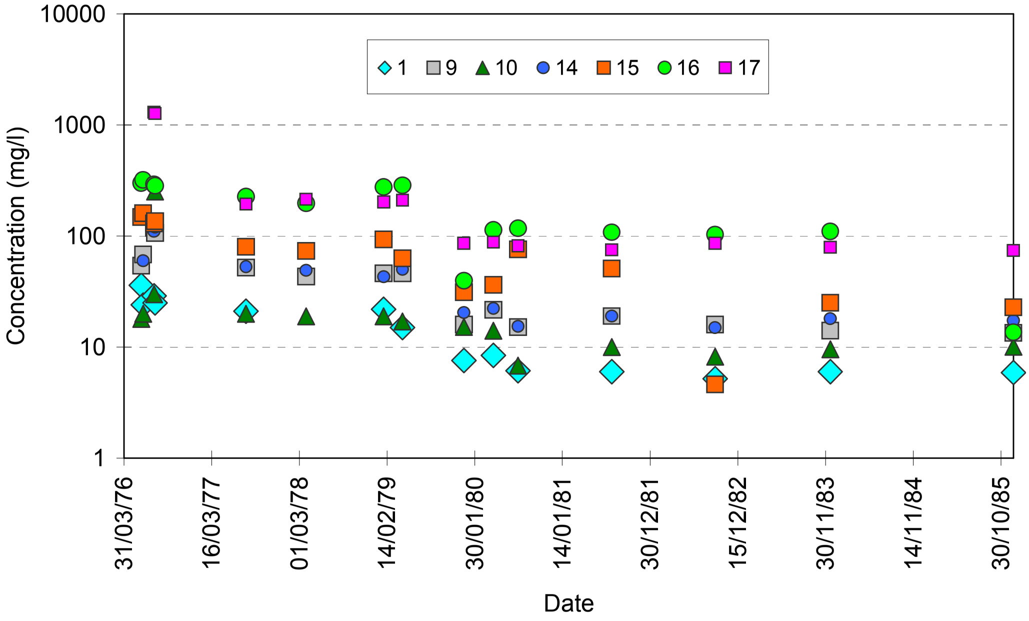


Fig. 4.3 Calcium concentrations

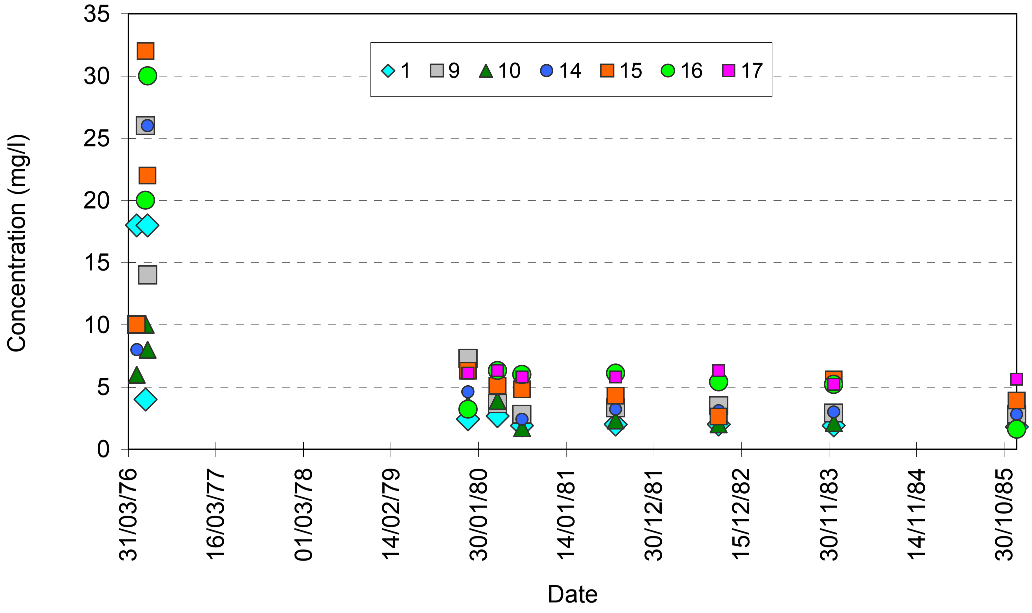


Fig. 4.4 Magnesium concentrations

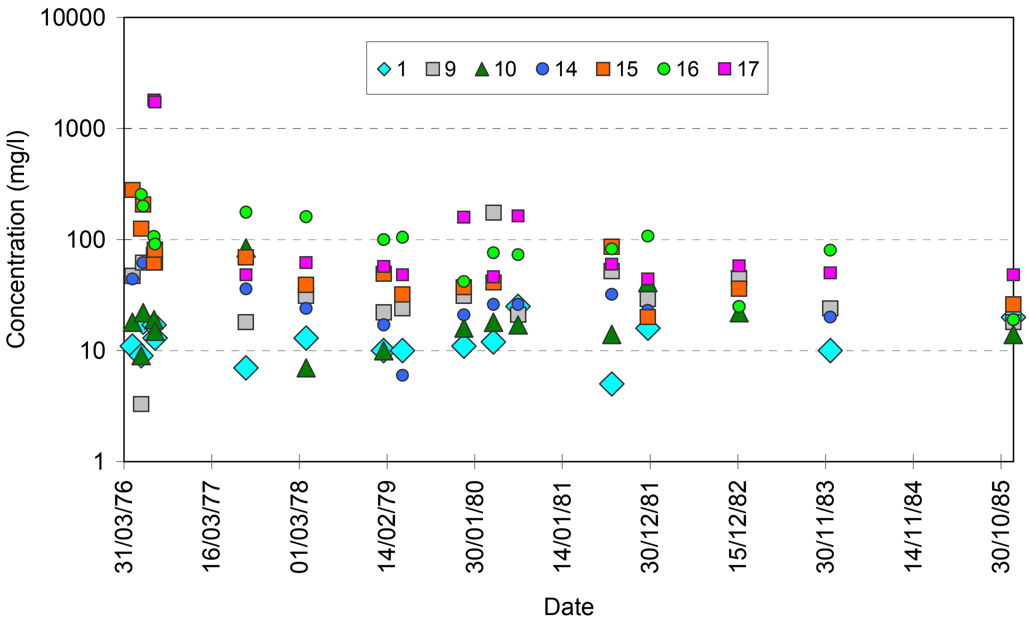


Fig. 4.5 Sulphate concentrations

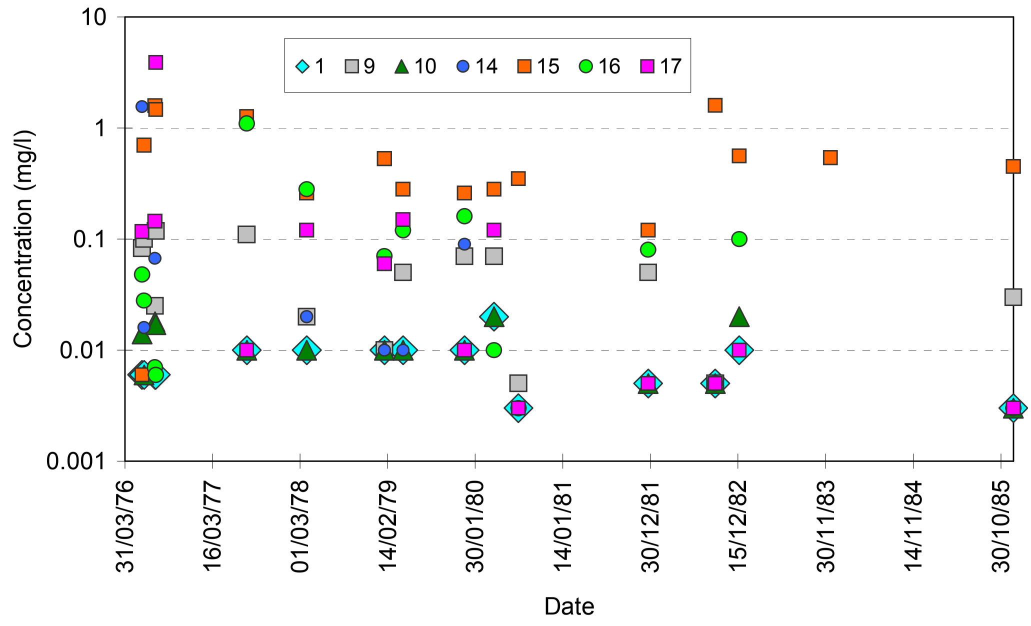


Fig. 4.6 Sulphide concentrations

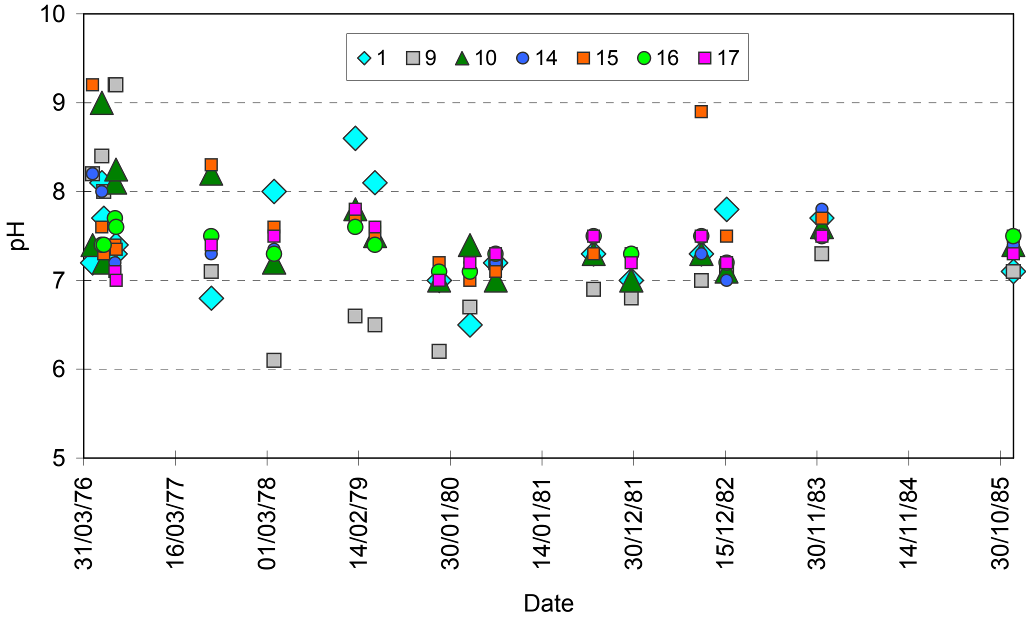


Fig. 4.7 pH values

4.2.6 Analysis of Original Data

In general terms, where sources of contamination leach into river systems, it is anticipated that sites upstream to the input source on the river will be free of the contaminants (unless there is another input source in the locality) and sites downstream of the river will exhibit signs of the contamination, depending on their distances from the source and the ability of the river flow to dilute these levels.

The sites from which water samples were obtained and analysed in the original study can initially be differentiated from each other by being geographically upstream or downstream of the A66 on their own river systems.

Wythop Beck becomes Dubwath Beck downstream of the A66. In the original study, Site 1 was upstream to the A66 on the Wythop Beck and Site 9 was downstream to the A66 on Dubwath Beck. For the purposes of this analysis Wythop Beck and Dubwath Beck have been taken to be one river and it has just been called Dubwath Beck. Site 10 was upstream and sites 14 and 15 downstream to the A66 on Tom

Rudd Beck, with Site 15 being the first downstream site and Site 14 further downstream and situated within the town of Cockermouth. Site 15 was a drainage outlet from the A66 where it emptied into the river. Site 16 was a surface water drain accepting drainage from the A66 and Site 17 was surface water also accepting drainage from the A66, both flowing into River Derwent, which is the river into which Tom Rudd Beck flows.

Comparisons between upstream and downstream site are undertaken below. It must be noted, however, that there are always flow variations between one river system and another. In the original construction of the A66, different quantities of BFS were deposited at different locations along the route of the A66. These different locations offered different contaminant sources, and consequently there were different quantities of contaminants available for input into the river systems. Due to these factors, an analysis of upstream vs. downstream sites on both river systems has been undertaken, with a comparison of one river with the other where appropriate.

Calcium and magnesium: *s*ites 16 and 17 mostly had the highest levels of calcium, with Site 15 having the next highest. In most cases downstream sites had higher levels than upstream sites, with levels at Site 14 being lower than those at Site 15, showing dilution from the river had occurred. This was also the case with magnesium on most occasions, but due to a large gap in the available data, it is more difficult to detect trends. On three occasions magnesium levels at Site 14 were marginally higher than at Site 15 (16/6/76, 14/4/80 and 15/9/82). This may have been due to a small input from another source at Site 14 in Cockermouth, or may have just been a slight variation in detection rates during analyses. Sites 15, 16, and 17 all had similar levels of magnesium, mainly being higher than the remaining water sample sites. These samples were obtained from sites receiving drainage directly from the A66, where levels had not been diluted by river water.

There were also marked increases in levels of calcium detected at most downstream sites during the drought of 1976. Due to the lack of available data for magnesium, it is impossible to know if the same trend would have been present. This could have been the result of an immediate calcium and magnesium washout from the slag in the early life of the road, or could have been due to a build-up of concentrated levels of contaminants within the drainage areas during the drought, whereby water draining from the A66 had been in contact with the BFS for excessive periods of time due to the lack of rain.

Sulphide and sulphate: as expected, in most cases Sites 1 and 10 (upstream) presented the lowest levels of sulphates and sulphides. Exceptions to this occurred on the 8/6/76, 21/7/80 and 19/12/85, when Site 9 had lower sulphate levels than Site 1 and 31/7/77 and 21/12/81, when Site 15 had lower sulphate levels than Site 10. In most cases on Tom Rudd Beck, levels of sulphide and sulphate reduced at Site 14 compared with Site 15, as dilution from the river occurred. On some occasions, Site 15 had higher levels of sulphides than for Sites 16 and 17. On some occasions, Site 17 had the highest levels of sulphates (particularly on 29/7/76 and 2/8/76), with Site 16 having the next highest levels, which were again higher than Site 15.

When sulphides are present in water, contact with the air may transform them into sulphates. The data in Table 4.8 doesn't clearly show progressive reductions in sulphides marked by corresponding increases in sulphates, partly because the concentrations of sulphates are several orders of magnitude larger than the sulphides (even allowing for the correction for the addition of O_2). Also, due to the large effect that dilution from the rivers would have had on the samples, any such transformation would have been extremely difficult to detect. Therefore sulphates detected within sample analyses in the original study have been assumed to have been directly released from the BFS within the A66. In the two samples obtained from Site 17 during 1976, levels of sulphate were extremely high. Conclusions may be drawn that this was due to the initial loss of sulphate during the very early life of the A66.

Another factor worth considering at this point is that the highest levels of sulphates occurred on 29/7/76 and 02/8/76 and the highest level of sulphides occurred on the 02/8/76. It can be seen in Table 4.2 that both these dates were during the drought period of 1976. Initially it could be assumed that because there was less water flow, there would be correspondingly lower levels of contaminated flows being flushed out of the road. This drought may have had a secondary effect. Because there was no rain to flush out water within the BFS matrix of the A66 or the embankments, any remaining water would have remained in contact with the slag for a longer period of time and would have a higher concentration of contaminants. This would have resulted in any subsequent water which may eventually have seeped out from the road containing highly detectable levels of contaminants. If that were the situation present during the drought, it can be assumed that the seepages would have been small in quantity but high in concentration. This would be another explanation as to why such high levels of sulphates were present at Site 17 and to a lesser extent at Site 16. Both these sites were surface water sites, and with a reduction of rainfall it would have taken longer for their contents to be flushed into the River Derwent. Because of this, their contaminant levels would have been readily detectable on water sample analyses.

pH: the sites, dates and contaminant levels corresponding with higher pH levels can be seen in Table 4.8. Although in some instances pH values indicated alkalinity at times of higher contaminant levels, it is evident that Sites 1 and 10, both upstream sites, also had higher pH levels.

The highest pH values occurred at Site 15 on 4/5/76 and Site 9 on 29/7/76 and 2/8/76. For the dates at Site 9, calcium levels were very raised and sulphide levels low. On several occasions when pH levels were higher there were no available data for calcium and magnesium in particular and, sometimes, sulphide and sulphate data were also missing. This limits analysis to quite an extent. In contrast, on 8/6/76 there was a pH of 9 and low calcium, magnesium, sulphide and sulphate levels (the latter two chemicals often associated with high pH values). This makes conclusions difficult and would indicate that other factors are responsible for the fluctuations in pH levels for which no relevant data are available to aid interpretation. These factors which may contribute to raised pH levels also appeared to have been present upstream of the A66 at Sites 1 and 10. Because of this, input from other sources must also be considered, such as runoff from adjacent farmland.

Summary: the analysis of the original data which is presented above should be considered only as a guidance to explain the possible different theories available to justify the differences in detected levels of calcium, magnesium, sulphide and sulphate during the original case study. Various anomalies exist within the data whereby actual reasons for levels are not known. An example of this is, as during the drought during 1976, there were other dates with abnormally high levels of the above elements. Construction of the A66 commenced in 1975, being quickly followed by the drought of 1976. It is difficult to assess, therefore, whether the raised levels of contaminants were due to the newly laid slag or due to the low water table level resulting from the drought, giving low drainage flows containing high concentrations of contaminants. Unfortunately there are no records of temperatures during other periods available and, therefore, it is not possible to know if the levels of contaminants again correlate with other periods of hot conditions.

It must also be stressed that the data presented here relate mainly to two different river systems, Dubwath Beck and Tom Rudd Beck. Two additional sites draining into a third river, River Derwent were also present, with that river receiving water from Tom Rudd Beck. For Dubwath Beck and Tom Rudd Beck it was possible to compare upstream versus downstream site contaminant concentrations. For the two sites draining into River Derwent, it is difficult to estimate whether contaminants from Tom Rudd Beck effected levels at those sites, or whether they would have been too diluted upstream to those sites to influence values.

Dubwath Beck and Tom Rudd Beck river systems had their own individual contaminant background levels as well as different flow rates, and both those factors would have influenced the contaminant concentrations detected within the water samples. Despite this, however, it does appear that on many occasions there were only small differences between background concentrations from the two river systems of calcium, magnesium, sulphide and sulphate upstream to the A66. On most occasions contaminant concentrations were quite raised at Site 15. As this was a site where water drained from the A66 before it entered the river it was to be expected. When comparing Sites 9 and 14 (both downstream sites where water obtained for sampling was taken directly from the river) the levels were much more similar, showing that resultant dilution from river water gave very similar contaminant levels. The contaminant concentrations obtained from the diluted downstream site samples, did not appear to have reflected the different tonnages of slag used within the A66 construction, whereby 150,000 tonnes were used in Dubwath Beck vicinity, in contrast to 65,000 tonnes being used in Tom Rudd Beck vicinity. A point that should be noted, however, is that there was less water in Tom Rudd Beck, which may have counteracted the effects of less slag.

A final point worth some consideration, is the fact that during the time of the original study (as is still the case today) there was a sewage works within the vicinity of Site 17, and its influence over the water sample analyses data for that site can not be totally dismissed. The fact that the trend of higher contaminant concentrations at Sites 15 and 16 (also receiving direct drainage from the A66) was very similar, however, makes the likelihood of a contribution from the sewage works to the contaminant concentrations minimal.

4.3 New Study

4.3.1 Introduction

In order to assess the long-term risks from the use of BFS in the A66, a new study was deemed appropriate, in order to compare the original data with those which would be obtained 25 years after the original contamination problems commenced. The main aims of the new study were to:

- Assess Dubwath Beck and Tom Rudd Beck for signs of continued contamination from the BFS used during the construction of the A66.
- Obtain new water samples in order to compare resultant data with those obtained in the original study.
- Assess the long-terms risks from the use of BFS used within the construction regimes employed during the construction of the A66.
- Obtain suitable data which could be entered into the risk assessment guide in order to assess its effectiveness in a real case study as opposed to computations alone.

In order to achieve the aims listed above it was necessary to:

- Become further acquainted with the original contamination problem during and after the construction of the A66 through meeting Law (2001). He would have access to more information and data than had been previously available for use by the University of Nottingham.

- Determine appropriate sites for obtaining new water samples based on safe access to sites, taking into consideration the current regulations regarding access to land. If possible the water sampling sites would be the same sites as those used in the original study, to enable direct comparisons to be undertaken.
- Obtain and store the water samples in the appropriate manner recommended by the laboratory analysing them, in order to obtain accurate data on analyses.

Now, approximately 25 years later, there is still some evidence of contamination, in the form of sulphide deposits on vegetation surrounding the rivers at some sites. There is continued avoidance by salmon of the rivers (Law 1999, 2001), which prior to the construction of the A66, were routes to spawning sites.

Field work for the new study relating to the construction of the A66 began on Monday, 3rd December, 2001. Law (2001) recommended three sites in particular from which samples should be obtained, both of which recently exhibited evidence of black sulphurous deposits and white filamentous Thiothrix on adjacent vegetation. Out of these three sites, only two eventually proved suitable from which to sample. The one which later proved unsuitable to sample from was a discharge drain flowing into River Derwent. On examination, a very high rainfall on preceding days had resulted in the river level having risen above the drain outlet, and therefore all discharges would have been too greatly diluted. Out of the other two recommended sites, one was a site sampled in the original study and was a discharge outlet stream draining the A66 which flowed into Dubwath Beck (Site 8), whilst the other was a discharge drain further along the A66, which flowed into River Derwent, but was not one of the sites sampled from within the original study (Site 18). Although Site 8 was a site from which samples were obtained within the original study, data were only available from the early life of the road and were considered insufficient to be included in the previous analyses of original data. Within this section on the new study, an analysis of Site 8 has been carried out in order to compare the original data with those obtained within the new study, as far as the limited data allowed.

Access was granted to original construction maps illustrating sites from which both acidic peat and other materials were excavated prior to the deposition of the BFS during the construction stage of the road. Copies of these maps were obtained for future use. These maps show tonnages of materials excavated and it is assumed that corresponding volumes of BFS were re-deposited in their places in ground level sites and in larger volumes in areas constructed into embankments.

4.3.2 Collection of Data

4.3.2.1 Water Sampling Sites

The sites and water flows were as follows:

Site 1: upstream to the A66 on Dubwath Beck; reasonably fast flowing through open farmland; clear in appearance.

Site 8: discharge drain in the form of a culvert flowing from the A66; sampled prior to discharging downstream into Dubwath Beck; fast flowing; black deposits; white filamentous Thiothrix on adjacent vegetation.

Site 9: downstream to the A66 on Dubwath Beck; slow flowing with signs of mild flooding to immediate river banks.

Site 12: upstream to the A66 on Tom Rudd Beck, but still receiving drainage from the A66 through a drainage ditch (not evident at the time of sampling); steep bank with thick vegetation; fast flowing; clear in appearance.

Site 14: downstream on Tom Rudd Beck in Cockermouth centre; fast flowing; black deposits.

Site 15: discharge drain flowing into Tom Rudd Beck downstream of A66; steep bank with thick vegetation; sampled at point where the discharge enters the river; large volume and fast flowing.

Site 18: discharge drain from the A66 mainly travelling below ground level but sampled at a 1.5 m length where the drain surfaces before going below ground again; reasonably fast flowing; evidence of silt due to its yellowish-brown colour.

It should be noted that at two sites, two sets of water samples were obtained. The second sets of samples were numbered separately. The sites selected for this represented both upstream and downstream sites on Dubwath Beck. The theory behind obtaining these second samples was to check the reliability of the laboratory analysing the samples. Both sets should, theoretically, give identical results because both sets were obtained on the same day, under the same conditions using the same apparatus and the same sampling method. The sites selected and their new numbers were as following:

Site 1: second set numbered 101.
Site 9: second set numbered 109.

4.3.2.2 Water Sampling Method

Water was obtained from each site in the following manner: in all cases a plastic bucket was used to abstract the water. Plastic was used so as not to influence the metal content of the water samples, which would have occurred should a metal bucket have been used. Access to each site varied depending on its geographic location.

Only at Site 8 could water be directly and safely obtained from the river bank. At all other sites a length of plastic cord was attached to the bucket and the bucket lowered into the water. At Site 1 access was gained by lowering the bucket with the cord over a fence surrounding the river bank. Sites 12, 14, 15 were accessed as low down the river bank as was possible and the bucket lowered on the cord from that point. Site 18 was a discharge drain flowing alone and not discharging into the river, and again the bucket on the cord was lowered after access was gained as near to the drain as possible.

In each case the bucket was filled and emptied twice with water from each new site, in order to eliminate any remaining water from the previous site, which would have adversely influenced results.

At each site 3 water samples were obtained. These samples were labelled and handled as follows:

Sample A: for analyses of metal content (Ca, Mg, Fe, and K). Water was filtered through 0.45 μm filter papers placed on tubing at the exiting side of a transfer vessel. The vessel was filtered by use of a foot pump. By pumping air into one tube entering the vessel, the build up of internal pressure forces the water out through the exiting tube and hence through the filter paper.

Filtered water samples were placed in 60 ml polyethylene bottles, into which 2.4 ml 70% AnalaR nitric acid was added (i.e. to give a 4% acid content). The effects of adding acid to water samples is to prevent the breakdown of the metal contents into precipitates of their metals.

Sample B: for analyses of total sulphate content. Water samples were placed in 250 ml polyethylene bottles in the same form as they were obtained from source. Sulphate samples do not degrade on abstraction and, therefore, require no treatment.

Sample C: for analyses of total sulphide content. Water samples were placed unfiltered in 250 ml polyethylene bottles with the addition of 10 ml zinc acetate. Zinc acetate preserves the sulphide contents within the samples by fixing them. Without fixing the samples, sulphide would begin to oxidise to sulphate immediately after abstraction and analyses would show incorrect concentrations.

At all sampling sites pH readings were recorded at the time of water abstraction and photographs were taken of each site for possible later use.

All samples were maintained at temperatures below 5°C whilst away from Nottingham in order to preserve them.

4.3.3 Presentation of New Data

The water samples collected during the field work were analysed for calcium, iron, magnesium, potassium, sulphide and sulphate through an external laboratory. Calcium, magnesium, iron and potassium were analysed by inductively-coupled plasma mass spectrometry, sulphate by ion chromatography and sulphide by colorimetric end point. It should be noted, however, that similar to the data obtained within the original study, no errors of margin or standard deviation in results were given. Detection limits of 0.2 mg/l for sulphide and 0.01 mg/l for iron were present. The detection limit for sulphide was higher than that within data from the original study, making subsequent comparisons of levels below this limit impossible. Analyses from samples numbered 101 and 109 (taken from Sites 1 and 9) correlated with official samples at those sites. Resultant data can be seen in Table 4.9.

Table 4.9 Chemical analyses of selected determinants

Site No.	**Chemical Analyses (mg/l)**					
	Ca	**Fe**	**Mg**	**K**	**S_2^{2-}**	**$S0_4^{2-}$**
1	10.4	<0.01	4.3	1.9	<0.2	5.6
8	95.0	0.01	4.1	9.3	0.8	92.0
9	21.0	<0.01	5.3	2.6	<0.2	10.0
12	16.0	<0.01	4.1	2.4	<0.2	6.6
14	32.0	<0.01	6.5	3.5	<0.2	10.0
15	23.0	<0.01	6.0	2.8	<0.2	7.9
18	110.0	0.01	9.7	4.5	0.4	44.0
< = below detection levels						

In order to determine whether the A66 is still responsible for increasing the levels of potential contaminants downstream from where it crosses the two river systems, graphs have been plotted for Sites 1, 8 and 9 on Dubwath Beck and Sites 12, 14 and 15 on Tom Rudd Beck from the data obtained within the new study (Figs. 4.8 to 4.11). These graphs illustrate upstream sites (Site 1 and 12) versus downstream sites (Sites 8, 9, 14 and 15) with relevant contaminant levels obtained for calcium, magnesium, potassium and sulphate for both river systems. Due to the low levels determined for iron and sulphide, they were excluded from the graphs and analysis, but a brief description of sulphide levels is given. It should be noted, however, that although Site 12 is upstream to the A66, construction maps indicate that some drainage from the A66 may be directed into the river prior to that sampling point, but whether the drainage received is the total drainage for that section of the A66 or not is unknown. This fact was unknown at the time of water sampling. Additionally Fig. 4.12 illustrates the pH values obtained at the same sample sites, in order to compare upstream versus downstream values.

Although a water sample was obtained from Site 18, it was taken as a stand-alone sample from a gutter draining the A66 further down the route of the road in the village of Chapel Brow, towards Workington. A graph has been plotted (Fig. 4.13) to illustrate the levels of calcium, magnesium, potassium, sulphate and sulphide as well as the pH value in order to make a general analysis of the water standard at that site.

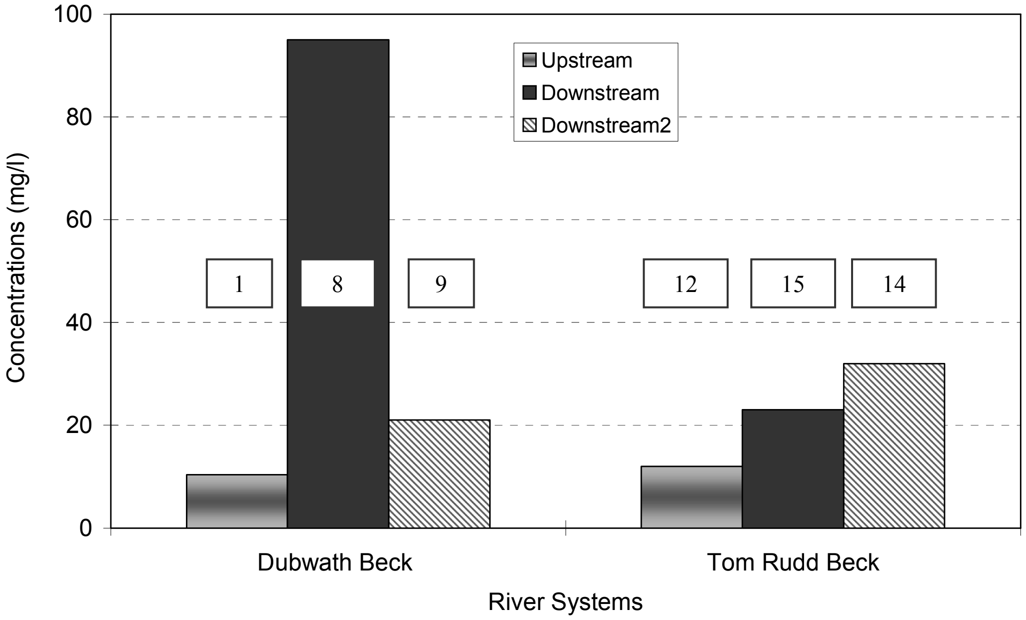


Fig. 4.8 Calcium upstream vs. downstream concentrations

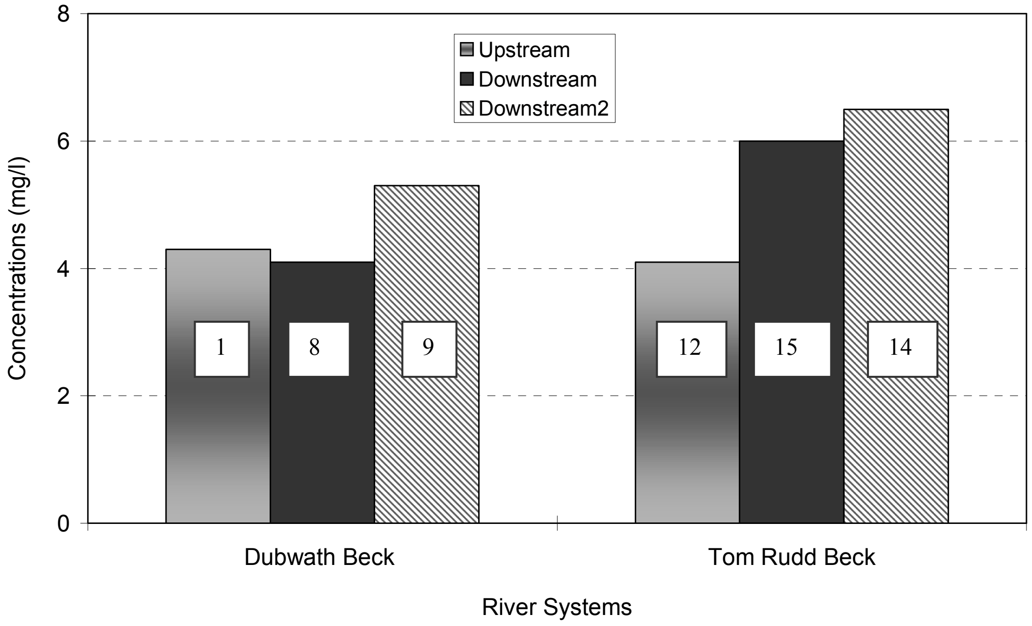


Fig. 4.9 Magnesium upstream vs. downstream concentrations

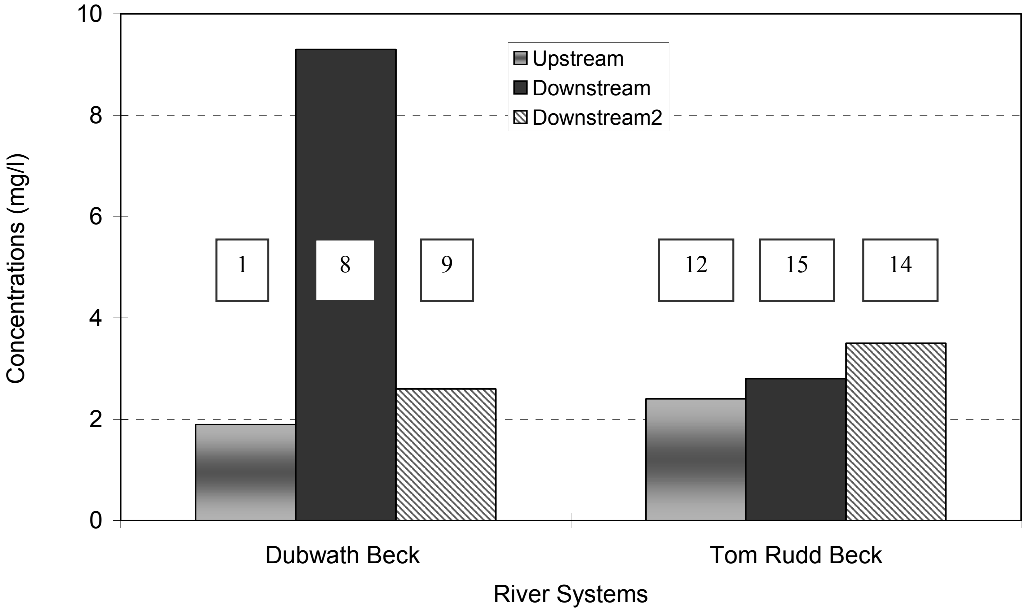


Fig. 4.10 Potassium upstream vs. downstream concentrations

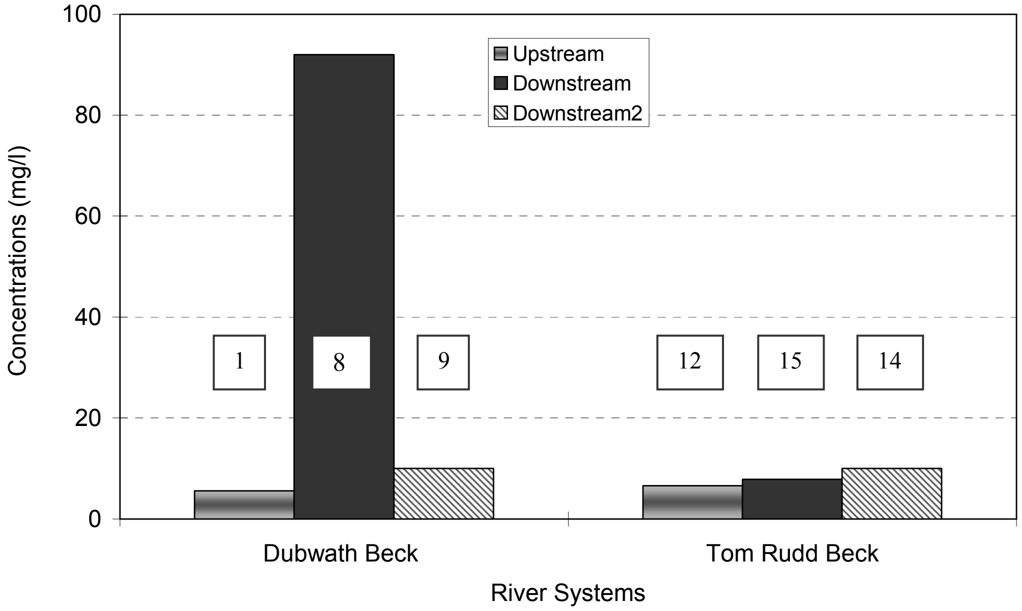


Fig. 4.11 Sulphate upstream vs. downstream concentrations

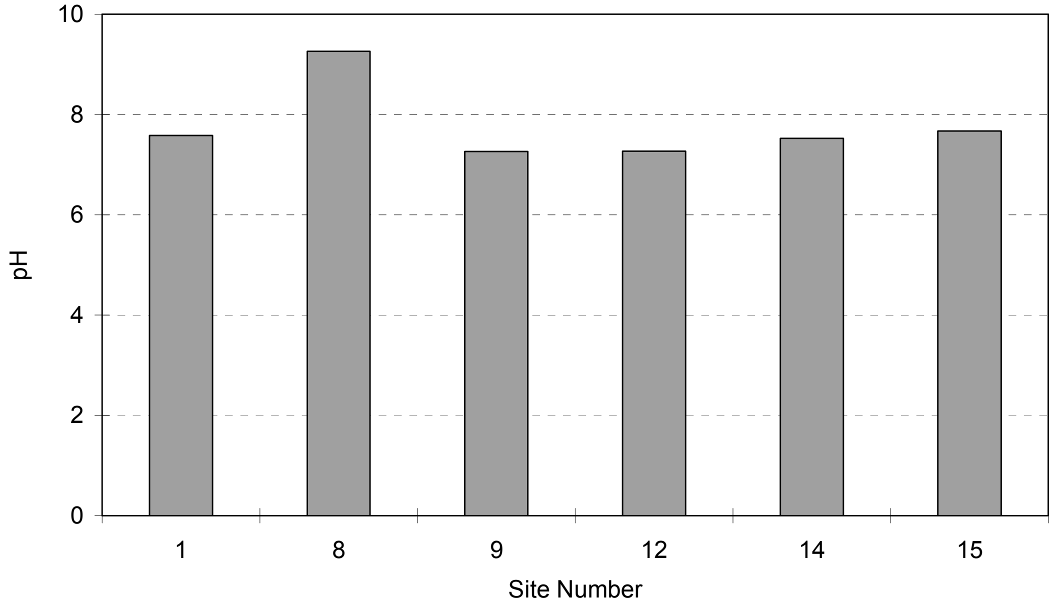


Fig. 4.12 pH values

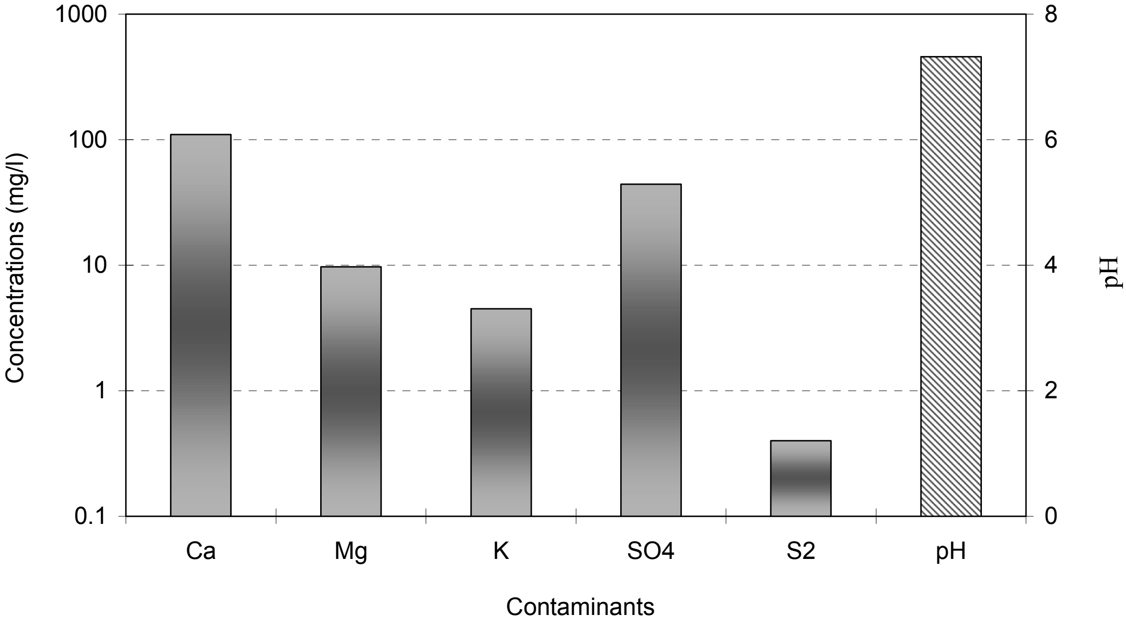


Fig. 4.13 Contaminant and pH values for Site 18

4.3.4 Analysis of New Data

Calcium, potassium and sulphate: on Dubwath Beck there was a significantly large increase in levels of these three determinants at Site 8, the first site downstream of the A66, being a drainage stream from the road before discharging into the river. This indicates that the A66 is still a source of input. Levels had significantly reduced at Site 9 further downstream.

On Tom Rudd Beck there was an increase in levels at Site 15, the first site downstream of the A66 (despite the fact that at Site 12 some drainage from the A66 was directed into it), but to lesser extents than for Dubwath Beck. This again indicates that the A66 is still a source of input. An anomaly present for each of these elements on Tom Rudd Beck was that levels increased still further at Site 14, the site further downstream again and situated within Cockermouth. This indicates that although the A66 is still a source of input, there is a further source within Cockermouth.

Magnesium: on Dubwath Beck there was a different trend to the other elements, because at Site 8 there were reduced levels of magnesium to those present at Site 1. This indicates that the A66 was not a current source of magnesium at Site 8. At Site 9 further downstream again, there were raised levels of magnesium, greater than at Site 1. This indicates a further source of magnesium downstream of Site 8. The input source for both upstream and downstream sites could possibly be runoff from adjacent land.

A similar trend for magnesium on Tom Rudd Beck was present as previously described for calcium, potassium and sulphate. Levels increased at Site 15, the first site downstream of the A66, indicating that the A66 is still a source of input (despite the fact that Site 12 may have already received some drainage from the A66). Levels increased further at Site 14, again leading to the assumption that there is a further source of input in Cockermouth.

Sulphide: the level detected at Site 8 (recommended for sampling by Law, 2001) was 0.8 mg/l, but because detection limits within the analyses were 0.2 mg/l, it is not possible to compare levels at the other sites (apart from Site 18 described below). It does indicate, however, that the A66 is still a source of input.

pH: apart from Site 8, the sites all had pH values of between pH 7.26 and pH 7.67. On Dubwath Beck, upstream Site 1 had a slightly higher pH (pH 7.58) to that of downstream Site 9 (pH 7.26), whilst on Tom Rudd Beck, upstream Site 12 had a slightly lower pH (pH 7.27) than downstream Site 15 (pH 7.67) and further downstream Site 14 (pH 7.52). The differences in values were so small, however, that any variations could reflect instrumentation error as much as the influences of contaminant levels. In the case of Site 8, the pH was a lot higher than for the other sites (pH 9.26), where the influence of high levels of alkaline calcium and potassium ions was greater than those of acidic sulphate ions.

Site 18: Fig. 4.13 was produced to analyse the water obtained in the sample from this stand-alone site and to compare levels of contaminants and pH with the other sites. For calcium, Site 18 had slightly higher levels than for Site 8, and a lot higher than the other sites. For magnesium, Site 18 had levels higher than all the other sites. Levels of potassium and sulphate were below those of Site 8, but higher than the rest. This would indicate that Site 18 had particularly high levels of all four determinants. Both Sites 8 and 18 were sites of direct drainage from the A66 and not river sample sites. Higher levels were to be expected, where river dilution had not occurred. A sulphide level of 0.4 mg/l was present. The pH value of pH 7.32 was very similar to all the other sites except Site 8.

4.4 Comparison of New with Original Data

4.4.1 Presentation of Combined Data

In order to compare data obtained through the new and original studies, graphs have been plotted showing chemical analyses for the three determinants (calcium, magnesium and sulphate) from the four identical sites (1, 9, 14 and 15) from which water samples were obtained within both studies (Figs. 4.14 to 4.16). Due to the low sulphide levels determined within the new study, it has been again excluded. Sites 1 and 9 were on Dubwath Beck and Sites 14 and 15 were on Tom Rudd Beck. Although Sites 8 and 12 were sites sampled from within both studies, in the original study they were only sampled from early on in the life of the road, and therefore insufficient data was available for comparisons to be undertaken. Fig. 4.17 has been produced in order to compare pH values generated in the new study with those generated within the original study for the same four sites.

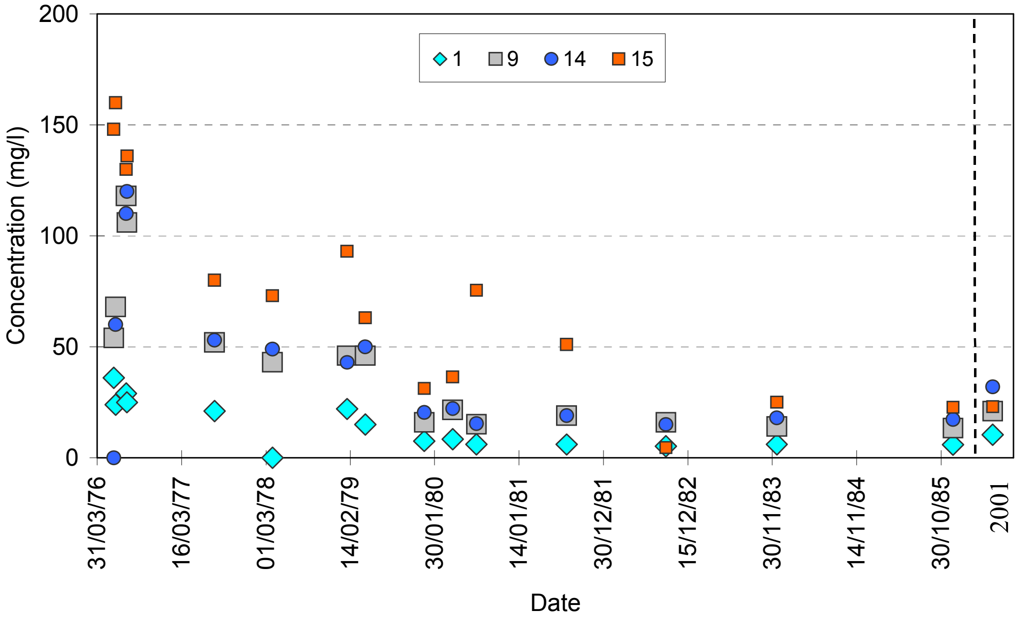


Fig. 4.14 Calcium concentrations

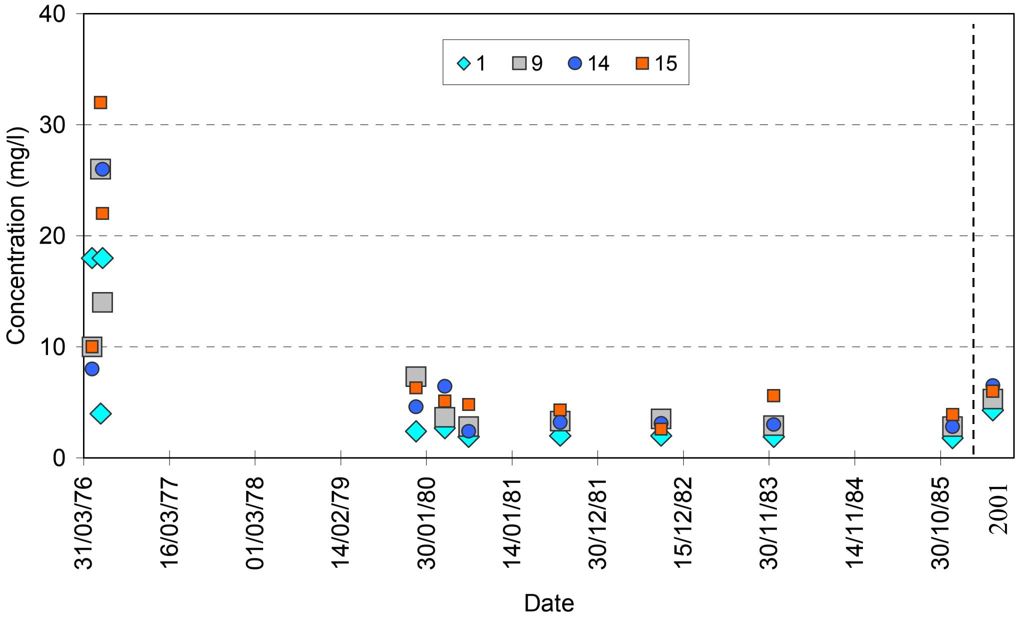


Fig. 4.15 Magnesium concentrations

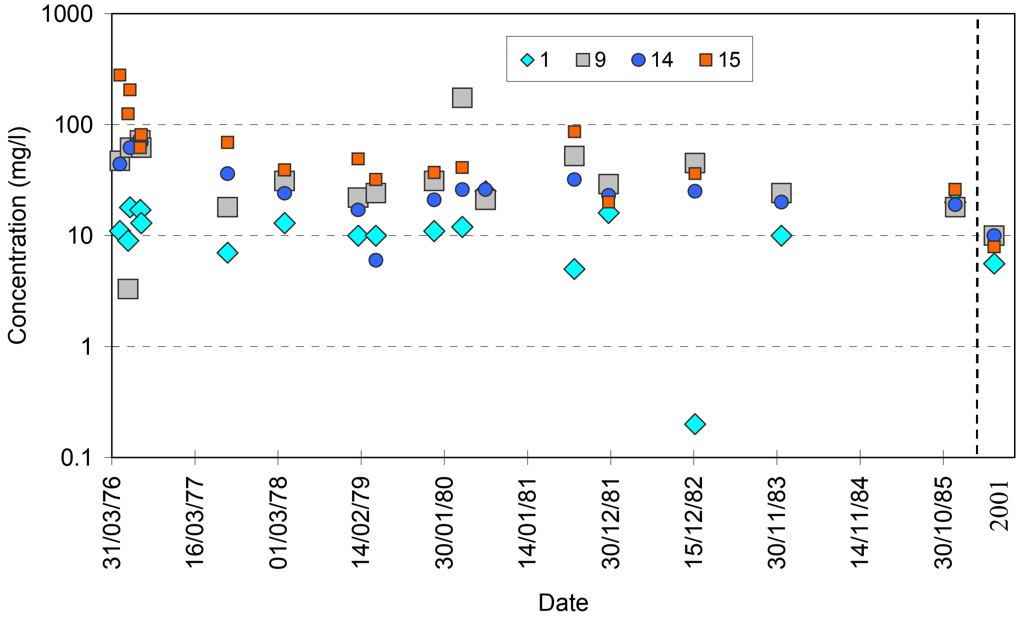


Fig. 4.16 Sulphate concentrations

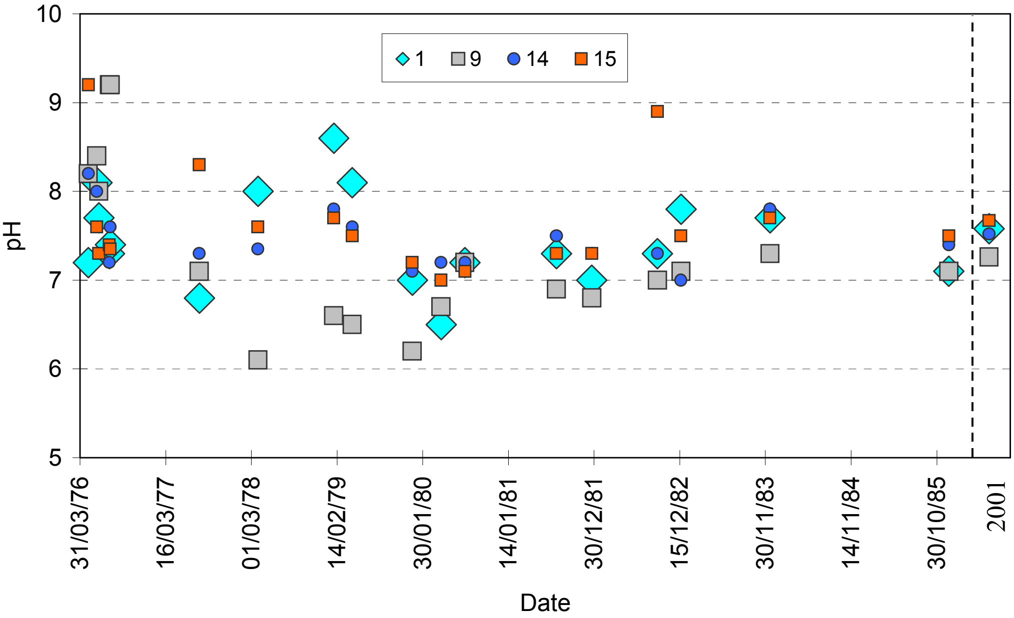


Fig. 4.17 pH values

4.4.2 Analysis of Combined Data

Site 1 and Site 9 represent upstream and downstream sites on Dubwath Beck, whilst Sites 14 and 15 both represent downstream sites on Tom Rudd Beck. Due to land access restrictions from the foot and mouth outbreak, it was not possible to obtain samples from the same upstream sites in the new field work to those in the original study on Tom Rudd Beck. A comparison of the same upstream site on Tom Rudd Beck from both studies has not, therefore, been possible.

Calcium: in the new study levels of calcium were similar to those within the original study from 1982 onwards (if not slightly raised). The significant difference was that in the original study levels on Tom Rudd Beck decreased from Site 15 to Site 14 (further downstream), whilst in the new study an apparent input within Cockermouth resulted in greater levels at Site 14. Results indicates that there is no further decay in calcium levels.

Magnesium: in the new study levels of magnesium were certainly raised to those within the original study from 1980 onwards. Again in contrast with the original study, in the new study an apparent input within Cockermouth resulted in greater levels at Site 14 compared with Site 15 on Tom Rudd Beck.

Sulphate: the levels of sulphate in the new study were lower than at almost any time in the original study. As a result, it appears that levels are still reducing, but at a slow rate. Again in contrast with the original study, levels were greater within Cockermouth at Site 14 compared with Site 15 on Tom Rudd Beck.

pH: pH values of the four sites assessed within both studies appear to have slowly risen since 1980 onwards, accept for some individual anomalies. They appear to follow the same trend of a slightly increase in calcium and magnesium, which both appear to be rising since 1980 too.

4.5 Interpretation of Study Results

The incident of river contamination from the use of BFS as aggregate during the construction of the A66 in Cumbria in 1975, was taken for use as a case study within this research. In order to assess the situation during the early life of the road, it was considered necessary to undertake new field work in order to compare current data with those obtained 25 years ago during the early life of the road.

Two cations (calcium and magnesium) and one anion (sulphate) were selected in order to compare current with original data. These determinants were selected because out of the ones sampled in the original study, they were the ones assessed on the most regular basis, and hence offered the most data for the comparison to be undertaken. When the new field work was undertaken, amongst the sites selected from which to obtain water samples, four were selected (Sites 1, 9, 14 and 15) which were identical ones from which the above three determinants were analysed within the original study. Again this was to enable an accurate comparison to be undertaken.

In all three cases, current data obtained within the new study showed contaminant concentrations well below those detected in the early life of the road, but reasonably similar to those detected within the last analyses in the original study.

Calcium and magnesium levels were greatly reduced towards the end of the original study compared with those towards the beginning of the study. For magnesium data was not available for six sample dates within the original study and this has limited data analyses. For calcium the first date when initially high concentrations within the original study appeared to reduce was 31/7/77. It is not possible to determine at which date this reduction in magnesium occurred, but due to its similar reduction to calcium towards the end of the original study, it is probably reasonably accurate to assume a similar reduction date.

Sulphate concentrations within the original study were lower for some sites towards the end of the original study compared with those towards the beginning. An anomaly to this was at Site 1, an upstream site, which in fact had raised concentrations towards the end of the original study, showing some increase in background level had occurred.

The highest concentrations of contaminants occurred within the first 2.5 years in the life of the road, the very highest being during 1976. During this period of time there was a drought which lasted for several months. In such a construction scenario, during periods of reduced rainfall any available water would have remained in contact with the BFS for long periods of time, rather than being washed out by larger influxes of water. The result of this would be that the remaining water would become more highly contaminated due to its long residence times. Any seepages of water which did discharge from the slag would, therefore, be very concentrated. When the drought was over and water flows increased, the build up of high concentrations of contaminants would be discharged into the drainage systems, to be detected on analyses. In the situation of the early life of the A66, it is quite probable that the reason for the high concentrations of contaminants from the BFS was a combination of initial contaminant wash-off and low rainfall due to the drought.

Other factors must also be considered within this study. When comparing pH values with contaminant concentrations, sometimes there was a relationship whereby higher concentrations of contaminants were accompanied by higher (more alkaline) pH values. In some cases these raised concentrations of contaminants corresponded with cation and sometimes with anion increases. Because of this, it is most likely that other factors were also involved, whose analyses were outside of the scope of this research. These factors may have been other contaminants present within the slag and/or other sources of contaminants which may have been in the vicinity of the A66 and river systems. Also, certain upstream sites also had raised contaminant concentrations, which could not have resulted from any input from the A66.

It should be noted that the general trend for rises in levels for calcium and magnesium in the new study also includes rises upstream at Site 1, indicating that the background concentration is higher than before. This may be attributed to an increase in farming fertiliser use, because many fertilisers contain calcium and magnesium (classed as secondary nutrients) and play a large part in modern-day farming (Donnan Landscape Services, 2004).

The important fact previously mentioned must be considered: no analytic techniques were reported within either studies and no margins of error were given. This puts some limitation to the comparison of both data sets, when analytic techniques may have varied considerably.

4.6 Conclusion to Case Study

The case of the A66 in Cumbria was selected as a Case Study in order to assess the long-term risks from the use of BFS as an alternative aggregate to traditional ones. As used in the construction regime described above, the BFS proved to be the cause of major contamination and has been shown to be a worthy example for analysis within this research.

There were large contamination problems early in the life of the road, which were most likely due to the leaching of contaminants from the slag. This leaching was at its greatest for the first 1 to 2 years in the life of the road. The reasons for this initially large increase in concentrations of leachates were probably two-fold: firstly, initial contaminant wash-off from rain on the slag resulted in high concentrations in the wash-off; and secondly due to the drought of 1976 less available rain resulted in water remaining in contact with the slag for longer than normal, leading to highly contaminated water when it did drain from the road.

One of the main problems with the construction of the road was that it was constructed on an area of peat bog, much of which lay below the water table, resulting in eventual drainage becoming highly contaminated. Recent recommendations by the Building Research Establishment (Dunster, 2001) are that "*unbound BFS should not be used below the water table or in waterlogged or poorly drained areas*". In the case of the A66 the BFS was used below the water table, because there were no such recommendations in place at the time of construction. The report also states that "*there is no migration of sulfur compounds from the interior of the BFS particles to replace the dissolved material on the surface. Therefore, after initial dissolution, the process rapidly slows down, only restarting if the slag is crushed to expose fresh surfaces*". Although the highest concentrations of contaminants occurred within the early life of the A66, data obtained in 2001 shows that continuing leaching of contaminants is an on-going process, although at a reduced rate, and the report does not reflect the reality of continued leaching.

It would appear, however, that if BFS were to be used in construction nowadays as an alternative to traditional aggregate above the water table in its unbound form, leaching of contaminants would probably be far below the levels that occurred in the case of the A66 in Cumbria. In such a situation any leachate would only reach high concentrations of contaminants if surface cracking deteriorated to a state that allowed a large infiltration of rainfall.

Fig. 4.18 Water sample sites from both the original and new studies

5 Computations, Results and Discussion

5.1 Introduction

The approach taken for the spreadsheet simulations is described in Chapter 3. This chapter contains a discussion of the results and their implications within pavement construction. It is divided into the two flow directions of water within pavements that have been modelled:

(1) vertical flow through aggregates and continuing through subgrades below, and

(2) horizontal flow through aggregates towards side drains.

5.2 Vertical Flow

As described in Chapter 3, the two important criteria used within this research relevant to vertical flows through subgrades have been:

(1) that sorption by partitioning takes place and can be described by equilibrium partition coefficients (K_d), and

(2) adequate residence times of water draining through subgrades must occur, to ensure that partitioning reaches equilibrium.

By multiplying the number of time intervals it takes for different breakthrough concentrations to reach a particular layer, by the residence time per layer, absolute residence times may be calculated.

It has been decided that calculated breakthrough times for 10% of input concentration would be an acceptable concentration upon which to base calculations (introduced in Chapter 3). It is important that the breakthrough times incorporated into the risk assessment guide (see Chapter 6) relate to times at which concentrations of contaminants in the breakthrough flows are acceptable to regulatory bodies (e.g. fall below WQS). It has been considered that for most of the contaminants studied, the output concentration at 10% of input concentration will be below WQS, thus ensuring the flows to be acceptable. Furthermore, if plug-flow occurs (as the model taken to a very fine discretisation would suggest) the time to achieve this (T_{10}) and for 50% breakthrough of input concentration (T_{50}) should be identical. Thus a T_{10} calculated for a coarser discretisation than desirable, meaning that some apparent diffusion takes place, would give a conservative estimate for T_{50}. Although the calculations for partitioning presented in Chapter 3 are based upon various K_d values, for convenience calculations presented in this chapter have been based upon a mid-range value, K_d=0.5 l/kg except where noted otherwise. Predicted breakthough times for larger K_d are presented in Chapter 6.

5.2.1 Real Times

Calculations using the model presented here have been based upon the 100 layer computational system, and it is necessary to relate them to real pavement scenarios. This is undertaken by selecting a certain depth from the subgrade surface and determining which layer within the 100 computational layers this corresponds to. The layer number is dependent on the overall subgrade depth. Using depths of 50 mm and 100 mm from the surface for a range of total subgrade depths as examples, corresponding layers are illustrated in Table 5.1.

Table 5.1 Corresponding layer numbers at depths of 50 mm and 100 mm for a range of total subgrade depths

Depth of Subgrade (mm)				
1000	**600**	**200**	**100**	**50**
Depth of Each Layer (mm)				
10	**6**	**2**	**1**	**0.5**
Corresponding Computational Layer Number at Depth of 50 mm from Surface				
5	8	25	50	100
Corresponding Computational Layer Number at Depth of 100 mm from Surface				
10	17	50	100	n/a
n/a=not applicable				

Computations have been undertaken for a range of total subgrade depths from 1000 mm to 50 mm at $k=3x10^{-9}$ to $k=3x10^{-13}$ m/s. This has been undertaken so as to identify computed breakthrough times for 10% of input concentrations to reach 50 mm and 100 mm depths from the surface. Because of the limits imposed by discretisation, breakthrough times depend not only on the depth at which breakthrough is assessed but also on the number of sub-layers traversed to reach that depth. Consequently, breakthrough times are presented in Tables 5.2 and 5.3 as mean values for several scales of discretisation.

Table 5.2 Breakthrough times (years) for 10% of input conc. to reach a depth of 50 mm

k Values (m/s)	**Depth of Subgrade (mm)**	
	1000 600 200	**100 50**
	Breakthrough Times for 10% of Input Conc. (years)	
$3x10^{-13}$	6330	6330
$3x10^{-12}$	633	633
$3x10^{-11}$	63	63
$3x10^{-10}$	6	6
$3x10^{-9}$	0.6	0.6

n.b: highlighted cells represent k values for different subgrade depths where residence times <16 days per layer

Table 5.3 Breakthrough times (years) for 10% of input conc. to reach a depth of 100 mm

k Values (m/s)	**Depth of Subgrade (mm)**	
	1000 600 200	**100 50**
	Breakthrough Times for 10% of Input Conc. (years)	
$3x10^{-13}$	14000	14000
$3x10^{-12}$	1400	1400
$3x10^{-11}$	140	140
$3x10^{-10}$	14	14
$3x10^{-9}$	1	1

n.b: highlighted cells represent k values for different subgrade depths where residence times <16 days per layer

The linear relationship between k values, subgrade depths and residence times can be seen in Tables 5.2 and 5.3.

As expected, for any subgrade depth being assessed, the lower the k value the longer the breakthrough times before contaminants show at any specific depth within the subgrade, with breakthrough times to the water table being the most important. In reality, however, k values of clay at sites being assessed prior to construction will be site-specific. So an assessment may be undertaken for compliance with the requirement for a minimum residence time of 16 days per computational layer within the 100 layer system. If this is not achieved then the breakthrough time may be over-estimated (i.e. a non-conservative solution) as the fullest sorbing action will not have occurred.

Example based on typical clay subgrade: Calculations are based upon the 100 layer model. Assuming a pavement construction site where the subgrade is a typical 600 mm total depth to the water table. Calculations are undertaken to determine breakthrough times for 10% of input concentration to reach the water table. A typical subgrade k value of $k=1.3x10^{-9}$ m/s is present (giving a residence time of exactly 16 days), assuming a typical clay porosity of n=0.3. Flows are based upon $K_d=0.5$ and $K_d=1$ l/kg. Breakthrough times can be seen in Fig. 5.1.

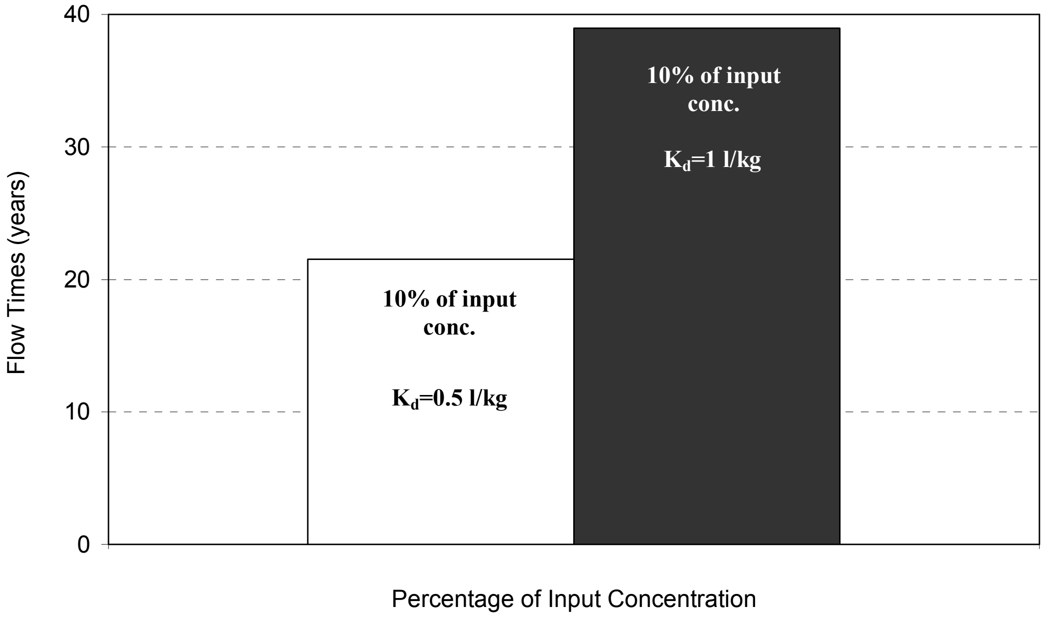


Fig. 5.1 Breakthrough times for 10% of input conc. to reach the water table for a 600 mm total subgrade depth

It can be seen from Fig. 5.1 that it takes 22 years for 10% of input concentration to reach the water table at $K_d=0.5$ l/kg, which increases to 39 years at $K_d=1$ l/kg. Similar flows would take considerably greater lengths of time for larger K_d values where, for example, K_d for chromium is $K_d=1500$ l/kg and K_d for lead is $K_d=550$ l/kg (Sheppard and Thibault, 1990). Breakthrough time predictions for larger K_d values can be seen in Chapter 6.

The importance of a stable water table is evident where an encroachment within the subgrade towards the contaminated levels would occur, were there to be a 5 mm or 10 mm rise in the water table. Consequently, were there to be a rise in the water table, a deeper subgrade would offer a lower risk of contaminants entering groundwater compared with a shallower subgrade.

When roads are constructed in the UK, they are frequently designed with an expected forty-year life (Dawson, 1998), and this is the timescale upon which guidelines have been developed. The risk assessment guide has, consequently, been developed based upon contaminant concentrations in output flows containing no more than 10% of input concentrations, and for the flows to reach the water table in not less than 40 years.

In order to assess whether the data generated above may be applied to real scenarios, they can be compared with similar requirements sought from clay barriers used at landfill sites, where clay is used as a means to prevent leachates from draining to groundwater below by retarding flow rates. Birtwhistle (1997) states that clay used as barriers should be at least 1000 mm deep, with a maximum k value of $k=10^{-9}$ m/s. A k value of $k=2.17\times10^{-9}$ m/s achieves the necessary 16 days residence time per computational layer (for the 1000 mm depth) and is only just larger than the maximum k value of $k=10^{-9}$ m/s required by Birtwhistle (1997). Based upon this value for a 1000 mm deep clay barrier, computations show that it will take 22 years for an output concentration at 10% of input concentration to reach the bottom of the clay, for $K_d=0.5$ l/kg using the present model. Although this calculation yields a breakthrough below the forty-year expected life of a pavement, for contaminants with larger K_d values, the breakthrough times would be greater. If used in combination with a GCL (described below), the breakthrough times would then achieve the forty-year criterion even for contaminants with similarly low K_d values. This confirms that the modelling developed might be used to assess landfill sites as defined by Birtwhistle (1997).

5.2.2 Geotextile Clay Liners

Computations have been undertaken for a range of realistic GCL thicknesses from 1 to 5 mm at $k=3x10^{-11}$ to $k=3x10^{-13}$ m/s for $K_d=0.5$ l/kg. This has been undertaken so as to calculate breakthrough times for 10% of input concentrations to reach the bottom of the GCL. Basing calculations on $K_d=0.5$ l/kg, calculated breakthrough times for 10% of input concentration to reach the bottom of each total GCL thickness can be seen in Table 5.4.

Table 5.4 Breakthrough times (years) for 10% of input conc. to reach the bottom of a GCL

k Value (m/s)	**Thickness of GCL (mm)**				
	5	**4**	**3**	**2**	**1**
	Breakthrough Times for 10% of Input Conc. (years)				
$3x10^{-13}$	800	600	500	300	150
$3x10^{-12}$	80	60	50	30	15
$3x10^{-11}$	8	6	5	3	1.5

n.b: highlighted cells represent k values for different GCL thicknesses where residence times <16 days per layer

Breakthrough times will be greater for contaminants with larger K_d values. When assessing thicknesses of GCLs prior to use, an important fact should be considered: a very thin GCL will be more easily damaged than a thicker one. Despite the fact, therefore, that in theory there will be sufficiently long breakthrough times for thin GCLs, in practice it may be more astute to use robust, thicker ones.

Example based on manufactured GCL: Bentonite is a type of clay commonly used within GCLs. GSE GundSeal is a GCL supplied by CETCO (CETCO, 2000) and consists of bentonite clay adhered to a backing. It is available in thicknesses of 0.4 mm to 2 mm. The bentonite clay has a k value of $k=10^{-11}$ m/s and when in combination with the backing an overall k value of $k=10^{-14}$ m/s is achieved. An assumption is made within the calculations that the thicknesses quoted for the GCLs are the thicknesess of the actual clay and do not include an allowance for the backing material. From Table 5.x, it is known that for clays with k values of $k=10^{-11}$ m/s a thickness of >5 mm is necessary to achieve the 16 days residence time per computational layer. The actual clay in the manufactured 2 mm thick GCL is, therefore, too thin. A k value of $k=4.3\times10^{-12}$ m/s is necessary to achieve the 16 days residence time per computational layer for the 2 mm thickness clay (taking the 100 layer model). When in combination with the backing, the combined k value of $k=10^{-14}$ m/s would, however, comply. Modelling based upon a K_d value of 0.5 l/kg shows that 10% of input concentration would take 3000 years to reach the bottom of a GCL with the k value of $k=10^{-14}$ m/s.

Taking into account previous recommendations, however, it may be advisable for a GCL to be manufactured with a greater thickness than the current maximum 2 mm, in order to resist damage. Based upon the previous tables, if a 4 mm thickness GCL were to be produced with a k value of $k=10^{-14}$ m/s, 10% of input concentration would take 6000 years to reach the bottom, and the layer would have greater potential to function even when there are small inconsistencies in use and composition.

As T_{10} values have been used within the thesis, their accuracy (and acceptability) have been further assessed as follows:

In the model analysis present in Chapter 3, it was suggested that T_{10} and T_{90} may be less accurately determined than T_{50}. If plug-flow occurs, then T_{10} and T_{90} would occur simultaneously to T_{50}. The research model adopted here may, or may not, give accurate T_{10} values – if non-equilibrium affects are marked, T_{10} might be accurately computed, if not, T_{10} is too small. Therefore, this tends to ensure that the model gives a lower bound evaluation of T_{10} – i.e. it is a conservative value for design. In order to determine whether the differences of T_{10} to T_{50} are of realistic magnitudes, the model has been used to calculate examples of T_{10} and T_{50} (Table 5.5).

Table 5.5 Breakthrough times for T_{10} and T_{50} at subgrade depths of 50 mm and 100 mm (K_d=0.5 l/kg)

Depth of Subgrade Breakthrough (mm)	(A) Breakthrough Times for 10% of Input Conc. (T_{10}) Calculated with Model (years)	(B) Breakthrough Times for 10% of Input Conc. (T_{10}) as Presented in this Chapter (years)	Breakthrough Times for 50% of Input Conc. (T_{50}) Calculated with Model (years)
50	68	63	87
100	148	140	175

In Table 5.5 it can be seen that there are two breakthrough times for T_{10} at both subgrade depths of 50 mm and 100 mm (A and B). Values for (A) have been calculated directly using the model and values for (B) have been taken from Tables 5.2 and 5.3. It can be seen that T_{10} values are less than, but of a similar magnitude to T_{50} (as expected), and calculations for T_{10} have, therefore, been considered acceptable as illustrations of breakthrough times calculated from the model. Although it is acknowledged that these latter breakthrough times contain a certain amount of conservatism, it is considered that this conservatism is acceptable. It is these times on which the risk assessment guide in Chapter 6 has been based.

5.2.3 Advection vs. Diffusion as a Transport Mechanism

Calculations undertaken in Chapter 3 and here have been based upon contaminant movement under advection as opposed to diffusion. In advection the contaminants are transported in a moving front of water, whilst in diffusion the contaminant movement is due to concentration gradients without water flow. In subgrades with relatively higher k values, it has been considered justifiable to assume that contaminant movement under diffusion will have little (if any) effect on total contaminant flow times compared with those modelled. It has been considered important, however, to compare flux values at breakthrough times for contaminant movement by diffusion with those by advection for subgrades with lower k values (e.g. clay) in order to determine the main influence on contaminant transportation.

In order to assess the differences in flux values at breakthrough for contaminants by diffusion rather than by advection, the following assessment has been undertaken, based upon a typical subgrade with a depth of 0.6 m to the water table:

Diffusion:

$$F_d = D^*\left(\frac{\Delta C}{l}\right) \qquad \text{[Eqn. 5.1a]}$$

where:

F_d: diffusive flux (mg/s/m^2)
D^*: effective diffusion coefficient = $D\alpha$
ΔC: change in concentration (mg/m^3)
l: length of flow path (m)
D: diffusion coefficient in water (m^2/s) (Fetter, 1999)
α: empirical coefficient (Freeze and Cherry, 1979)

N.B: the concentration gradient assumed here is very conservative because a uniform value throughout the subgrade has been assumed which, in truth, will not be established for a long time.

Example 1:

Assuming the following parameters:

ΔC: 500 mg/m^3 = 0.5 mg/l
l: 0.6 m
D: $9.5\text{x}10^{-10}$ m^2/s
α: 0.01

then:

F_d=$7.9\text{x}10^{-8}$ mg/s/m^2 [Eqn. 5.1b]

Example 2:

Assuming α changes to 0.5, but the other parameters remain constant, then:

F_d=$4\text{x}10^{-7}$ mg/s/m^2 [Eqn. 5.1c]

The two examples have been given in Eqn. [5.1b] and [5.1c], based upon two values of α (which are either end of the range presented in Freeze and Cherry, 1979) and where the value of D is the largest presented in Fetter (1999) (in order to generate largest flux values - worst-case).

To compare the flux for contaminant transportation by diffusion presented above with that by advection, a further calculation has been undertaken:

Advection:

$F_a = C_b \times (1000q)$ [Eqn. 5.2a]

where:

f_a: advective flux (mg/s/m^2)
C_b: breakthrough concentration (mg/l)
q: [Eqn. 3.2a]

Example 3:

Assuming the following parameters:

C_i: 0.5 mg/l (initial concentration)
C_b: 0.05 mg/l
A: 1 m^2
k: 1×10^{-8} m/s
i: 1

then:

$F = 5 \times 10^{-8}$ mg/s/m^2 [Eqn. 5.2b]

It can be seen that in Eqn. [5.2b] the flux has been assessed for 0.05 mg/l, being 10% of the input concentration of a 0.5 mg/l contaminant concentration, where Example 3 is based upon a typical k value of a clay subgrade.

From the two examples for diffusion [Eqns. 5.1b and c] fluxes of 7.9×10^{-8} mg/s/m^2 and 4×10^{-7} mg/s/m^2 have been generated, and in the example for advection [Eqn. 5.2b] a flux of 5×10^{-8} mg/s/m^2 has been generated. This indicates that in the calculations contaminant transportation by diffusion is slightly larger than that by advection.

In the calculations three pessimistic assumptions for diffusion have been made, however:

(1) the highest diffusivity has been assumed,

(2) no allowance for sorption by partitioning occurs during diffusion, and

(3) there is a constant concentration gradient from the onset.

In reality, sorption by partitioning will occur during diffusion, as it does during advection, resulting in the flux at breakthrough times being greatly reduced from those presented above. Breakthrough by diffusion will occur in a similar manner to that by advection, whereby initially the output concentration will be a small percentage of the input concentration and the percentage will increase with time (dependent on sorption as with advection). Thus, in practice, at a point in time when sorption reduces the advective output flux to 10% of the input flux a similar proportional reduction in diffusive flux might also be anticipated due to sorption. Furthermore the flux at breakthrough for advection is based upon 10% of input concentration whereas the flux at breakthrough for diffusion is based upon a constant gradient from the onset. Taken together these considerations indicate that advective fluxes will be larger than diffusive fluxes in all but the lowest permeability soils. In practice, moderately permeable sorbent soils with contaminants having moderate or low diffusive properties will experience relatively little diffusive contaminant transport compared to that transported by advection.

5.3 Horizontal Flow

5.3.1 Infiltration Rates

Water entering by infiltration through surface cracks has been the main route upon which computations have been based. Testing to quantify the rate of infiltration was undertaken as previously described. A mean infiltration rate of 3.33 l/h was determined and is the rate below which rainfalls may be said to infiltrate, providing surface cracking is great enough to facilitate this. Rainfall data sets for twelve-hour periods numbered R1 to R4 have been used. This has been to determine the movement of contaminants within a pavement, and rainfall values are given in Table 5.6.

Table 5.6 Four rainfall events simulated within computations. R1: Adapted for Notts.; R2: 0.07 $l/h/m^2$ from R1 x 4; R3: Aberdeen; R4: London. (Source: R1: Hill, 2000; R2: adaptation of R1: Hill, 2000; R3 and R4: Ward, 1975)

End of Time (h)	**R1 (mm/h) or ($l/h/m^2$)**	**R2 (mm/h) or ($l/h/m^2$)**	**R3 (mm/h) or ($l/h/m^2$)**	**R4 (mm/h) or ($l/h/m^2$)**
1	0.07	0.28	0.08	0.08
2	0	0.28	0.08	0.05
3	0.07	0.28	0.08	0.05
4	0	0.28	0.08	0.05
5	0.07	0.28	0.08	0.08
6	0	0.28	0.13	0.10
7	0.07	0.28	0.13	0.13
8	0	0.28	0.15	0.10
9	0.07	0.28	0.15	0.13
10	0	0.28	0.15	0.10
11	0.07	0.28	0.13	0.08
12	0	0.28	0.13	0.10

R1 has been determined by averaging rainfall data presented in Hill (2000) to an hourly rate. Due to the fact that the rain would not normally fall at that rate for a complete twelve-hour period, it is presented for use within the calculations as an hourly rate every alternate hour.

R2 has been determined by multiplying the average hourly rainfall rate presented within R1 by four, as if it fell at that rate per hour. This has been undertaken to simulate a rainfall event of a large magnitude.

R3 and R4 have been determined from rainfall events previously presented in Chapter 3, for Aberdeen and London (Ward, 1975). These events have been selected because they offer data from areas distant to each other, with different magnitudes. Due to this, they offer a broader variation in rainfall data than if two areas geographically close to each other had been selected.

The four different rainfall events offer data of different magnitudes to allow calculations to reflect a range of infiltration rates, and consequently flow rates, through pavements. R1 offers an adaptation of real rainfall rates, R3 and R4 offer real rainfall rates, and R2 offers a higher rainfall rate following a greater adaptation of R1.

It is important to appreciate the fact that the calculations in this thesis are based upon rainfall events which may be classed as worst-case scenarios. This is because the calculations assume that the rainfall events fall at the same quantities every day throughout the year, where in reality this is not the case. The approach developed (details of which are presented further on), has been to initially determine the mass of each contaminant released from a half-pavement per hour, where the mass is dependent on the rainfall event. The next approach has been to determine quantities of water required to dilute the contaminants to WQS. Consequently, it is assumed that if acceptable dilution rates are achieved for rainfalls classed as worst-cases which will only periodically occur, in reality the dilution rates will be definitely acceptable during rainfalls either below the assumed rainfall events or periods of time when no rain falls at all. Another factor illustrating that this worst-case scenario has an in-built bias on the side of caution is that the conditions will only occur after several years, when surface cracking reaches maintenance levels, resulting in high rainfall infiltration rates.

5.3.2 Pavement Drainage

In Chapter 3 it is shown that a method has been developed to assess minimum degrees of saturation (S_{min}) that will remain within an aggregate after drainage, below which further drainage will not occur. It has also been demonstrated that drainage per hour can be predicted for different percentages of drainage (T_f). As a result, the quantity of water draining from half-pavement sections per hour, and consequently the rates of contaminants leaving the pavement per hour, may also be calculated. The sequence of rainfall infiltrating and draining horizontally towards the side drain may be seen in Chapter 3, Fig. 3.5.

Quantities of water draining from a half-pavement section over a twelve-hour period are presented in Figs. 5.2 to 5.13 (shown as output water as a percentage of input water), based upon simulations of rainfall events, R1 to R4. They represent a range of k values (where for k values of k<0.00003 m/s no drainage occurs at all), based upon aggregates with porosity values of n=0.2, n=0.3, and n=0.4. In all cases it can be seen that drainage from inputs during the first hour will occur during the second hour, and drainage from inputs during the twelfth hour will occur during the thirteenth hour etc.

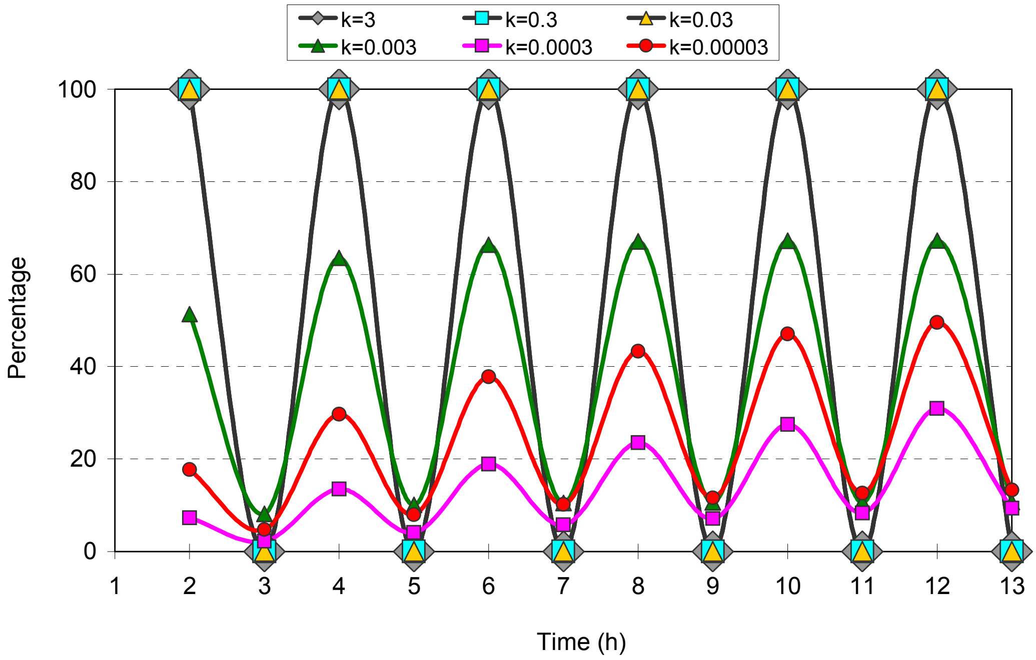


Fig. 5.2 Output water as percentage of input water for range of k values (m/s) (R1 and n=0.2)

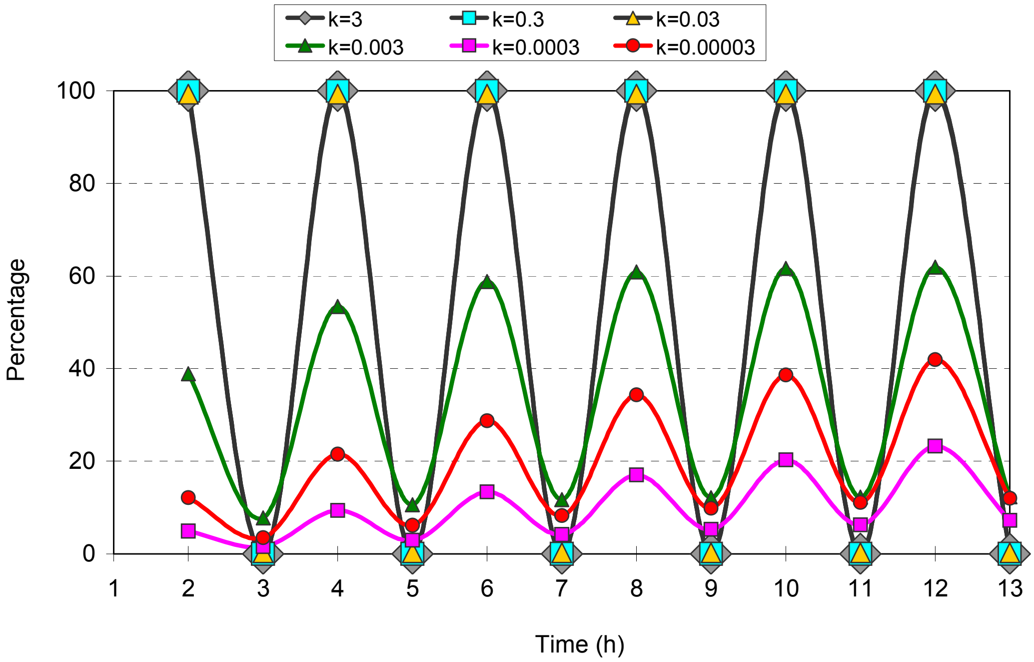


Fig. 5.3 Output water as percentage of input water for range of k values (m/s) (R1 and n=0.3)

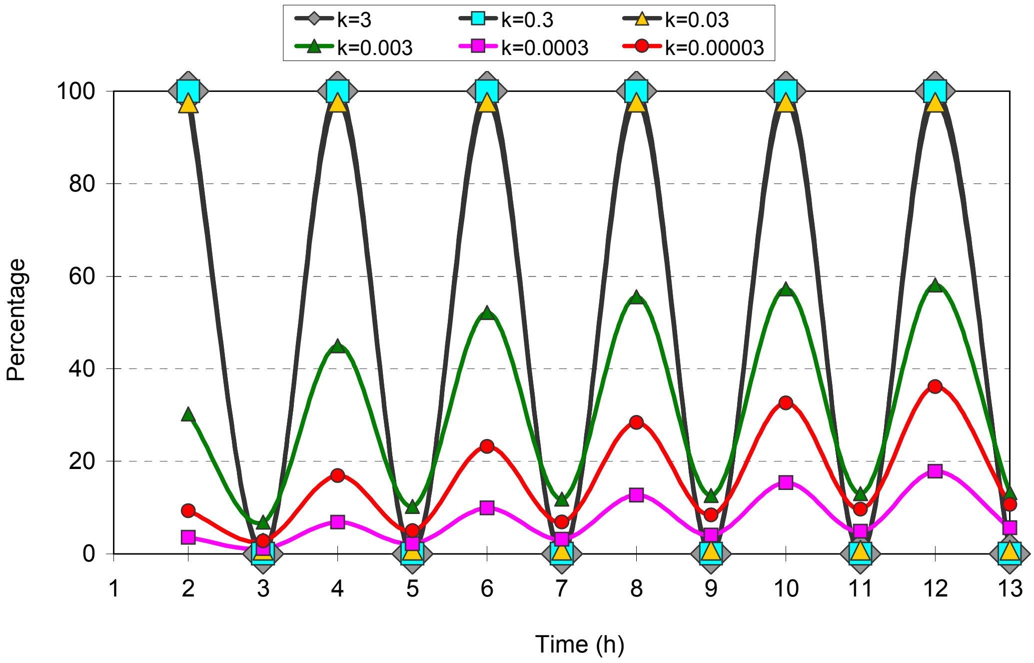


Fig. 5.4 Output water as percentage of input water for range of k values (m/s) (R1 and n=0.4)

Figs. 5.2 to 5.4 show that for k values of 3 and 0.3 m/s 100% of input water per hour drains the following hour. This results in no drainage the subsequent hour if there is no further infiltration. For k values of k=0.03 m/s 100% of input water drains for n=0.2, 99% of input water drains for n=0.3 and 98% of input water drains for n=0.4. Lower percentages of input water drains for lower k values. When values of below 100% of input water per hour drain the following hour, additional water will drain the subsequent hour regardless of infiltration occurring. There are overall increases in output as percentages of input over the twelve-hour period due to accumulations of water within the pavement. For all three porosity values at each hour there is a decrease in output at a k value of k=0.0003 m/s. This matches findings presented in Chapter 3, illustrating reduced drainage rates at that k value.

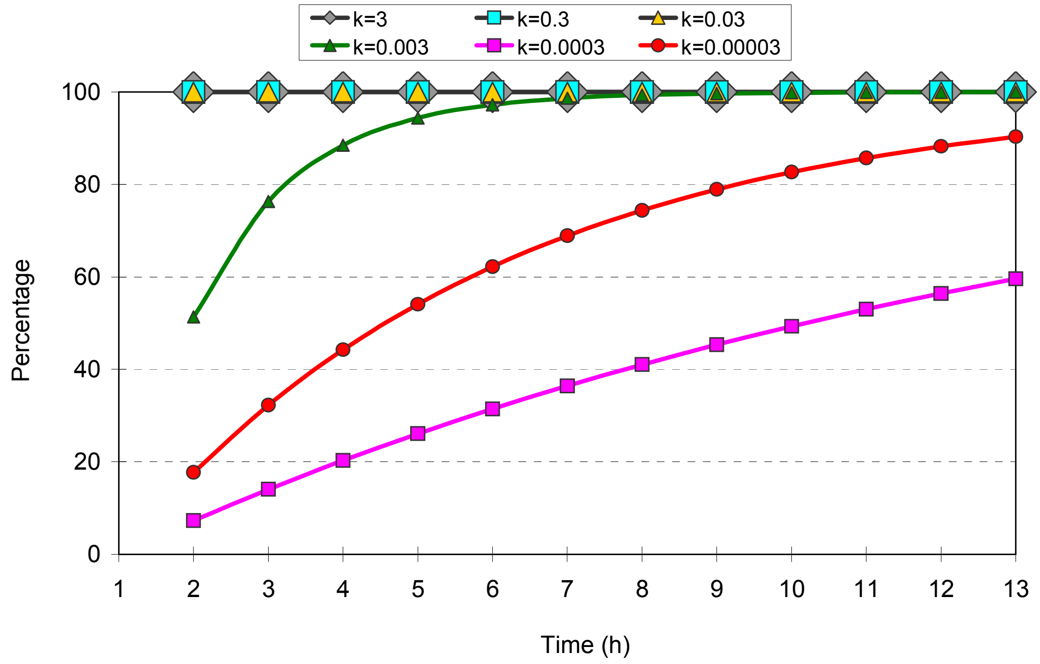


Fig. 5.5 Output water as percentage of input water for range of k values (m/s) (R2 and n=0.2)

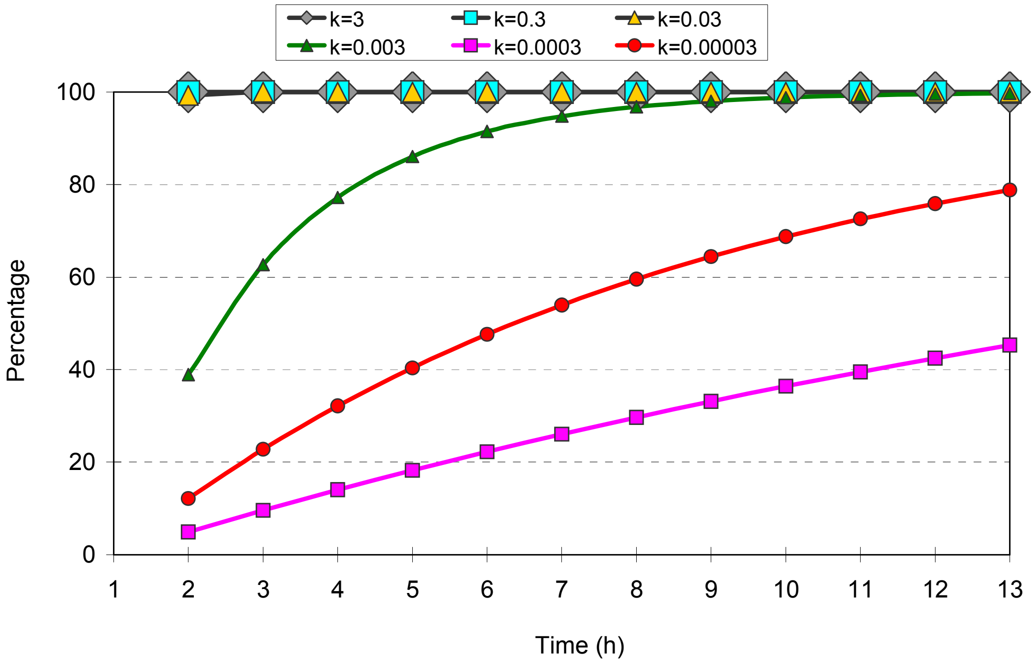


Fig. 5.6 Output water as percentage of input water for range of k values (m/s) (R2 and n=0.3)

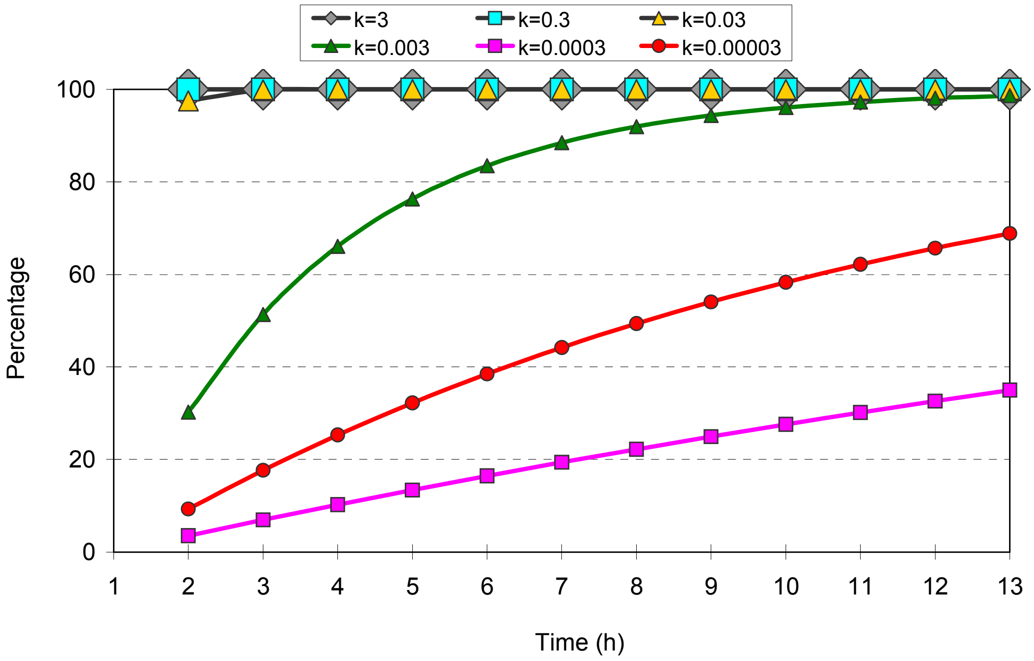
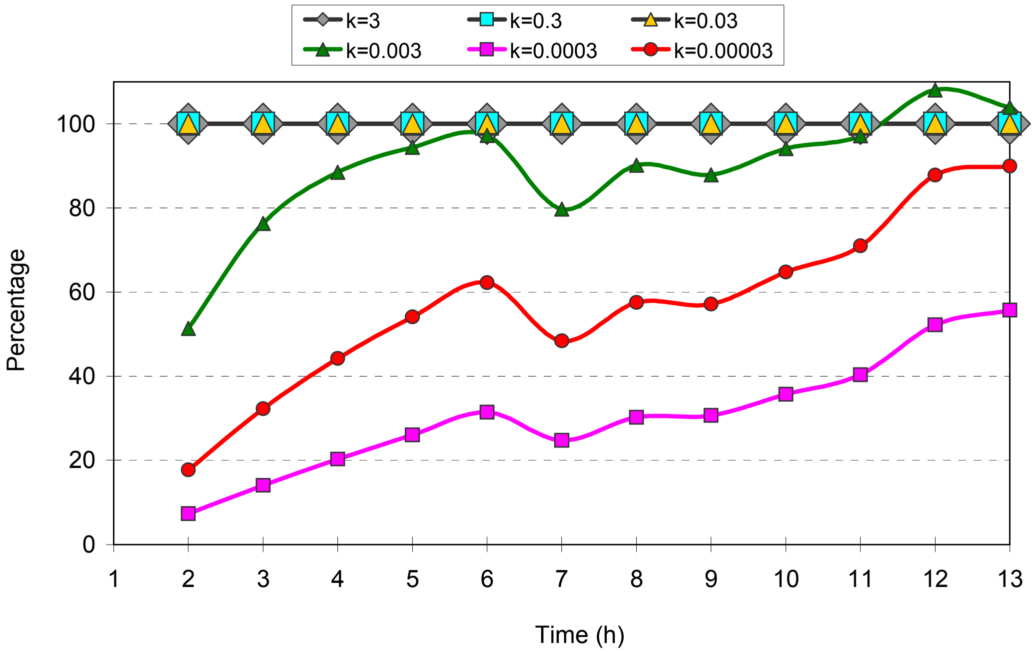


Fig. 5.7 Output water as percentage of input water for range of k values (m/s) (R2 and n=0.4)

Figs. 5.5 to 5.7 again show overall increases in output as percentages of input over the twelve-hour period, with a similar trend being present whereby a k value of k=0.0003 m/s has lowest rates of output, due to reduced drainage rates.



5.8 Output water as percentage of input water for range of k values (m/s) (R3 and n=0.2)

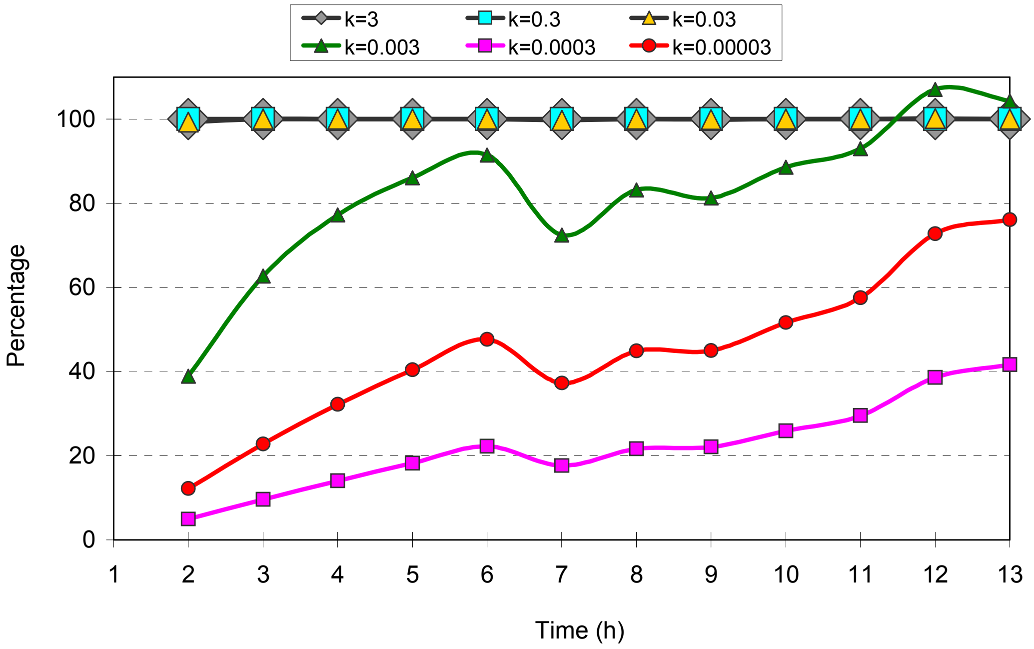


Fig. 5.9 Output water as percentage of input water for range of k values (m/s) (R3 and n=0.3)

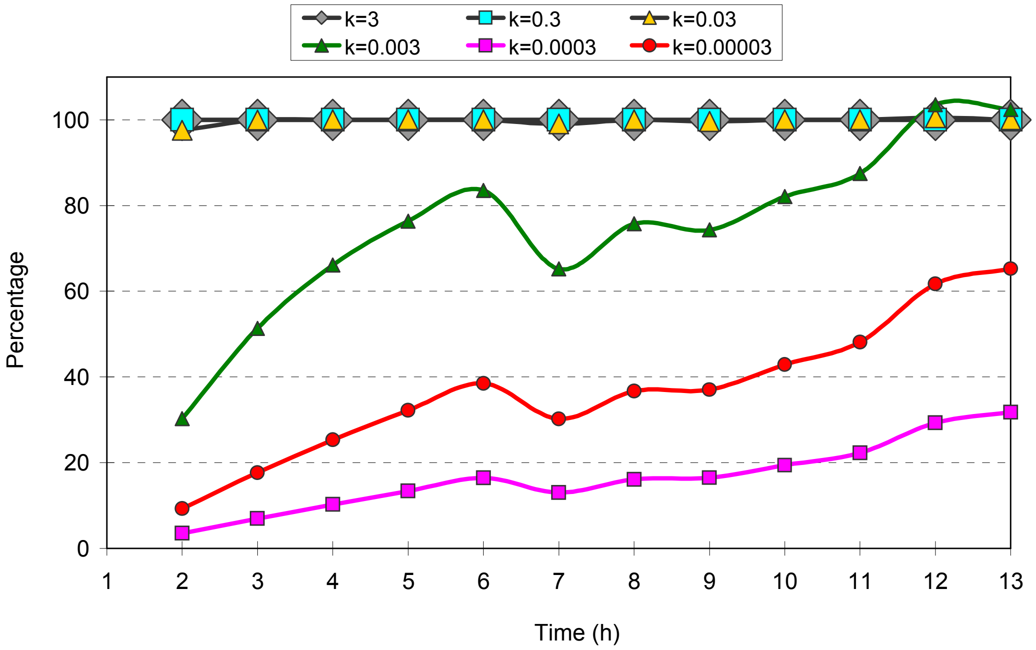


Fig. 5.10 Output water as percentage of input water for range of k values (m/s) (R3 and n=0.4)

Figs. 5.8 to 5.10 again show overall increases in output as percentages of input over the twelve-hour period, with a similar trend being present whereby a k value of k=0.0003 m/s has lowest rates of output, due to reduced drainage rates. It is evident for n=0.2, 0.3 and 0.4 for the 12th and 13th hour at a k value of k=0.003 m/s outputs are larger than inputs in the same hour. This is due to the fact that drainage occurs the hour following input. When the input rate decreases from one hour to the next, drainage at a rate higher than the input may occur due to previously stored water being liberated, particularly with lower k values, where drainage will be slower and may continue over several hours. This will consequently give greater ratios of output to those of input, as drainage continues regardless of input.

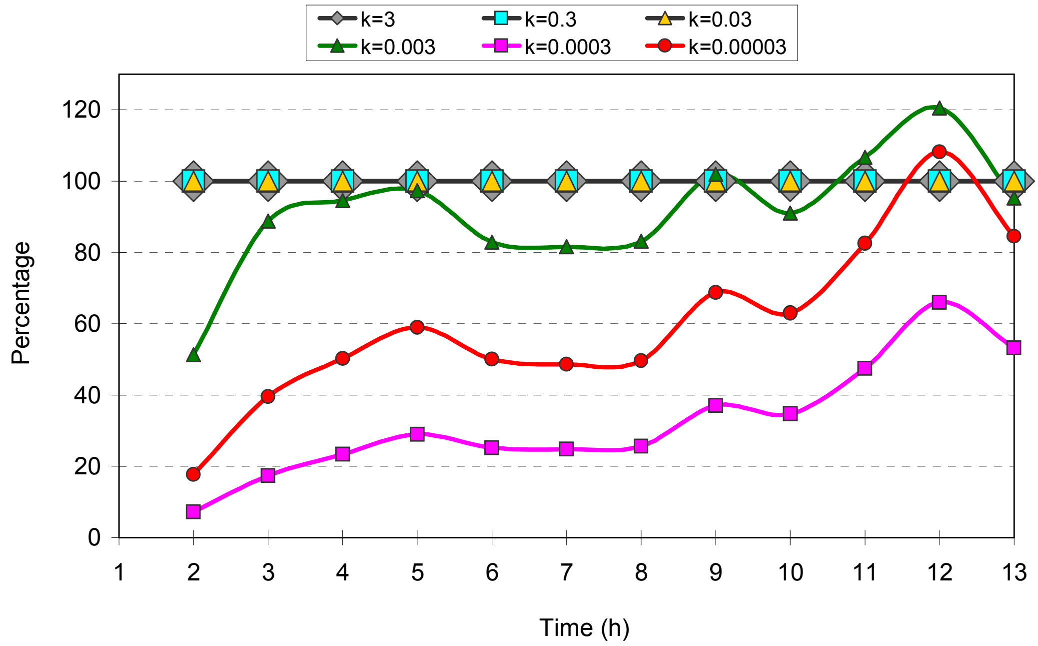


Fig. 5.11 Output water as percentage of input water for range of k values (m/s) (R4 and n=0.2)

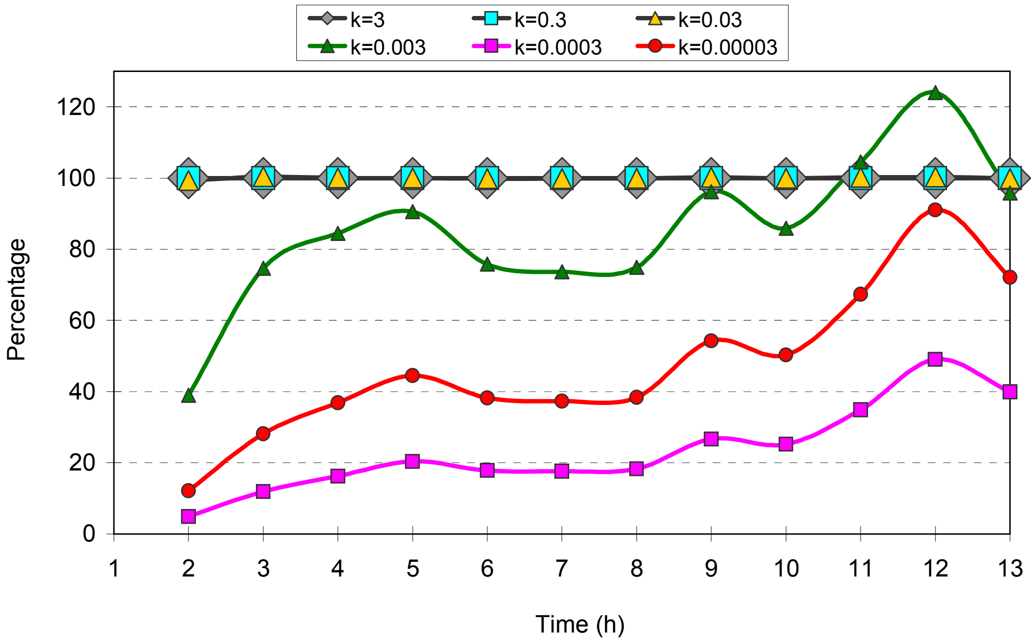


Fig. 5.12 Output water as percentage of input water for range of k values (m/s) (R4 and n=0.3)

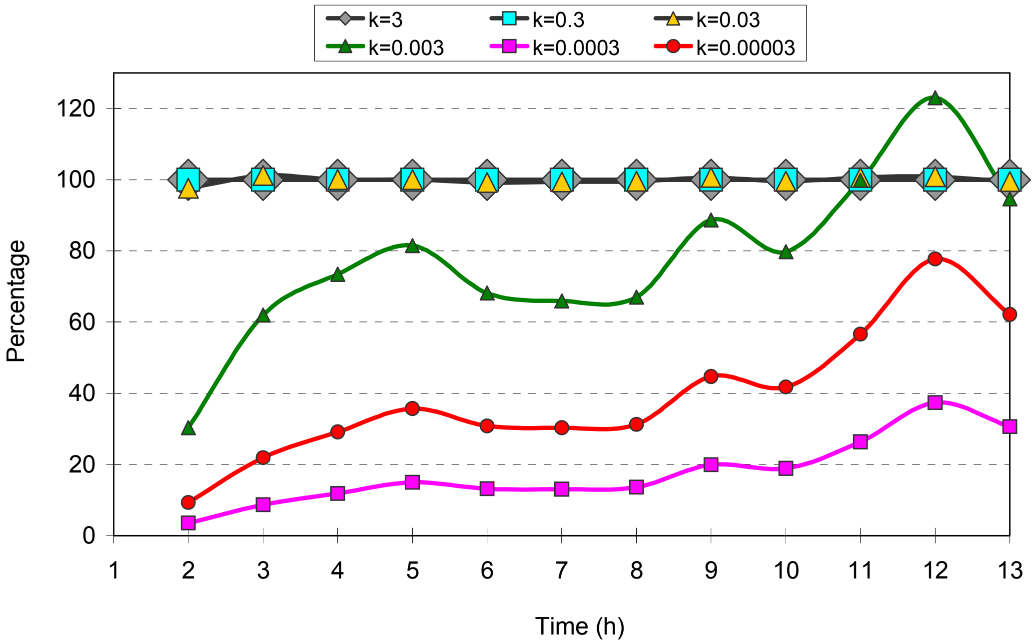


Fig. 5.13 Output water as percentage of input water for range of k values (m/s) (R4 and n=0.4)

Figs. 5.11 to 5.13 again show overall increases in output as percentages of input over the twelve-hour period, with a similar trend being present whereby a k value of k=0.0003 m/s has lowest rates of output, due to reduced drainage rates. Outputs for n=0.2 for the 9th, 11th and 12 hour at a k value of 0.003 m/s, for n=0.3 for the 11th and 12th hour at a k value of k=0.003 m/s and for n=0.4 for 3rd, 9th, 11th and 12th hour at a k value of k=0.03 m/s and 11th and 12 hour at a k value of k=0.003 m/s are larger than inputs. These ratios again are greater than 100%.

5.3.3 Release of Contaminants

It is evident from the above section that computations allow rates of drainage per hour per half-pavement sections to be determined. Data extracted from Hill (2000) give concentrations of contaminants in leachate draining from the nine lysimeters. By combining both data sets, rates of contaminants released per hour can be determined. Maximum rates of contaminants are released from aggregates with k values of k=3, k=0.3 and in some instances k=0.03 m/s, due to their higher permeability rates.

Clay lined side drains may themselves act as sorption sites for contaminants carried in water discharged through them, the capacity of which is outside the scope of this thesis. Although the quantification of sorption by side drains cannot be calculated here, a broad estimation may be undertaken: if lined with clay, contaminants in water may be sorbed by the clay particles. Based upon sorption by partitioning presented within Chapter 3 and previously within this chapter, residence times within the clay would not be sufficient for partitioning to reach equilibrium (not sufficiently deep), but some sorption would occur to a lesser extent. In Chapter 3, it was shown that if a K_d value of K_d=0.5 l/kg was present, at the 100th computational layer after 100 input times the output concentration as a factor of input concentration will be $3.7x10^{-75}$. If an estimation of only 50% of contaminants are removed from contaminated water by partitioning not reaching equilibrium in the side drains, the quantity of water required for diluting the contaminated water would still be greatly reduced, if not completely removed in some instances. The capacity for determining rates of sorption by side drains is an area recommended for further research. It follows, therefore, that output from side drains may be classed as worst-case scenarios, because in reality if some contamination is removed by the side drains, concentrations would be lower than those estimated.

5.3.4 Treatments for High Levels of Contaminants

5.3.4.1 Dilution

At sites of lesser sensitivity (an area addressed further on) it is anticipated that the EA may allow the dilution of raised contamination levels as a form of treatment, providing the dilution occurs *prior* to drainage actually discharging from the pavement profile (i.e. dilution by runoff where the combined water is discharged through the same drain). Computations based upon the highest rate of contaminant-release from the aggregates assessed allow the quantities of water required to reduce any raised contaminant levels to WQS to be calculated. As previously stated, this is based upon worst-case scenarios, where in reality these maximum contaminant levels will only occur during short rainfall periods, *once* maintenance level cracking is reached. The computations have been determined for the same rainfall events (R1-R4) for which drainage rates have already been determined and have been calculated using the same porosity values (n=0.2, n=0.3 and n=0.4) previously used. These quantities of water are illustrated in Figs. 5.14 to 5.17, and relate to l/h drainage for a 1 m section of a half-pavement.

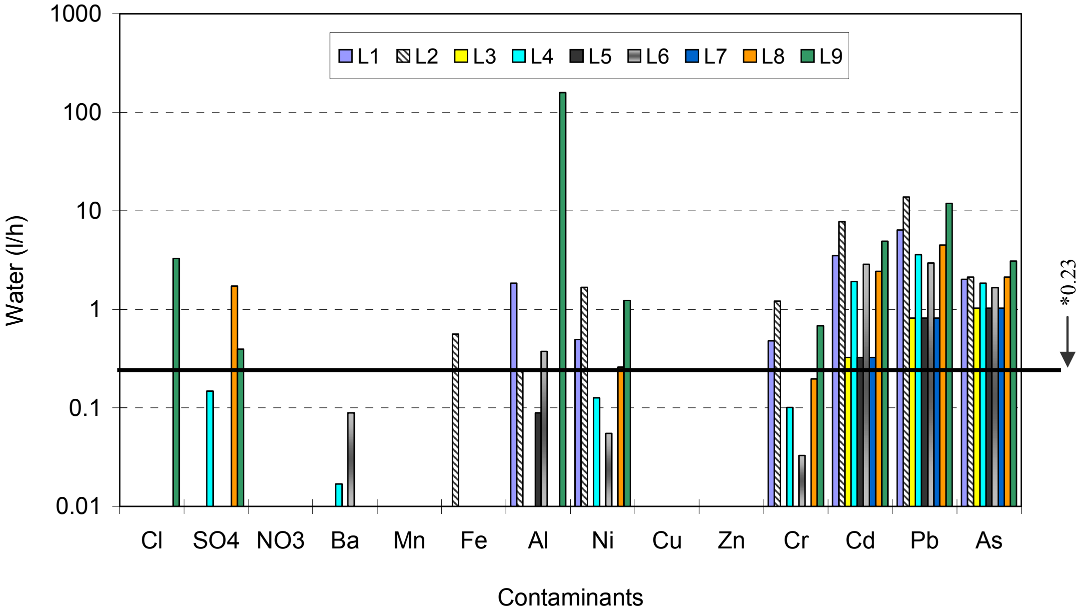


Fig. 5.14 Quantities of water required to dilute contaminant levels in the nine lysimeters under review to WQS, for those determinants which exceed them. Values are for a 1 m half-pavement section. Contaminant levels below WQS are omitted (R1). *see Chapter 6, Section 6.3.4.1

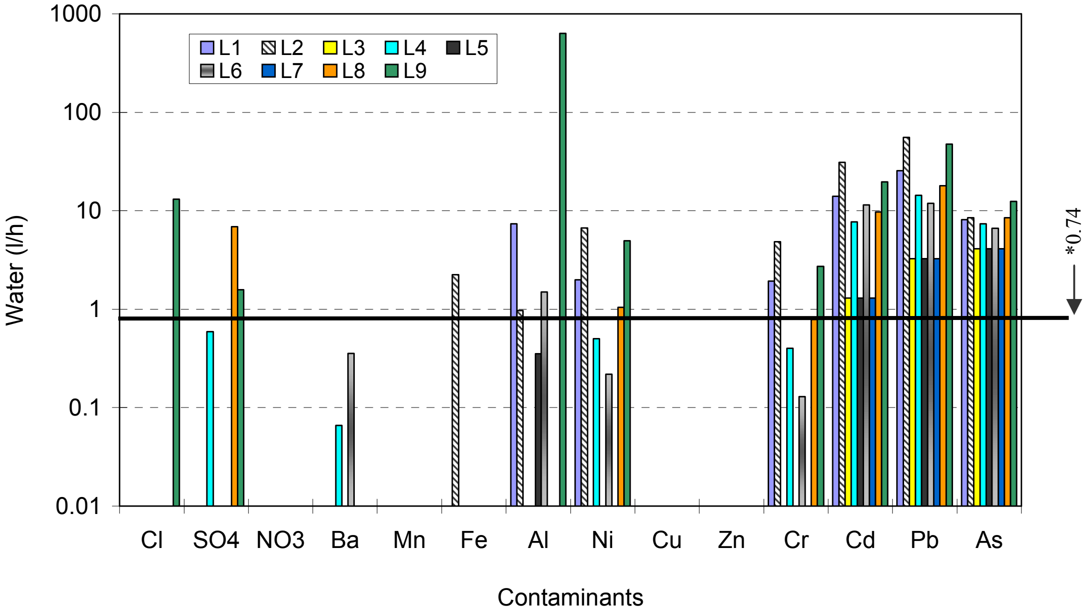


Fig. 5.15 Quantities of water required to dilute contaminant levels in the nine lysimeters under review to WQS, for those determinants which exceed them. Values are for a 1 m half-pavement section. Contaminant levels below WQS are omitted (R2). *see Chapter 6, Section 6.3.4.1

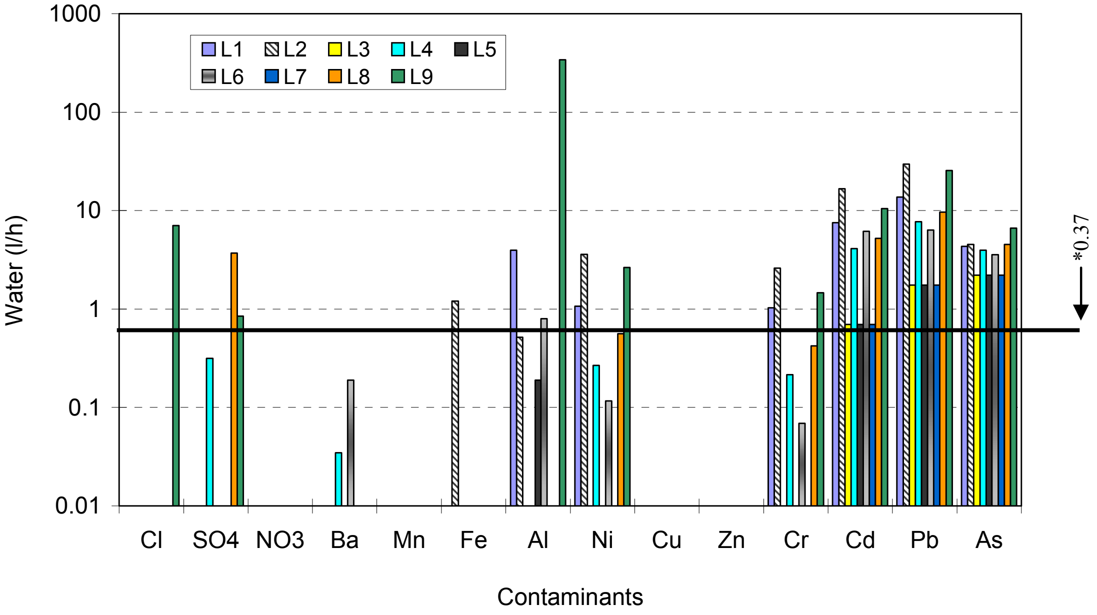


Fig. 5.16 Quantities of water required to dilute contaminant levels in the nine lysimeters under review to WQS, for those determinants which exceed them. Values are for a 1 m half-pavement section. Contaminant levels below WQS are omitted (R3). *see Chapter 6, Section 6.3.4.1

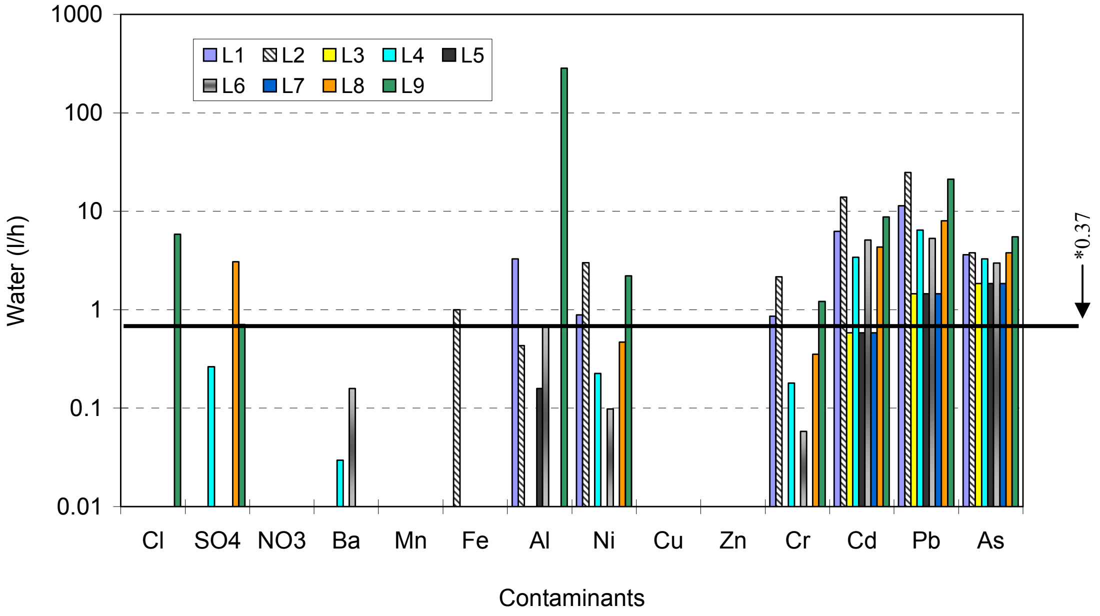


Fig. 5.17 Quantities of water required to dilute contaminant levels in the nine lysimeters under review to WQS, for those determinants which exceed them. Values are for a 1 m half-pavement section. Contaminant levels below WQS are omitted (R4). *see Chapter 6, Section 6.3.4.1

From Figs. 5.14 to 5.17 it can be seen that nitrates, manganese, copper and zinc do not exceed the WQS in any of the nine aggregates in the lysimeters and do not require diluting. Chloride only exceeds WQS in the aggregate in Lysimeter 9, barium in the aggregates in Lysimeters 4 and 6 and iron in the aggregate in Lysimeter 2. In contrast cadmium, lead and arsenic consistently exceed WQS in the aggregates in all the lysimeters. Sulphate, aluminium, nickel and chromium exceed WQS in the aggregates in some of the lysimeters. In most cases, the quantity of water required to dilute contaminant concentrations back to WQS is below 10 l/h for a 1 m stretch of a half-pavement section. In some cases greater quantities of water are required with the maximum requirements being for aluminium in the aggregate in Lysimeter 9, where requirements are for R1=158 l/h, R2=633 l/h, R3=339 l/h and R4=223 l/h for a 1 m stretch of a half-pavement section. None of the aggregates in the lysimeters contain levels below WQS for all the contaminants, but aggregates in Lysimeters 3 and 7 require the least number of contaminants to be diluted.

Although in theory dilution could be undertaken by water being piped into a construction area, the cost would be prohibitory. The most feasible option would be to dilute contaminants with surface runoff, providing sufficient surface runoff is available. A method by which to quantify dilution requirements for contaminants at construction sites with different rainfall ranges is given below. Following this, a quantitative estimation of surface runoff is undertaken in order to determine whether it may provide sufficient water.

If dilution of drainage by surface runoff is feasible, it is recommended that surface runoff and pavement drainage be combined within one discharge pipe, to enable the combined outflow to be monitored. The outflow should then be subsequently directed into a series of settling pools constructed within the natural subgrade in the vicinity of a pavement construction site, to allow the final disposal of the water to be controlled. It is acknowledged that the surface runoff and the pavement drainage may not flow together for the whole rainfall event. The surface runoff will initially drain through the side drain before the pavement drainage. This is because (as previously described) rainfall that infiltrates through the surface in an hour will discharge through the side drain the following hour. Both the surface runoff and the pavement drainage will flow together during the main part of the rainfall and the pavement drainage will continue to drain after the surface runoff ceases when the rainfall stops. The length of time that pavement drainage will continue to flow after the rainfall stops depends on the k value and porosity of the aggregate. All of the rainfall that falls in one hour will drain during the following hour for aggregates with k values of $k=3$, $k=0.3$ and $k=0.003$ m/s when $n=0.2$ and for aggregates with k values of $k=3$, $k=0.3$ m/s when $n>0.2$. The length of time that pavement drainage continues to discharge through the side drain increases to 12 hours after the rainfall stops as k values decrease to $k=0.00003$ m/s, at which point the drainage is very small. Due to the low volumes of water draining in the subsequent hours after the rainfall stops, the mass of contaminants draining will be sufficiently low to fall within WQS and thus requiring no dilution.

5.3.4.1.1 Further Calculations for Dilution

The quantity of water required for dilution of contaminants will vary for each of the four rainfall events. Although the twelve-hour rainfalls for each of the events was presented in Table 5.6, the maximum hourly rainfall for each of the four events is presented in Table 5.7.

Table 5.7 Maximum rainfalls for R1 to R4 events (Source: R1: Hill, 2000; R2: adaptation of R1; R3 and R4: Ward, 1975)

Rainfall Event	Max. Rainfall (mm/h)
R1	0.07
R2	0.28
R3	0.15
R4	0.13

Actual quantities of water required to dilute contaminants to WQS have been previously presented in this chapter. In order to differentiate between the amounts of water required, the quantities of water have been grouped in ranges of dilution values (where they have been rounded up to certain values) and have been additionally given dilution classes. This results in actual quantities of water required for dilution being allocated dilution values of 0 to 1000 l/h and dilution classes of D0 to D7. The dilution values and classes can be seen in Table 5.8.

Table 5.8 Dilution values and classes given for ranges of water quantities required for the dilution of contaminants in output from side drains to WQS. Values are for 1 m half-pavement sections

Dilution Class	Actual Vol. of Water (v) Required for Dilution (l/h)	Dilution Value (Vol. of Water to be Used for Dilution) (l/h)
D0	0	0
D1	$0<v\leq1$	1
D2	$1<v\leq5$	5
D3	$5<v\leq10$	10
D4	$10<v\leq50$	50
D5	$50<v\leq100$	100
D6	$100<v\leq500$	500
D7	$500<v$	1000

Graphs illustrating water required to dilute contaminant concentrations to WQS have been plotted based upon the allocated dilution values. These graphs can be seen in Figs. 5.18 to 5.21.

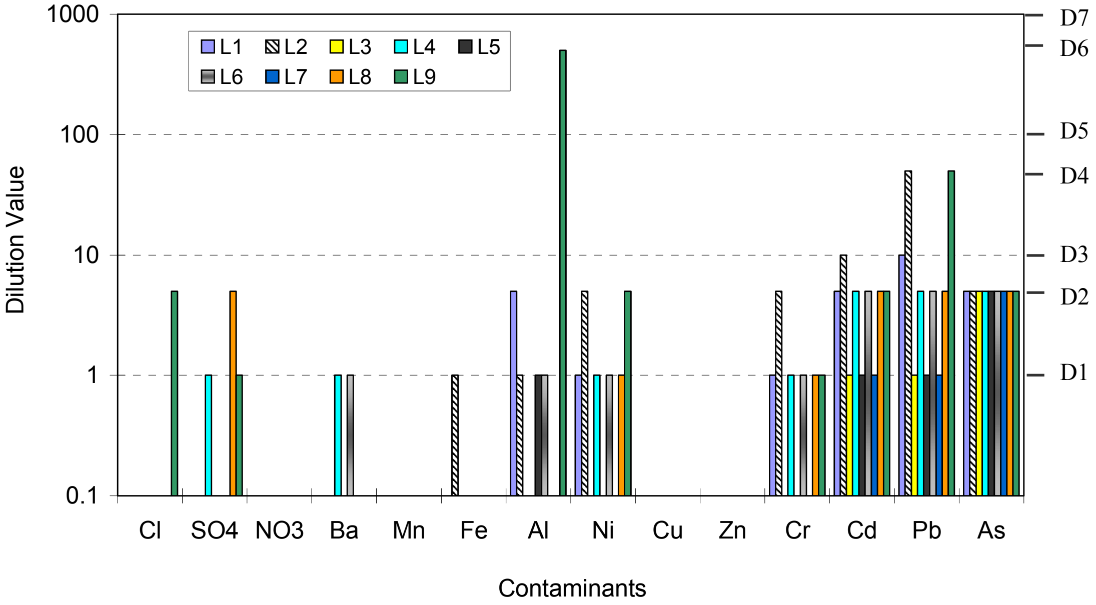


Fig. 5.18 Ranges of water required to dilute contaminants in outflow from side drains to WQS (R1). Values are for a 1 m half-pavement section

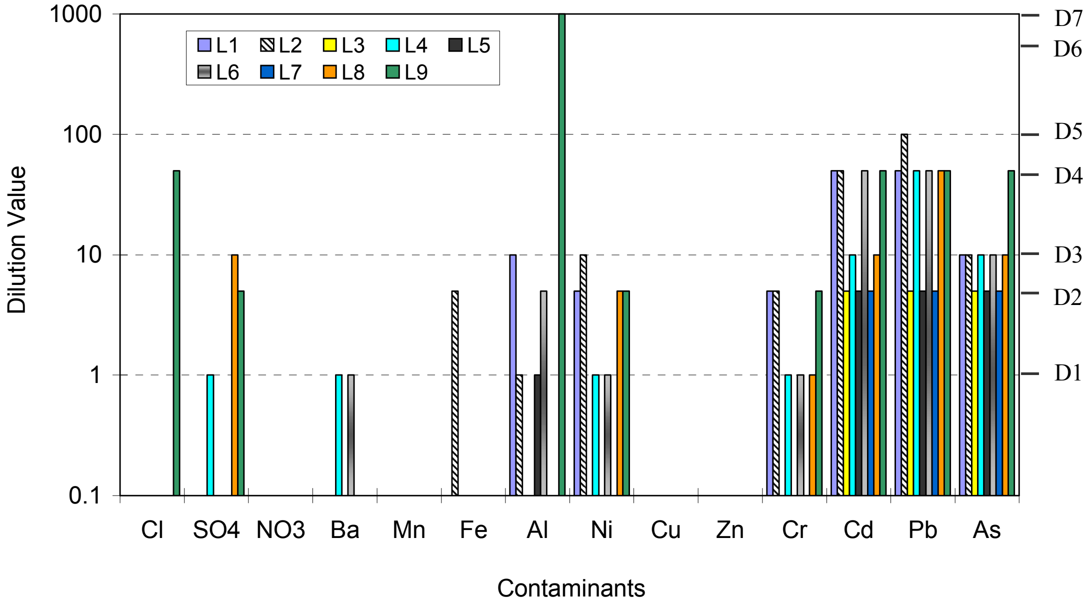


Fig. 5.19 Ranges of water required to dilute contaminants in outflow from side drains to WQS (R2). Values are for a 1 m half-pavement section

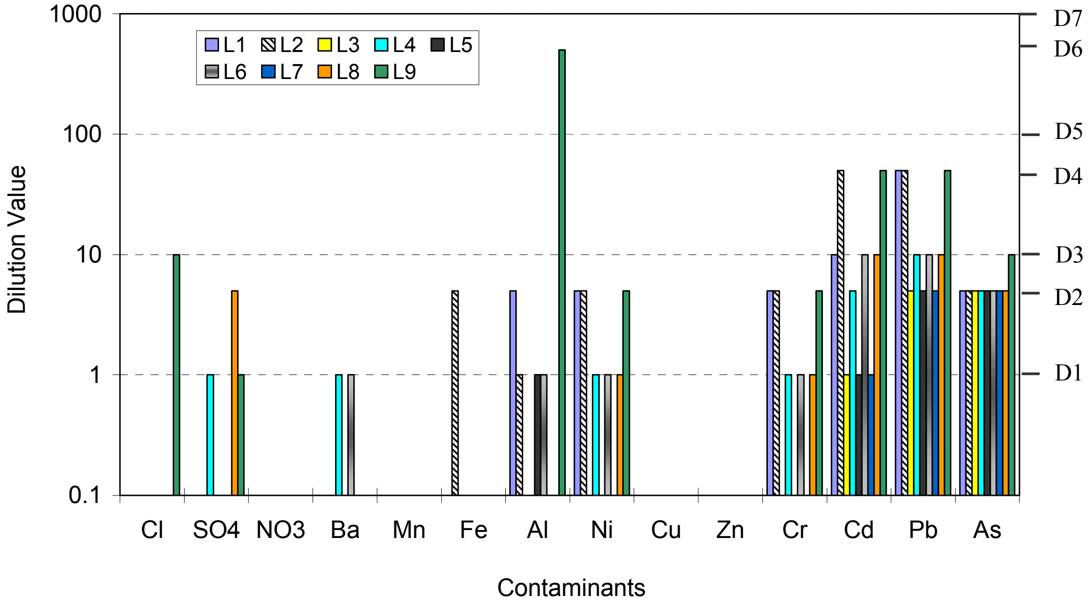


Fig. 5.20 Ranges of water required to dilute contaminants in outflow from side drains to WQS (R3). Values are for a 1 m half-pavement section

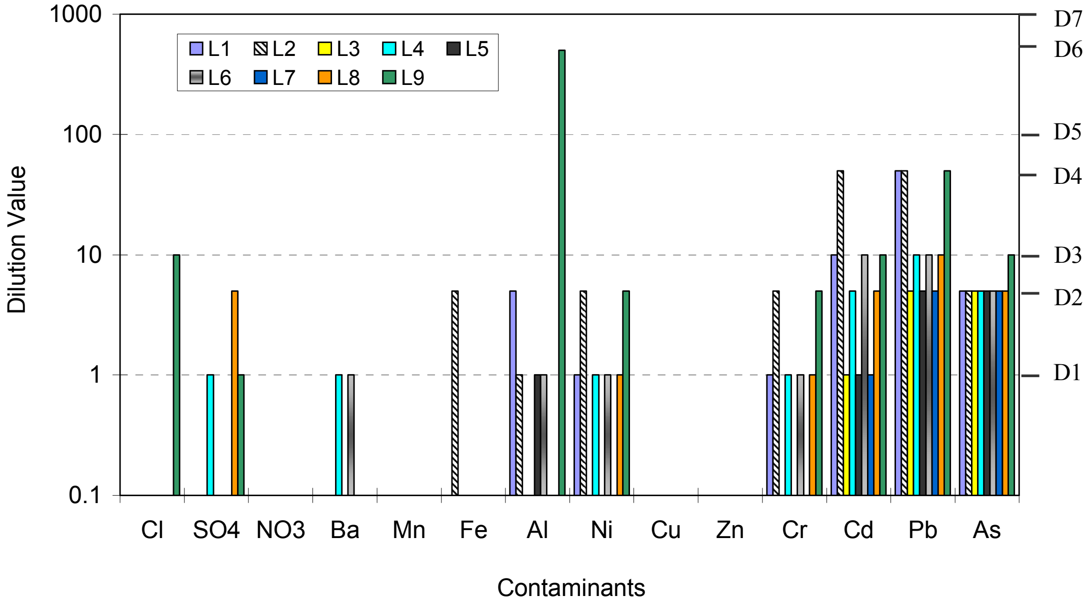


Fig. 5.21 Ranges of water required to dilute contaminants in outflow from side drains to WQS (R4). Values are for a 1 m half-pavement section

It can be seen from Figs. 5.18 to 5.21 that the majority of chemical species are allocated dilution classes of D≤D3, representing actual requirements of v≤10 l/h of water (from Table 5.8), for a 1 m half-pavement section. Lysimeter 9 (MSW incinerator ash) requires greatest quantities of water for aluminium, where at R2 it is designated dilution class D7 (equivalent to actual requirements of v>500 l/h), for a 1 m half-pavement section. When calculating the amount of water required for diluting contaminant levels for each lysimeter aggregate, quantities have been based upon the contaminant in each lysimeter aggregate requiring the maximum amount of water. From the calculations, the maximum dilution class for each lysimeter aggregate for the four rainfall events is summarised in Table 5.9.

Table 5.9 Summary of dilution classes necessary to dilute contaminants in each lysimeter for the four rainfall events, based upon the contaminant in each lysimeter requiring the maximum quantity of water for dilution. Values are for a 1 m half-pavement section

Lysimeter	**Rainfall Events**			
	R1	**R2**	**R3**	**R4**
	Dilution Class			
1	D3	D4	D4	D4
2	D4	D5	D4	D4
3	D2	D2	D2	D2
4	D2	D4	D3	D3
5	D2	D2	D2	D2
6	D2	D4	D3	D3
7	D2	D2	D2	D2
8	D2	D4	D3	D3
9	D6	D7	D6	D6

Aggregate: 1=china clay sand + cement + cement kiln dust, 2=foundry sand (alkali phenolic), 3=crumbed rubber (2-8 mm), 4=BFS + granulated BFS + lime, 5=MSW incinerator ash + bitumen, 6=lean mix (limestone + cement), 7=limestone, 8=BFS, 9=MSW incinerator ash.

It can be seen that of the four rainfall events, R2 has the highest dilution class because it is the highest hourly rainfall (Table 5.7). As previously discussed, highest rainfalls produce highest discharge drainage and consequently highest masses of contaminants.

The maximum rainfall in the calculations (R2) has been compared with rainfall events for the UK, Scotland, N. Ireland and Wales over a five-year period, as previously presented in Chapter 3, Fig. 3.2 (Inst. of Hydrology, 1993 to 1997). This is in order to compare R2 with maximum rainfalls over varied geographic locations. From Fig. 3.2, it can be seen that the greatest rainfalls occurred in Scotland, with the maximum hourly rainfall intensity being 0.41 mm/h during a January, and with 80% of values being below 0.35 mm/h. The second greatest rainfall was for Wales, with the maximum monthly rainfall being 0.37 mm/h during a December. Because these maximum values exceed the maximum rainfall for R2, another category of rainfall being >0.28 mm/h has been added to the rainfall events already modelled (new category R5). Dilution classes for this new R5 category of rainfalls (>0.28 mm/h) have been determined. Because the greatest dilution values are required at R2, it has been considered justifiable to determine the dilution class for R5 by increasing the dilution class for each lysimeter for R2 to the next dilution class upwards to the maximum dilution class of D7 (from Table 5.9). This has been considered justifiable, because from Table 5.9 it can be seen that *when* dilution classes are greater for R2 than for the other rainfall events for each lysimeter, they exceed the next highest dilution classes by one order of magnitude (the next dilution class upwards). The new dilution classes for R5 are illustrated in Table 5.10.

Table 5.10 Dilution classes allocated to rainfall events >0.28 mm/h (R5) determined from those for R2. Values are based upon for a 1 m half-pavement section

Lysimeter	**Dilution Classes for R2**	**Dilution Classes for Rainfall Events >0.28 mm/h (R5)**
1	D4	D5
2	D5	D6
3	D2	D3
4	D4	D5
5	D2	D3
6	D4	D5
7	D2	D3
8	D4	D5
9	D7	D7

Aggregate: 1=china clay sand + cement + cement kiln dust, 2=foundry sand (alkali phenolic), 3=crumbed rubber (2-8 mm), 4=BFS + granulated BFS + lime, 5=MSW incinerator ash + bitumen, 6=lean mix (limestone + cement), 7=limestone, 8=BFS, 9=MSW incinerator ash.

From Table 5.9 it is evident that the dilution classes required to dilute contaminant levels to WQS are the same for R3 and R4 rainfall events. This is because the actual quantities of water required for dilution have been rounded up in order to form the dilution values and subsequent dilution classes. In order to present the rainfall events in a format acceptable for use by a contractor, the rainfalls for each of the rainfall events (R1 to R5) have been incorporated into a format to give ranges of rainfall, rather than the R categories used until now. Because the dilution classes are the same for R3 and R4 rainfall events (from Table 5.9), their corresponding maximum rainfalls (Table 5.7) have been incorporated into the same new rainfall range category. The new rainfall range categories can be seen in Table 5.11. The new category for rainfalls >0.28 mm/h (R5) is included.

Table 5.11 Old rainfall events incorporated into new rainfall ranges

Old R Values (from Table 5.7)			
Rainfall Event	**Max. Rainfall (mm/h)**	**New Rainfall Ranges (mm/h)**	**Determined from Old R Value**
R1	0.07	≤0.07	R1
R2	0.28	>0.07-0.15	R3 and R4
R3	0.15	>0.15-0.28	R2
R4	0.13	>0.28	New Category R5

To enable a contractor to assess the suitability of a potential construction site according to regional rainfall, the new rainfall categories presented in Table 5.11 have been combined with the dilution classes for rainfall events presented in Tables 5.9 and 5.10. Combined they give dilution classes for ranges of rainfall and can be seen in Table 5.12.

Table 5.12 Dilution classes for proposed aggregate at corresponding mean site rainfall. Values are for a 1 m half-pavement section

Aggregate	**Mean Site Rainfall (mm/h)**			
	≤0.07	**>0.07-0.15**	**>0.15-0.28**	**>0.28**
	Dilution Class			
1. China clay sand + cement + cement kiln dust	D3	D4	D4	D5
2. Foundry sand (alkali phenolic)	D4	D4	D5	D6
3. Crumbed rubber (2-8 mm)	D2	D2	D2	D3
4. BFS + granulated BFS + lime	D2	D3	D4	D5
5. MSW incinerator ash + bitumen	D2	D2	D2	D3
6. Lean mix (limestone + cement)	D2	D3	D4	D5
7. Limestone	D2	D2	D2	D3
8. BFS	D2	D3	D4	D5
9. MSW incinerator ash	D6	D6	D7	D7

It should be noted that even limestone, an apparently inert aggregate, requires dilution before WQS may be achieved. In reality, however, it is unlikely that this natural aggregate, with a long history of use in construction industries, would ever be deemed unsuitable for use. Again the important fact that these values are worst-case scenarios must be noted, where these situations would only occur at the heaviest point in a rainfall event after maintenance level surface cracking is reached. In reality, for most of the life of the pavement the dilution values and classes will be far less than these and for most of the time it is likely that limestone (as well as others in the table) will easily be diluted by runoff such that the discharge water has concentrations of contaminants below WQS.

Within the risk assessment guide that has been developed, in order to assess an aggregate at a potential construction site according to regional rainfall, a contractor must undertake chemical analysis of the aggregate to determine its contamination potential. The approach that has been developed has been to allocate contamination classes for the percentages by which concentrations of contaminants exceed WQS, and the classes can be seen in Table 5.13 (where the relevant WQS can be seen in Appendix 3). The method behind the classification of contamination classes is presented below.

Table 5.13 Contaminant classification (contamination classes) giving percentages by which contaminant concentrations exceed relevant WQS

Contamination Class	Percentages by which Contaminants Exceed WQS (%)	Contaminant Concentration/WQS
C0	0	<1
C1	>0-10	1-1.1
C2	>10-100	>1.1-2
C3	>100-500	>2-6
C4	>500-800	>6-9
C5	>800-2000	>9-21
C6	>2000-10000	>21-101
C7	>10000	>101

For each of the nine lysimeters aggregates, contamination classes have been determined for those contaminants that exceed WQS and are presented in Table 5.14.

Table 5.14 Quantification of the percentage by which contaminants exceed WQS using contamination classes (empty cells indicate that contamination is within WQS)

Lysimeter	Contamination Classes for the Contaminants Assessed													
	Cl	SO_4	NO_3	Ba	Mn	Fe	Al	Ni	Cu	Zn	Cr	Cd	Pb	As
1							C4	C3			C3	C5	C4	C4
2						C3	C2	C3			C3	C6	C6	C4
3												C3	C3	C3
4		C2		C1				C2			C2	C4	C5	C4
5							C2					C3	C3	C3
6				C2			C3					C5	C5	C3
7												C3	C3	C3
8		C4						C2			C2	C4	C5	C4
9	C5	C3					C7	C3			C3	C5	C6	C5
Aggregate: 1=china clay sand + cement + cement kiln dust, 2=foundry sand (alkali phenolic), 3=crumbed rubber (2-8 mm), 4=BFS + granulated BFS + lime, 5=MSW incinerator ash + bitumen, 6=lean mix (limestone + cement), 7=limestone, 8=BFS, 9=MSW incinerator ash.														

It can be seen from Table 5.14 that some contaminants in each aggregate do not exceed WQS, but all the aggregates require dilution for some of the contaminants. The highest contamination class for each aggregate can be seen in Table 5.15.

Table 5.15 Highest class of contamination for each aggregate mix

Aggregate	Highest Contamination Class
1. China clay sand + cement + cement kiln dust	**C5**
2. Foundry sand (alkali phenolic)	**C6**
3. Crumbed rubber (2-8 mm)	**C3**
4. BFS + granulated BFS + lime	**C5**
5. MSW incinerator ash + bitumen	**C3**
6. Lean mix (limestone + cement)	**C5**
7. Limestone	**C3**
8. BFS	**C5**
9. MSW incinerator ash	**C7**

The method that has been used to develop the classification of contamination classes becomes evident when comparing Table 5.12 with Table 5.15. It may be seen that the aggregates allocated the same dilution classes for the greatest rainfall event (>0.28 mm/h) as seen in Table 5.12, are also allocated the same contamination classes, as seen in Table 5.15.

Dilution classes (Table 5.8) have been matched with contamination classes (Table 5.13) and can be seen in Table 5.16.

Table 5.16 Matching of contamination classes with dilution classes

Contamination Class	Dilution Class
C0	D0
C1	D1
C2	D2
C3	D3
C4	D4
C5	D5
C6	D6
C7	D7

In order to match contamination classes with dilution classes presented for the aggregates at different rainfall events, the information within Tables 5.12 and 5.15 have been combined to form Table 5.17. Initially, contamination classes have been matched with dilution classes (as presented in Table 5.16), where the dilution classes have been taken to represent the greatest rainfall event (>28 mm/hr in Table 5.12). As previously outlined, the aggregates allocated the same dilution classes for the greatest rainfall event (Table 5.12) also have with the same contamination class (Table 5.15) and these can be see within Table 5.17. The allocation of dilution classes for the lesser rainfall events can also be seen.

Table 5.17 Dilution classes for contamination classes for mean local annual rainfall

Lysimeters with Same Dilution Classes for Rainfalls >0.28 mm/h	**Highest Contamination Class**	**Mean Local Annual Rainfall (mm/h)**			
		<0.07	**>0.07-0.15**	**>0.15-0.28**	**>0.28**
		Dilution Classes for Contamination Classes (Obtained by Combining Tables 5.12 and 5.15) for a 1 m Half-Pavement Section			
	C0	D0	D0	D0	D0
	C1	D0	D0	D1	D1
	C2	D1	D1	D2	D2
3,5,7	**C3**	D2	D2	D2	D3
	C4	D3	D3	D4	D4
1,4,6,8	**C5**	D3	D4	D4	D5
2	**C6**	D4	D4	D5	D6
9	**C7**	D6	D6	D7	D7

Aggregate: 1=china clay sand + cement + cement kiln dust, 2=foundry sand (alkali phenolic), 3=crumbed rubber (2-8 mm), 4=BFS + granulated BFS + lime, 5=MSW incinerator ash + bitumen, 6=lean mix (limestone + cement), 7=limestone, 8=BFS, 9=MSW incinerator ash.

The method used to match dilution classes for the lesser rainfall events can be seen by referring to Table 5.12. From Table 5.12, it can be seen that for aggregates 3, 5 and 7 (contamination class C3 in Table 5.15), all aggregates in that class are allocated the same dilution classes for all the rainfall events (in Table 5.12) and these have been entered directly into Table 5.17. From Table 5.12, however, aggregate 1 has been allocated greater dilution classes for the lowest two rainfall events than aggregates 4, 6 and 8 (contamination class C5 in Table 5.15). Due to the fact that the risk assessment guide is based upon worst-case scenarios, the greater dilution classes for aggregate 1 have been selected as the classes that have been entered into Table 5.17. For aggregates 2 and 9 that have been allocated dilution classes that do not correspond with other aggregates (contamination classes 6 and 7 in Table 5.15), the dilution classes from Table 5.12 have been entered directly into Table 5.17. For the contamination classes with no corresponding aggregates in Table 5.17 (contamination classes C0, C1, C2 and C4) dilution classes have been selected which follow the generalised pattern of the other dilution classes. This means that for contamination classes C1, C2 and C4 the two highest rainfall events have been allocated the same dilution classes and the lowest two rainfall events have been allocated a dilution class reduced by one class. Contamination class C0 has been allocated dilution class D0 for all rainfall events.

5.3.4.1.2 Dilution According to Site Sensitivity

Consideration has been given to the information in Table 5.17 in order to present it in a format required within a risk assessment document. A risk assessment document is usually presented in a format to reflect site sensitivity. This is exemplified in Marsland and Carey (1999), who state that an assessment and action should reflect sensitivity of the receptor. Examples given by the authors regarding the location of a site which are relevant to the research described here, include its location to different designated aquifers (e.g. major, minor or non-aquifer), the use of the groundwater resource (e.g. potable water), the groundwater protection status of the site (e.g. an inner or outer Source Protection Zone) and existing surface or groundwater quality (Marsland and Carey, 1999). In order to present Table 5.17 in a format to reflect site sensitivity, site sensitivity has been presented in three site sensitivity classes which can be seen in Table 5.18. The level of sensitivity presented at each of the three sites reflects the classification of strata for groundwater protection by the EA (1998).

Table 5.18 Site sensitivity classes (*classification by EA, 1998)

Site Sensitivity Class	**Site Sensitivity Parameters**	
S1	Highly sensitive site	*Major aquifer or source protection zone. Highly productive strata of regional importance, often used for large potable abstractions. Background contamination below WQS.
S2	Sensitive site	*Minor aquifer or source protection zone. Variably porous/permeable strata, but without significant fracturing. Generally only supports locally important abstractions. Background contamination below WQS.
S3	Less-sensitive site	*Non-aquifer. Negligible permeability. Only supports very minor abstraction, if any. Background contamination may exceed WQS.

In order to allow the selection of dilution classes to reflect site sensitivity, the dilution classes presented in Table 5.17 have been linked to the two sites of greatest sensitivity, S1 and S2. It is anticipated that at sites of lesser sensitivity (S3), site-specific WQS will be in place rather than the 'normal' generic ones commonly used. The dilution classes have consequently been reduced by one class for site sensitivity S3 to reflect this, and the new dilution classes can be seen in Table 5.19. A detailed explanation for this adaptation is given in Chapter 6, Section 6.3.4.1.

Table 5.19 Dilution required for classes of contamination for mean local annual rainfall according to site sensitivity (taken from Table 5.21)

		Mean Local Annual Rainfall (mm/h)			
		<0.07	**>0.07-0.15**	**>0.15-0.28**	**>0.28**
Highest Contamination Class	**Site Sensitivity Class**	**Dilution Class for Half Pavement Section Required for Highest Contamination Class According to Site Rainfall**			
C0	**S1,S2,S3**	D0	D0	D0	D0
C1	**S1,S2**	D0	D0	D1	D1
	S3	D0	D0	D0	D0
C2	**S1,S2**	D1	D1	D2	D2
	S3	D0	D0	D1	D1
C3	**S1,S2**	D2	D2	D2	D3
	S3	D1	D1	D1	D2
C4	**S1,S2**	D3	D3	D4	D4
	S3	D2	D2	D3	D3
C5	**S1,S2**	D3	D4	D4	D5
	S3	D2	D3	D3	D4
C6	**S1,S2**	D4	D4	D5	D6
	S3	D3	D3	D4	D5
C7	**S1,S2**	D6	D6	D7	D7
	S3	D5	D5	D6	D6

Table 5.19 has been presented based upon contamination classes and not the lysimeter aggregates as presented in Table 5.17. This ensures that providing chemical analysis of an aggregate under review is undertaken prior to use and site sensitivity and mean annual rainfall is determined, any aggregate (alternative or traditional) can be assessed. From Table 5.19 it can be seen that for the aggregates assessed within this research, the maximum dilution requirements are for contamination class C7 aggregates at S1 and S2 sites (includes aggregate 9), which require 1000 l/h for a 1 m half-pavement section for the greatest two rainfalls. For a 200 m length of pavement the dilution requirement will be 400,000 l/h.

Due to the protection of sites of higher sensitivity (S1 and S2 from Table 5.18), it is unlikely that any form of dilution will be acceptable at those sites. It is anticipated, however, that some leniency in the enforcement of water protection (i.e. the dilution of raised contaminant levels by surface runoff) will be acceptable at S3 sites alone. The suitability of surface runoff providing the quantities of water required to dilute contaminants at S3 sites is assessed below.

5.3.4.1.3 Dilution by Surface Runoff

An analysis of surface runoff as a source of water by which to dilute contaminant concentrations is undertaken below in order to assess whether sufficient is potentially available in order to meet requirements as presented in Table 5.19 at S3 sites.

Two important adverse factors are evident, however. Firstly, an immediate problem with using surface runoff as a source for dilution is the fact that the runoff may itself contain contaminants. Research undertaken by Luker and Montague (1997) describe pollutants in highway runoff. The contaminants listed which are relevant to this research include chloride, sulphate, nitrate, manganese, iron, nickel, copper, zinc, chromium, cadmium, lead and arsenic. Quantities of the above will be washed off pavement surfaces by runoff and will vary according to factors including weather. These will include raised chloride concentrations in winter due to salting of pavements and local micro-climate that influence precipitation and evaporation rates during dry periods. 'First flush' effects describe the first runoff generated by a storm carrying unusually high contaminant loading after contaminants have accumulated during previous dry periods. In the case of sediment particles, they may have accumulated in the drainage system after previous runoff events (Luker and Montague, 1997). A comparison may be undertaken for concentrations of contaminants detected in runoff from two motorways. One is from a study on a section of the MI, 56 km NW of London, UK (Colwill, et al., 1984) and the other of the northern bypass of Nantes, France (Legret and Pagotto, 1999) and data may be seen in Table 5.20. Mean contaminant concentrations for the nine lysimeter aggregates (Hill, 2000) are included for comparison.

Table 5.20 Concentrations of contaminants in motorway runoff ([1]Colwill, et al., 1984; [2]Legret and Pagotto, 1999) compared with mean values determined in drainage from the nine lysimeters ([3]Hill, 2000)

Contaminant	[1]	[2] **Raw Waters**	[2] **Filtered Waters**	[3]
	Levels of Contaminants (mg/l)			
Chloride	1-11	n/a	388	366
Sulphate	n/a	n/a	54	340
Nitrate	n/a	n/a	5.8	6
Nickel	0.036-1.55	n/a	n/a	0.042
Copper	0.007-0.03	0.045	0.025	0.407
Zinc	0.12-4	0.356	0.222	0.277
Chromium	0.018-0.085	n/a	n/a	0.086
Cadmium	<0.003-0.1	0.001	0.00053	0.028
Lead	0.1-8	0.058	0.0039	0.166

n/a=not available

From Table 5.20 it can be seen that for nickel, zinc, cadmium and lead on some occasions runoff may contain higher contaminant concentrations than in some of the lysimeters, whereby dilution by the runoff would not be possible. In periods of higher rainfalls, however, it is anticipated that the contamination concentrations would be more diluted due to the greater quantities of available water as runoff. The concentrations presented from Hill (2000) are, however, mean values from all nine lysimeter aggregates and concentrations from aggregates with lower contamination levels are significantly less.

When considering using runoff as a form of dilutant, larger quantities of water will be required to dilute levels of contaminants back to WQS for some contaminants than computations show. This will be to compensate for the additional contaminant loading from the runoff itself.

Secondly, another problem is that the quantity of surface runoff available for dilution will be rainfall and season-dependent. In dryer periods there will be reduced flows of water and in warm weather surface evaporation will again result in reduced flows. In periods of excessive rainfall, infiltration will reach its maximum rate whilst excessive runoff will provide larger quantities of water for dilution. In periods of reduced rainfall, however, a greater proportion of water will seep into the pavement leaving less behind to act as a dilutant.

In order to quantify runoff so as to assess availability with demand, calculations given by Luker and Montague (1997) have been adapted. They give an annual collectable amount of 500 mm of rainfall from rain falling on highways in eastern England, as potential runoff from impermeable highways in chalk areas. This has been done to determine quantities of water available as a source of recharge into chalk. Although based on a small geographical area, this equates to a potential annual runoff of 500 l/m^2. This is equivalent to 0.06 $l/h/m^2$ or 0.28 l/h for a 1 m half-pavement section. For a 200 m length of pavement this gives an available rate of 112 l/h. From Table 5.19 it is evident that the available runoff of 0.28 l/h is insufficient to dilute contaminants for many of the aggregates.

5.3.4.1.4 Acceptable Levels of Surface Cracking

If at this point it is assumed that only D0 dilution class is acceptable, from Table 5.19 it is evident that when pavement surface cracking reaches maintenance levels, only contamination class C0 aggregates and contamination class C1 aggregates for the lowest two rainfall events, are acceptable at S1, S2 sites. The other contamination class aggregates (contamination classes C2 to C7) are unacceptable at all S1 and S2 sites. Contamination class C0 and C1 aggregates and C2 aggregates for the lowest two rainfall events, are acceptable at S3 sites. The other contamination class aggregates (contamination classes C3 to C7) are unacceptable at all S3 sites. This ultimately limits the use of many alternative aggregates at potential construction sites if surface cracking is likely to reach maintenance levels. It is important, therefore, to determine levels of cracking at which point subsequent drainage is below WQS for S1 and S2 sites and where surface runoff is sufficient to dilute contaminants to WQS at S3 sites. This importance of this is that, consequently, it would make the use of alternative materials more widely acceptable in a greater number of construction scenarios. The method used to determine the variations in contaminant concentrations in drainage resulting from different levels of surface cracking, as well as the method used by which to quantify the amount of potential runoff available for the four rainfall ranges, is detailed in Chapter 6, Section 6.3.4.1.

5.4 Summary of Results

Vertical flows: within this chapter it is evident that in vertical flows a site assessment should be undertaken. This will enable the suitability of a site to be determined, based upon the in-situ subgrade permeability and the depth to the water table. Sorption of contaminants from contaminated water to the subgrade is through partitioning and modelling has indicated that only low permeability clay subgrades have sufficiently low k values to enable sorption to reach equilibrium.

Ranges of published K_d values are presented in Chapter 3. The only one in ConSim (Golder Associates, 1998) (see Chapter 3, Table 3.5) where $K_d<10^0$ l/kg is for chromium at $K_d=9\times10^{-2}$ l/kg. Other known values in the table range from 10^0 to 10^5 l/kg. Within this research, most computations have been based upon a K_d value of $K_d=0.5$ l/kg. Calculations using $K_d=10$ l/kg give output concentration at the 100th computational layer (water table level) of 2.09×10^{-196} mg/l for an input concentration of 5 mg/l, indicating how effective partitioning is, even at this relatively low value.

Recommendations for aggregate-use in the risk assessment guide are presented in Chapter 6, based upon the correct combinations of subgrade k values and depths to the water table, where an allowance is made for site sensitivity. Breakthrough times are given for $K_d=0.5$ l/kg as well as predicted flow times for larger K_d values. The breakthrough times for the larger K_d values exceed those for $K_d=0.5$ l/kg by an enormous magnitude. An important conclusion resulting from this is that providing the contaminants within an aggregate have minimum K_d values similar to those presented in Chapter 6, there is absolutely no chance of any contamination reaching the water table in vertical flow within 40 years (the average expected life of a pavement).

If the parameters at a site (e.g. subgrade k value and depth to the water table) are found to be unacceptable (the residence time per computational layer is less than the 16 days, or the total breakthrough time is less than 40 years), the use of a GCL is recommended. A GCL will allow further sorption by partitioning onto its clay particles providing the correct combination of GCL k value and thickness is present.

Horizontal flows: calculations for horizontal flow rates have been matched with rainfall events in order to determine quantities of water required to dilute contaminants to WQS. Due to excessive costs of piping water to construction sites, the most feasible option would be to use surface runoff as a source of dilutant. This would only be acceptable, however, at sites of lower sensitivity, where in this research they have been designated as S3 sites. No treatment of contaminated water by dilution from runoff at the more sensitive S1 and S2 sites would be acceptable (see Table 5.18 for site sensitivity classifications). It has been demonstrated that when surface cracking is at maintenance level, which is the point when the greatest infiltration of rainfall occurs, quantities of water generated by surface runoff in the example previously given will be insufficient to dilute contaminants to WQS at S3 sites for all the aggregates assessed here. This limits the potential use of alternative materials when surface cracking is likely to reach maintenance levels. Because of this, the risk assessment guide has been developed to illustrate the fact that surface runoff *will* be sufficient to dilute contaminants to WQS for some contamination classes at S3 sites for some rainfall events *even* at maintenance level surface cracking and, to a greater extent, when surface cracking is maintained below the 'normal' level. The method by which the risk assessment guide has been developed through calculations and modelling is presented in Chapter 6.

6 Risk Assessment Guide

6.1 History

Early in the life of the research, Britpave (The British In-situ Concrete Paving Association) became a financial contributor, and the research became a focus for their Environmental Task Group. This industrial collaboration was initiated because an input other than from academia was considered a positive move in order to gain feedback from contractors using alternative construction aggregates. It became evident through discussions with Britpave members that a user-friendly industrially relevant risk assessment guide against which pavement construction aggregates could be assessed prior to use was lacking. Such a guide would, however, be considered a valuable contribution to the industry. A guide should be capable of assessing traditional as well as alternative construction aggregates. The usefulness of such a guide should:

(1) provide contractors with a generic guide to assess the suitability of a potential construction aggregate at a site under review, without having to undertake full-scale lysimeter tests, and

(2) prevent having to implement costly clean-up procedures after construction aggregates are inappropriately used.

6.2 Justification/Need for New Method

As discussed in Chapter 1, there are few guidelines currently available for pavement contractors when determining the suitability of alternative aggregates in different construction scenarios. Most guidelines (if available at all) assess an aggregate's ability to meet mechanical criteria rather than their potential to contaminate water bodies. The recommended standard leaching tests which are available do not use aggregates in the same forms as they are used in pavement construction (CEN, 1996). It is difficult, therefore, to relate results to real-pavement scenarios. It was this lack of available guidelines for contractors and a consequent need for a new method for assessing alternative aggregates in pavement construction, which led to the development of the risk assessment guide within this research.

The factors selected as a basis for the risk assessment guide are presented in Table 6.1. These factors have been selected as they are considered to be the important pathways when assessing risks from using alternative materials in pavement construction and can be summarised in three phases:

(1) water entering the pavement,

(2) water flowing through the pavement profile, and

(3) water discharging from the pavement profile.

The reasons behind the selection of the pathways assessed and the justification for the elimination of other ones are discussed in Chapter 1. A further justification for selecting the important factors is given below.

Table 6.1 Main sections contributing to risk assessment guide together with relevant sub-sections

SITE ASSESSMENT
A. Infiltration Through Surface Cracks
i. Local Rainfall Determining Water Flows
B. Aggregate Assessment
i. Aggregate
1. China clay sand + cement + cement kiln dust
2. Foundry sand (alkali phenolic)
3. Crumbed rubber (2-8 mm)
4. BFS + granulated BFS + lime
5. MSW incinerator ash + bitumen
6. Lean mix (limestone + cement)
7. Limestone (Type 1)
8. BFS
9. MSW incinerator ash
ii. Contaminant Concentrations
C. Vertical Flow of Contaminants Below Pavement
i. Clay Subgrade ($k \leq 10^{-10}$ m/s)
1. Depth of subgrade to water table
2. GCL
ii. Clay Subgrades ($k > 10^{-10}$ m/s) or Other Subgrade
1. GCL
D. Horizontal Flow of Contaminants Through Aggregate With Discharge From Side Drains
i. Contaminant Release From Side Drains
1. Quantity of water and contaminants discharged
2. Dilution of contaminant levels by surface runoff

6.2.1 Justification

(A) Infiltration Through Surface Cracks: all flows within pavements have been taken to be dependent upon infiltration of water through surface cracks. The importance of this infiltration is that it will determine the amount of water within a pavement profile available for the transportation of contaminants. An assessment of infiltration rates was undertaken and is described in Chapter 3.

(i) Local Rainfall Determining Water Flows: the infiltration rate will be dependent on local rainfall assuming surface cracking is great enough to facilitate it. This should only occur after several years in the life of a pavement, when surface cracking develops. In Chapter 3 results of infiltration testing within this research are described, where a mean infiltration rate of 3.33 l/h/m^2 has been determined. Because of this, it has been considered justifiable to consider all rainfall below 3.33 mm/h to have the potential to infiltrate through surface cracks when maintenance level cracking occurs, although heavy rainfalls may exceed infiltration rates for short periods of time. The quantity of water that infiltrates through surface cracks determines the quantity of available water within a pavement.

(B) Aggregate Assessment:

(i) Aggregate*:* aggregates which have been assessed are those presented in Hill and Dawson (2000). They have been selected because firstly, data has been readily available from the previous project and secondly, they represent a selection of alternative aggregates available for use as construction aggregates. In addition limestone (a traditional aggregate) has been included to act as a control, and

(ii) Contaminant Concentrations*:* it has been considered justifiable to consider water within a pavement to be fully concentrated with contaminants. This represents a worst-case scenario, because in some circumstances the water may not actually be in contact with the aggregate for sufficient time for this to occur. Basing calculations on worst-case scenarios allows for a maximum potential for contaminated water to exceed WQS.

(C) Vertical Flow of Contaminants Below Pavement: vertical flow through subgrades has been considered important because contaminated water will eventually reach the groundwater below. The rate at which it will reach the groundwater will be dependent on the permeability of the subgrade material at a construction site. This has been considered justifiable, because calculations show that sorption through partitioning removes contaminants sufficiently to render the resultant flow reaching the water table with contaminants in concentrations below WQS, providing the flow rate is sufficiently low to allow sorption to reach equilibrium.

For vertical flows the parameters of the site (e.g. subgrade k value and depth to groundwater) are more important than the chemistry of the contaminants. This is because if the recommended parameters are present at a site under review, any contaminants in the water flow will be sorbed onto the subgrade sufficiently so that the resultant concentrations in the flow at the water table level will be below WQS. It has been considered that the important parameters in vertical flow are:

(i) Clay Subgrade ($k \leq 10^{-10}$ m/s)

(1) depth of subgrade below pavement to water table, and

(2) GCL use.

(ii) Clay Subgrades ($k > 10^{-10}$ m/s) or Other Subgrade

(1) GCL use.

In Chapters 3 and 5 flow times for different subgrade k values and depths to the water table are presented. In this chapter subgrade k values are divided into two, being $k \leq 10^{-10}$ m/s and $k > 10^{-10}$ m/s. This is because modelling has determined that sorption of contaminants onto soil particles by partitioning will reach equilibrium when subgrades have a permeability of $k \leq 10^{-10}$ m/s (determined for a range of subgrade depths), because the flow times are sufficient to allow 16 days residence times per computational layer. Providing the correct combinations of k values and depths to the water table are present, this will result in flows reaching the water table with contaminants in concentrations below WQS. When subgrades have k values of $k > 10^{-10}$ m/s, sorption will not reach equilibrium due to faster flow rates (and consequently lower residence times). This then results in flows reaching the water table with contaminants in concentrations greater than WQS. Sorption of contaminants by partitioning has been modelled mainly using a K_d value of $K_d = 0.5$ l/kg. As a result, breakthrough times for contaminants reaching the water have been determined. In Chapter 3, Table 3.5 most listed K_d values for contaminants in clay subgrades have values of $K_d > 0.5$ l/kg where, for example, the average value for zinc is $K_d = 2400$ l/kg (Sheppard and Thibault, 1990). Predicted breakthrough times for contaminants reaching the water table with greater K_d values than those modelled so far have been determined and the method for doing this is presented below, along with way by which recommendations in the risk assessment guide have been developed to allow for these predicted times.

When subgrades have either k values too great or depths too shallow to allow sorption to reach equilibrium, GCLs are recommended to extend flow times and allow further sorption by partitioning to occur. If in the risk assessment guide the site subgrade does not comply with the required combinations of k value and depth to the water table, recommendations regarding the correct combinations of a GCL k value and thickness are then presented.

(D) Horizontal Flow of Contaminants Through Aggregate With Discharge From Side Drains: horizontal flow through construction aggregates has been considered important because large quantities of contaminated water have the potential to be discharged through pavement side drains. If uncontrolled, the discharges may either enter surface ditches or surface waters or may flow vertically through surrounding subgrades towards groundwater below. It has been considered that the important factors in horizontal flow are:

(i) Contaminant Release from Side Drains

(1) quantity of water and contaminants discharged. The k value of a construction aggregate under review will be one of the factors which will determine the rate of flow and quantity of water discharged. In Chapters 3 and 5 results from modelling horizontal flows for different aggregate k values are given. A method has been presented for determining minimum aggregate saturation levels (McEnroe, 1994). When an aggregate has a k value of $k \leq 3x10^{-6}$ m/s no drainage occurs at all. From a combination of the quantity of water discharged per hour and the concentration of contaminants (Hill and Dawson, 2000) the quantity of contaminants released into the side drain per hour is readily determined, and

(2) dilution of contaminant levels by surface runoff. In Chapter 5 a method by which to determine quantities of water required to dilute levels of contaminants to WQS is presented. This would only be acceptable at sites of lower sensitivity (designated S3 sites), where surface runoff would be the only financially viable source of such water.

6.3 Development of the Risk Assessment Guide

The development of the risk assessment guide is given below. This includes the principles by which research data has been transformed into a document ready for use. Each of the sections presented within Table 6.1 is described in order. An example using the risk assessment guide is presented further on, whilst the risk assessment guide as a complete document may be found in Appendix 6.

6.3.1 Infiltration Through Surface Cracks

As described in Chapter 3, surface cracking has been assessed according to two types of surface distress identification, taken from SHRP (1993). The two types of cracking have been:

(1) surface distress cracking where an area of pavement surface is distressed with either 'alligator-type' cracking or ravelling, called 'alligator-type' cracking from this point on in the risk assessment guide, and

(2) linear cracking or patch junction on an otherwise intact pavement surface, called 'longitudinal cracking' from this point on in the risk assessment guide.

Field work for both types of surface cracking is described in Chapter 3. For the former type of surface cracking infiltration rates have been simply extrapolated to 1 m^2, and for the latter the infiltration rates have been equivalenced to that due to 10% longitudinal cracking, which is the maintenance level for surfacing cracking according to Baldwin, et al. (1997). The method which has been used to base this equivalency is given later in Section 6.3.4.1. A method which has been used to match 100% alligator-type cracking with 10% longitudinal cracking is also given later. Infiltration rates were similar for both types of cracking and the determined mean rate of 3.33 $l/h/m^2$ has been taken in this research as the maximum infiltration rates when surface cracking reaches maintenance levels. Such a condition would only occur after several years' wear, if resurfacing/surface dressings are not undertaken.

6.3.1.1 Local Rainfall Determining Water Flows

The amount of rain available to infiltrate through surface cracks will depend on local rainfall at a potential construction site. In order to simulate different rainfall events for calculations, four rainfall events referred to as R1 to R4, have been used. The basis for the selection of these four rainfall events is presented in Chapter 5, where the actual amount of rain within each event is shown in Table 5.6. A fifth rainfall event (R5) has been deemed necessary and can also be seen in Chapter 5, where R1-R5 are finally combined into four actual rainfall values for use in the risk assessment guide.

6.3.2 Aggregate Assessment

6.3.2.1 Aggregate Selection

The rationale behind the selection of the aggregates used for assessment is described earlier (see Chapter 2), where the aggregates are the same as those assessed within Hill, et al. (2001).

6.3.2.2 Contaminant Concentrations

Computations have been based upon contaminant concentrations at the outlets of the lysimeters in the leaching project. Mean concentrations of contaminants are shown in Table 6.2. The lysimeters were designed to simulate real pavement conditions. Due to the fact that the lysimeters were unsurfaced, all rainfall had the potential to flow through, and residence times may have been less than in surfaced pavements. This is because in surfaced pavements infiltration rates are related to surface cracking, resulting in lower quantities of water entering the pavement profile. This could lead to the contaminant concentrations in the water in surface pavements reaching maximum values (lower flow rates resulting in the aggregates being in contact with the water for longer), which may not have occurred in the unsurfaced lysimeters. Data from tank leaching tests in the leaching project, however, show that maximum cumulative releases plotted against time are similar to those for the lysimeters (Hill, 2000), thus allowing the lysimeter concentrations to be used here as fully concentrated values (see Chapter 2).

Table 6.2 Mean contaminant concentrations for lysimeters, data of which have been used within this research (Hill, 2000)

L	Mean Contaminant Concentrations for Lysimeters (mg/l)													
	Cl	SO_4	NO_3	Ba	Mn	Fe	Al	Ni	Cu	Zn	Cr	Cd	Pb	As
1	201	221	1.0	0.02	0.01	0.07	1.3	0.05	0.04	0.11	0.12	0.04	0.21	0.07
2	19	76	0.38	0.13	0.04	0.82	0.35	0.12	1.6	0.28	0.24	0.07	0.44	0.08
3	6.4	31	16	0.05	0.09	0.01	0.03	0.01	0.01	1.6	0.02	0.01	0.04	0.04
4	177	363	4.2	0.74	0.00	0.25	0.16	0.03	0.03	0.07	0.07	0.02	0.12	0.07
5	74	99	4.7	0.03	0.00	0.01	0.25	0.01	0.01	0.06	0.02	0.01	0.04	0.04
6	3.4	6.3	3.4	0.89	0.00	0.02	0.43	0.02	0.02	0.08	0.05	0.03	0.10	0.06
7	16	136	26	0.06	0.00	0.08	0.03	0.01	0.01	0.08	0.02	0.01	0.04	0.04
8	37	1571	0.71	0.04	0.12	0.05	0.15	0.04	0.02	0.09	0.08	0.03	0.15	0.08
9	2764	554	1.6	0.03	0.01	0.05	97	0.10	1.9	0.13	0.15	0.05	0.37	0.11

Aggregate: 1=china clay sand + cement + cement kiln dust, 2=foundry sand (alkali phenolic), 3=crumbed rubber (2-8 mm), 4=BFS + granulated BFS + lime, 5=MSW incinerator ash + bitumen, 6=lean mix (limestone + cement), 7=limestone, 8=BFS, 9=MSW incinerator ash.

Calculations for horizontal flows have been undertaken for the nine lysimeter aggregates, where their porosity values (which control the flow of water through a soil, where flow rate is related to the ratio of pore space to total volume) have been grouped into three groups, with three of the aggregates falling into each group. The three groups have been designated n=0.2, n=0.3 and n=0.4. In order to determine worst-case outputs of contaminants, results have been based upon the greatest contaminant output per hour. This occurs for aggregate k values where maximum drainage results in a 10% minimum saturation (equivalent to 90% drainage). In this case most rainfall input per hour flowing horizontally actually drains through the aggregate and is discharged into the side drains in the next hour. For aggregates with lower k values drainage is slower and results in a minimum saturation greater than 10% (equivalent to drainage <90%). This results in not all the rainfall input per hour draining through the aggregate being discharged into the side drains in the next hour. The actual rate of discharge per hour is related to the k value and porosity. Although the aggregate porosity values have been required for the modelling, a risk assessment guide user is not required to know them, but the knowledge of contaminant concentrations is necessary. These can be determine through standard leaching tests such as the CEN batch leaching test (CEN, 1996), or tank leaching tests (see Chapter 2).

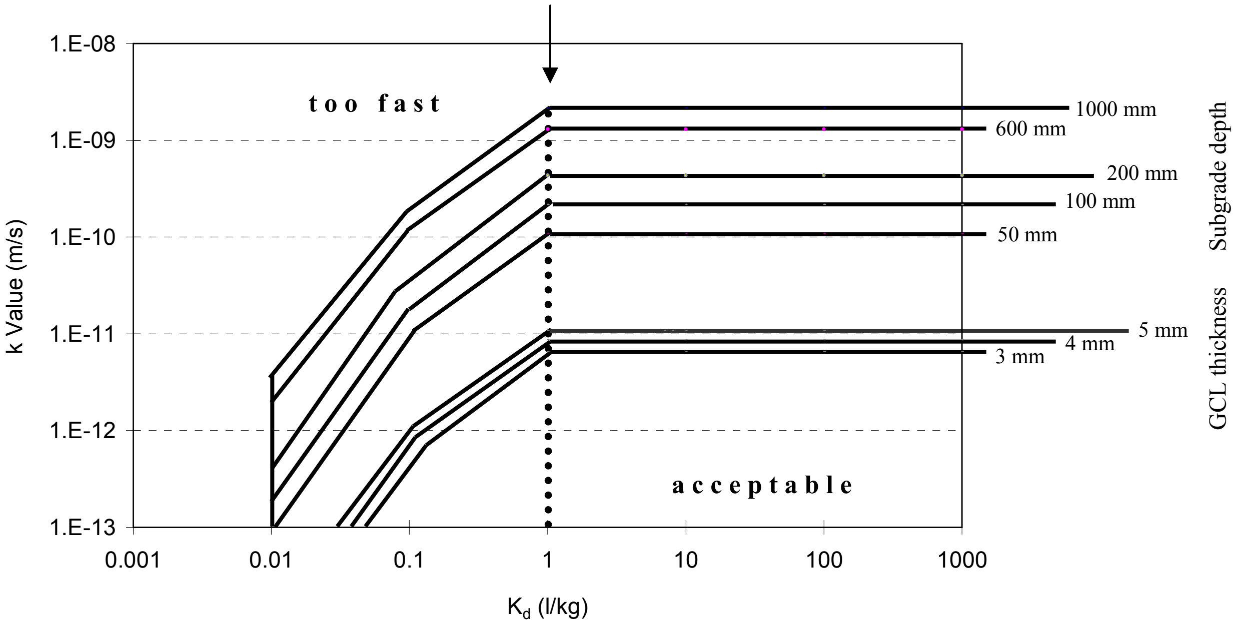
6.3.3 Vertical Flow of Contaminants Below Pavement

6.3.3.1 Clay Subgrade ($k \leq 10^{-10}$ m/s)

Due to the fact that 80% of UK roads are constructed on clay subgrades (Dawson, 1998), these are the subgrades on which most of the computations have been based. Permeability values of clays are far lower than for most of the alternative aggregates under review. If the flow through the subgrade is slow it is likely that the flow will be saturated or partially-saturated. This will be due to the fact that there will be a constant supply of water available at the aggregate/subgrade border, before the water takes the preferential horizontal route (due to the higher permeability values of the aggregate). This water will be able to flow vertically though the subgrade at a constant rate as the flow front advances towards the water table. The correct combination of subgrade k value and depth to water table for sorption of contaminants to reach equilibrium at a breakthrough concentration of 10% of input concentration is the determining factor when the risk assessment guide user assesses an aggregate under review for a particular construction site.

At a breakthrough concentration of 10% of input concentration, most contaminants are below WQS. Although out of the nine aggregates assessed five do exceed WQS at a breakthrough concentration of 10% of input concentration for some contaminants, the quantity of contaminants that exceed are low compared with those that do not exceed them: two aggregates exceed WQS for only 10% of the contaminants, two aggregates exceed WQS for only 20% of contaminants and only one aggregate exceeds WQS for 40% of contaminants. Another reason considered justifiable for basing calculations (and recommendations) on breakthrough times for 10% of input concentrations, is the fact that most contaminants will have K_d values greater than K_d=0.5 l/kg (as presented further on), where breakthrough times for 10% of input concentration will far exceed the forty-year criterion (see below).

During the development of the risk assessment guide it has been considered that the forty-year expected life of a road (described in Chapter 5) to be an appropriate timescale against which recommendations may be based. This means that despite computational modelling showing 16 days residence times per computational layer for contaminated flows in certain subgrades, a further parameter within the risk assessment guide is that a breakthrough concentration of 10% of input concentrations should not reach the water table in less than 40 years. When assessing contaminant concentrations at the forty-year criterion for contaminants with high K_d values (where predictions for high K_d values are presented below), breakthrough concentrations will be far lower than 10% of input concentration. The necessary combinations of subgrade depths/GCL thicknesses and k values required to achieve the above criteria can be seen in Fig. 6.1.



Maximum k value per subgrade depth/GCL thickness for 10% of input contaminant conc. to achieve at least 40 years breakthrough time to the water table. Breakthrough times increase from 40 years at K_d=1 l/kg with increases in K_d values, or with decreases in k values from the max. k value per subgrade depth/GCL thickness for each K_d value (see Chapters 3 and 5)

Fig. 6.1 Illustration of combinations of k values, subgrade depths/GCL thicknesses and K_d values necessary to achieve both 16 days residence times per computational layers and a 40-year breakthrough time (for 10% of input contaminant concentration)

It can be seen in Fig. 6.1 that breakthrough times increase from 40 years as K_d values increase from K_d=1 l/kg, or as k values decrease for each K_d value from the maximum k value per subgrade depth/GCL thickness. Larger k values per subgrade depth/GCL thickness than those illustrated would, however, result in residence times per computational layer reducing from the necessary minimum 16 days.

Illustrations of breakthrough times for 10% of input concentrations to reach the bottom of different subgrade depths and the base of different GCL thicknesses are presented in Chapter 5. Similar tables are presented below in a format to include the additional criterion of a 40-year breakthrough time. Table 6.3 illustrates this combined information for subgrades, whilst Table 6.4 illustrates this combined information for GCLs.

Table 6.3 Times for 10% of input concentration to reach the water table

k Values (m/s)	**Depth of Subgrade (mm)**				
	1000	**600**	**200**	**100**	**50**
	Breakthrough Times for 10% of Input Concentration (years)				
$3x10^{-13}$	160000	96000	32000	16000	8000
$3x10^{-12}$	16000	9600	3200	1600	800
$3x10^{-11}$	1600	960	320	160	80
$3x10^{-10}$	160	96	32	16	8
$3x10^{-9}$	16	6	3	1	1

n.b: highlighted cells represent k values for different subgrade depths where residence times <16 days and/or where breakthrough times <40 years. Highlighted cells require the use of GCLs

Table 6.4 Times for 10% of input concentration to reach the base of the GCL

k Value (m/s)	**Thickness of GCL (mm)**				
	5	**4**	**3**	**2**	**1**
	Breakthrough Times for 10% of Input Concentration (years)				
$3x10^{-13}$	800	600	500	300	150
$3x10^{-12}$	80	60	50	30	15
$3x10^{-11}$	8	6	5	3	1.5

n.b: highlighted cells represent GCL thicknesses for different k values where residence times <16 days and/or where breakthrough times <40 years

Based upon Table 6.3, Table 6.5 has been designed in a format suitable for use in a risk assessment guide and shows acceptable subgrade parameters, without real times being presented.

Table 6.5 Acceptability of construction site parameters (S1-described below)

k Value (m/s)	**Depth of Subgrade (mm)**				
	1000	**600**	**200**	**100**	**50**
$3x10^{-13}$	A	A	A	A	A
$3x10^{-12}$	A	A	A	A	A
$3x10^{-11}$	A	A	A	A	A
$3x10^{-10}$	A	A	U	U	U
$3x10^{-9}$	U	U	U	U	U
A=Acceptable					
U=Unacceptable – GCL Essential					

It can be seen from Table 6.5 which subgrade k values and corresponding depths are unacceptable for use by a contractor and consequently require the use of a GCL.

Site sensitivity has been classified into three classes as illustrated in Table 5.18 (Chapter 5), where the classification is based upon the principle that sensitivity reduces from S1 to S3. A ranking system for horizontal flow is given in Chapter 5, and a similar ranking has also been introduced in the context of vertical flow here. The ranking system allows an increase in acceptability per increase in subgrade k value (by one order of magnitude per total depth) as site sensitivity decreases from S1 to S3 sites. This equates, for example, to a k value of $k=3x10^{-9}$ m/s being unacceptable at an S1 site, but becoming acceptable at an S2 site. Similarly, a k value of $k=3x10^{-8}$ m/s is unacceptable at an S1 and S2 site but becomes acceptable at an S3 site. The ranking of acceptable combinations of subgrade k values and depths to the water table can be seen in Tables 6.6 and 6.7. Table 6.5 represents S1 sites, Table 6.6 represents S2 sites and Table 6.7 represents S3 sites.

Table 6.6 Acceptability of construction site parameters (S2)

k Value (m/s)	Depth of Subgrade (mm)				
	1000	**600**	**200**	**100**	**50**
$3x10^{-13}$	A	A	A	A	A
$3x10^{-12}$	A	A	A	A	A
$3x10^{-11}$	A	A	A	A	A
$3x10^{-10}$	A	A	A	A	A
$3x10^{-9}$	A	A	A	A	A
$3x10^{-8}$	U	U	U	U	U
A=Acceptable					
U=Unacceptable – GCL Essential					

Table 6.7 Acceptability of construction site parameters (S3)

k Value (m/s)	Depth of Subgrade (mm)				
	1000	**600**	**200**	**100**	**50**
$3x10^{-13}$	A	A	A	A	A
$3x10^{-12}$	A	A	A	A	A
$3x10^{-11}$	A	A	A	A	A
$3x10^{-10}$	A	A	A	A	A
$3x10^{-9}$	A	A	A	A	A
$3x10^{-8}$	A	A	A	A	A
$3x10^{-7}$	U	U	U	U	U
A=Acceptable					
U=Unacceptable – GCL Essential					

Guidelines in Tables 6.5 to 6.7 have been combined to form Table 6.8, where the acceptability level is classified according to site sensitivity (AS1-AS3), illustrating that AS1 is acceptable at S1, S2 and S3 sites, AS2 is acceptable at S2 and S3 sites and AS3 is acceptable at S3 sites alone.

Table 6.8 Acceptability of construction site parameters

k Value (m/s)	**Depth of Subgrade to Water Table (mm)**				
	1000	**600**	**200**	**100**	**50**
$3x10^{-13}$	AS1	AS1	AS1	AS1	AS1
$3x10^{-12}$	AS1	AS1	AS1	AS1	AS1
$3x10^{-11}$	AS1	AS1	AS1	AS1	AS1
$3x10^{-10}$	AS1	AS1	AS2	AS2	AS2
$3x10^{-9}$	AS2	AS2	AS2	AS2	AS2
$3x10^{-8}$	AS3	AS3	AS3	AS3	AS3
$3x10^{-7}$	U	U	U	U	U
AS1-AS3=Acceptability class: acceptable at appropriate site sensitivity class. See 'Acceptability Analysis' below					
U=Unacceptable – GCL Essential					

Acceptability Analysis			
Acceptability Class	**Site Sensitivity Class**		
	S1	**S2**	**S3**
AS1	A	A	A
AS2	U	A	A
AS3	U	U	A
A=Acceptable			
U=Unacceptable – GCL Essential			

It can be seen from Table 6.8 that the ranking system can only be applied to clay subgrades where $k \leq 10^{-8}$ m/s (so far). As described earlier, when contaminants have K_d values greater than K_d=0.5 l/kg (the K_d value on which most computations have so far been based), breakthrough times for contaminants will be increased due to greater sorption of contaminants by the subgrade. Breakthrough times for contaminants for K_d values where K_d>0.5 l/kg have been predicted through the following method:

Known contaminant breakthrough times for both 10% and 90% of input concentration have been calculated for K_d=0.005, K_d=0.05 and K_d=0.5 l/kg at both computational Layers 1 and 100. The 10% value has been selected as it is the percentage on which the risk assessment guide has been based and the 90% value has been selected in order to allow a comparison to be made of the trend. The *calculable differences in breakthrough times* between computational Layer 1 and Layer 100 for both percentages at the above K_d values have been plotted and may be seen in Fig. 6.2. *Calculable breakthrough times* for 10% of input concentration at Layer 1 for K_d=5, K_d=50 and K_d=500 l/kg and 90% of input concentration for K_d=5 and K_d=50 l/kg have also been plotted. The lines for the *calculable differences in breakthrough times* for 10% and 90% of input concentrations between Layers 1 and 100 for K_d=0.005, K_d=0.05 and K_d=0.5 l/kg have been extended to *predict differences in breakthrough times* for higher K_d values which are not obtainable through the calculations. The *predicted differences in breakthrough times* at these higher K_d values have been obtained directly from the graph. These *predicted differences in breakthrough times* have then been added to the c*alculable breakthrough times* for K_d=5, K_d=50 and K_d=500 l/kg at Layer 1 in order to *predicted breakthrough times at Layer 100* for these higher K_d values.

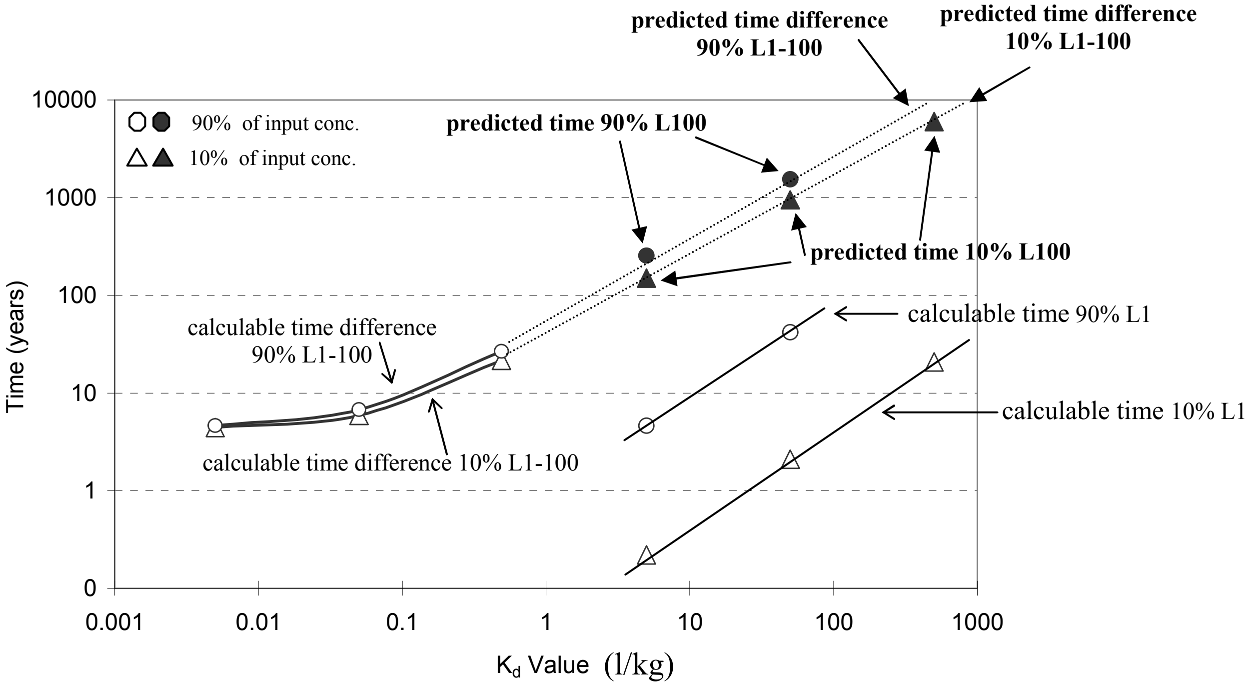


Fig. 6.2 Predicted differences in calculable breakthrough times between Layers 1 and 100 have been obtained for K_d=0.005, K_d=0.05 and K_d=0.5 l/kg, and then used to predict breakthrough times at Layer 100 for K_d=5, K_d=50 and K_d=500 l/kg

The predicted values obtained through the above method and using Fig. 6.2 are summarised in Table 6.9.

Table 6.9 Breakthrough times at the water table (Layer 100) have been predicted for K_d=5, K_d=50 and K_d=500 l/kg from known breakthrough times for K_d=0.005, K_d=0.05 and K_d=0.5 l/kg

	Breakthrough Times (years)					
	10%			**90%**		
	L1	**L100**	**L1-100**	**L1**	**L100**	**L1-100**
K_d	**Known Time**	**Known Time**	**Known Time Difference**	**Known Time**	**Known Time**	**Known Time Difference**
0.005	0.0002	4	4	0.01	5	5
0.05	0.002	6	6	0.09	7	7
0.5	0.02	22	22	0.5	27	27
	L1	**L100**	**L1-100**	**L1**	**L100**	**L1-100**
	Known Time	**Predicted Time**	**Predicted Time Difference**	**Known Time**	**Predicted Time**	**Predicted Time Difference**
5	0.2192	**150**	150	5	**255**	250
50	2	**952**	950	42	**1542**	1500
500	21	**6021**	6000	>21	**>6021**	>6000

The large breakthrough times obtained with large K_d values is evident in Table 6.9, where it can be seen that at K_d=50 l/kg it will take a predicted time of 952 years for 10% of input concentration to reach the water table and at K_d=500 l/kg this will increase to 6021 years. Although breakthrough times for 90% of input concentration at the water table have not been calculated at K_d=500 l/kg, they will be greater than those for 10% of input concentration. These predicted times at L100 have been produced as a result of predicting time differences between Layers 1 and 100 at higher K_d values, by drawing straight lines from the known time differences at lower K_d values (Fig. 6.2). It is likely, however, that the line would be curved rather than straight, resulting in greater breakthrough times. Due to these large breakthrough times, it has been considered justifiable to adapt the ranking system presented above (Table 6.8) in order to reflect breakthrough times at these high K_d values.

The ranking system introduced into Table 6.8 has been adapted further to allow for the large predicted breakthrough times presented above. The further adaptation has been based upon the largest two K_d values. It has been considered justifiable to say that a user of the risk assessment guide may take recommendations in Table 6.8 as they stand for all contaminant K_d values where K_d<50 l/kg. For contaminant K_d values where 50≤K_d<500 l/kg the user may increase the acceptability classes by one order of magnitude, and for contaminant K_d values where K_d>500 l/kg the user may increase the acceptability class by two orders of magnitude. This includes the upgrading of the unacceptable class to acceptable by the same orders of magnitude for subgrades with a k value of $k=10^{-7}$ m/s. At this k value the subgrade is still clay and sorption by the subgrade will reduce contaminant concentrations to a large extent, especially with large K_d values (even if sorption does not reach equilibrium). As a result, at $50 \leq K_d < 500$ l/kg unacceptable becomes AS3, AS3 becomes AS2 and AS2 becomes AS1. Similarly, for $K_d > 500$ l/kg unacceptable becomes AS2, AS3 becomes AS1 and AS2 also becomes AS1. The implementation of this can be seen in an example calculation using the risk assessment guide further on in this chapter and also in the complete risk assessment guide in Appendix 6, where it is implemented in Table 2.

It should be noted that despite calculations in Chapters 3 and 5 illustrating that only subgrades where $k \leq 10^{-10}$ m/s allow sorption of contaminants by partitioning to reach equilibrium, due to the ranking system developed above which allows for site sensitivity and K_d values, in the risk assessment guide the user must determine whether the site subgrade is $k \leq 10^{-7}$ m/s and *not* $k \leq 10^{-10}$ m/s as previously used.

For the combinations of subgrade depths and k values which are unacceptable, despite the ranking system, GCL-use is essential. Based upon Table 6.4, Table 6.10 has been designed in a format suitable for use in a risk assessment guide and illustrates acceptable GCL k values and thicknesses, without real times being presented. The acceptability within the table relates to the capacity of the GCL to facilitate sorption of contaminants by partitioning onto the clay within the GCL, similarly to sorption within a subgrade. Due to the fact that the GCL will be used when sorption is insufficient to remove contaminants from the flow through the subgrade despite the ranking system, it is advisable to use the GCL as presented in Table 6.10. No ranking system has been introduced into it.

Table 6.10 Assessment of GCL for construction site suitability

k Value (m/s)	**Thickness of GCL (mm)**				
	5	**4**	**3**	**2**	**1**
$3x10^{-13}$	A	A	A	A	A
$3x10^{-12}$	A	A	A	U	U
$3x10^{-11}$	U	U	U	U	U
A=Acceptable					
U=Unacceptable					

For recommendations regarding GCL use see Section 6.3.3.2.

6.3.3.2 Clay ($k>10^{-10}$ m/s) or Other Subgrade

Computations based on the subgrade total depths modelled show that only subgrades where $k \leq 10^{-10}$ m/s allow flows to remain within the subgrade for sufficient time to allow partitioning of contaminants to reach equilibrium. This means that if subgrades with k values greater than this value are present at construction sites under review, partitioning will occur to some extent, but not to equilibrium. Because the estimation of the extent to which partitioning to non-equilibrium has been outside the scope of this research, it is recommended that GCLs be used below pavements and above subgrades for construction scenarios for subgrades where $k \geq 10^{-10}$ m/s. In the previous section the development of a ranking system within the risk assessment guide based on the sensitivity of a site under review is presented. This is only the case, however, for subgrades with k values where $k \leq 10^{-7}$ m/s (i.e. clay). This is due to the capacity of clay subgrades to facilitate partitioning to a greater extent than other subgrade materials. When subgrades do not comply with required parameters (e.g. subgrade k values and depths to the water table) previously outlined, the use of GCLs is essential.

As initially addressed in Chapter 5, thinner GCLs are more likely to become damaged than thicker ones. Recommendations are therefore given that when used in pavement construction, GCLs should have a minimum thickness of 4 mm. In Chapter 5 the current available thicknessess of GSE GundSeal, a form of GCL are given (CETCO, 2000), and these range from 0.4 mm to 2 mm. These GCLs are mainly used as landfill liners, where after their initial application, they remain undisturbed. Within pavement construction GCLs will constantly suffer the loading of vehicles from above. It has been considered justifiable to recommend here that the maximum thickness available for GSE GundSeal (2 mm) be produced at double the current maximum thickness in order to compensate for any potential damage from vehicles.

Although breakthrough times for contaminant movement in clay subgrades and GCLs has been presented in this thesis, an important fact which was introduced earlier is that the role of diffusion within contaminant transportation has not been assessed within this research. Calculations indicate that advection in the more permeable soil to breakthrough at 10% of input concentration gives similar flux of contaminant to the flux due to diffusion, where very conservative assumptions are made for diffusive flow. In reality, we expect diffusive flux to be much lower because it will take a long time for a constant contaminant gradient to be established. Therefore, the estimated breakthrough times are slightly over-estimated in the foregoing text (based upon advective fluxes). The amount of over-estimation will be very small at the highest permeabilities (where advection will be faster) but *may* be more significant at very low permeabilities (e.g. GCLs) where advection will be slower and this is a subject for further research.

6.3.4 Horizontal Flow of Contaminants Through Aggregate With Discharge From Side Drains

6.3.4.1 Contaminant Release from Side Drains

Quantities of water and contaminants discharged: the rainfall at a potential construction site will influence the quantity of water within a pavement profile and consequently the quantity of contaminant released into the side drain per hour. The equations behind the calculations and the methods used in this research to quantify the water and contaminants discharged are presented in Chapters 3 and 5.

Dilution: for sensitive sites (S1 and S2 sites) contaminant levels must be below WQS. For less sensitive sites (S3 sites) the dilution of contaminants by surface runoff to WQS may be more acceptable to the EA, especially where background contamination is already above 'regular' standards. The quantities of runoff required to dilute contaminant levels in water draining through pavement side drains to WQS at S3 sites for different rainfalls is a parameter on which the risk assessment guide has been developed. Calculations presented in Chapter 5 to determine dilution requirements are based upon surface cracking reaching maintenance levels, which is the point at when 10% of the surface is cracked (Baldwin, et al., 1997). The quantities of water required for dilution at different percentages of surface cracking have been proportioned accordingly, and these are presented later.

The example of available surface runoff presented in Chapter 5 is extracted from literature for a small geographical area. In order to calculate infiltration for different rainfalls it is more important to quantify a percentage of rainfall from any area that may form surface runoff. Luker and Montague (1997) state that runoff is dependent on site conditions such as depth, duration, frequency and pattern of rainfall, surface conditions and exposure of site, and tend to be site and event specific, so making predictions of quantity difficult. Bellinger, et al. (1982) give 75-100% and Ellis, et al. (1986) give 34-83% of rainfall as estimated quantities of rain that may form runoff from pavement surfaces. In order to compare available runoff with the four rainfalls categories developed for use in the risk assessment guide, a value of 73% of rainfall has been selected as suitable. This number has been selected because it is halfway between the mean values of both ranges presented above. The potential runoff for the four rainfalls can be seen in Table 6.11.

Table 6.11 Potential runoff for four rainfalls based upon 73% of each rainfall, where for the two middle ranges of rainfall this has been calculated for the middle of each range

Mean Local Rainfall (mm/h)	**<0.07**	**>0.07-0.15**	**>0.15-0.28**	**>0.28**
Potential Runoff (l/h/m^2)	0.05	0.08	0.16	0.21
Potential Runoff for Half-Pavement Section (l/h)	**0.23**	**0.37**	**0.74**	**0.98**

As discussed in Chapter 5, when allocating dilution values and classes to actual quantities of water required to dilute contaminated drainage to WQS, all values between >0 to 1 l/h per metre length of a half-pavement have been rounded up to form dilution class D1, which is equivalent to 1 l/h (Chapter 5, Table 5.8). This means that although a contaminant may have been allocated a dilution value of 1 l/h, the actual value required may be below 1 l/h. It can be seen from Table 6.11 that only runoff from rainfalls >0.28 mm/h has the potential to provide sufficient water for dilution at the required l l/h (where potential runoff is 0.98 l/h). In Figs. 5.14 to 5.17 (Chapter 5), the appropriate available water from runoff is marked, where data from R1 has been transformed into rainfalls <0.07 mm/h, R2 has been transformed into rainfalls between >0.15 and 0.28 mm/h, and R3 and R4 have been transformed into rainfalls between >0.07 and 0.15 mm/h (Chapter 5, Table 5.11). From those graphs it is evident that although for some of the aggregates assessed some of the contaminants have been allocated a dilution class of D1, other contaminants for the same aggregate have been allocated dilution classes greater than D1. When determining the dilution requirements for the aggregates assessed, the maximum dilution class for contaminants in each aggregate has been selected (to represent a worst-class scenario). This results in all the aggregates assessed here being minimum D2 aggregates (thus requiring at least 5 l/hr dilution for a half-pavement section) (Chapter 5, Table 5.8) and it is anticipated that this contaminant concentration trend will be similar for other aggregates not assessed.

Initially, from the section above it appears that surface runoff is not sufficient to dilute contaminant concentrations. Consideration should be given, however, to the fact (previously discussed) that sorption of some contaminants onto the clay in side drains may well result in the concentration of contaminants in the drainage being below those on which the calculations have been based. This would result in the actual water required for dilution being lower than that modelled, and dilution by surface runoff may *then* become acceptable. Additionally, at sites of lesser sensitivity (S3) it is anticipated that WQS may be set at higher regulatory limits. As a result, it has been considered justifiable to introduce a ranking system into the dilution requirements to reflect both these facts (introduced in Chapter 5). The ranking system that has been developed specifies that if any dilution at all of contaminants in an aggregate is required at more sensitive S1 and S2 sites, the aggregate is unacceptable for use (where only dilution class D0 is acceptable). Due to the fact that it is anticipated that at less sensitive S3 sites the permissible limits will be set higher than 'normal' WQS, it is has been considered acceptable to reduce dilution classes for an aggregate by one class, compared with that required at S1 and S2 sites. As a result of this and the fact that sorption in drains will have previously occurred, the method used implies that at S3 sites any aggregate is acceptable for use when dilution requirements have been reduced to 1 l/hr (D1) where, originally, they were 5 l/h (D2) at S1 and S2 sites. This then assumes that runoff *will* provide sufficient water for the dilution (taking into account the facts presented above).

Table 5.19 (Chapter 5) is presented below in a format suitable for use in a risk assessment guide as Table 6.12, where only dilution classes of D0 are acceptable at S1 and S2 sites, and dilution class of D1 is acceptable at S3 sites. Dilution requirements greater than 1 l/h cannot be obtained from run-off. An important conclusion can be drawn by assessing Table 6.12, which is that at maintenance level surface cracking (10% longitudinal cracking/100% alligator-type cracking – the matching of these is given later) for the aggregates assessed (all having contamination classes between C3 and C7), none are acceptable at S1 and S2 sites. Those with contamination class C3 are acceptable at S3 sites for some rainfalls, but those with contamination classes C4-C7 are not acceptable at S3 sites for any rainfalls.

If the quantities of water required for dilution of contamination classes presented in Chapter 5, Table 5.19 are based upon 10% longitudinal cracking/100% alligator-type cracking, it follows that if based upon lesser percentages of surface cracking, less infiltration of rain will occur and consequently the amount of water required to dilute contaminant levels to WQS will be proportionally reduced, despite quantities of surface runoff remaining the same. Calculations have been undertaken for a range of different percentages of surface cracking and confirm that results from Table 6.12 are applicable for all percentages of cracking from 5% to 10% longitudinal cracking/50% to 100% alligator-type cracking. Acceptability for other percentages of cracking are given in Tables 6.13 to 6.14, where they have been grouped according to the percentages of cracking presenting similar results. In all cases, dilution classes at S1 and S2 sites have been reduced by one dilution class for S3 sites, and in all cases only dilution class D0 is acceptable at S1 and S2 sites and dilution class D1 at S3 sites.

Table 6.12 Acceptability of use of aggregates according to mean site annual rainfall (5% to 10% longitudinal cracking /50% to 100% alligator-type cracking)

Highest Contamination Class	**Site Sensitivity Class**	**Mean Site Annual Rainfall (mm/h)**			
		<0.07	**>0.07-0.15**	**>0.15-0.28**	**>0.28**
		Acceptability of Construction Scenarios			
C0	**S1,S2,S3**	A	A	A	A
C1	**S1,S2**	A	A	U	U
	S3	A	A	A	A
C2	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C3	**S1,S2**	U	U	U	U
	S3	A	A	A	U
C4	**S1,S2**	U	U	U	U
	S3	U	U	U	U
C5	**S1,S2**	U	U	U	U
	S3	U	U	U	U
C6	**S1,S2**	U	U	U	U
	S3	U	U	U	U
C7	**S1,S2**	U	U	U	U
	S3	U	U	U	U
A=Acceptable					
U=Unacceptable					

Table 6.13 Acceptability of use of aggregates according to mean site annual rainfall (>0.1% to <5% longitudinal cracking/>1% to <50% alligator-type cracking)

Highest Contamination Class	**Site Sensitivity Class**	**Mean Site Annual Rainfall (mm/h)**			
		<0.07	**>0.07-0.15**	**>0.15-0.28**	**>0.28**
		Acceptability of Construction Scenarios			
C0	**S1,S2,S3**	A	A	A	A
C1	**S1,S2**	A	A	U	U
	S3	A	A	A	A
C2	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C3	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C4	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C5	**S1,S2**	U	U	U	U
	S3	A	A	A	U
C6	**S1,S2**	U	U	U	U
	S3	A	A	U	U
C7	**S1,S2**	U	U	U	U
	S3	U	U	U	U
A=Acceptable					
U=Unacceptable					

Table 6.14 Acceptability of use of aggregates according to mean site annual rainfall (≤0.1% longitudinal cracking/≤1% alligator-type cracking)

Highest Contamination Class	**Site Sensitivity Class**	**Mean Site Annual Rainfall (mm/h)**			
		<0.07	**>0.07-0.15**	**>0.15-0.28**	**>0.28**
		Acceptability of Construction Scenarios			
C0	**S1,S2,S3**	A	A	A	A
C1	**S1,S2**	A	A	U	U
	S3	A	A	A	A
C2	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C3	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C4	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C5	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C6	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C7	**S1,S2**	U	U	U	U
	S3	A	A	U	U
A=Acceptable					
U=Unacceptable					

It is evident from Tables 6.13 and 6.14 that with a reduction in percentage surface cracking there is an increase in acceptability at S3 sites, where at ≤0.1% longitudinal cracking/≤1% alligator-type cracking, contamination class 7 aggregates become acceptable for some rainfall events.

Longitudinal/alligator-type cracking: In order to develop guidelines for the risk assessment guide users, a method by which to match the two type of surface cracking (introduced in Chapter 3) has been undertaken. According to Baldwin, et al. (1997), 10% surface cracking equals 0.002 cm of crack/cm^2 (or 0.2 m/m^2). As presented in Chapter 3, it can be seen that infiltration rates obtained from testing infiltration through single cracks (in units of l/h/m of crack) on an otherwise intact pavement surface may be multiplied by 0.2 m/m^2, in order to extrapolate the infiltration rate of the single longitudinal crack to the infiltration through multiple cracking, should surface cracking reach maintenance levels. From the infiltration testing, a mean infiltration rate of 1.46 l/h/m^2 was thereby obtained for longitudinal surface cracking.

A mean infiltration rate of 3.8 l/h/m^2 was obtained for alligator-type surface cracking. Despite the mean infiltration rate for the alligator-type surface cracking being greater than that for the longitudinal surface cracking, the mean infiltration rate for the alligator-type surface cracking was determined from a larger number of tests to that obtained for the longitudinal surface cracking. The actual infiltration rate for the longitudinal cracking was similar to three of the infiltration rates for the alligator-type cracking (see Chapter 3). As a consequence it was decided that the similarity between the infiltration rates for both types of surface cracking was sufficient to confirm the fact that when the infiltration rate for longitudinal surface cracking is multiplied to a point when 10% of the surface is cracked, it is broadly equivalent to the infiltration rate when the surface is 100% covered by alligator-type cracking. This basic link has been used to differentiate between types of surface cracking in the risk assessment guide. This means that, for guideline purposes, 10% longitudinal surface cracking = 100% surface coverage by alligator-type cracking and 5% longitudinal surface cracking = 50% surface coverage by alligator cracking and so on. This enables the risk assessment guide user to identify/set the levels at which a pavement under review will be maintained for both longitudinal and alligator-type cracking.

Through the use of the risk assessment guide a contractor will be able to assess a potential construction site scenario at the aggregate assessment stage. The contractor must determine the realistic level of maintenance that may be achieved, and assess the suitability of the aggregate for the site under review at that level of maintenance. If that level of maintenance is subsequently not achieved and contamination does occur, the EA may enforce costly clean-up procedures.

6.3.5 Project Risk Assessment Approach

An introduction to main risk assessment approaches is undertaken in Chapter 2. It is appropriate to determine their relationship to the approach used in the development of the risk assessment guide within this thesis.

The main aim of this research has been to develop a generic risk assessment guide for use by industry to assess alternative aggregates prior to construction. The definition of a quantitative risk assessment presented by all authors researched has been that they are designed to be site-specific (see Chapter 2). This is in contrast to the approach developed here which may not, therefore, be classified as quantitative according to the typical definition. An assessment is necessary in order to see if it may be identified as either qualitative or semi-quantitative according to the typical definitions associated with both approaches.

The risk assessment guide has been developed based upon certain criteria similar to those in a qualitative approach. One is that generic guidelines are used as a surrogate for the relevant conditions and that a detailed understanding of the basis of the generic values and the inherent assumptions are known. Within this risk assessment guide guidelines have been based upon comparisons with drinking-water WQS which, although not completely relevant to the actual receptor in every case, are the most relevant ones to adopt. Another qualitative criterion is that an assessment is based on someone else's data. Within this research calculations are based upon Hill, et al. (2001).

Although the approach used for the development of the risk assessment guide has been based on similar criteria associated with qualitative risk assessments, a comparison may also be undertaken with criteria seen in a semi-quantitative approach. A similar criterion within a semi-quantitative risk assessment to one within this risk assessment guide is that both may be used for assessing either a single or large number of sites. There are some differences, however, between the present approach and semi-quantitative approaches. The main contrast is that in some situations a semi-quantitative approach may be used as a preliminary risk assessment, prior to a further qualitative or quantitative assessment. Within this research, the approach developed is that the risk assessment guide is available for use '*per se*', and not as an initial risk eliminator.

It appears that although the approach adopted has some similarities with both qualitative and semi-quantitative risk assessments, there are more similarities between this risk assessment approach and qualitative risk assessments. One main similarity, however, between the three approaches is that all the results may be presented as either 'high', 'low' or 'no' risk.

Although the approach developed may be classified as qualitative/semi-quantitative, it could be further adapted into a quantitative approach. The method suggested for the development of this risk assessment into a quantified approach is given in Chapter 7.

6.4 Method of Use

The risk assessment guide is a document for use by pavement designers and contractors, against which an aggregate may be assessed in the context of a potential site, prior to construction. It is assumed that initially there will be virtually no infiltration of water through the intact pavement surface. This will consequently result in virtually no contamination leaving the pavement profile in the form of leachate. The guidelines within the guide offer recommendations as to site suitability as a means for the prevention of contamination *when* surface cracks develop after several years of wear. The user should follow the risk assessment guide to assess vertical and horizontal flows, of which a flow chart may be seen in Fig. 6.3. An example scenario using the guide may be found at the end of this section.

Vertical flow: the user determines: (1) the permeability of the site subgrade, (2) the depth of the subgrade to the water table level, (3) the site sensitivity (the latter will be obtainable by contacting the local EA), and (4) the partition coefficients (K_d) of the contaminants within the aggregate. If the permeability of the subgrade is $k \leq 10^{-7}$ m/s, the user determines from a table in the guide whether the subgrade k value and depth to water table are a correct combination to render the use of an aggregate at that site to be acceptable, reflecting both the site sensitivity and the lowest K_d value of the contaminants within the aggregate. If the correct combination is not present, the use of a GCL will be essential before construction at the site is acceptable. From another table the user may determine the necessary combinations of GCL k values and thicknesses to render the GCL as acceptable for use. If a GCL is not available in order to render the site as acceptable, recommendations for construction cannot be given. If the site is acceptable for use in vertical flow, then an assessment of horizontal flow must be undertaken:

Horizontal flow: the user determines (1) the local rainfall, (2) the concentration of contaminants that may leach out of the potential aggregate (through chemical analysis of the aggregate), (3) the site sensitivity, and (4) a realistic cracking maintenance level that will be achieved at the site. The contamination classes for the concentrations of contaminants determined from the analysis is calculated. From a series of tables in the guide the user determines the acceptability of the aggregate at the site according to the contamination class and rainfall, reflecting the site sensitivity and the likely maintenance level which will be achieved.

It is also recommended that horizontal drainage be directed into a series of settling pools constructed adjacent to the pavement, so that the subsequent disposal of drainage can be controlled.

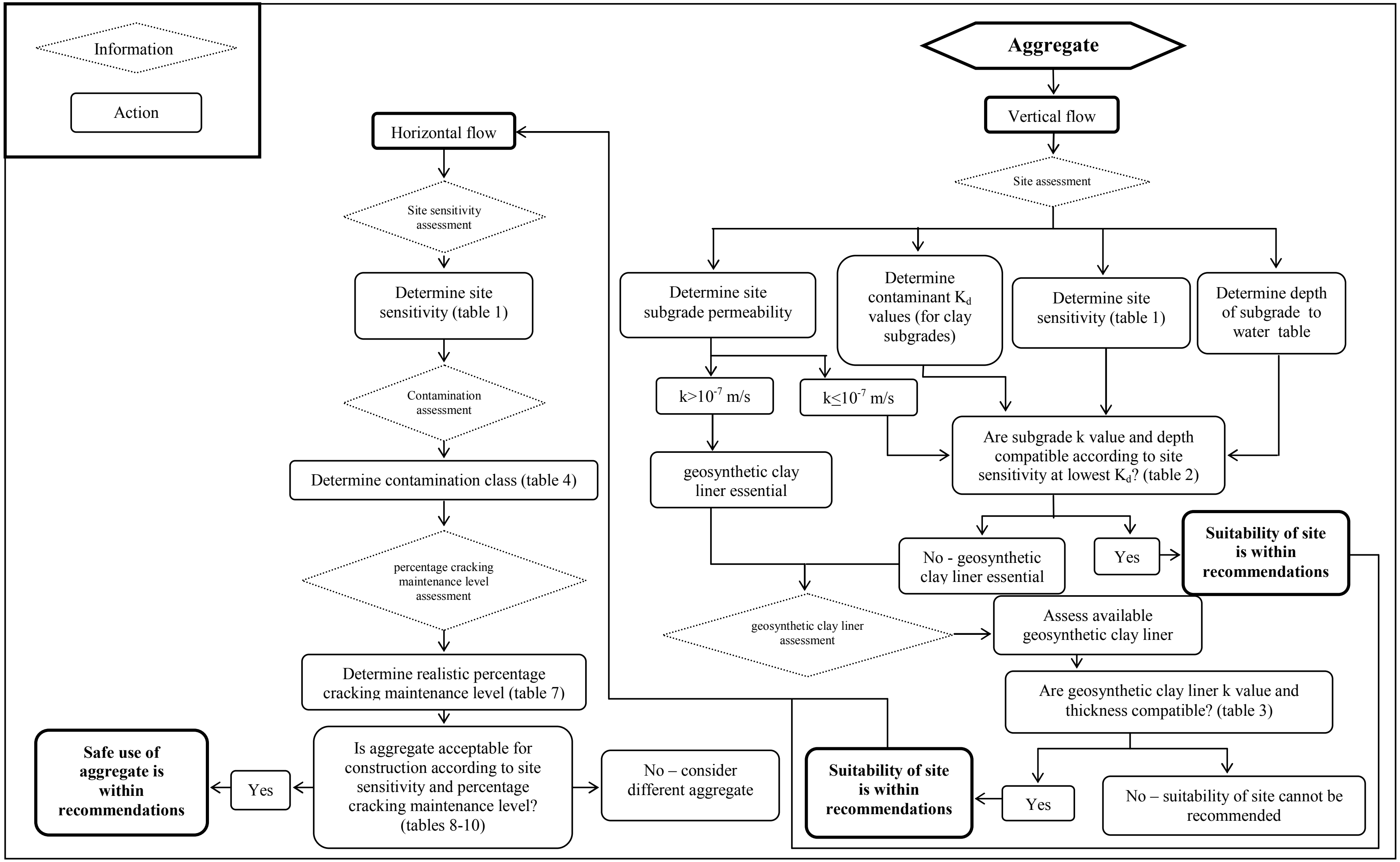


Fig. 6.3 Flow chart to illustrate risk assessment guide

An example using the risk assessment guide is given below, where the complete document with an introduction to the user may be found in Appendix 6.

Example using risk assessment guide: based upon the aggregate being MSW incinerator ash + bitumen (aggregate 5 in this research). Assuming the subgrade has a k value of $k=10^{-8}$ m/s, a depth of 600 mm to the water table, a local rainfall of 0.09 mm/h, the construction is at a S2 sensitive site, the lowest K_d value for the contaminants is 40 l/kg and it is anticipated that the maintenance level will be set at >0.1% to <5% longitudinal cracking/>1% to <50% alligator-type cracking. The chemical analysis of the aggregate may be found in Table 6.2 earlier in this chapter. Also assuming that a GCL is available with a k value of $k\leq 10^{-12}$ m/s and in a 4 mm thickness (N.B. in the risk assessment guide the tables are numbered separately to the main thesis).

Risk Assessment Guide:

****

(1) Vertical Flow of Contaminants Below Pavement

(a)

INSTRUCTION:

- DETERMINE AVERAGE VERTICAL PERMEABILITY OF SITE SUBGRADE.

Does subgrade consist of a material with k value of $k \leq 10^{-7}$ m/s?

YES **– go to (b)**	**answer**	

NO **– go to (d)**

(b)

INSTRUCTION:

- SELECT SITE SENSITIVITY FROM TABLE 1:

Table 1 Site sensitivity selection (*classification by EA, 1998)

Select Correct Site Sensitivity Class	Site Sensitivity Parameters	
S1	Highly sensitive site	*Major aquifer or source protection zone. Highly productive strata of regional importance, often used for large potable abstractions. Background contamination below WQS.
S2	Sensitive site	*Minor aquifer or source protection zone. Variably porous/permeable strata, but without significant fracturing. Generally only supports locally important abstractions. Background contamination below WQS.
S3	Less-sensitive site	*Non-aquifer. Negligible permeability. Only supports very minor abstraction, if any. Background contamination may exceed WQS.

FILL IN BOX:

Site sensitivity selected:
S ….. 2 **answer**

Go to (c)

(c)

INSTRUCTION:

- DETERMINE SUBGRADE DEPTH FROM BELOW PAVEMENT TO WATER TABLE.
- DETERMINE THE K_d VALUES (PARTITION COEFFICIENTS) FOR THE CONTAMINANTS IN THE AGGREGATE FROM A READY-MADE TABLE, FOR FLOWS THROUGH CLAY SUBGRADES. SELECT THE LOWEST K_d VALUE.
- BASED ON SITE SENSITIVITY SELECTED FROM TABLE 1, SELECT THE CORRECT COMBINATION OF SITE SUBGRADE PERMEABILITY AND DEPTH TO WATER TABLE FROM TABLE 2:

Table 2 Site acceptability selection – where the lowest K_d value for contaminants is K_d<50 l/kg

Subgrade k Value (m/s)	Depth of Subgrade to Water Table (mm)					
	1000	600	200	100	50	
$3x10^{-13}$	AS1	AS1	AS1	AS1	AS1	
$3x10^{-12}$	AS1	AS1	AS1	AS1	AS1	
$3x10^{-11}$	AS1	AS1	AS1	AS1	AS1	
$3x10^{-10}$	AS1	AS1	AS2	AS2	AS2	
$3x10^{-9}$	AS2	AS2	AS2	AS2	AS2	
$3x10^{-8}$	AS3	AS3	AS3	AS3	AS3	answer
$3x10^{-7}$	U	U	U	U	U	

For lowest K_d value where $50 \leq K_d < 500$ l/kg:
U becomes AS3
AS3 becomes AS2
AS2 becomes AS1

For lowest K_d value where $K_d \geq 500$ l/kg:
U becomes AS2
AS3 becomes AS1
AS2 becomes AS1

AS1-AS3=Acceptibility class: acceptable at appropriate site sensitivity class. See 'Acceptability Analysis' below

U=Unacceptable for construction – Geosynthetic Clay Liner Essential

Acceptability Analysis

Acceptability Class	Site Sensitivity Class			
	S1	S2	S3	
AS1	A	A	A	
AS2	U	A	A	
AS3	U	U	A	answer

A=Acceptable for construstion

U=Unacceptable for construction – Geosynthetic Clay Liner Essential

FILL IN BOX:

Acceptability Analysis - Is the combination of site subgrade k value and depth acceptable for construction at appropriate site sensitivity according to acceptability analysis?

YES… ***NO…*** **no** **answer**

YES
RISK: LOW – construction on subgrade is within recommendations for vertical flow

Go to (2) 'Horizontal Flow of Contaminants Through Aggregate With Discharge Into Side Drains'

NO
RISK: HIGH – Geosynthetic Clay Liner is essential **answer**

Go to (d)

(d)

INSTRUCTION:

- IF (1a) OR (1c) IS NO, GEOSYNTHETIC CLAY LINER IS ESSENTIAL. SELECT ACCEPTABLE COMBINATION OF GEOSYNTHETIC CLAY LINER PERMEABILITY AND THICKNESS FROM TABLE 3:

Table 3 Geosynthetic clay liner assessment

Geosynthetic Clay Liner k Value (m/s)	**Thickness of Geosynthetic Clay Liner (mm)**				
	5	**4**	**3**	**2**	**1**
$3x10^{-13}$	A	A	A	A	A
$3x10^{-12}$	A	A	A	U	U
$3x10^{-11}$	U	U	U	U	U
A=Acceptable for construction					
U=Unacceptable for construction					
N.B: Despite acceptable geosynthetic clay liner thicknesses determined in table, it is strongly recommended that a 4 mm minimum thickness be selected in order to resist damage					

answer

FILL IN BOX:

Can Geosynthetic Clay Liner be obtained with k value and thickness shown in above table rendering it acceptable for construction?

Yes … **yes** **answer** ***No…***

YES
RISK: LOW – <u>providing geosynthetic clay liner of acceptable k value and thickness is used, construction at site is within recommendations for vertical flow</u> **answer**

Go to (2) 'Horizontal Flow of Contaminants Through Aggregate With Discharge Into Side Drains'

NO
RISK: HIGH - <u>suitability of construction at site cannot be recommended</u>

(2) Horizontal Flow of Contaminants Through Aggregate With Discharge Into Side Drains

(e)

INSTRUCTIONS:

- AGGREGATE MUST BE ANALYSED FOR CONCENTRATION OF POTENTIAL CONTAMINANTS THAT MAY LEACH OUT.
- COMPARE LEVELS OF EACH CONTAMINANT WITH WATER QUALITY STANDARDS (WQS) RELEVANT FOR CONSTRUCTION SITE (YOU WILL NEED TO LIASE WITH THE LOCAL ENVIRONMENT AGENCY).
- CALCULATE THE PERCENTAGES BY WHICH CONTAMINANT CONCENTRATIONS EXCEED WQS (IN THOSE EXCEEDING THEM) AND DETERMINE CONTAMINATION CLASSES FROM TABLE 4:

Table 4 Contamination classes for each contaminant exceeding WQS

Contamination Class	Percentages by which Contaminants Exceed WQS (%)	Contaminant Concentration/WQS
C0	0	<1
C1	>0-10	1-1.1
C2	>10-100	1.1-2
C3	>100-500	2-6
C4	>500-800	6-9
C5	>800-2000	9-21
C6	>2000-10000	21-101
C7	>10000	>101

Go to (f)

(f)

INSTRUCTION:

- ENTER CONTAMINATION CLASS FOR CONTAMINANTS OBTAINED FROM TABLE 4 INTO TABLE 5 AND SELECT HIGHEST CLASS OF CONTAMINANT IN THE LAST COLUMN (Example may be seen in Table 6):

Table 5 Enter Contamination classes and highest class of contamination

Aggregate	Cl	SO_4	NO_3	Ba	Mn	Fe	Al	Ni	Cu	Zn	Cr	Cd	Pb	As	*	*	*	*	*	*	Highest Class of Contamination
							C2					C3	C3	C3							C3

* additional contaminants of concern may be entered

answer

FILL IN BOX:

Highest contamination class for aggregate mix:

Contamination class … *C*3 **answer**

EXAMPLE OF CONTAMINATION CLASSES FOR NINE AGGREGATE MIXES MAY BE SEEN IN TABLE 6 BELOW:

Table 6 Example of contaminant classes for nine aggregates (N.B: empty cells indicate that contamination is within WQS)

Aggregate	Cl	SO_4	NO_3	Ba	Mn	Fe	Al	Ni	Cu	Zn	Cr	Cd	Pb	As	Highest Contamination Class
1							C4	C3			C3	C5	C4	C4	C5
2						C3	C2	C3			C3	C6	C6	C4	C6
3												C3	C3	C3	C3
4		C2		C1				C2			C2	C4	C5	C4	C5
5							C2					C3	C3	C3	C3
6				C2			C3					C5	C5	C3	C5
7												C3	C3	C3	C3
8		C4						C2			C2	C4	C5	C4	C5
9	C5	C3					C7	C3			C3	C5	C6	C5	C7

Aggregates: 1=china clay sand + cement + cement kiln dust, 2=foundry sand (alkali phenolic), 3=crumbed rubber (2-8 mm), 4=blast furnace slag (BFS) + granulated BFS + lime, 5=municipal solid waste (MSW) incinerator ash + bitumen, 6=lean mix (limestone + cement), 7=limestone, 8=BFS, 9=MSW incinerator ash.

Go to (g)

(g)

INSTRUCTION:

- DETERMINE REALISTIC SURFACE CRACKING LEVEL AT WHICH MAINTENANCE WILL BE UNDERTAKEN, FROM TABLE 7. IT IS BASED UPON AN ASSESSMENT OF A 1 m^2 AREA, TAKEN TO BE REPRESENTATIVE OF THE WHOLE PAVEMENT SURFACE:

Table 7 Realistic surface cracking maintenance levels for percentage longitudinal and percentage alligator-type cracking

Select the Percentage Cracking Which Corresponds to the Two Measurements			(2) Percentage Alligator-Type Cracking (%)
(1) Percentage Longitudinal Cracking (%)	Longitudinal Cracking		
	cm/cm^2	m/m^2	
5 to 10	0.001 to 0.002	0.1 to 0.2	50 to 100
>0.1 to <5	>0.00002 to 0.001	>0.002 to <0.1	>1 to <50
$\leq$0.1	$\leq$0.00002	$\leq$0.002	$\leq$1

answer

FILL IN BOX:

Realistic surface cracking maintenance level:

Percentage Longitudinal ... **>0.1% to <5 %**
Percentage Alligator-Type ... **>1% to < 50 %**

answer

Go to (h)

(h)

INSTRUCTIONS:

- DETERMINE MEAN LOCAL RAINFALL.
- DETERMINE ACCEPTABILITY OF USE OF AGGREGATE ACCORDING TO MEAN SITE ANNUAL RAINFALL FOR HIGHEST CONTAMINATION CLASS FOR MEAN SITE ANNUAL RAINFALL FROM TABLES 8-10, ACCORDING TO SITE SENSITIVITY (SEE TABLE 1):

Table 8 Acceptability of use of aggregate according to mean local rainfall

Realistic Maintenance Level at:
Percentage Longitudinal Cracking: 5% to 10% Surface Cracking
Percentage Alligator-Type Cracking: 50% to 100% Surface Cracking

Highest Contamination Class	Site Sensitivity Class	Mean Local Rainfall (mm/h)			
		<0.07	>0.07-0.15	>0.15-0.28	>0.28
		Acceptability of Construction Scenarios			
C0	S1,S2,S3	A	A	A	A
C1	S1,S2	A	A	U	U
	S3	A	A	A	A
C2	S1,S2	U	U	U	U
	S3	A	A	A	A
C3	S1,S2	U	U	U	U
	S3	A	A	A	U
C4	S1,S2	U	U	U	U
	S3	U	U	U	U
C5	S1,S2	U	U	U	U
	S3	U	U	U	U
C6	S1,S2	U	U	U	U
	S3	U	U	U	U
C7	S1,S2	U	U	U	U
	S3	U	U	U	U

A=Acceptable

U=Unacceptable

Table 9 Acceptability of use of aggregate according to mean local rainfall

Realistic Maintenance Level at:
Percentage Longitudinal Cracking: >0.1% to <5% Surface Cracking
Percentage Alligator-Type Cracking: >1% to <50% Surface Cracking

Highest Contamination Class	Site Sensitivity Class	Mean Local Rainfall (mm/h)			
		<0.07	**>0.07-0.15**	**>0.15-0.28**	**>0.28**
		Acceptability of Construction Scenarios			
C0	**S1,S2,S3**	A	A	A	A
C1	**S1,S2**	A	A	U	U
	S3	A	A	A	A
C2	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C3	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C4	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C5	**S1,S2**	U	U	U	U
	S3	A	A	A	U
C6	**S1,S2**	U	U	U	U
	S3	A	A	U	U
C7	**S1,S2**	U	U	U	U
	S3	U	U	U	U

A=Acceptable

U=Unacceptable

answer

Table 10 Acceptability of use of aggregate according to mean local rainfall

Realistic Maintenance Level at:
Percentage Longitudinal Cracking: ≤0.1% Surface Cracking
Percentage Alligator-Type Cracking: ≤1% Surface Cracking

Highest Contamination Class	Site Sensitivity Class	Mean Local Rainfall (mm/h)			
		<0.07	>0.07-0.15	>0.15-0.28	>0.28
		Acceptability of Construction Scenarios			
C0	**S1,S2,S3**	A	A	A	A
C1	**S1,S2**	A	A	U	U
	S3	A	A	A	A
C2	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C3	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C4	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C5	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C6	**S1,S2**	U	U	U	U
	S3	A	A	A	A
C7	**S1,S2**	U	U	U	U
	S3	A	A	U	U

A=Acceptable

U=Unacceptable

FILL IN BOX:

answer

Highest contamination class ... ***C*3**

and

Site sensitivity ... ***S*2**

and

Mean local rainfall ... **0.09 mm/h**

and

Realistic cracking maintenance level:

Percentage Longitudinal ... **>0.1% to <5%**

Percentage Alligator-type ... **>1% to 50%**

Acceptability Analysis:
Are the combinations of the above factors acceptable according to acceptability analysis:

YES … ***No …*** **no**

YES
RISK: LOW - Providing combination of contamination class, site sensitivity, mean local rainfall and realistic cracking maintenance results in 'acceptable' for construction, construction at site is within recommendations for horizontal flow

NO
RISK: HIGH – suitability of construction at site cannot be recommended **answer**

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From this example, the aggregate is acceptable for vertical flow, providing a GCL is placed below the pavement and above the subgrade. For horizontal flow the aggregate in unacceptable at an S2 site. A different aggregate must be considered.

If the aggregate were to be used at an S3 site, however, it would be acceptable for use without a GCL in vertical flow and would also be acceptable in horizontal flow.

The example above has been assessed in relation to a method developed by Marsland and Carey (1999), which offers a hard-copy approach for assessing a contaminated site to determine remediation requirements at different tiers. This comparison has been undertaken in order to determine which tier(s) within the hard-copy approach is/are equivalent to the assessment potential of the risk assessment guide. Although certain criteria within some of the tiers have been related to what appear to be slightly different stages of the risk assessment guide, the overall impacts on the contaminant concentrations are sufficiently similar at these points so as to make such a comparison acceptable.

Soil contamination Tier 1 in Marsland and Carey (1999) assesses pore water concentration, measured total soil concentration, partition coefficient of contaminants and contaminant properties. Tier 2 assesses those properties within Tier 1 plus the effects of infiltration, dilution by groundwater and other factors (e.g. background water quality). Tiers 3 and 4 assess the additional effects from attenuation (in addition to partitioning) in the soil and within an aquifer. It appears appropriate to compare Tier 1 assessment with the first point of contamination assessment within the risk assessment guide – an assessment of contaminant concentrations at the point they leach from the aggregate and enter the subgrade (in vertical flow) and where they initially leach from the aggregate before discharging into the side drain (in horizontal flow). Tier 1 recommends either leaching tests or direct measurements be used to obtain chemical concentrations, which are equivalent to the method used to obtain contamination concentrations upon which calculations within this thesis have been based. The resultant concentrations can be compared with the appropriate WQS for either the tiered or risk assessment guide approaches. In the risk assessment guide there are no other contamination assessments. Due to the fact that Tier 2 allows for dilution of contaminants when a site of contamination is being assessed, it appears appropriate to equate this tier with the second point of contamination assessment within the risk assessment guide developed here – the point where the water reaches the water table level (vertical flow), and the point where the water is discharged through the side drains (horizontal flow). The dilution of contaminants at Tier 2 has been equated with partitioning within vertical flow in the risk assessment guide. Although dilution by groundwater is not acceptable for new sites of construction, partitioning within the subgrade will also reduce contaminant concentrations, although through a different process (resultant contaminant concentrations will be reduced in both approaches). For horizontal flow in the risk assessment guide, dilution from surface run-off is the only form of dilution that may be acceptable, because again dilution by water bodies is not acceptable for new sites of construction. Dilution by surface runoff in the risk assessment guide has been equated with the dilution of contaminants at Tier 2, because contaminant concentrations are reduced in both approaches. Tier 2 allows for infiltration, which is the same factor which influences the contaminant output at the side drains from horizontal flow in the risk assessment guide. This again links Tier 2 with the second point of contaminant assessment in the risk assessment guide. Tiers 3 and 4 include additional attenuation factors (where dilution within an aquifer is included) which would not be appropriate with the risk assessment guide. It can be concluded that the risk assessment guide complies with Tiers 1 and 2 in Marsland and Carey (1999), the initial assessment stage of their tiered approach, before further attenuation and remediation are addressed.

6.5 Data from the Case Study

The case study was undertaken in order to assess the long-term environmental effects from the use of BFS as a pavement construction aggregate. The case of the A66 in Cumbria was selected because this is a site with a known history of contamination following construction. Along part of the road, marshy material was removed and the areas backfilled with the slag. During certain times of the year the water table is known to rise above the base of the slag. Current guidelines recommend this condition does not occur.

By comparing the construction sequence with computations presented in this thesis, it is evident that there is insufficient subgrade below the slag and above the water table through which sorption of contaminants by partitioning may occur to any extent and certainly not to equilibrium. This means that the constructions conditions within the A66 are not compatible with the requirements necessary within the risk assessment guide for an assessment of vertical flow.

The maximum leaching of contaminants from the A66 occurred during the first 2.5 years after construction. Through this research it has been shown that significant leaching of contaminants will only occur after maintenance cracking occurs, providing construction recommendations are followed. The result of the construction sequence used within the A66 was that the BFS was saturated with water soon after construction when the pavement foundations were below the water level at certain times of the year. The leachates washed out from the BFS in the flooded pavement flowed either directly into the river systems or into side drains before discharging into the rivers.

To some extent this means that the route of contaminant-release from the A66 was more similar to the release of contaminants flowing horizontally through an aggregate towards the side drains as presented within the risk assessment guide. In the risk assessment guide the release of contaminants in horizontal flow is quantifiable, as leaching is determined by rainfall infiltration rates. In the construction sequence of the A66, however, the rate of release of contaminants in flooded pavements was not (and is still not) quantifiable, especially where saturation and flooding occurred (and still does). Despite the release of contaminants within the A66 being into side drains, the manner of this release (non-quantifiable during periods of flooding) means that the constructions conditions within the A66 are not compatible with the requirements necessary within the risk assessment guide for an assessment of horizontal flow either.

The contamination that occurred due to the construction of the A66 was, in fact, likely to be worse than the risk assessment model would predict, as more water was available due to the flooding causing saturation of the BFS, than provided by rainfall infiltration described here. Due to the fact that concentrations of contaminants reduced after 2.5 years, it indicates that the desorption of contaminants from the aggregate was the controlling factor, until desoption reduced. These initial high concentrations of contaminants had little opportunity of being diluted by rainfall, being a small influence compared with the flooding river water. This is in contrast to the risk assessment model, in which the concentrations of contaminants which result from desorption from the aggregate in rainfall water infiltrating through surface cracking are diluted by surface runoff. In this case the amount of leachate is much smaller and surface runoff will, consequently, have a greater influence.

It is evident, therefore, that the construction requirements necessary in order for the risk assessment guide to be used at a site were (and are still not) present when considering the construction sequences in the case study of the A66 in Cumbria. If such a guide had been available prior to its construction, it is probable that the contamination events may have been prevented.

6.6 Analysis of the Guide

The risk assessment guide has been developed for use prior to construction, and assesses the suitability of an aggregate under review at a potential construction site. The guide assumes the main route for water entering a pavement profile is through surface cracks. The impact on the flow regimes within a pavement from water entering through other routes has been outside the scope of the research. They are, however, assumed to contribute only a small amount of water to the total water flow compared with entry through surface cracks.

Standard WQS have been the standards upon which computations have been based. In some circumstances, such as sites with raised background contamination levels, permissible limits may be set at higher values. Although the modelling has been carried out for standard WQS, in the risk assessment guide an allowance has been made for site sensitivity. Site sensitivity has been divided into three levels. This is on the basis that in some situations the EA assesses sites on a site-by-site basis, and sites of lower sensitivity may have a less stringent enforcement of WQS (or standards set at higher limits) than those of higher sensitivity. Consultation with local EA officials is recommended for a site-by-site analysis.

During pavement construction, changes in specifications will require the risk assessment guide to be reapplied. An example of this would be the removal of more subgrade in order to lay base and sub-base layers closer to the water table. A reassessment would confirm whether there is sufficient depth of subgrade to ensure that the sorption of contaminants is within recommendations.

Although there are no risk assessment guides currently available for pavement construction, there are guidelines available for contaminated land scenarios. Other authors have developed risk assessments based upon allocating weighted numbers to represent degrees of risk (Cairney, 1995). In contrast, this guide allows the user to assess the physical parameters of a potential construction site in relation to the aggregate under review and results are presented as either acceptable or unacceptable, rather than in degrees of risk. This is because the EA requires contaminants in discharge waters to be below WQS, particularly at sensitive sites. Even low risks of contaminants exceeding these standards are unacceptable at the sensitive sites. This is particularly important for the nine aggregates assessed within this research, where all exceed WQS for cadmium in initial water concentrations. Cadmium is listed as a List I ('black list') substance (described in Chapter 2). Due to the stringent regulations for the use of List I listed substances, any possible leniency would only be shown at sites of less sensitivity.

It is envisaged that this risk assessment guide will be a useful tool for the pavement construction industry in order for the contamination potential of an aggregate under review (alternative and traditional) to be assessed prior to use.

7 Conclusions and Future Work

7.1 Introduction

This thesis results from an identified lack of research into environmental risks from the use of alternative materials in pavement construction, where a detailed literature review indicates that there is no current document available by which to assess the risks prior to construction. Discussions with industry indicate that such a document would be a valuable contribution to pavement construction. Through the literature review it became evident that the current specification requirements for alternative materials for use as construction aggregates are that they meet mechanical criteria set for traditional aggregates, but there are no provisions for their potential to contaminate water bodies. A previous project at the University of Nottingham (Hill, et al., 2001) was concerned with alternative aggregates, but was concerned with leaching and not subsequent risks.

The overall aim of this research has been to develop and assess a methodology for quantifying risks from alternative materials in pavement construction and to present them in a user-friendly format for use by industry prior to construction. In many situations risk is defined as *"the probability of the occurrence of an event"* (Stefanis and Pistikopoulos, 1997). For the present purposes it has been adapted to mean the occurrence of risk to health from the use of alternative materials in pavement construction. An assessment of hazards to health has been beyond the scope of this research and, therefore, the main aim has been to address the risk of contaminants reaching water bodies. This is because if contaminants exceed WQS there is a possibility that they may consequently be hazardous to health.

Research has been undertaken by means of simulating water flows (with and without contaminants) through pavements via computations. They have been designed to initially simulate infiltration through surface cracks (without contaminants) and subsequently to simulate vertical and horizontal flows (with contaminants in leachate) towards water bodies. These flow paths include the deposition of contaminants either in the subgrade (vertical flow) or in side drains (horizontal flow).

For vertical flow, computations simulate breakthrough times for contaminants reaching the water table. Due to the fact that UK pavements have an average forty-year life span, it has been decided that site recommendations should be based upon a parameter that breakthrough times for 10% of input contaminants reaching the water table should be at not less than 40 years. At this percentage calculations show that for the aggregates studied most contaminants will be below WQS. Site guidelines have been developed which give recommended combinations of subgrade permeability and depth to the water table. If a user complies with the recommendations, the retardation of contaminants by sorption onto the subgrade particles will allow the main breakthrough time constraint to be achieved.

For horizontal flow, computations simulate discharge drainage through side drains, where an estimation of mass of contaminants released per hour can be calculated. This is dependent on local rainfall, which facilitates the transportation of the contaminants and forms the drainage. Following on, the quantities of water required to dilute levels of contaminants to WQS have been determined. The only viable source of water for dilution is from surface runoff and recommendations offer guidelines on quantities of water required for dilution reflecting local rainfall.

Data from modelling have been incorporated into a risk assessment guide. This guide is a qualitative/semi-quantitative guide, generic in origin, and has been adapted to reflect site sensitivity. This is because it is anticipated that the EA will be less stringent in their enforcement of control over discharge drainage at sites of lesser sensitivity compared with that at sites of higher sensitivity. It is also likely that sites of lesser sensitivity may have higher regulatory WQS limits. The user is required to obtain some parameters (subgrade depth to the water table and permeability, availability of GCLs, local rainfall, chemical analysis of the aggregate and realistic pavement surface maintenance levels) and then follows through the guide for both vertical and horizontal flows. For vertical flow the user must determine if the correct combination of subgrade depth to water table and permeability are present. If not, a GCL must be used, which is also required to be of the correct combination of thickness and permeability. Guidelines for vertical flow reflect site sensitivity. If after assessing vertical flow, recommendations for the use of an aggregate at a potential construction site are not given the user must consider a different aggregate.

If recommendations for use are given, the user must then assess horizontal flow. In horizontal flow the aggregate must be analysed for contaminant concentrations and the user must determine the water required for dilution according to local rainfall and achievable maintenance levels. Guidelines for horizontal flow also reflect site sensitivity. If the user is able to comply with these requirements, recommendations for the use of the aggregate at the potential construction are then given. Similarly as with vertical flow, if the user is unable to comply with recommendations, a different aggregate must be considered. As the guide is in a qualitative/semi-quantitative approach, recommendations are presented as 'Yes – Risk Low' or 'No – Risk High' format and not in a quantitative manner, which is more usual in a site-specific risk assessment.

Guidelines developed result from modelling where, in most circumstances, this has been based upon worst-case scenarios. Consequently, contamination concentrations will in reality be below those modelled for several years in many situations. Worst-case scenarios will only occur when surface cracking eventually deteriorates and the infiltration of water will be sufficiently great to facilitate the transportation of the maximum mass of contamination. The idea is that if construction at a site under worst-case scenarios is acceptable, construction under 'normal' scenarios would definitely be acceptable. The risk assessment guide has been developed, however, with a ranking system, to reflect the pessimistic outlook.

A case study in Cumbria has been undertaken, where contamination from the use of BFS as bulk-fill 25 years ago is still having an impact on the local river system. If a risk assessment guide similar to the one described here had been available at the time of construction, the contamination problems may have been avoided. It is anticipated that the risk assessment guide will provide a useful document to assess an aggregate at a potential construction site prior to use rather than having to implement a costly clean-up procedure, should an aggregate be inappropriately used.

In order to conclude this research three areas are presented below:

(1) the initial detailed objectives identified and presented in Chapter 1 are now revisited in order to determine whether they have been addressed to a sufficient depth in order to achieve the main research aim,

(2) a full list of conclusions generated through the research is presented, and

(3) during the progress of the research certain limitations have become apparent. They are identified with recommendations for future research so as to allow for further developments and increased accuracy.

7.2 Reviewing Objectives

To assess the 'pathways' of possible contaminants from 'source' to 'receptor':

Risks from contaminants have been assessed within 'source-pathway-receptor' scenarios. The 'source' is an aggregate from which the contaminants may leach, the 'receptor' is a water body into which the contaminated water may enter. Consequently the 'pathway' is the facility by which the contaminants reach the receptor. The source aggregates were assessed within Hill, et al. (2001) from which data has been readily available for use in this research. Because 'receptor' water bodies are protected by WQS enforced by the EA, these have been the standards used. The pathway commences with water entering the pavement as a result of rain infiltrating through surface cracks. Infiltration provides the facility for the contaminant desorption, the area assessed within Hill et al. (2001), and subsequent transportation to the receptor. Here, (the reasons for which are presented in Chapter 1) the transportation has been taken to be two directional:

(1) vertical flow of contaminants through the subgrade towards the groundwater below, and

(2) horizontally through the aggregate towards the side drains. Both flows have been assessed and recommendations for the treatment of horizontally flowing water discharged through side drains have been made where, in some circumstances, concentrations of contaminants may be greater than WQS.

To adapt reasonable models of the movement of water through pavements:

The pathways described above have been addressed by developing computations in order to simulate their routes from source to receptor. The initial pathway is provided by rainfall infiltrating through surface cracks and provides water into which contaminants may enter in the form of leachates. It has been this rainfall on which the modelling of water both with and without contaminant loading to simulate both (1) vertical and (2) horizontal flows has been based. Computations have been developed to model the vertical movement of water through the subgrade towards groundwater based upon saturated flows and the horizontal movement of water through the aggregates towards the side drains based upon partially saturated flows. Modelling allows the quantification of water and contaminant discharged through the side drains per hour to be calculated.

To quantify contaminant movement within pavements by predicting their carriage and deposition:

For vertical flows one method identified by which to quantify contaminant movement has been to simulate breakthrough times based upon the principle of sorption by partitioning. Computations have been undertaken to simulate the transportation and deposition of contaminants for a range of subgrade types using different 'partition coefficients' (K_d). An important factor in the transportation of contaminants is the permeability of the subgrade through which the front advances and it has become apparent that only clay subgrades have k values sufficiently low to allow partitioning to reach equilibrium. In subgrades with higher k values, contaminant concentrations are not sufficiently reduced to comply with WQS. Partition coefficients for most contaminants are larger than those modelled within the research and predicted breakthrough times for larger K_d values have been calculated. Should sorption in a subgrade not reach equilibrium, recommendations regarding the use of GCLs have been made. These recommendations result from modelling flows through GCLs, where the clay will provide a further site for sorption. The modelling allows breakthrough times for different percentages of input concentrations at the water table to be calculated.

For horizontal flows computations have been developed to quantify the movement of water and contaminants through an aggregate to be discharged into side drains. The quantification of contaminant mass discharged through the side drains is possible through the modelling. The part played by clay-lined side drains as sites for sorption during horizontal flow has not been quantified, but it is likely that they do contribute to the reduction of contaminant levels in the water flow. As a result, flows leaving the side drains may have lower contaminant concentrations than those modelled. The deposition of drainage with contaminants into constructed settling pools has been suggested in order to control its eventual disposal.

To formulate a risk assessment methodology drawing on the studies undertaken to meet the previous objectives:

The sections above describe the way by which water flows within pavement profiles and these have been simulated and assessed. They include the infiltration of water through surface cracks and a subsequent vertical and horizontal flow through the pavement profile. The calculations and models used to assess the flows and contaminant movement in order to meet the previous objectives have enabled the formulation of a methodology to assess risks from traditional and alternative construction aggregates. The risk assessment approach is a qualitative/semi-quantitative one, which allows a user to asses a potential construction site according to certain site parameters and to assess a potential aggregate according to levels of contamination. This has allowed the movement and deposition of contaminants to be assessed so as to determine whether resultant flows are below WQS and whether an aggregate is acceptable for use or not.

To summarise the approach developed as a user-friendly generic 'Risk Assessment Guide':

The main aim of quantifying risks from using alternative materials in pavement construction has been achieved. This has been through the development of computations which simulate flows of contaminated water through pavements. Results of these computations have been summarised into a generic risk assessment guide. The guide requires the user to establish the required site parameters, to undertake some form of leaching test on the proposed aggregate in order to determine contamination classes and likely dilution requirement, set a realistic pavement maintenance level, know the environmental sensitivity of the construction site and have a knowledge of available GCL products. From a series of tables the user must establish whether the aggregate under review is acceptable for construction at the proposed construction site. For vertical flow if the site parameters do not comply with recommendations, further tables enable the user to select the correct GCL for use. For horizontal flow if the contaminants are above WQS, guidelines are given as to whether surface runoff is sufficient to reduce the concentration of contaminants to acceptable levels. Although the risk assessment guide has been developed to asses the risks of contamination from alternative materials in pavement construction, the guide may be used against which to assess any construction aggregate. A contractor with no prior computational knowledge may assess a potential aggregate *prior* to construction.

7.3 Full Conclusions

Infiltration Testing:

- Further infiltration data has been generated through fieldwork using apparatus designed during this research.
- Infiltration testing using constant head apparatus is an efficient method for determining infiltration rates.
- A mean infiltration rate of 3.33 mm/l/m^2 has been determined through the fieldwork and has been taken to represent the maximum amount of water than can

infiltrate a pavement through surface cracks. This is similar in magnitude to data obtained from literature.

- The amount of surface cracking will determine the infiltration rate of rainfall into the pavement profile, which will provide the mechanism for leachate to migrate towards water bodies from materials used as bulk fill in the pavement.

Case Study:

- Environmental contamination resulted from the use of BFS construction during the construction of the A66 in Cumbria 25 years ago.
- A new study of the water systems undertaken within this research confirms that although now reduced in concentration, contaminants from the BFS still have an impact on local water quality.
- This confirms that contamination from BFS aggregate can effect water systems for over 25 years.
- The construction sequence was such that periodically the water table rises to encroach the lower pavement layers and thus saturates the aggregate. This is contrary to current guidelines.
- The above points indicate that if the water table at a potential pavement construction site rises to a level that encroaches an aggregate, contaminated water will be discharged immediately, regardless of the general maintenance level of the pavement.
- If guidelines such as the risk assessment guide had been available at the time of construction, the sequence used may have been avoided.

Sorption Rates During Vertical Flow:

- Computations have been developed to simulate the movement of contaminants through the subgrade using a grid model based upon a finite 100 layer system, where the time that it takes for a contaminant to travel from one layer to the next is termed a 'time interval'.

- Calculations allow sorption rates of contaminants moving through the subgrade to be determined, where sorption is based upon 'partitioning'. Partitioning is in turn determined by 'partition coefficient' (K_d).
- The K_d values are contaminant and subgrade-dependent. The sorption capacity of the subgrade through which the contaminated water advances is determined by the K_d value, providing the residence time within the subgrade is sufficient for sorption to reach equilibrium. The subgrade k value determines the rate by which the water moves.
- Calculations indicate that only clay subgrades enable sorption to reach equilibrium. In the system adopted within the research, a maximum range of k values of $3x10^{-9}<k\leq3x10^{-10}$ m/s for sorption to reach equilibrium has been determined for subgrades with depths $\geq$200 mm, where the exact value for a typical 600 mm subgrade is $k=1.3x10^{-9}$ m/s. These numbers are given for hydraulic gradients of 1. Other hydraulic gradients which can reasonably to expected in pavement foundations are not expected to greatly change these numbers.
- Guidelines have been issued to determine the correct combinations of subgrade depth to the water table and permeability for sorption to reach equilibrium, for a range of subgrade depths from 50 mm to 1000 mm.
- If the combinations of subgrade depth to water table and permeability are not compatible for sorption to reach equilibrium, the use of a GCL will offer a further site for sorption on the clay lining.
- Correct combinations of GCL thickness and permeability are again necessary for sorption to reach equilibrium and guidelines have been issued to determine this. Within the research system, sorption to equilibrium will occur at a maximum range of k values of $3x10^{-11}<k\leq 3x10^{-12}$ m/s for GCLs with thicknesses $\geq$2 mm, where the exact value for a recommended 4 mm GCL is $k=8.7x10^{-12}$ m/s.
- Breakthrough times for different percentages of input concentration vary according to K_d value and subgrade permeability.
- As there are limited published accurate K_d values, an element of uncertainty enters calculations, where data for some contaminants range over several orders of magnitude.

- Calculations have mainly been undertaken for K_d=0.5 l/kg, in order to determine breakthrough times for 10% of input concentration to reach the water table for different subgrade depths. These breakthrough times are pessimistic when compared with those determined using large K_d values.
- An important parameter adopted within the research has been that breakthrough times for 10% of input concentration to reach the water table must be greater than 40 years, which is the average life of a pavement.
- Despite limitations within the computations, predicted breakthrough times at larger K_d values (e.g. K_d=50 and K_d=500 l/kg) have been determined.
- The greater the K_d value, the longer the breakthrough time for a particular percentage of input concentration. At K_d=0.5 l/kg the breakthrough time for 10% of input concentration to reach the water table is 22 years, whilst at K_d=500 l/kg this increases to 6000 years.
- By predicting the breakthrough times at larger K_d values, it has enabled a ranking system to be introduced into the guidelines, where it is anticipated that less stringent regulations will be enforced by the EA at sites of lesser sensitivity. This enables subgrades originally deemed as unacceptable for use to become acceptable at these less sensitive sites.
- The method used within the model has been checked against established partitioning equations and gives comparable results.
- The method is sensitive to discretisation. However, there is some evidence that the apparent dispersion due to discretisation that is too coarse could be representative of the effect of insufficient time to achieve equilibrium.

Drainage Through Horizontal Flow:

- A method has been developed by which to determine the mass of contaminants discharged through the pavement side drain per hour, which is influenced by local rainfall.
- Another method has been developed by which to determine the quantity of water required to dilute concentrations of contaminants in the drainage to WQS.

- Surface runoff is the only financially viable potential source of water available for dilution, although initial calculations indicate that there will be insufficient when considering 73% of rainfall to be a potential source.
- A ranking system has been introduced to allow for higher regulatory limits at sites of lesser sensitivity, where the concentrations of contaminants will consequently require less water for dilution.
- It is anticipated that surface runoff will be sufficient to dilute contaminant concentrations in some circumstances at the sites of lesser sensitivity (introduced by the ranking system).
- During horizontal flows, calculation show that at 'normal' maintenance level cracking (10% longitudinal/100% alligator-type cracking), out of the aggregates assessed none are acceptable at any S1 and S2 sites, those with contamination class 3 (crumbed rubber (2-8 mm), MSW incinerator ash + bitumen and limestone) are acceptable at S3 sites for some rainfalls, but those with contamination classes 4-7 (china clay sand + cement + cement kiln dust, foundry sand (alkali phenolic), BFS + granulated BFS + lime, lean mix (limestone + cement), BFS and MSW incinerator ash) are not acceptable at S3 sites for any rainfalls.
- To increase the potential for use of these aggregates, pavement surfaces must be maintained at lower levels of surface cracking, through which less water will infiltrate.
- Sorption of contaminants by clay in side drains will reduce contaminant concentrations in drainage, despite the fact that it is unlikely to reach equilibrium. Although mentioned in the thesis, an allowance for this in the calculations has not been possible due to limited data on the subject.
- Due to the effects of sorption by side drains, the concentrations of contaminants determined within the modelling may be a pessimistic estimation where, in reality, concentrations would be lower.

Risk Assessment Guide:

- The generic risk assessment guide has been developed in order to assess an aggregate at its assessment stage.

- From a series of tables, the user may determine whether the aggregate is suitable for use at a proposed construction site.
- Guidelines have been developed based upon worst-case scenarios (e.g. maintenance level surface cracking), when the infiltration of rainfall is at its greatest.
- The quantity of water recommended for dilution of contaminant concentrations will only be required once cracking has occurred.
- The user must anticipate the maintenance level that may realistically be achieved in order to avoid any later incidences of contamination.
- A ranking system has been introduced to the guidelines in order to allow for site sensitivity. This is because it is anticipated that the EA may be less stringent in enforcing WQS at sites of lesser sensitivity than at sites of greater sensitivity.

7.3 Project Limitations and Recommendations for Future Research

Infiltration testing: infiltration rates generated from infiltration testing have formed the basis of computations, because they provide a means to quantify the maximum potential for water ingress into pavement profiles. To predict rates of water infiltration more accurately, it is recommended that a greater numbers of tests need to be undertaken on different aged pavements. Each test needs to be repeated at different times of the year to determine seasonal influences.

Chemical data: data on contaminant concentrations have been extracted from Hill (2000). It is recommended that further laboratory/lysimeter testing be undertaken. This may result in different leachate concentrations from pavement materials used in different scenarios (e.g. different background chemistry or climatic conditions). Possible synergistic reactions from the contaminants assessed within the research have not been assessed because it has been considered that they would have occurred prior to water sampling in the leaching project. It is recommended that further research be undertaken to determine whether any synergistic reactions from the contaminants assessed within pavement scenarios are, in fact, significant.

Partition coefficients: partitioning is a process describing sorption from one phase to another, the rate of which is partly dependent on partition coefficients. There is a current lack of accurate data, due to limited research. It is recommended that further laboratory-based experimentation be undertaken in order to increase the database of known partition coefficients. This database should include partitioning through different soil types (other than clays), so that assessments may be undertaken when sorption by partitioning does not reach equilibrium.

Soil homogeneity: sorption through partitioning has assumed soil homogeneity resulting in calculations being based upon equal flows throughout a soil profile. In reality, clays in particular tend to form 'clods' (tightly compacted areas). These areas can have a significant influence on permeability of the subgrade (LaGrega, et al., 1994). It is recommended that further research into varying homogeneity of clays in relation to k values be undertaken, to enable calculations to reflect this.

Sorption by side drains: the process of sorption by clay-lined side drains into which horizontal flows are discharged has been highlighted but not quantified. It is recommended that research be undertaken to quantify this (where sorption will not reach equilibrium) and develop methods by which the drains may be replaced or cleaned of contaminants so as to maintain their value as important sorption sites.

Advection vs. diffusion: Modelling has been based upon contaminant fluxes from advective flows, which follow Darcy's law. Although a brief comparison with fluxes from diffusive flows has been undertaken, the actual impact from diffusion on subgrades of lower permeability is not fully understood. It is recommended that further research into the role of diffusion be undertaken in order to ascertain the dominant transportation mechanism through subgrades of lower permeability.

Contaminant input concentrations: calculations for vertical flow through subgrades have been based upon constant contaminant input concentrations from source aggregates over time. In reality, after initial contaminant desorption from aggregates into water, the rate of contaminant release will reduce over time. This has been exemplified in the case study where the greatest amount of contaminant desorption occurred early after construction where, in that situation, the aggregate was saturated from a high water table immediately after construction. It is recommended that computations be repeated based upon water input concentrations reducing over time.

Flow rates: computations have been undertaken for total flows both vertically and horizontally. In reality, both flows will occur simultaneously, where horizontal flow will be the preferential route, providing the aggregate k values are higher than those of the subgrade. It is recommended that a method should be determined to calculate the percentage of flow that moves in each direction during any timescale, so as to more accurately predict the rate of contaminant movement.

GCLs: the use of GCLs as a method to retard flows of contaminated water so as to increase the sorption capacity has been recommended. Giroud, et al. (1997) suggest that k values should be based upon an assumption that holes are present within membranes, with the distribution of holes being based upon holes per hectare. Firstly this gives more realistic flow rates should damage to the GCL occur, and secondly the increased k values allow realistic flow rates to be determined based upon, for example, a realistic value of $k \simeq 10^{-11}$ m/s. This is instead of a value of say, $k \simeq 10^{-14}$ m/s, which would not be realistic should any damage to the GCL occur. It is recommended that further research be undertaken based upon Giroud, et al. (1997) so as to adapt generated data to reflect this.

GCLs have been recommended for the retardation of vertical contaminated flows below a pavement through a subgrade towards ground water below, where necessary. It is recommended that further research into the use of GCLs as a means to facilitate the sorption of contaminants in other areas such as embankments, to which computations have not been extended.

Model development: there appears at present to be no current computer model simulating the movement of contaminated flows from pavement constructions to water bodies. Whilst the risk assessment guide developed is a qualitative/semi-quantitative approach, the development of a fully quantitative model would be well received by contractors wanting to undertake detailed site-specific assessments. There are two quantitative models currently available, Landsim for landfill sites (Golder Associates, 1996) and Consim for contaminated sites (Golder Associates, 1998). It is recommended that the development of such a model for pavement construction along a similar user-friendly style be undertaken. Treatment regimes (including those recommended within this research) could be included, in order to allow users to vary input parameters for different construction scenarios. The risk assessment model currently being developed and described in Chapter 2 (Apul, 2001, 2003) may prove to be a detailed, quantitative model when complete.

Confirmation of theoretical ideas: this thesis is a result of a current lack of research on risks resulting from the use of alternative materials in pavement construction. Computations using theoretical ideas have been undertaken. These have been based upon modelling: (1) contaminated water flowing vertically through the subgrade, where sorption by partitioning occurs, and (2) rates of contaminant movement and discharge through side drains in horizontal flow, using calculations to simulate variations in aggregate properties (e.g. different k values, porosities and saturation rates). Resultant data have been the basis for the development of guidelines described here. It is recommended that field work should be undertaken in order to confirm the accuracy of these calculations.

Pavement decommissioning: calculations are based upon pavements during their working lives. Recommendations have been made regarding resurfacing/surface dressing to maintain the pavement integrity. It is recommended that guidelines be issued for protecting water bodies from contaminants when decommissioning of the pavement occurs.

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Glossary of Terms

aggregate	natural rock or mineral that has developed over thousands of years and is often extracted as broken stone by mining or quarrying for use in construction.
alternative material	material which is a by-product of a previous use in another industry or a naturally sourced material not normally used in road construction.
breakthrough time	the time it takes for a chemical or substance to reach a selected reference point within an advancing water front, often quoted as 10% or 15% of input concentration.
brownfield sites	a site that has been previously used and requires preparation before it may be used again.
coefficient of permeability	measure of the speed by which water moves through either a 'subgrade' or 'aggregate' under reference conditions. It is specific for that medium.
contaminant	chemical with the potential to cause 'harm'.
desorption	process by which contaminants are removed from 'source' aggregate into water flow.
equilibrium	used about chemical process to define the condition at which there are no further transfers between two phases and/or no further chemical reactions.
finite layer	individual layer in which modelled process occurs.
finite resource	'resource' of limited quantity (i.e. non-renewable).
generic risk assessment guide	non site-specific risk assessment guide.
geomembrane	engineered material fabricated to be virtually impermeable.
groundwater	a body of sub-surface water occupying pore space in the ground.
harm	"harm to the health of living organisms and their ecological systems and in the case of humans, harm also to his property".
horizontal flow	water flow moving near-horizontally through a pavement aggregate towards side drains.

infiltration	process by which rainfall enters pavement through surface cracks.
input time	time step for water to enter pavement profile in computational model.
leachant	water into which contaminants from 'source' migrate.
leachate	water containing contaminants that have migrated from 'source'.
leaching	process by which contaminants leach from 'source'.
lysimeter	outdoor testing cells composed of compacted aggregates designed to represent real-pavement construction.
minimum saturation	minimum degree of saturation that remains within an aggregate after maximum drainage occurs.
partitioning	process by which contaminants are transferred from one phase to another in soil or aggregate.
partition coefficient	Equilibrium ratio between contaminant concentration in solid and water phases and is contaminant and medium-dependent, expressed in units of volume divided by mass.
pathway	route by which 'source' contaminants reach 'receptor'.
pavement	any ground surface which is covered in construction materials with the purpose of providing an improved surface for people or vehicles to move over.
pavement surface	bound top layer of 'pavement'.
pavement base/sub-base	bulk layers of aggregate providing a pavement with stability and strength.
phreatic surface	see 'water table'.
porosity	ratio of voids to total volume of aggregate or soil.
receptor	pre-determined point at which contaminants migrating from 'source' are assessed.
recycled material	material that has had a previous use.
residence time	time that water remains within each computational layer.
risk	"the chance that a particular adverse effect actually occurs in a particular time period".

risk assessment	"identification, estimation and evaluation of risk".
risk assessment guide	guide against which a user may assess the suitability, in terms of risk, of a potential construction aggregate prior to use.
saturated medium	when voids in a medium are all filled with water.
settling pool	man-made area of containment into which pavement drainage water may be directed.
side drains	constructed at intervals along a pavement route into which horizontal water flow will drain.
sorbant	subgrade (or other material) onto/into which contaminant affixes itself.
sorption	process by which contaminants in water migrate onto subgrade (or other material).
source	aggregate from which contaminants migrate.
subgrade	natural soil or soil fill below a pavement.
surcharged flow	water flow under additional pressure other than normal gravitational attraction.
surface cracking	distress cracking to pavement surface.
surface runoff	water washed off pavement surface which may carry contaminants from degraded pavement or from passing vehicles.
sustainable development	"development that meets the needs of the present without compromising the ability of future generations to meet their own needs".
time interval	time step for water to flow from one layer to the next in computational model.
T_f	time that it takes for a particular percentage (f) of drainable water to actually drain from an aggregate.
traditional aggregate	'aggregate' that has been used in construction over a long period of time.
unsaturated medium	when voids in a medium are partially filled with water.
unsurcharged flow	water flow under normal gravitational attraction.
vertical flow	flow moving vertically through a pavement aggregate and then through the subgrade towards the water table below.
water bodies	groundwater and surface water.

water table	used in this document as synonymous with 'phreatic surface' – level in ground at which groundwater as at atmospheric pressure.
worst-case scenario	represents the worst conditions which are credible to imagine.

' also defined within Glossary of Terms
" definition referenced in thesis text

Appendices

Appendix 1 – Lysimeter Data

Lysimeters: Lysimeters are outside testing cells representative of real-pavement conditions. The data given below result from Hill, et al. (2001), where nine lysimeters containing different aggregates or mixtures were constructed. They were designed with a surface area of 1 m^2 and an overall depth of aproximately 0.6 m, where a 0.35 m layer of test material was placed upon a gravel drainage layer in the base. Single-sized coarse gravel was used to top the cells. Being unsurfaced, the lysimeters replicated worst-case scenarios during construction, before surfacing was undertaken. The cells were exposed to normal rainfall for nine months and leachates draining from them were periodically analysed. The following data from the lysimeters are those on which calculations within this thesis are based, and do not contain data from all the lysimeter analyses. Further details of the research behind Hill, et al. (2001) is presented in Chapter 2, where a lysimeter cross-section is illustrated.

Chemical Analysis – Lysimeter 1

mg/l

Date	Ca	Mg	Na	K	Total Alk (HCO_3)	Cl	SO_4	NO_3	Br	NO_2	F	TOC	TIC	Total P	Total S	NH_4	Si	Ba	Sr	Mn	Total Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B	As
21/10/99	2.01	0.52	110	1705	2101	113	163	<0.80	3.95	0.629	2.30	16.2	125	2.68	143	2.62	5.48	0.016	0.016	0.004	0.088	0.160	<0.044	<0.032	0.029	0.085	0.082	0.067	<0.024	<0.140	0.153	0.389	0.26	<0.075
01/11/99	2.41	0.15	53.5	831	1209	112	97.4	<0.40	3.62	0.138	2.36	16.2	157	1.20	36.2	<2.00	14.1	0.006	0.016	0.004	0.056	0.999	<0.022	<0.016	0.018	0.085	<0.038	0.030	<0.012	<0.070	0.104	0.196	0.11	<0.050
24/11/99	2.07	0.14	81.9	1269	1925	176	99.2	<0.40	5.59	0.203	2.51	114	277	1.48	35.0	2.19	18.8	0.006	0.015	0.006	0.057	1.930	<0.033	<0.024	0.032	0.087	<0.057	0.027	<0.018	<0.105	0.091	0.346	0.10	<0.075
19/01/00	2.16	<0.30	68.5	1067	1580	152	135	2.48	4.97	1.54	2.23	19	138	1.52	41.9	2.71	16.6	<0.020	0.040	<0.010	<0.060	2.550	<0.110	<0.080	<0.050	0.130	<0.190	<0.160	<0.060	<0.350	<0.100	0.312	<0.30	<0.075
07/02/00	2.98	0.66	198	2977	3687	594	677	2.62	18.4	2.63	4.73	10.3	370	5.26	226	2.30	19.6	0.060	0.080	0.020	0.150	4.656	<0.110	0.111	0.090	0.080	0.284	<0.400	<0.060	<0.350	0.250	0.673	0.36	<0.075
28/02/00	1.71	<0.30	48.9	749	1096	103	89.0	<0.40	3.14	0.238	1.51	14.9	159	1.11	30.6	<2.00	11.5	<0.02	0.030	<0.010	<0.060	0.543	<0.110	<0.080	<0.050	0.153	<0.190	<0.080	<0.060	<0.350	<0.100	0.204	<0.30	<0.075
24/03/00	1.27	<0.15	111.7	1705	2033	299	395	1.94	9.33	5.10	3.70	73.0	280	2.83	133.6	3.02	11.54	<0.010	0.035	<0.005	0.030	0.000	<0.055	<0.04	<0.025	0.132	0.104	0.081	<0.03	<0.175	0.065	0.318	<0.15	<0.075
10/04/00	2.175	<0.15	90.3	1387	1734	232.97	304.85	<0.20	1.437	<0.050	3.30	60.4	234	2.04	103.5	3.27	21.71	<0.010	0.040	<0.005	0.040	1.018	<0.055	<0.04	<0.025	0.151	<0.095	0.042	<0.03	<0.175	0.083	0.327	0.20	<0.075
26/09/00	1.68	<0.12	13.5	207	313	26.1	27.2	<0.04	0.88	<0.01	0.82	1.44	11.25	0.33	8.94	<0.04	5.67	<0.008	0.008	<0.004	0.11	0.13	<0.044	<0.032	<0.020	0.060	<0.076	<0.032	<0.024	<0.14	<0.040	0.069	<0.12	<0.075

Chemical Analysis – Lysimeter 2

mg/l

Date	Ca	Mg	Na	K	Total Alk (HCO_3)	Cl	SO_4	NO_3	Br	NO_2	F	TOC	TIC	Total P	Total S	NH_4	Si	Ba	Sr	Mn	Total Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B	As
21/10/99	11.9	10.5	1011	7263	14746	56.6	273	<0.40	<0.30	<0.100	30.5	2192	2191	1.56	65.2	<2.00	17.0	0.450	0.105	0.090	1.52	<0.420	<0.165	0.237	2.111	0.529	<0.285	0.129	<0.090	<0.525	0.159	0.326	<0.45	<0.075
01/11/99	8.33	7.82	901	6567	12741	42.4	226	<0.40	<0.30	<0.100	29.3	1759	1975	0.89	53.5	2.35	15.4	0.165	0.090	0.090	1.40	<0.420	<0.165	0.157	1.331	0.358	<0.285	<0.120	<0.090	<0.525	<0.150	0.266	<0.45	<0.075
24/11/99	7.02	5.45	785	5729	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.84	44.9	2.96	14.4	0.144	0.072	0.072	1.36	<0.336	<0.132	0.127	1.551	0.326	<0.228	<0.096	<0.072	<0.420	<0.120	0.239	<0.36	<0.075
19/01/00	4.36	2.08	296	2243	4320	13.8	37.8	<0.40	<0.300	<0.100	26.6	150	846	1.55	15.1	2.84	12.8	0.090	0.040	0.020	0.730	<0.280	<0.110	<0.080	1.504	0.215	<0.190	<0.080	<0.060	<0.350	<0.100	0.106	<0.30	<0.075
07/02/00	4.18	2.00	239	1827	3611	19.4	29.8	<0.80	<0.600	<0.200	24.6	222	552	3.94	13.3	7.66	13.4	0.090	0.040	0.020	0.720	<0.280	<0.110	0.106	1.564	0.215	<0.190	<0.080	<0.060	<0.350	<0.100	0.100	<0.30	<0.075
28/02/00	2.14	0.72	86.1	657	1297	5.78	13.1	<0.20	<0.150	<0.050	11.3	57.3	269	ns	4.59	3.65	10.4	0.030	0.010	<0.010	0.350	<0.280	<0.110	<0.080	1.137	0.177	<0.190	0.000	<0.060	<0.350	<0.100	<0.030	<0.30	<0.075
24/03/00	4.57	1.38	125.15	976	1892	7.32	16.8	0.70	<0.150	0.125	17.1	134	375	4.45	6.6	8.95	16.27	0.070	0.030	0.010	0.600	<0.280	<0.110	<0.080	2.445	0.403	<0.190	<0.080	<0.060	<0.350	<0.100	0.043	<0.30	<0.075
10/04/00	3.81	0.94	102.5	816	1579	7.66	11.51	<0.04	0.035	<0.010	<0.05	84.8	312	3.33	5.0	7.69	16.73	0.050	0.020	<0.01	0.490	<0.280	<0.110	<0.080	1.947	0.188	<0.190	<0.080	<0.060	<0.350	<0.100	<0.030	<0.30	<0.075
26/09/00	1.94	<0.60	18.2	184	180	1.96	3.63	<0.08	<0.06	<0.02	3.55	9.10	11.60	<1.00	1.32	<0.04	22.3	0.040	<0.020	<0.020	0.20	<0.560	0.22	<0.160	1.151	0.106	<0.380	<0.160	<0.120	<0.700	<0.200	<0.060	<0.60	<0.075

Chemical Analysis – Lysimeter 3

mg/l

Date	Ca	Mg	Na	K	Total Alk (HCO_3)	Cl	SO_4	NO_3	Br	NO_2	F	TOC	TIC	Total P	Total S	NH_4	Si	Ba	Sr	Mn	Total Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B	As
21/10/99	15.4	2.21	5.85	4.82	46.4	9.6	26.7	6.30	1.909	1.235	0.20	53.39	9.11	0.99	10.74	10.37	1.39	0.056	0.063	0.055	0.012	<0.028	<0.011	<0.008	<0.005	0.487	<0.019	<0.008	<0.006	<0.035	<0.010	0.003	0.075	<0.025
01/11/99	10.6	1.45	2.72	2.42	44.6	2.4	11.1	2.99	0.769	0.979	0.13	27.22	6.03	0.65	6.53	<2.00	1.25	0.049	0.043	0.046	0.013	<0.028	<0.011	<0.008	<0.005	0.423	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	0.050	<0.025
24/11/99	22.8	3.52	5.70	6.01	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.73	11.67	6.52	1.89	0.087	0.094	0.092	0.020	<0.028	<0.011	<0.008	0.006	0.714	<0.019	<0.008	<0.006	<0.035	<0.010	0.006	0.067	<0.025
19/01/00	22.1	3.32	5.69	2.74	38.0	8.5	33.1	25.85	2.119	2.477	0.13	27.54	8.90	1.06	11.06	7.64	1.58	0.059	0.090	0.100	<0.006	<0.028	<0.011	<0.008	<0.005	0.846	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	0.054	<0.025
07/02/00	22.9	3.43	6.89	2.60	24.5	13.8	48.4	18.31	2.880	2.070	0.21	48.62	5.67	1.32	17.27	4.82	1.43	0.054	0.092	0.124	0.018	<0.028	<0.011	<0.008	<0.005	1.181	<0.019	<0.008	<0.006	<0.035	<0.010	0.004	0.098	<0.025
28/02/00	10.4	1.24	2.83	1.26	<22.0	3.6	15.4	4.14	1.045	1.051	0.13	26.23	6.75	0.58	6.19	<2.00	0.79	0.023	0.034	0.054	0.013	<0.028	<0.011	<0.008	0.009	0.719	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	0.034	<0.025
24/03/00	18.07	2.70	4.18	1.63	24.0	4.8	35.4	17.04	2.454	1.251	0.12	50.23	<5.00	0.79	13.89	4.63	1.31	0.046	0.067	0.108	0.016	<0.028	<0.011	<0.008	0.011	1.410	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	0.073	<0.075
10/04/00	26.859	4.54	6.391	2.23	<22.0	7.1	39.6	>50	1.009	2.030	0.09	11.41	<5.00	0.10	13.90	3.04	2.22	0.060	0.103	0.112	<0.006	<0.028	<0.011	<0.008	<0.005	1.431	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	ns	<0.075
26/09/00	11.5	1.34	1.01	1.10	<22	1.7	35.7	3.88	2.610	0.350	0.06	8.00	<0.50	0.25	13.64	0.94	1.08	0.027	0.033	0.151	0.019	<0.030	0.017	<0.008	0.015	7.206	<0.019	<0.008	<0.006	<0.035	<0.010	0.003	0.080	<0.075

Chemical Analysis – Lysimeter 4

mg/l

Date	Ca	Mg	Na	K	Total Alk (HCO_3)	Cl	SO_4	NO_3	Br	NO_2	F	TOC	TIC	Total P	Total S	NH_4	Si	Ba	Sr	Mn	Total Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B	As
21/10/99	482	<0.03	111	323	1190	117.4	436.4	2.84	0.839	3.225	<1.00	13.13	16.14	0.05	278.25	4.02	2.17	0.160	2.176	0.001	<0.006	0.036	<0.011	<0.008	0.006	0.073	<0.019	<0.008	<0.006	<0.035	<0.010	1.455	0.153	<0.025
01/11/99	649	<0.06	308	937	1921	325.2	945.2	<2.00	2.172	3.820	<2.50	21.33	10.87	0.11	645.69	4.75	0.83	0.152	6.418	0.002	<0.012	<0.056	<0.022	0.017	0.044	0.059	<0.038	<0.016	<0.012	<0.070	<0.020	4.185	0.318	<0.050
24/11/99	536	<0.09	397	1240	1887	422.8	1,067.4	2.60	2.545	4.983	<2.50	40.47	2.73	<0.15	896.00	4.58	0.82	0.120	6.636	0.003	<0.018	<0.084	<0.033	<0.024	0.049	0.074	<0.057	<0.024	<0.018	<0.105	<0.030	5.620	0.441	<0.075
19/01/00	38.0	<0.15	243	844	981	273.7	247.4	2.06	1.652	4.151	<1.00	11.05	19.60	<0.25	1,009.48	4.76	0.44	0.080	2.900	<0.005	<0.030	<0.140	<0.055	<0.040	<0.025	0.110	<0.095	<0.040	<0.030	<0.175	<0.050	4.126	0.450	<0.075
07/02/00	53.0	<0.15	233	754	934	226.5	280.1	6.87	1.210	9.525	<1.00	11.90	39.88	<0.25	693.54	5.17	1.10	0.150	3.310	<0.005	<0.030	<0.140	<0.055	<0.040	<0.025	0.084	<0.095	<0.040	<0.030	<0.175	<0.050	3.744	0.325	<0.075
28/02/00	479	<0.30	72.7	284	1742	80.0	29.2	1.04	0.450	0.809	0.37	12.40	13.08	<0.50	162.62	3.07	0.70	2.540	5.800	<0.010	<0.060	<0.280	<0.110	<0.080	<0.050	0.092	<0.190	<0.080	<0.060	<0.350	<0.100	1.580	<0.300	<0.075
24/03/00	330.62	<0.15	53.515	196	1044	44.7	85.8	5.07	0.255	3.731	0.32	12.23	31.31	<0.05	106.09	4.04	2.67	2.104	3.609	<0.001	<0.006	0.275	<0.011	<0.008	<0.005	0.044	<0.019	<0.008	<0.006	<0.035	<0.010	1.123	0.061	<0.075
10/04/00	1.431	<0.30	128.87	464	596	>100	111.0	11.59	0.636	<0.010	0.49	9.82	44.78	0.06	189.63	2.56	4.38	0.364	1.229	<0.001	0.007	0.172	<0.011	<0.008	0.022	0.059	<0.019	0.017	<0.006	<0.035	<0.010	2.569	0.129	<0.075
26/09/00	186	<0.09	8.54	72.6	422	6.3	66.5	3.73	0.090	1.044	0.37	2.18	0.65	<0.15	214.30	0.32	2.94	0.948	1.851	0.012	2.121	0.233	<0.033	<0.024	<0.015	0.042	<0.057	<0.024	<0.018	<0.105	<0.030	0.414	0.111	<0.075

Chemical Analysis – Lysimeter 5

Date	mg/l																																	
	Ca	Mg	Na	K	Total Alk (HCO_3)	Cl	SO_4	NO_3	Br	NO_2	F	TOC	TIC	Total P	Total S	NH_4	Si	Ba	Sr	Mn	Total Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B	As
21/10/99	36.1	2.21	41.4	28.3	29.3	85.9	70.8	4.83	0.376	0.204	0.21	17.74	7.38	0.20	25.10	<2.00	0.81	0.041	0.127	0.008	0.045	0.394	<0.011	<0.008	0.020	0.072	<0.019	0.012	<0.006	<0.035	<0.010	0.005	0.044	<0.025
01/11/99	31.4	1.22	43.4	25.2	61.9	84.4	64.1	2.09	0.378	0.563	<0.10	10.43	6.07	<0.05	21.74	4.28	0.79	0.030	0.106	0.002	0.024	0.125	<0.011	<0.008	<0.005	0.078	<0.019	0.017	<0.006	<0.035	<0.010	0.004	0.032	<0.025
24/11/99	52.7	3.61	39.8	25.5	55.4	77.7	98.3	5.77	0.348	0.775	0.19	14.35	11.50	<0.05	33.27	<2.00	1.58	0.045	0.172	0.008	0.013	0.212	<0.011	<0.008	0.015	0.056	<0.019	0.012	<0.006	<0.035	<0.010	0.006	0.095	<0.025
19/01/00	86.2	4.11	59.2	29.69	49.7	112.3	191.2	4.41	0.475	0.259	0.15	6.63	10.05	<0.05	64.37	2.68	0.96	0.047	0.265	0.003	<0.006	0.112	<0.011	<0.008	<0.005	0.059	<0.019	0.014	<0.006	<0.035	<0.010	0.005	0.125	<0.025
07/02/00	60.8	3.16	48.6	24.2	24.1	91.3	147.0	3.47	0.482	0.344	0.22	7.84	4.72	<0.05	49.24	2.93	0.82	0.030	0.195	0.004	<0.006	0.373	<0.011	<0.008	0.008	0.051	<0.019	0.012	<0.006	<0.035	<0.010	0.004	0.087	<0.025
28/02/00	18.3	0.64	14.4	8.85	23.8	24.5	36.9	1.43	0.121	0.088	0.14	14.31	7.63	<0.05	11.99	<2.00	0.64	0.006	0.050	0.001	<0.006	0.572	<0.011	<0.008	<0.005	0.040	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	0.031	<0.025
24/03/00	43.67	2.14	34.16	18	33.5	56.6	94.3	8.56	0.237	0.453	0.17	13.70	14.87	<0.05	32.28	3.50	1.01	0.021	0.132	0.004	0.007	0.216	<0.011	<0.008	0.012	0.072	<0.019	0.014	<0.006	<0.035	<0.010	<0.003	0.074	<0.075
10/04/00	66.29	5.40	44.65	17	47.2	96.6	114.6	11.85	0.398	0.164	0.13	7.94	9.30	<0.05	38.98	<0.40	1.22	0.030	0.240	<0.001	<0.006	0.082	<0.011	<0.008	<0.005	0.077	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	ns	<0.075
26/09/00	34.2	1.22	22.1	13.8	42	37.4	70.1	<0.04	0.137	<0.010	0.10	3.48	1.02	<0.05	23.96	<0.04	1.58	0.014	0.084	0.001	0.007	0.202	<0.011	<0.008	0.013	0.071	<0.019	0.009	<0.006	<0.035	<0.010	0.006	0.090	<0.075

Chemical Analysis – Lysimeter 6

Date	mg/l																																	
	Ca	Mg	Na	K	Total Alk (HCO_3)	Cl	SO_4	NO_3	Br	NO_2	F	TOC	TIC	Total P	Total S	NH_4	Si	Ba	Sr	Mn	Total Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B	As
21/10/99	286	<0.06	173	591	2146	6.8	9.8	5.95	<0.030	0.920	0.51	25.82	2.55	<0.10	3.70	<2.00	2.01	1.366	4.442	<0.002	<0.012	0.704	<0.022	<0.016	<0.010	0.082	<0.038	<0.016	<0.012	<0.070	<0.020	1.025	<0.060	<0.050
01/11/99	238	<0.06	150	516	1866	1.2	2.7	1.76	<0.030	0.227	0.38	8.09	<1.00	<0.10	3.16	<2.00	2.38	1.382	3.860	<0.002	<0.012	0.436	<0.022	<0.016	<0.010	0.072	<0.038	<0.016	<0.012	<0.070	<0.020	0.968	<0.060	<0.050
24/11/99	4.56	<0.06	206	676	1680	5.6	12.0	7.62	<0.030	0.982	0.91	15.57	65.83	<0.10	4.24	<2.00	5.02	0.228	1.120	0.002	0.024	0.499	<0.022	<0.016	<0.010	0.103	<0.038	<0.016	<0.012	<0.070	<0.020	1.227	<0.060	<0.050
19/01/00	1.85	0.03	158	499	1280	3.7	6.0	3.31	0.034	0.504	0.73	8.80	130.00	<0.05	2.14	<2.00	3.60	0.093	0.598	0.002	0.016	0.527	<0.011	0.010	0.010	0.071	0.020	0.011	<0.006	<0.035	0.015	1.118	<0.030	<0.025
07/02/00	2.11	<0.15	212	654	1674	4.3	8.7	4.00	<0.030	0.519	0.65	11.85	95.15	<0.25	3.47	<2.00	3.27	0.055	0.500	<0.005	<0.030	0.539	<0.055	<0.040	<0.025	0.090	<0.095	<0.040	<0.030	<0.175	<0.050	1.569	<0.150	<0.075
28/02/00	251	<0.30	37.6	133	967	1.4	2.1	1.21	<0.030	0.123	0.26	8.58	14.47	<0.50	1.06	4.90	1.12	1.090	2.200	<0.010	<0.060	<0.280	<0.110	<0.080	<0.050	0.073	<0.190	<0.080	<0.060	<0.350	<0.100	0.341	<0.300	<0.075
24/03/00	315.31	<0.30	101.15	303	1555	2.4	5.1	4.30	<0.030	0.407	0.27	15.22	16.86	<0.05	2.32	<2.00	1.51	1.933	4.750	<0.001	<0.006	0.436	<0.011	<0.008	<0.005	0.087	<0.019	<0.008	<0.006	<0.035	<0.010	0.934	<0.030	<0.075
10/04/00	1.734	<0.30	109.05	295	764	3.6	8.7	0.08	<0.030	3.031	0.55	<5.00	162.05	0.21	3.34	<0.40	3.85	0.040	0.169	<0.001	0.018	0.197	<0.011	0.009	0.011	0.074	<0.019	0.011	<0.006	<0.035	0.013	0.933	<0.030	<0.075
26/09/00	373	<0.06	9.79	33.0	1055	1.5	1.7	2.82	<0.030	0.330	0.26	2.07	2.73	<0.10	1.39	0.07	0.82	1.828	3.384	<0.002	<0.012	0.252	<0.022	<0.016	<0.010	0.029	<0.038	<0.016	<0.012	<0.070	<0.020	0.234	<0.060	<0.075

Chemical Analysis – Lysimeter 7

mg/l

Date	Ca	Mg	Na	K	Total Alk (HCO_3)	Cl	SO_4	NO_3	Br	NO_2	F	TOC	TIC	Total P	Total S	NH_4	Si	Ba	Sr	Mn	Total Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B	As
21/10/99	45.9	4.83	6.20	2.50	83.1	8.2	51.8	12.13	0.068	0.013	1.90	6.66	16.13	<0.05	17.84	3.21	1.68	0.037	0.551	<0.001	<0.006	<0.028	<0.011	<0.008	<0.005	0.060	<0.019	<0.008	<0.006	<0.035	<0.010	0.006	0.067	<0.025
01/11/99	61.7	8.54	19.0	3.08	76.2	32.0	78.1	46.29	0.267	0.018	1.55	8.74	14.47	<0.05	26.67	<2.00	2.53	0.049	0.598	<0.001	<0.006	<0.028	<0.011	<0.008	<0.005	0.073	<0.019	<0.008	<0.006	<0.035	<0.010	0.009	0.110	<0.025
24/11/99	59.8	8.32	17.6	3.39	76.5	24.3	86.2	36.56	0.202	0.036	1.47	8.71	15.00	0.06	29.40	2.73	2.51	0.042	0.579	0.001	0.014	<0.028	<0.011	<0.008	<0.005	0.084	<0.019	<0.008	<0.006	<0.035	<0.010	0.009	0.110	<0.025
19/01/00	51.7	7.42	9.52	2.39	81.6	7.0	88.4	10.32	0.049	0.011	1.31	4.48	16.52	<0.05	29.51	10.37	2.29	0.041	0.510	<0.001	<0.006	<0.028	<0.011	<0.008	<0.005	0.091	<0.019	<0.008	<0.006	<0.035	<0.010	0.005	0.091	<0.025
07/02/00	53.0	7.91	10.6	2.70	79.1	6.5	102.6	11.17	0.037	0.043	1.44	3.85	14.95	<0.05	33.24	2.63	2.81	0.041	0.492	<0.001	<0.006	<0.028	<0.011	<0.008	<0.005	0.050	<0.019	<0.008	<0.006	<0.035	<0.010	0.007	0.120	<0.025
28/02/00	35.7	3.30	2.90	1.57	85.8	4.4	20.4	6.34	<0.030	0.052	1.84	<5.00	26.33	<0.05	6.78	<2.00	1.20	0.073	0.496	<0.001	<0.006	<0.028	<0.011	<0.008	<0.005	0.069	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	<0.030	<0.025
24/03/00	34.13	84.44	3.183	1.96	90.8	3.2	26.9	5.92	<0.030	0.039	1.73	6.98	17.94	<0.05	8.90	<2.00	1.50	0.056	0.397	0.002	<0.006	0.075	0.011	<0.008	0.009	0.069	<0.019	0.021	<0.006	<0.035	0.011	0.007	ns	<0.075
10/04/00	51.39	6.99	7.01	3.26	88.2	53.6	754.2	100.84	<0.300	1.165	13.07	<5.00	17.73	<0.05	26.37	1.26	2.15	0.062	0.520	<0.001	<0.006	<0.028	<0.011	<0.008	<0.005	0.102	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	ns	<0.075
26/09/00	32.3	2.28	0.33	1.24	33	0.6	16.5	5.58	<0.030	0.026	1.69	1.42	2.82	<0.05	5.54	<0.04	0.97	0.134	0.382	0.006	0.658	<0.030	<0.011	<0.008	<0.005	0.088	<0.019	<0.008	<0.006	<0.035	<0.010	<0.003	<0.030	<0.075

Chemical Analysis – Lysimeter 8

mg/l

Date	Ca	Mg	Na	K	Total Alk (HCO_3)	Cl	SO_4	NO_3	Br	NO_2	F	TOC	TIC	Total P	Total S	NH_4	Si	Ba	Sr	Mn	Total Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B	As
21/10/99	518	10.9	147	470	<22.0	156.5	1,879.8	<0.40	1.226	0.160	4.36	7.76	3.94	<0.25	669.89	2.47	14.98	0.055	1.575	0.105	0.040	0.221	<0.055	<0.040	0.034	0.091	<0.095	0.046	<0.030	<0.175	0.091	2.942	2.945	<0.075
01/11/99	530	11.0	92.5	396	33.1	67.6	1,709.2	<0.40	0.549	0.178	3.92	7.49	6.50	0.31	642.41	2.28	14.68	0.050	1.615	0.125	0.040	0.160	<0.055	0.043	<0.025	0.094	<0.095	<0.040	<0.030	<0.175	0.058	1.910	2.950	<0.075
24/11/99	530	13.1	64.9	332	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.35	603.38	2.61	15.20	0.055	1.580	0.160	0.040	0.182	<0.055	0.045	0.026	0.101	<0.095	<0.040	<0.030	<0.175	0.076	1.481	2.730	<0.075
19/01/00	533	10.4	16.6	150	45.3	12.6	1,459.6	<0.40	<0.300	<0.100	3.53	4.44	9.37	0.12	500.59	2.34	20.71	0.032	1.308	0.166	0.012	<0.056	<0.022	<0.016	<0.010	0.109	<0.038	<0.016	<0.012	<0.070	0.031	0.571	2.192	<0.050
07/02/00	538	13.6	20.8	175	70.1	15.8	1,557.7	0.64	<0.300	0.788	3.70	5.11	11.13	0.10	517.74	3.01	20.06	0.036	1.420	0.110	<0.012	0.058	<0.022	<0.016	<0.010	0.081	<0.038	<0.016	<0.012	<0.070	0.025	0.640	2.296	<0.050
28/02/00	544	11.8	9.93	98.4	27.6	10.6	1,619.4	<0.20	<0.150	<0.050	4.16	7.34	6.47	<0.50	483.18	<2.00	24.94	0.020	1.270	0.220	<0.060	<0.280	<0.110	<0.080	<0.050	0.103	<0.190	<0.080	<0.060	<0.350	<0.100	0.416	2.030	<0.075
24/03/00	579.2	10.98	10.655	110.95	<22.0	18.7	1,568.0	0.61	<0.300	0.235	3.73	7.19	<5.00	<0.05	510.96	<2.00	23.53	0.015	1.360	0.130	<0.030	<0.140	<0.055	<0.040	<0.025	0.069	<0.095	<0.040	<0.030	<0.175	<0.050	0.430	2.145	<0.075
10/04/00	568.93	10.85	10.88	108	59.1	9.5	1,228.9	2.97	<0.300	0.166	2.57	5.79	13.91	<0.10	491.31	0.53	18.99	0.032	1.320	0.076	<0.006	<0.140	<0.022	<0.016	<0.010	0.093	<0.038	<0.016	<0.012	<0.070	<0.020	0.400	2.024	<0.075
26/09/00	599	7.12	5.14	57.7	<22	2.9	1,549.0	<0.04	<0.030	<0.010	3.87	1.79	<0.50	<0.10	496.64	<0.04	21.50	0.042	1.292	0.018	0.184	0.122	<0.022	0.028	0.015	0.044	<0.038	<0.016	<0.012	<0.070	0.054	0.313	2.024	<0.075

Chemical Analysis – Lysimeter 9

mg/l

Date	Ca	Mg	Na	K	Total Alk (HCO_3)	Cl	SO_4	NO_3	Br	NO_2	F	TOC	TIC	Total P	Total S	NH_4	Si	Ba	Sr	Mn	Total Fe	Al	Co	Ni	Cu	Zn	Cr	Mo	Cd	Pb	V	Li	B	As
21/10/99	23.5	<0.12	1892	1564	1699	3,125.4	346.5	<2.00	15.907	1.214	<2.50	298.09	20.91	0.74	131.76	17.43	2.03	0.056	0.264	0.016	0.028	337.275	<0.044	0.060	3.623	0.237	<0.076	1.029	0.029	0.713	<0.040	0.013	0.288	0.251
01/11/99	6.54	<0.15	3175	2453	1413	5,879.8	969.4	<2.00	28.361	1.859	<2.50	249.80	135.60	0.61	355.50	23.02	1.66	0.030	0.110	0.010	<0.030	182.266	<0.055	0.138	4.500	0.096	0.100	1.520	<0.030	0.412	<0.050	<0.015	0.645	0.169
24/11/99	2.01	0.24	3440	2714	1422	6,688.1	1,263.5	<2.00	33.030	0.830	<2.50	170.00	197.90	0.34	430.60	22.77	1.15	<0.012	0.012	0.006	<0.036	49.860	<0.066	0.129	3.299	0.137	<0.114	1.580	<0.036	<0.210	<0.060	<0.018	0.636	<0.075
19/01/00	1.42	0.30	1863	1415	1180	3,383.6	731.8	<2.00	18.034	2.834	<2.50	111.60	172.40	<0.50	225.69	10.19	0.73	<0.020	<0.010	0.010	<0.060	31.657	<0.110	0.105	1.673	0.116	<0.190	0.876	<0.060	<0.350	<0.100	<0.030	0.390	<0.075
07/02/00	2.59	0.62	2247	1722	1324	3,661.4	893.6	<2.00	14.525	1.313	<2.50	95.10	238.20	0.71	321.72	26.90	0.78	<0.020	0.010	0.010	<0.060	12.420	<0.110	0.119	1.589	0.101	<0.190	1.127	<0.060	<0.350	<0.100	<0.030	0.510	<0.075
28/02/00	7.76	<0.30	471	407	756	627.8	164.6	1.15	3.171	0.387	<0.50	42.96	37.94	<0.50	58.54	5.52	0.97	0.020	0.170	<0.010	<0.060	143.303	<0.110	<0.080	0.591	0.111	<0.190	0.343	<0.060	0.368	<0.100	<0.030	<0.300	<0.075
24/03/00	1.239	<0.30	798.77	651	740	1,249.7	418.3	1.29	5.220	2.715	0.73	45.15	107.85	0.23	144.95	13.83	0.51	0.007	0.012	0.003	0.008	34.169	<0.011	0.031	0.525	0.149	0.056	0.499	0.009	0.096	0.018	0.018	0.334	<0.075
10/04/00	2.57	<0.45	1527.98	1161	1030	>100	67.8	<0.04	1.238	0.282	<0.05	65.30	198.25	<0.75	230.73	16.87	0.63	<0.030	0.090	<0.015	<0.090	3.563	<0.165	<0.120	0.889	0.113	<0.285	0.848	<0.090	<0.525	<0.150	<0.045	<0.450	<0.075
26/09/00	54.4	<0.30	157	165	<500	164.0	132.0	1.89	0.950	1.570	0.31	4.03	<0.50	<0.50	39.63	0.32	1.18	0.090	0.560	<0.010	<0.060	82.920	<0.110	<0.080	0.391	0.135	<0.190	0.198	<0.060	<0.350	<0.100	0.036	<0.300	<0.075

Appendix 2 – List I and List II Substances

List I (Black List) Substances (NRA, 1992)
Organohalogen compounds and substances which may form such compounds in the aquatic environment.
Organophosphorus compounds.
Organotin compounds.
Substances which possess carcinogenic, mutagenic or teratogenic properties in or via the aquatic environment (including substances which have those properties which would otherwise be in List II.
Mercury and its compounds.
Cadmium and its compounds.
Mineral oils and hydrocarbons.
Cyanides.

A substance is not in List I if it has been determined by the Agency to be inappropriate to List I on the basis of a low risk of toxicity, persistence and bioaccumulation.

List II (Grey List) Substances (NRA, 1992)	
The following metalloids and metals and their compounds:	
Zinc	**Tin**
Copper	**Barium**
Nickel	**Beryllium**
Chromium	**Boron**
Lead	**Uranium**
Selenium	**Vanadium**
Arsenic	**Cobalt**
Antimony	**Thallium**
Molybdenum	**Tellurium**
Titanium	**Silver**
Biocides and their derivatives not appearing in List I.	
Substances which have a deleterious effect on the taste or odour of groundwater, and compounds liable to cause the formation of such substances in such water and to render it unfit for human consumption.	
Toxic or persistent organic compounds of silicon, and substances which may cause the formation of such compounds in water, excluding those which are biologically harmless or are rapidly converted in water into harmless substances.	
Inorganic compounds of phosphorus and elemental phosphorus.	
Fluorides.	
Ammonia and nitrites.	

Appendix 3 – Water Quality Standards

Water Quality Standards Used Within Research

Contaminant	*WQS (mg/l)
Cl	250
SO4	250
NO3	50
Ba	0.7
Mn	0.5
Fe	0.3
Al	0.2
Ni	0.02
Cu	2
Zn	3
Cr	0.05
Cd	0.003
Pb	0.01
As	0.01

*Guidelines for Drinking-Water Quality (1993), 2nd Edition, vol. 1 Recommendations. World Health Organization, Geneva.

Appendix 4 – Cumbrian Water Sample Site Grid References

Original Study

See Chapter 4, Fig. 4.18 for map

1	Wythop Beck	NY 1765 3040
2	Surface water drain to gutter below Embleton SDW	NY 179 305
3	48" culvert 15 yds d/s discharging to open gutter	NY 179 305
4	S.W. drain discharging to open gutter	NY 184 307
5	S.W. drain discharging to open gutter	NY 1855 3075
6	Small stream u/s any A66 drains	NY 1880 3085
7	Surface/river water from culvert	NY 1880 3095
8	Surface/river water from 48" culvert to open gutter	NY 1915 3095
9	River water Dubwath Beck	NY 197 311
10	River water Tom Rudd Beck (u/s S.W. drain)	NY 1520 3015
11	Surface water from gutter u/s Tom Rudd Beck	NY 152 302
12	River water Tom Rudd Beck	NY 146 299
13	River water Tom Rudd Beck	NY 140 297
14	River water Tom Rudd Beck at Skinner SE, Cockermouth	NY 126 305
15	Drainage gutter d/s culvert at Strawberry How	≃ NY 146 299
16	Surface water drain to River Derwent (300 yds u/s Boughton Bridge on left hand bank)	NY 0845 313
17	Surface water from A66 west at Brigham Station discharging to un-named trib.	
	of River Derwent	NY 082 308
A	Pool of water between A66 embankment and marsh	≃ NY 233 244

New Study

See Chapter 4, Fig. 4.18 for map

1	Wythop Beck	NY 1765 3040
8	Surface/river water from 48" culvert to open gutter	NY 1915 3095
9	River water Dubwath Beck	NY 197 311
12	River water Tom Rudd Beck	NY 146 299
14	River water Tom Rudd Beck at Skinner SE, Cockermouth	NY 126 305
15	Drainage gutter d/s culvert at Strawberry How	≃ NY 146 299
18	Discharge drain at Chapel Brow	NY 0530 2920

Appendix 5 – Cumbrian Water Sample Data

Data from Original Study

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang. 27°C/4 hrs	C.O.D	B.O.D 5 days 20oC	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate										
4.5.76	sunny, dry, rain previous 3 days	1	10.05	7.8	pale straw, clear	7.2	96.0	n/a	n/a	n/a	n/a	n/a	n/a	2.2	9.0	n/a	n/a	10.6	n/a	18.0	n/a	11.0
		2	10.25	n/a	colourless, clear	9.6	470.0	n/a	n/a	n/a	n/a	n/a	n/a	4.4	8.0	n/a	n/a	n/a	n/a	3.0	n/a	153.0
		3	10.30	n/a	colourless, v. sl. cloudy	8.7	420.0	n/a	n/a	n/a	n/a	n/a	n/a	2.8	12.0	n/a	n/a	n/a	n/a	26.0	n/a	111.0
		4	10.40	n/a	colourless, clear	7.3	380.0	n/a	n/a	n/a	n/a	n/a	n/a	1.4	12.0	n/a	n/a	n/a	n/a	26.0	n/a	95.0
		5	10.45	n/a	colourless, clear	7.2	340.0	n/a	n/a	n/a	n/a	n/a	n/a	1.2	13.0	n/a	n/a	n/a	n/a	33.0	n/a	67.0
		6	10.50	n/a	v. pale straw, v. sl. cloudy	7.4	200.0	n/a	n/a	n/a	n/a	n/a	n/a	4.6	8.0	n/a	n/a	n/a	n/a	20.0	n/a	24.0
		7	11.00	n/a	v. pale straw, v. sl. cloudy	8.8	350.0	n/a	n/a	n/a	n/a	n/a	n/a	2.4	15.0	n/a	n/a	n/a	n/a	17.0	n/a	78.0
		8	11.10	n/a	v. pale straw, v. sl. cloudy	7.4	950.0	n/a	n/a	n/a	n/a	n/a	n/a	12.0	81.0	n/a	n/a	n/a	n/a	15.0	n/a	353.0
		9	11.20	9.6	v. pale straw, v. sl. cloudy	8.2	205.0	n/a	n/a	n/a	n/a	n/a	n/a	2.6	14.0	n/a	n/a	9.8	n/a	10.0	n/a	47.0
		10	11.45	11.7	v. pale straw, v. sl. cloudy	7.4	89.0	n/a	n/a	n/a	n/a	n/a	n/a	2.4	114.0	n/a	n/a	10.0	n/a	6.0	n/a	18.0
		11	12.00	n/a	v. pale straw, v. sl. cloudy	10.8	560.0	n/a	n/a	n/a	n/a	n/a	n/a	12.2	22.0	n/a	n/a	n/a	n/a	16.0	n/a	131.0
		12	12.10	11.7	v. pale straw, v. sl. cloudy	9.4	156.0	n/a	n/a	n/a	n/a	n/a	n/a	2.4	15.0	n/a	n/a	10.2	n/a	7.0	n/a	62.0
		13	13.05	n/a	v. pale straw, clear	9.0	730.0	n/a	n/a	n/a	n/a	n/a	n/a	2.4	36.0	n/a	n/a	n/a	n/a	12.0	n/a	91.0
		14	13.15	11.6	v. pale straw, sl. cloudy	8.2	159.0	n/a	n/a	n/a	n/a	n/a	n/a	2.2	13.0	n/a	n/a	n/a	n/a	8.0	n/a	44.0
		15	13.30	n/a	v. pale straw, f. cloudy	9.2	210.0	n/a	n/a	n/a	n/a	n/a	n/a	16.4	18.0	n/a	n/a	n/a	n/a	10.0	n/a	279.0
		A	14.4	n/a	pale straw, clear	10.9	1510	n/a	n/a	n/a	n/a	n/a	n/a	142	158	n/a	n/a	n/a	n/a	15.0	n/a	211

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
8.6.76	sunny, dry	1	11.00	15.2	colourless, clear	8.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.8	<4	n/a	n/a	9.4	36	4.0	<.006	9
		2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	11.05	n/a	colourless, clear	7.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.8	<4	n/a	n/a	n/a	86	38.0	1.3	50
		4	11.10	n/a	colourless, clear	7.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1	<4	n/a	n/a	n/a	132	36.0	0.04	111
		5	11.15	n/a	colourless, clear	7.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.4	4	n/a	n/a	n/a	92	44.0	0.014	76
		6	11.20	n/a	pale straw, sl. cloudy	7.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6.2	16	n/a	n/a	n/a	46	24.0	0.014	71
		7	11.25	n/a	v. pale straw, v. sl. cloudy	8.9	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.8	<4	n/a	n/a	n/a	120	24.0	1.0	89
		8	11.50	n/a	colourless, clear	11.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	65	70	n/a	n/a	n/a	356	12.0	38.9	199
		9	11.55	16.8	v. pale straw, clear	8.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3	8	n/a	n/a	8.8	54	26.0	0.083	3.3
		10	12.45	19.6	colourless, clear	9.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.2	<4	n/a	n/a	9.0	18	10.0	0.014	9
		11	13.00	n/a	colourless, clear	10.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.4	<4	n/a	n/a	n/a	142	32.0	1.8	139
		12	13.05	n/a	colourless, clear	8.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.2	<4	n/a	n/a	n/a	36	8.0	0.007	40
		13	13.10	n/a	colourless, clear	8.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.2	<4	n/a	n/a	n/a	48	18.0	n/a	46
		14	13.30	18.6	colourless, clear	8.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.4	<4	n/a	n/a	n/a	n/a	n/a	1.56	n/a
		15	13.15	n/a	colourless, v. sl. cloudy	7.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	<4	n/a	n/a	n/a	148	32.0	0.006	125
		16	13.45	n/a	colourless, v. sl. cloudy	7.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	300	20.0	0.048	254
		16a	13.50	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.117	n/a
		A	10.35	n/a	colourless, clear	10.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	74	115	n/a	n/a	n/a	482	4	45.9	575

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang. 27°C/4 hrs	C.O.D	B.O.D 5 days 20oC	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate										
16.6.76	showers	1	13.05	13.7	colourless, clear,	7.7	93	n/a	n/a	n/a	n/a	n/a	n/a	1.8	3.0	n/a	n/a	10.4	24	18	<.006	18
		2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	13.10	n/a	colourless, clear,	7.5	260	n/a	n/a	n/a	n/a	n/a	n/a	1.2	13.0	n/a	n/a	n/a	82	26	1.38	49
		4	13.15	n/a	colourless, clear,	7.2	400	n/a	n/a	n/a	n/a	n/a	n/a	0.2	<1	n/a	n/a	n/a	140	28	0.014	104
		5	13.20	n/a	colourless, clear,	7.0	320	n/a	n/a	n/a	n/a	n/a	n/a	3.2	5.0	n/a	n/a	n/a	88	36	<.006	75
		6	13.25	n/a	colourless, clear,	7.2	210	n/a	n/a	n/a	n/a	n/a	n/a	1.6	11.0	n/a	n/a	n/a	48	16	<.006	24
		7	13.30	n/a	colourless, clear,	8.8	350	n/a	n/a	n/a	n/a	n/a	n/a	9.2	<1	n/a	n/a	n/a	114	26	0.89	88
		8	13.40	n/a	colourless, clear,	11.2	1000	n/a	n/a	n/a	n/a	n/a	n/a	12	50.0	n/a	n/a	n/a	312	2	22.5	173
		9	13.45	14	v. pale straw, clear	8.0	230	n/a	n/a	n/a	n/a	n/a	n/a	n/a	9.0	n/a	n/a	n/a	68	14	0.1	62
		10	10.55	13.9	v. pale straw, clear	7.2	86	n/a	n/a	n/a	n/a	n/a	n/a	6.2	15.0	n/a	n/a	10.6	20	8	<.006	22
		11	11.00	n/a	colourless, clear,	10.3	450	n/a	n/a	n/a	n/a	n/a	n/a	7.4	13.0	n/a	n/a	n/a	38	18	5.5	130
		12	11.05	n/a	colourless, clear,	8.7	144	n/a	n/a	n/a	n/a	n/a	n/a	2.4	5.0	n/a	n/a	n/a	40	16	<.006	44
		13	11.15	n/a	v. pale straw, clear	7.8	153	n/a	n/a	n/a	n/a	n/a	n/a	2.4	3.0	n/a	n/a	n/a	48	16	0.2	44
		14	11.30	14.1	pale straw, v. sl. cloudy	7.3	260	n/a	n/a	n/a	n/a	n/a	n/a	5.6	22.0	n/a	n/a	7.0	60	26	0.016	62
		15	11.10	n/a	pale straw, sl. cloudy	7.3	470	n/a	n/a	n/a	n/a	n/a	n/a	6.8	19.0	n/a	n/a	n/a	160	22	0.7	206
		16	11.45	n/a	colourless v. sl. cloudy	7.4	900	n/a	n/a	n/a	n/a	n/a	n/a	1.6	7.0	n/a	n/a	n/a	320	30	0.028	200
		A	14.05	n/a	colourless, clear	11.0	1500	n/a	n/a	n/a	n/a	n/a	n/a	45	124	n/a	n/a	n/a	440	40	47.6	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang. 27°C/4 hrs	C.O.D	B.O.D 5 days 20oC	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate										
29.7.76	overcast, dry	1	10.35	13.8	v. pale straw, v. sl. cloudy	7.3	150	n/a	n/a	n/a	n/a	n/a	n/a	1.8	11.0	n/a	n/a	10.0	29	n/a	<.006	17
		2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	10.45	n/a	colourless, v. sl. cloudy	6.9	245	n/a	n/a	n/a	n/a	n/a	n/a	1.4	10.0	n/a	n/a	n/a	83	n/a	0.64	43
		4	11.00	n/a	colourless, clear	7.5	350	n/a	n/a	n/a	n/a	n/a	n/a	0.8	7.0	n/a	n/a	n/a	125	n/a	<.006	81
		5	11.05	n/a	pale straw, clear	7.2	290	n/a	n/a	n/a	n/a	n/a	n/a	0.3	7.0	n/a	n/a	n/a	86	n/a	<.006	64
		6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	11.10	n/a	colourless, v. sl. cloudy	9.1	370	n/a	n/a	n/a	n/a	n/a	n/a	10.2	23.0	n/a	n/a	n/a	146	n/a	6.02	113
		8	11.35	n/a	colourless, clear	11.2	1000	n/a	n/a	n/a	n/a	n/a	n/a	60.0	n/a	n/a	n/a	n/a	333	n/a	31.6	140
		9	11.45	14.3	colourless, v. sl. cloudy	9.2	330	n/a	n/a	n/a	n/a	n/a	n/a	2.2	17.0	n/a	n/a	4.9	118	n/a	0.025	72
		10	13.45	15.9	pale straw, clear	8.1	130	n/a	n/a	n/a	n/a	n/a	n/a	2.2	69.0	n/a	n/a	10.0	30	n/a	0.018	19
		11	13.55	n/a	colourless, clear	10.6	600	n/a	n/a	n/a	n/a	n/a	n/a	17.4	34.0	n/a	n/a	n/a	234	n/a	12.65	181
		12	14.00	n/a	v. pale straw, clear	8	290	n/a	n/a	n/a	n/a	n/a	n/a	1.4	53.0	n/a	n/a	n/a	96	n/a	0.01	87
		13	14.10	n/a	colourless, clear	8.3	360	n/a	n/a	n/a	n/a	n/a	n/a	1.6	20.0	n/a	n/a	n/a	120	n/a	0.16	104
		14	14.25	15.2	v. pale straw, f. cloudy	7.2	400	n/a	n/a	n/a	n/a	n/a	n/a	12.4	54.0	n/a	n/a	n/a	110	n/a	0.067	74
		15	14.05	15.2	colourless, v. sl. cloudy	7.4	420	n/a	n/a	n/a	n/a	n/a	n/a	1.0	9.0	n/a	n/a	n/a	130	n/a	1.58	62
		16	15.15	n/a	v. pale straw, v. sl. cloudy	7.7	650	n/a	n/a	n/a	n/a	n/a	n/a	<0.2	49.0	n/a	n/a	n/a	292	n/a	0.007	106
		17	15.30	n/a	v. pale straw, sl. cloudy	7.1	4400	n/a	n/a	n/a	n/a	n/a	n/a	38.0	43.0	n/a	n/a	n/a	1300	n/a	0.145	1805
		A	12.50	n/a	pale straw, v. sl. cloudy	10.9	1460	n/a	n/a	n/a	n/a	n/a	n/a	62.4	137	n/a	n/a	n/a	480	n/a	63.27	420

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D 5 days 20oC	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27^{o}C/4 hrs								
2.8.76	overcast, dry, rain previously	1	10.25	13.3	v. pale straw, clear	7.4	118	n/a	n/a	n/a	n/a	n/a	n/a	2.0	4.0	n/a	n/a	9.8	25	n/a	<.006	13.0
		2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	10.35	n/a	colourless, clear	6.9	235	n/a	n/a	n/a	n/a	n/a	n/a	1.6	15.0	n/a	n/a	n/a	77	n/a	0.65	30.0
		4	10.40	n/a	v. pale straw, clear	7.2	367	n/a	n/a	n/a	n/a	n/a	n/a	1.1	8.0	n/a	n/a	n/a	130	n/a	<.006	80.0
		5	10.45	n/a	colourless, clear	6.9	296	n/a	n/a	n/a	n/a	n/a	n/a	1.0	8.0	n/a	n/a	n/a	86	n/a	<.006	64.0
		6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	10.50	n/a	v. pale straw, clear	9.4	398	n/a	n/a	n/a	n/a	n/a	n/a	10.4	21.0	n/a	n/a	n/a	156	n/a	4.9	106.0
		8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	11.15	n/a	v. pale straw, clear	9.2	351	n/a	n/a	n/a	n/a	n/a	n/a	2.2	11.0	n/a	n/a	4.6	106	n/a	0.118	62.0
		10	12.45	n/a	v. pale straw, clear	8.3	150	n/a	n/a	n/a	n/a	n/a	n/a	2.0	13.0	n/a	n/a	10.2	252	n/a	0.017	15.0
		11	12.55	n/a	v. pale straw, clear	10.6	640	n/a	n/a	n/a	n/a	n/a	n/a	34.0	46.0	n/a	n/a	n/a	68	n/a	9.48	149.0
		12	13.00	n/a	v. pale straw, clear	n/a	214	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	13.10	n/a	pale straw, sl. cloudy	8.2	269	n/a	n/a	n/a	n/a	n/a	n/a	2.2	20.0	n/a	n/a	n/a	84	n/a	0.137	62.0
		14	13.25	n/a	pale straw, clear	7.6	356	n/a	n/a	n/a	n/a	n/a	n/a	3.8	26.0	n/a	n/a	8.3	120	n/a	<.006	69.0
		15	13.05	n/a	pale grey, f. cloudy	7.4	491	n/a	n/a	n/a	n/a	n/a	n/a	2.0	11.0	n/a	n/a	n/a	136	n/a	1.47	81.0
		16	13.40	n/a	colourless, clear	7.6	702	n/a	n/a	n/a	n/a	n/a	n/a	1.2	10.0	n/a	n/a	n/a	284	n/a	<.006	91.0
		17	13.50	n/a	pale staw, f. cloudy	7.0	4720	n/a	n/a	n/a	n/a	n/a	n/a	12.4	60.0	n/a	n/a	n/a	1270	n/a	3.9	1730.0
		A	11.30	n/a	pale straw, clear	11.0	1490	n/a	n/a	n/a	n/a	n/a	n/a	139	230	n/a	n/a	n/a	104	n/a	51.5	446

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
31.7.77	overcast, rain, rain previously	1	9.50	4.6	v. pale straw	6.8	108	n/a	n/a	n/a	n/a	n/a	n/a	1.4	9.0	n/a	n/a	12.0	21	n/a	<.01	7
		2	14.30	n/a	colourless	8.2	580	n/a	n/a	n/a	n/a	n/a	n/a	1.6	6.0	n/a	n/a	n/a	212	n/a	0.2	189
		3	10.00	n/a	pale straw	7.2	460	n/a	n/a	n/a	n/a	n/a	n/a	7.0	28.0	n/a	n/a	n/a	176	n/a	0.53	94
		4	10.10	n/a	pale straw	6.8	440	n/a	n/a	n/a	n/a	n/a	n/a	2.6	13.0	n/a	n/a	n/a	119	n/a	0.21	97
		5	10.20	n/a	pale straw	6.6	440	n/a	n/a	n/a	n/a	n/a	n/a	2.0	17.0	n/a	n/a	n/a	111	n/a	0.1	31
		6	10.30	n/a	pale straw	6.6	440	n/a	n/a	n/a	n/a	n/a	n/a	1.6	12.0	n/a	n/a	n/a	121	n/a	<.01	62
		7	10.40	n/a	pale straw	7.2	400	n/a	n/a	n/a	n/a	n/a	n/a	1.6	17.0	n/a	n/a	n/a	115	n/a	0.15	65
		8	11.15	n/a	pale straw	8.4	750	n/a	n/a	n/a	n/a	n/a	n/a	6.4	32.0	n/a	n/a	n/a	264	n/a	<.01	239
		9	11.25	4.7	pale straw	7.1	200	n/a	n/a	n/a	n/a	n/a	n/a	2.0	16.0	n/a	n/a	11.0	52	n/a	0.11	18
		10	12.55	4.7	v. pale straw	8.2	122	n/a	n/a	n/a	n/a	n/a	n/a	0.2	13.0	n/a	n/a	11.8	20	n/a	<.01	84
		11	13.05	n/a	v. pale straw	8.6	390	n/a	n/a	n/a	n/a	n/a	n/a	2.2	22.0	n/a	n/a	n/a	113	n/a	0.75	175
		12	13.15	n/a	pale straw	7.4	151	n/a	n/a	n/a	n/a	n/a	n/a	1.2	7.0	n/a	n/a	n/a	29	n/a	<.01	20
		13	13.30	n/a	pale straw	7.3	156	n/a	n/a	n/a	n/a	n/a	n/a	1.0	7.0	n/a	n/a	n/a	44	n/a	0.04	21
		14	13.45	4.8	pale straw	7.3	215	n/a	n/a	n/a	n/a	n/a	n/a	2.0	7.0	n/a	n/a	12.0	53	n/a	<.01	36
		15	13.25	n/a	pale straw	8.3	290	n/a	n/a	n/a	n/a	n/a	n/a	2.4	14.0	n/a	n/a	n/a	80	n/a	1.27	69
		16	14.00	n/a	v. pale straw	7.5	650	n/a	n/a	n/a	n/a	n/a	n/a	4.6	57.0	n/a	n/a	n/a	226	n/a	1.1	176
		17	14.15	n/a	pale straw	7.4	480	n/a	n/a	n/a	n/a	n/a	n/a	1.6	45.0	n/a	n/a	n/a	194	n/a	<.01	48
		A	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
28.3.78	overcast, rain, rain previously	1	11.55	6.2	n/a	8.0	105	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4	n/a	n/a	11.6	n/a	n/a	<.01	13.0
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	13.15	6.1		6.1	195	n/a	n/a	n/a	n/a	n/a	n/a	n/a	20	n/a	n/a	11	43.0	n/a	0.02	31.0
		10	11.35	6.2		7.2	100	n/a	n/a	n/a	n/a	n/a	n/a	n/a	34	n/a	n/a	11.2	19.0	n/a	<.01	7.0
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	11.00	6.0		7.4	210	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6	n/a	n/a	11.2	49.0	n/a	0.02	24.0
		15	11.20	n/a		7.6	305	n/a	n/a	n/a	n/a	n/a	n/a	n/a	<4	n/a	n/a	n/a	73.0	n/a	0.26	39.0
		16	10.45	n/a		7.3	850	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4	n/a	n/a	n/a	197.0	n/a	0.28	160.0
		17	10.30	n/a		7.5	618	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10	n/a	n/a	n/a	214.0	n/a	0.12	62.0
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
1.2.79	n/a	1	12.35	2.0	n/a	8.6	108	n/a	n/a	n/a	n/a	n/a	n/a	n/a	15.0	n/a	n/a	12.8	22.0	n/a	<.01	10
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	13.15	2.0		6.6	159	n/a	n/a	n/a	n/a	n/a	n/a	n/a	19.0	n/a	n/a	11.7	46.0	n/a	<.01	22
		10	12.10	2.0		7.8	90	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12.0	n/a	n/a	12.8	19.0	n/a	<.01	10
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	11.40	2.0		7.8	158	n/a	n/a	n/a	n/a	n/a	n/a	n/a	24.0	n/a	n/a	12.4	43.0	n/a	<.01	17
		15	n/a	11.6		7.7	700	n/a	n/a	n/a	n/a	n/a	n/a	n/a	13.0	n/a	n/a	n/a	93.0	n/a	0.53	49
		16	n/a	11.3		7.6	700	n/a	n/a	n/a	n/a	n/a	n/a	n/a	19.0	n/a	n/a	n/a	276.0	n/a	0.07	100
		17	n/a	11.1		7.8	400	n/a	n/a	n/a	n/a	n/a	n/a	n/a	23.0	n/a	n/a	n/a	202.0	n/a	0.06	57
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO$_4$	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S$_2$	SO$_4$
								Cl	NH$_3$	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
17.4.79	n/a	1	12.15	8.0	n/a	8.1	91	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8.0	n/a	n/a	12.2	15.0	n/a	<.01	10
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	13.00	8.0		6.5	152	n/a	n/a	n/a	n/a	n/a	n/a	n/a	9.0	n/a	n/a	13.0	46.0	n/a	0.05	24
		10	12.05	8.0		7.5	91	n/a	n/a	n/a	n/a	n/a	n/a	n/a	11.0	n/a	n/a	11.8	17.0	n/a	<.01	n/a
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	11.40	7.5		7.6	156	n/a	n/a	n/a	n/a	n/a	n/a	n/a	9.0	n/a	n/a	11.8	50.0	n/a	<.01	6
		15	11.55	n/a		7.5	215	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8.0	n/a	n/a	n/a	63.0	n/a	0.28	32
		16	11.25	n/a		7.4	600	n/a	n/a	n/a	n/a	n/a	n/a	n/a	7.0	n/a	n/a	n/a	286.0	n/a	0.12	105
		17	11.10	n/a		7.6	440	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10.0	n/a	n/a	n/a	210.0	n/a	0.15	48
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		$27^{o}C$/4 hrs		5 days 20oC						
18.12.79	rain, cold, overcast, showers	1	11.35	5.0	n/a	7.0	104	n/a	n/a	n/a	n/a	n/a	n/a	n/a	15.0	n/a	n/a	11.4	7.6	2.4	<0.01	11.0
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	12.30	5.0		6.2	154	n/a	n/a	n/a	n/a	n/a	n/a	n/a	40.0	n/a	n/a	10.4	16.0	7.3	0.07	31?
		10	11.05	6.0		7.0	144	n/a	n/a	n/a	n/a	n/a	n/a	n/a	9.0	n/a	n/a	11.3	15.2	3.6	<0.01	16.0
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	10.35	5.0		7.1	157	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12.0	n/a	n/a	11.6	20.4	4.6	0.09	21.0
		15	10.50	n/a		7.2	260	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12.0	n/a	n/a	n/a	31.2	6.3	0.26	37.0
		16	10.15	n/a		7.1	260	n/a	n/a	n/a	n/a	n/a	n/a	n/a	19.0	n/a	n/a	n/a	39.6	3.2	0.16	42.0
		17	9.55	n/a		7.0	460	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8.0	n/a	n/a	n/a	86.0	6.1	<0.01	159.0
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO$_4$	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S$_2$	SO$_4$
								Cl	NH$_3$	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
14.4.80	mild, mod. cloud, overcast, light rain	1	12.50	8.6	n/a	6.5	102	n/a	n/a	n/a	n/a	n/a	n/a	n/a	11.0	n/a	n/a	11.4	8.4	2.67	0.02	12
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	13.35	8.7		6.7	200	n/a	n/a	n/a	n/a	n/a	n/a	n/a	13.0	n/a	n/a	10.4	21.6	3.65	0.07	174
		10	12.25	8.5		7.4	124	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8.0	n/a	n/a	10.8	14.0	3.89	0.02	18
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	11.50	8.5		7.2	205	n/a	n/a	n/a	n/a	n/a	n/a	n/a	25.0	n/a	n/a	10.8	22.2	6.44	<0.01	26
		15	12.10	n/a		7.0	270	n/a	n/a	n/a	n/a	n/a	n/a	n/a	18.0	n/a	n/a	n/a	36.4	5.1	0.28	41
		16	11.35	n/a		7.1	560	n/a	n/a	n/a	n/a	n/a	n/a	n/a	7.0	n/a	n/a	n/a	113.6	6.32	<0.01	76
		17	11.20	n/a		7.2	440	n/a	n/a	n/a	n/a	n/a	n/a	n/a	7.0	n/a	n/a	n/a	88.0	6.32	0.12	46
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO$_4$	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S$_2$	SO$_4$
								Cl	NH$_3$	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
21.7.80	mild, mod. cloud, dry	1	11.20	12.7	n/a	7.2	71	n/a	n/a	n/a	n/a	n/a	n/a	n/a	13.0	n/a	n/a	10.6	6.1	1.9	<0.003	25
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	11.40	12.6		7.2	114	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8.0	n/a	n/a	9.6	15.1	2.8	0.005	21
		10	11.05	12.7		7.0	70	n/a	n/a	n/a	n/a	n/a	n/a	n/a	<4	n/a	n/a	10.7	6.8	1.7	n/a	17
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	10.30	12.6		7.2	106	n/a	n/a	n/a	n/a	n/a	n/a	n/a	13.0	n/a	n/a	10	15.4	2.4	0.003	26
		15	10.50	10.50		7.1	300	n/a	n/a	n/a	n/a	n/a	n/a	n/a	14.0	n/a	n/a	n/a	75.5	4.8	0.350	n/a
		16	10.05	10.05		7.3	370	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.0	n/a	n/a	n/a	117.4	6	0.003	73
		17	9.50	9.50		7.3	650	n/a	n/a	n/a	n/a	n/a	n/a	n/a	37.0	n/a	n/a	n/a	81.5	5.8	<0.003	163
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
30.7.81	mild, overcast, occ. rain, mod. cloud dry	1	11.15	14.6	n/a	7.3	80	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12	n/a	n/a	10.0	6	2	n/a	<5
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	12.05	n/a		6.9	190	n/a	n/a	n/a	n/a	n/a	n/a	n/a	19	n/a	n/a	n/a	19	3.3	n/a	52.0
		10	10.40	n/a		7.3	120	n/a	n/a	n/a	n/a	n/a	n/a	n/a	15	n/a	n/a	9.7	10	2.3	n/a	14.0
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	10.10	n/a		7.5	200	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8	n/a	n/a	n/a	19	3.2	n/a	32.0
		15	10.30	14.2		7.3	400	n/a	n/a	n/a	n/a	n/a	n/a	n/a	21	n/a	n/a	n/a	51	4.3	n/a	86.0
		16	9.50	n/a		7.5	650	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10	n/a	n/a	n/a	108	6.1	n/a	82.0
		17	9.30	n/a		7.5	500	n/a	n/a	n/a	n/a	n/a	n/a	n/a	19	n/a	n/a	n/a	75	5.8	n/a	60.0
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
15.9.82	mild, overcast, dry, sl. cloud	1	14.2	15.0	n/a	7.3	n/a	n/a	0.08	n/a	n/a	n/a	0.01	n/a	5.0	n/a	n/a	10.0	5.2	2.0	<0.005	n/a
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	14.3	14.8		7.0	n/a	n/a	0.07	n/a	n/a	n/a	0.01	n/a	5.0	n/a	n/a	8.2	16.0	3.5	<0.005	n/a
		10	14.0	15.0		7.3	n/a	n/a	<0.01	n/a	n/a	n/a	<0.01	n/a	5.0	n/a	n/a	9.8	8.2	2.0	<0.005	n/a
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	13.2	14.0		7.3	n/a	n/a	0.14	n/a	n/a	n/a	0.02	n/a	8.0	n/a	n/a	9.4	15.0	3.1	<0.005	n/a
		15	13.3	n/a		8.9	n/a	n/a	0.22	n/a	n/a	n/a	0.01	n/a	23.0	n/a	n/a	n/a	4.6	2.6	1.6	n/a
		16	12.6	n/a		7.5	n/a	n/a	<0.01	n/a	n/a	n/a	<0.01	n/a	5.0	n/a	n/a	n/a	103.0	5.4	<0.005	n/a
		17	12.4	n/a		7.5	n/a	n/a	0.02	n/a	n/a	n/a	9.01	n/a	9.0	n/a	n/a	n/a	86.0	6.3	<0.005	n/a
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27^{o}C/4 hrs		5 days 20oC						
20.12.82	cold, overcast, showers, mod. cloud,	1	12.00	5.9	n/a	7.8	98	n/a	n/a	n/a	n/a	n/a	n/a	n/a	15.0	n/a	16.0	11.2	n/a	n/a	0.01	<.2
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	12.25	5.8		7.1	300	n/a	n/a	n/a	n/a	n/a	n/a	n/a	13.0	n/a	5.0	8.5	n/a	n/a	n/a	45.0
		10	11.25	5.8		7.1	110	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.0	n/a	11.0	11.2	n/a	n/a	0.02	22.0
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	10.40	5.8		7.0	170	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.0	n/a	5.0	11.2	n/a	n/a	<0.01	25.0
		15	11.00	n/a		7.5	260	n/a	n/a	n/a	n/a	n/a	n/a	n/a	7.0	n/a	3.0	n/a	n/a	n/a	0.56	36.0
		16	10.10	n/a		7.2	130	n/a	n/a	n/a	n/a	n/a	n/a	n/a	9.0	n/a	19.0	n/a	n/a	n/a	0.1	25.0
		17	9.45	n/a		7.2	550	n/a	n/a	n/a	n/a	n/a	n/a	n/a	17.0	n/a	10.0	n/a	n/a	n/a	<0.01	58.0
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
19.12.83	cold, overcast, dry, mod. cloud	1	12.15	6.8	n/a	7.7	100	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.0	n/a	n/a	10.9	6.0	1.9	0.0	10.0
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	13.05	6.8		7.3	170	n/a	n/a	n/a	n/a	n/a	n/a	n/a	7.0	n/a	n/a	10.2	14.0	2.9	0.0	24.0
		10	11.35	7.0		7.6	120	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.0	n/a	n/a	10.8	9.6	2.1	0.0	0.5
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	10.55	6.5		7.8	200	n/a	n/a	n/a	n/a	n/a	n/a	n/a	17.0	n/a	n/a	10.7	18.0	3.0	0.0	20.0
		15	11.15	n/a		7.7	290	n/a	n/a	n/a	n/a	n/a	n/a	n/a	35.0	n/a	n/a	n/a	25.0	5.6	0.5	n/a
		16	10.35	n/a		7.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.0	n/a	n/a	n/a	110.0	5.2	<0.01	80.0
		17	10.0	n/a		7.5	550	n/a	n/a	n/a	n/a	n/a	n/a	n/a	<4	n/a	n/a	n/a	79.0	5.2	0.0	50.0
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Date	Weather	Site No.	Time	Temp	Colour	pH	Conduc.	Chloride		Nitrogen			PO_4	Permang.	C.O.D	B.O.D	Suspended Solids	Dissolved O2	Ca	Mg	S_2	SO_4
								Cl	NH_3	Organic	Nitrite	Nitrate		27°C/4 hrs		5 days 20oC						
19.12.85	n/a	1	14.55	n/a	n/a	7.1	101.0	11.0	n/a	n/a	n/a	n/a	n/a	n/a	6.0	n/a	n/a	n/a	5.9	1.80	<0.003	20.0
		2	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		3	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		4	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		5	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		6	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		7	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		8	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		9	15.15	n/a		7.1	171.0	15.0	n/a	n/a	n/a	n/a	n/a	n/a	10.0	n/a	n/a	n/a	13.4	2.80	0.03	18.0
		10	14.35	n/a		7.4	134.0	13.0	n/a	n/a	n/a	n/a	n/a	n/a	8.0	n/a	n/a	n/a	10.1	2.10	<0.003	14.0
		11	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		12	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		13	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		14	14.05	n/a		7.4	191.0	16.0	n/a	n/a	n/a	n/a	n/a	n/a	6.0	n/a	n/a	n/a	17.3	2.80	<0.003	19.0
		15	14.2	n/a		7.5	240.0	17.0	n/a	n/a	n/a	n/a	n/a	n/a	4.0	n/a	n/a	n/a	22.7	3.90	0.45	26.0
		16	13.45	n/a		7.5	150.0	13.0	n/a	n/a	n/a	n/a	n/a	n/a	6.0	n/a	n/a	n/a	13.6	1.60	<0.003	19.0
		17	13.3	n/a		7.3	577.0	28.0	n/a	n/a	n/a	n/a	n/a	n/a	10.0	n/a	n/a	n/a	74.0	5.60	<0.003	48.0
		A	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a=not available

Data from New Study

Date	Weather	Site No.	Flow	pH	Ca	Fe	Mg	K	S2	SO4
5.12.01	wet, windy	8	normal	9.26	95.0	0.01	4.1	9.3	92.0	0.8
7.12.01	cloudy, sl.drizzle	1	fast	7.58	10.4	<0.01	4.3	1.9	5.6	<0.2
		9	v. slow, flooded banks	7.26	21.0	<0.01	5.3	2.6	10.0	<0.2
		12	fast	7.27	16.0	<0.01	4.1	2.4	6.6	<0.2
		14	fast	7.52	32.0	<0.01	6.5	3.5	10.0	<0.2
		15	normal, large volume	7.67	23.0	<0.01	6.0	2.8	7.9	<0.2
		18	fast	7.32	110.0	0.01	9.7	4.5	44.0	0.4

Appendix 6 – Risk Assessment Guide