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AN EVALUATION OF MODIFIED PERVIOUS PAVEMENTS FOR WATER HARVESTING FOR IRRIGATION PURPOSES

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AN EVALUATION OF MODIFIED PERVIOUS PAVEMENTS
FOR
WATER HARVESTING FOR IRRIGATION PURPOSES

By

ERNEST OKWUDIRI NNADI

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A thesis submitted in partial fulfillment of the University's requirements for the Degree of Doctor of Philosophy (PhD)

In Collaboration with

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AN EVALUATION OF MODIFIED PERVIOUS PAVEMENTS

FOR

WATER HARVESTING FOR IRRIGATION PURPOSES

SUBMITTED

BY

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ABSTRACT

The pervious pavement system has been identified as an effective source control device capable of removing urban stormwater pollution by trapping pollutants within the system and biodegradation. Recent studies have further demonstrated that the pervious pavement system could be used as a source of renewable energy capable of reducing household energy bill by about 80%. In view of ever increasing demand for water and the continued reduction in available fresh water resources in the world, stormwater has been recognized as a potential valuable source of water which could be harnessed.

The overall aim of this multi disciplinary research was to evaluate the suitability of a modified pervious pavement system (PPS) for water harvesting and re-use, particularly focussing on potential third world applications and taking advantage of the latest developments in materials that are available for such applications. The aim was a holistic one in which water re-use was examined in terms of both the potential advantages from an irrigation point of view without ignoring the very important public health concerns that are often of concern when water is stored in circumstances which do not fit the normally used criteria for potable supplies.

The results of this study confirmed the pollution control capability of the porous pavement system as earlier determined by previous studies. Also, a novel experimental rig was designed to reproducibly create very high and realistic rainfall events over model pavement structures. Furthermore, the performance of a new geotextile, Inbitex Composite® in the pervious pavement system was determined for the first time. Furthermore, this study also tested for the first time, the performance of a pervious pavement system modified by the incorporation of Inbitex Composite® geotextile with slits and made prescriptions as to how this new geotextile could be best installed in a modified pervious pavement system in order to achieve high infiltration without compromising pollution control.

This study tested the practical use of the pervious pavement system for water harvesting and storage for reuse in irrigation. In order to achieve this, the author took what could be considered as a holistic approach to water quality issues and determined the chemical, electrochemical and microbiological quality of water stored in the system as well as investigated the public health concern of the potential of pathogenic organisms in waters stored in unconventional water storage system as the pervious pavement system. It also determined that the pervious pavement system have the capability to recycle water with physical, chemical and microbiological qualities that will meet international standards for irrigation and that the system does not offer a conducive environment for potential pathogenic organisms if contamination incident occurs from adjoining areas.

This study also became the first to practically relate Sustainable Urban Drainage System (SUDS) to agricultural benefit by demonstrating how a SUDS device (pervious pavement system) could be used in addition to its urban drainage control role, as a source of supply of high quality irrigation water to cultivate crops fit for human and animal consumption despite high application of pollutants. This study determined contrary to the observation of earlier studies that the use of slow-release fertilizer could lead to eutrophication problems in cases where the water is channeled to natural water courses. Furthermore, active response of potential pathogenic bacteria to the presence of slow-release fertilizer was observed in this study. This raises a huge question on the need to add fertilizer to the pervious pavement system. Coupe, (2004) had demonstrated that oil degrading microbes would respond positively to food sources in the system and hence, there was no significant need for simulation by nutrient addition, the author concluded in the study presented here that fertilizer addition should only be conducted if the waters are to be used for irrigation where the nutrients would be beneficial to the plants and that even in this case, the microbiological water quality should be constantly monitored and the addition suspended if the risk of contamination from adjoining areas is high.

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Structure of the Thesis

This thesis is presented as follows:

- Chapter one (1) is the introduction to the thesis.
- Chapter two (2) consists of the literature review and an overview of past work done by earlier researchers in the Porous Pavement Research Group in Coventry University.
- Chapters from three (3) to eight (7) represent a section of work or set of experiments designed to achieve specific objective(s). This is a deviation from the traditional way of writing which the author chose in order to enable the reader to understand the progression of work which involved an integration of many areas of science. This method of arrangement of thesis was used in the research group by previous researchers: Bond (1999); Coupe (2004) and Puehmeier, (2008).
- Chapter 8 is the conclusion and recommendation for further studies. This chapter is followed by detailed references of cited literature.
- Appendices contain information on specific research methods, statistical methods and published work.

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Chapter 1

1.1 Introduction

The importance of water to human survival cannot be over-emphasized. Life on earth depends to a large extent on the availability of water. However, over the years, man has taken the availability of water for granted and has mismanaged this important resource. Urbanization has affected natural rainfall attenuation and infiltration processes as well as altered natural rainfall-run-off relationships resulting in flooding and pollution of waterways. The channeling of urban run-off and wastewater to streams and rivers has continued to degrade the aquatic ecosystem, change the pattern of flow of these natural water systems and increase the frequency of flooding as water overflow their banks (Vaes and Berlamount 1999). The construction of impervious surfaces has significantly increased the natural flow rates of stormwater, decreased run-off periods and created the need for alternative measures to deal with urban run-off (MMSD 2005, Lassabatere *et al.* 2007). This project represents an attempt to simultaneously deal with both issues of flood prevention mentioned above and the equally important issue of water shortage through the utilization of pervious pavement systems as storage devices.

Rainfall which replenishes the world's supply of surface water is unevenly and seasonally distributed. World rainfall and temperature distributions are affected by climatic change (Adee 2007); and many places in the world today especially in Sub-Saharan Africa are experiencing acute water scarcity and drought (NASA 2008). However, it is undisputable that water is still wasted, both in the United Kingdom and other parts of the world. The use of potable and high quality water for agricultural and horticultural irrigation, watering of both domestic and public gardens, flushing of toilets, car washing and other uses which do not require such quality water is affecting the availability of water from the mains (Vaes and Berlamount 1999). Furthermore, there is increasing demand for water across the globe due to the ever increasing world population and industrial activities. More water is required by farmers for irrigation in order to increase agricultural output to feed the ever growing world population, and this at a time when rainfall patterns are reportedly changing in response to anthropogenic climate change (Bakkenes *et al.* 2002).

There is no doubt that whilst lack of water in certain places and at certain times is an issue, an excess of stormwater constitutes a problem in many places in the world, often in the same places where at other times of the year, there is a shortage of water and little or no attempt is being made to derive benefit from it.

In response to these issues; rainwater harvesting, storage and re-use have been recognized as important ways of tackling water scarcity (Pratt 1999, Vaes and Berlamount 1999, McAlister 1999, Bhattacharys and Rane 2003, Shukla and Jaber 2006). There is an increasing awareness that stormwater is a valuable resource that can be harnessed

(NHDES 2001, Miller 2002, NMED 2006, NSWA 2006, Shukla and Jaber 2006, Kindade-Levario 2007). The potential applications of harvested stormwater can be categorized as residential, agricultural, industrial, decorative ponds; water displays aquifer storage and recovery (Texas Water Development Board 2005, Seymour 2005).

This highlights the need for sustainable water resource management strategy that will take into account water harvesting for reuse. It has been widely suggested in both academic (Miller 2002, Seymour 2005, Shukla and Jaber 2006) and trade literature (NHDES 2001, NMED 2006, NSWA 2006, SIAV 2006) that harnessing stormwater to add to the available water resources and reduction in water pollution is a potential component of a sustainable water management strategy. A good example to illustrate the variability of these problems in both space and time might be Nigeria. This country has uneven and seasonal distribution of rainfall, with the length of rainy season decreasing from the south to the north (March to November and mid-May to September in the south and north respectively with a break of rainfall in August referred to as “August break”) and rainfall heavier in the south especially south east (about 3,000mm and 1,800mm a year in the south east and south west respectively); and less in the northern parts of the country with annual precipitation not exceeding 500mm (Encyclopedia Britannica 2007). Such rainfall conditions in this and other countries further support the advantages of harvesting and storing rainwater runoff for reuse. If the infrastructure required for such approaches can be of dual use, such as the storage of water under a parking lot there are great advantages. This strategy would go a long way to meeting the objectives of Sustainable Urban Drainage System (SUDS) as it would help to manage runoff as close to source as possible (Stahre 2002, Newman *et al.* 2004a, b) and at the same time offer what would seem to be additional benefits at very little extra costs.

As early as 1999, Pratt (1999) was proposing that porous pavements would possess the capability to store water for reuse and since then, a number of practical examples have been built (Ferguson 2005, UniSA Researcher 2007). In most countries in the world, car parks in hotels and shopping plazas, sidewalks and residential compounds are accompanied by landscaped areas (Newman *et al*. 2004b). Indeed landscaping around such hard paved areas is often seen as an aesthetic necessity. For example, the famous Environmentalist-Artist, Friedensreich Hundertwasse (1928-2000) once said "… *If man walks in nature's midst, then he is nature's guest and must learn to behave as a well-brought-up guest."* (TripAtlas 2009). Thus, stressing the need for architectural designs to accommodate nature in the spaces taken up by man.

In the area of SUDS, the landscaped part of a paved car park or city square is capable of being used as part of the stormwater disposal route. A good example of how this has been used is in the City of Portland Oregon, USA. When this city was faced with the challenge of designing improvements for the 4046.86 m^2 development of the Auto Warehousing Corporation (AWC) auto storage facility at the Port of Portland (Port) Terminal 6, the design team considered all options to manage the large volume of stormwater that would be generated from surfacing the site (Rogers and Faha 2007). The preferred alternative which was constructed in the summer of 2006 was a porous pavement system with vegetated swales that provided for infiltration of 100% of the stormwater onsite (Rogers and Faha 2007). These developments are not static. For example, in the literature from Hanson-Formpave (Hanson-Formpave 2007), we have seen examples of the use of specially engineered soils to allow tree planting in association with pervious pavements and some very exciting developments are being made by Permavoid in the Netherlands which utilize specially designed tree planting chambers (TES 2007). However, landscaping makes demands on water resources. For example, according to the University Gardener, at Coventry University about 350 litres of water is used weekly during summer to provide irrigation to a single floral display planter next to the James Starley Building (Smith 2007). The impact of demands for watering landscaped areas can be particularly problematic where the supply from rainfall is highly variable and in certain countries of the world, there are conflicting demands for water especially during dry seasons, and particularly for agricultural irrigation purposes which would make irrigation for aesthetic reasons at best socially unattractive and at worst could initiate regulatory action by the authorities if precious potable waters are used for such purposes.

This is also the case even in temperate countries during summer seasons for example, during the summer of 2006, most water companies in the UK imposed hosepipe bans and restrictions on their customers due to dry a winter and low rainfall recorded in the previous year in the country (Jowit 2006, South East Water 2006, BBC 2006, Water Guide 2007). With the potential impact of global warming likely to push water shortage problems ever further in the developed world, the demand for cost effective local water storage and re-use systems can only increase. This highlights the importance of any SUDS technique that would harness and store stormwater during the wet season of abundance and make them available for reuse during the dry season of scarcity and at the same time would not increase the demand for land in a development.

Pervious pavement systems are usually installed in open spaces such as car parks, city squares, pavement (sidewalks), etc where the possibility of dropping animal faeces (dogs, pigeons, cats, etc) on the pavements and accidental cross contamination by waste waters from adjoining areas exists. There is no doubt that the situations mentioned above could pose a problem of occurrence of potential pathogenic micro-organisms (e.g. *Escherichia coli, Legionella* spp., *Acanthamoeba* spp., etc) to waters stored underneath the pavement system. In view of public health issues which may arise as a result of the threat of potential pathogenic organisms to the stored water and in order to meet standards for re-use of recycled water, it is necessary to investigate the microbial quality of waters stored in this manner before it could be used for agricultural irrigation as well as for recreational purposes.

1.2 Aim and Objectives

In view of the issues raised earlier in the introduction, the author's overall aim in this multi disciplinary research project was to evaluate the suitability of a modified pervious pavement system (PPS) for water harvesting and re-use, particularly focussing on potential third world applications and taking advantage of the latest developments in materials that are available for such applications. The aim was intended to be a holistic one in which water re-use was examined using the physical, chemical and biological key processes in terms of the potential advantages for irrigation. This study took into consideration the very important public health issues that are often of concern when water is stored in circumstances which do not fit the normally used criteria for potable supplies.

From this aims, a number of objectives were developed;

- Review of related literature on the concept of sustainable urban drainage, low impact development, use of pervious pavements in urban drainage, use of recycled water for irrigation, effects of irrigation water on soil structure, plant growth and development as well as chemical and microbiological water quality of recycled water
- Review of completed research work in the University's pervious pavement research group in order to show the progression of research work in the group from which this study derived benefit and the gaps in knowledge which this study was designed to fill.
- Determination of pollutant (hydrocarbons and suspended solids) retention capability of the porous asphalt and concrete in comparison to the traditional block pervious pavement system in other to assess the opportunity offered by these systems in water recycling applications
- Investigation of water storage capability of the pervious pavement system with emphasis on infiltration through the system at various rainfall intensities and effect of evaporation on stored water. This included the design of a test rig for

investigation of the performance of the system under high rainfall intensities as may occur in the tropical countries of the world

- Determination of the chemical and electrochemical quality of waters stored in a pervious pavement system with a view of their application as irrigation fluid. Including the investigation of the effects of hydrocarbons (pollutant) and nutrients (added to encourage microbial degradation) may have on the stored water quality as well as the possible short and long term effects of recycled water on soil structure
- Pot trial experiments in the greenhouse to investigate the suitability of stored water in the pervious pavement system for irrigation. Determination of the effects of recycled water on seed germination, plant growth and development. Investigation of effects of use of the recycled water on the level of metals in soil and plant parts. Furthermore, investigate the effects on soil pH and electrical conductivity.
- Determination of the microbial water quality of stored water in the pervious pavement system as well as the fate of potential pathogenic micro-organisms (e.g. *Escherichia coli* and *Acanthamoeba spp*.) in the system in view of the potential threat they pose in recycled water applications.

The author accepts that these aims and objectives were very ambitious in a three year PhD programme and as such only partial progress was expected to be made within the specified period of the academic programme. However, since this is a novel research work in the area of application of pervious pavement system as a water recycling device, this research work provides preliminary and in some cases conclusive information that helps to lay the foundation for further research in this area.

Chapter 2: Literature Review

Due to the inter-disciplinary nature of this study, the literature review is structured to look at work done in the areas of sustainable urban drainage, low impact development and pervious pavements. The review of literature is continued in chapters 3, 4, 5, 6 and 7 of this thesis. This was conducted in order to clearly introduce the reader to the concept(s), aim(s) and objectives of each set of experiments presented in each these chapters as earlier stated in the structure of the thesis.

2.1 Concept of Sustainable Urban Drainage (SUDS)

The definition of urban drainage includes both wastewater and stormwater disposal systems either as combined or separate sewers (Butler and Davies 2000). The need to manage these fluids effectively led to the creation of various urban drainage designs. A separate sanitary sewer system is designed to carry only wastewater to the treatment plant while stormwater is carried in a separate system, and is not transported to the treatment plant, but disposed of separately. However, in a combined sewer system, both wastewater and stormwater are carried in the same set of pipes. There is continued debate among researchers, drainage engineers and regulatory agencies on the best system of conveyance of stormwater in relation to quantity and treatment costs (Butler and Davies 2000, EPA 2000b, DEQ 2001, Suárez and Puertas 2005, Schultze and Rohde 2005), with the pro-combined system lobby claiming that at least all stormwater passes through a treatment plant prior to discharge and the separate system lobby pointing, for example to stormwater overflows (SWOs).

Historically, the design of urban drainage systems have been driven at different time periods by different objectives and influenced by climate, topography, geology, engineering and construction capabilities, scientific knowledge, societal values, religious beliefs, etc (Burian and Edwards 2002). Accounts of ancient civilizations (e.g., Indus and Minoan) indicates that drainage systems were carefully made with trial and error construction methods to achieve the primary objectives of rainwater collection, prevention of flooding and waste removal (Kirby *et al.* 1956, Mumford 1961,Webster 1962, Burian and Edwards 2002).

As urban populations have increased, there have been local increases in the removal of natural vegetation in order to establish urban infrastructures and industries (Galatchi 2007). The impacts of this urban development on a catchment's hydrology are now well understood and its general hydrological effects have also been identified (Blackham, Breen and Barret 2006): increase in run-off volume, peak flow and reduction in time to peak and base flow of urban run-off as well as increase in the frequency of dominant discharge (Dunne and Leopold 1978, Codner *et al.* 1988, Neller 1989).

Conventional urban drainage systems have contributed to the pollution of natural water courses by channeling pollutants carried by stormwater into these water courses and increased the risk of flooding as well as erosion (Monk 2006). Furthermore, increase in the number of impervious surfaces used to cover the soil have reduced natural infiltration, increased run-off volumes and pollution and have often distorted the natural ecology of receiving rivers and streams (MDEP, DPS and MCPPC 2009).

Also, it is now clear that the pollution of natural waterways and coastal waters from non-point sources have resulted in major environmental problems (Heal, Mclean, and D’arcy 2004). Examples of pollutants includes oil and petrol drips from cars, pet faeces, dusts from construction and industrial activities, refuse bins, excessive soil erosion, farming and forestry activities as well as car washing (Newman *et al.* 2004b, Newman *et al.* 2002a,c, Newman *et al.* 2006a, Monk 2006). Detailed classification of stormwater pollutants was conducted elsewhere by Iwugo, Andoh and Feest (2002). According to the United States Environmental Protection Agency (USEPA 2003), sediments, nutrients, oil and grease, bacteria and heavy metals are the common stormwater pollutants in the United States of America. It is now well established that urban runoff contains heavy metals and micro organisms (Pratt, Mantle and Schofield 1995, Newman *et al.* 2002a,b). It has also been shown that some of these microbes are even pathogenic in nature (Coupe *et al.* 2006a, Coupe, Nnadi and Oyelola 2008a)

Nitrogen and phosphorus have been recognized as two common nutrients found in stormwater runoff (Collins, Hunt and Hathaway 2006). Atmospheric deposition, fertilizer and sediment transportation have also been identified as the major sources of the nitrogen and phosphorus found in stormwater (Collins, Hunt and Hathaway 2006) as well as animal and human wastes (NCDENR 1999). Table 2.1 below shows pollutant concentrations in storwmater run–off from different land uses. High concentrations of these nutrients in surface waters can lead to increased level of cyanobacteria, depletion of oxygen, health risk to humans and animals, and death of marine animals (NCDENR 1999, Collins, Hunt and Hathaway 2006). Since nutrients deposited on impervious surfaces can easily be carried away by runoff and end up in surface water more than those deposited on more natural areas (NCDENR 1999); the need to address this problem in urban drainage design cannot be over emphasized. Hence, it is ironic that researchers investigating biodegradation of stormwater pollutants by micro organisms had to apply nutrients to encourage the growth and development of these organisms as these nutrients had been identified as being necessary for biodegradation process (see Chapter 4). Bond (1999) concluded that addition of nutrients to the pervious pavement system was essential for the persistence of hydrocarbon-degrading microbes within the system in order to achieve oil biodegradation/retention efficiency of 98.7%. Bond (1999) also observed that the application of liquid fertilizer led to high losses of nitrogenous compounds which was not the case with the use of slow release fertilizer. This study contrary to the observation of Bond (1999), determined that the use of slow-release fertilizer could lead to eutrophication problems in cases where the water is channeled to natural water courses. Furthermore, active response of potential pathogenic bacteria to the presence of slow-release fertilizer was observed in this study. This raises a huge question on the need to add fertilizer to the pervious pavement system. While Coupe (2004) had demonstrated that oil degrading microbes would respond positively to food sources in the system and hence, there was no significant need for simulation by nutrient addition, the author concluded in the study presented here that fertilizer addition should only be conducted if the waters are to be used for irrigation where the nutrients would be beneficial to the plants and that even in this case, the microbiological water quality should be constantly monitored and the addition suspended if the risk of contamination from adjoining areas is high (see section 8.3, Chapter 8).

Unfortunately, urban drainage pollution control approaches pursued before the emergence of sustainable urban drainage systems (SUDS) did not solve this problem of conveyance of nutrients to natural water courses as it focused on point source discharges such as sewage and industrial effluents resulting in widespread pollution of watercourses, underground aquifer and disruption of ecosystems (Mitsch *et al.* 1999, CASQA 2003, Wolch 2007). Consequently, diffuse pollution which usually accompanies storm events continued to disperse pollutants from both rural and urban surfaces resulting in many years of runoff contamination (Heal, Mclean and D'arcy 2004, Berry 2000).

The concept of long-term sustainability in development was introduced by the Rio Declaration and Agenda 21 at the United Nations summit in Brazil in 1992. The adoption of this set of principles (Agenda 21) which defines people’s right to development and the need to protect the common environment was in recognition of the integral and interdependency of all things in nature (UN 2005).

Consequently, there has been recognition of the need for an integrated approach to urban water systems: surface water, ground water, and water quality, water quantity and ecology which may inspire new solutions to water problems (Geldof and Stahre 2006). This integrated and sustainable approach to urban drainage is known as *Sustainable Urban Drainage System (SUDS).* In the United States of America, similar philosophies have been termed *Best Management Practice (BMP) or Compensating Techniques* (Urbonas and Stahre 1993, Iwugo, Andoh and Feest 2002*).*

Berry (2000) described Sustainable Urban Drainage System as a philosophy that incorporates surface water systems into drainage design to alleviate the effects of pollution and run off on the environment. It is a concept that makes use of all aspects of the urban drainage system for hydraulic considerations and environmental protection (Bryant 2006). SUDS is also referred to as a concept or philosophy that manages quantity and quality of urban runoff while providing biodiversity benefit (CIRIA 2006). It involves the consideration of long term environmental and social factors in urban drainage decision making (SuDSWales 2006, RCEP 2007). Under Sustainable Drainage Systems (SUDS), water quantity; water quality and amenity are considered together. This is known as the ‘Sustainable Urban Drainage (SUDS) triangle’ (Heal, Mclean and D’arcy 2004) as shown in Figure.2.1.

The SUDS treatment train (see Figure 2.2) is designed to ensure that pollution is managed as close to source as possible (CIRIA 2006, UWTC 2007, CIRIA 2007b). This treatment train employs the concept of surface water management train adopting a top down approach (Globalwatch 2006)

Figure 2.1: The SUDS triangle (UWTC 2007)

Figure 2.2: SUDS treatment train (SuDS Wales 2006, UWTC 2007, CIRIA 2007b)

SUDS approaches have been recognized as one effective means of reducing urban water pollution and flood risks (Pratt 1999) and confirmed through government legislation urban planning guidance and industry practice guidance (example: PPS 1 and 25) (CIRIA 2007a, Gray 2007) as well as regional spatial strategies for local authorities (example: RSS policy 4A.2i) (Local Government Association 2006). One of the benefits of the introduction of the concept of sustainability in the area of urban water systems is the increased interest in the achievement of source control and open drainage of stormwater within the urban areas (Stahre 2002). Hence, the basic principle of SUDS is source control which involves the control of runoff volume and improvement of runoff quality as close as possible to the point where the rainfall hits the earth surface (Newman *et al.* 2004b).

In the UK, despite availability so many programmes, manuals and project guidelines from organizations such as the Construction Industry Research and Information Association (CIRIA), Scottish Environmental Protection Agency (SEPA), Environmental

Agency (EA) in England and Wales on the benefits from the application of SUDS, the adoption of SUDS paradigm is being slowed down by concerns about its operation and maintenance in the long run (Andoh and Iwugo 2002). However, the adoption of SUDS is not just a proposal which could benefit the temperate countries of the higher altitudes. In hotter countries of the world with two main seasons: rainy and dry (e.g. Nigeria); stormwater is often channeled to natural courses and flooding is a problem during the rainy season. Whilst water scarcity is a problem during the dry season especially for agricultural irrigation purposes; stormwater harvesting could encourage the use of sustainable urban drainage system in this region of the world where one might expect the adoption of this concept to be unlikely.

2.2 Relationship between Integrated Water Resources Management (IWRM) and Sustainable Urban Drainage System (SUDS)

According to Weng (2009), the concept of International Water Resource Management (IWRM) was formally recognised at the international conference on water and the environment held in Dublin, Republic of Ireland in 1992.

In order to provide a common working framework for all stakeholders, Global Water Partnership (GWP) defined IWRM as "…*a process which promotes the co-ordinated development and management of water, land and resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*" (GWP 2000, Weng 2009).

The four principles of IWRM (adopted at the Dublin conference) are:

1. *“Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment*
2. *Water development and management should be based on a participatory approach, involving users, planners and policy makers at all levels*
3. *Women play a central part in the provision, management and safeguarding of water*
4. *Water has an economic value in all its competing uses and should be recognized as an economic good.”* (GWP 2000).

IWRM takes into consideration human groups, environmental factors and natural water water systems in the manangement of man-made and natural water resources for sustainable beneficial use (Grigg 2009).

SUDS is designed to achieve the three essential elements of stormwater quantity, quality and amenity (including biodiversity) as shown in the SUDS triangle in page 16. The collaboration of different disciplines is required for SUDS to achieve its multi-functional design (Darlow *et al.* 2003). There is also need to address spatial planning issues in order to enhance the benefits from amenity and management of biodiversity especially where larger development or retro-fitting is being considered. There is also opportunity for involvement of stakeholders (as reflected in CIRIA Guidiance manual (CIRIA 2007b)) in the application of SUDS due to the interest the system generates because of its multiple objectives and potential benefits (Darlow *et al.* 2003).

This shows that SUDS is an Integrated Water Resource Management (IWRM) strategy as it employs the multidisciplinary and even cross-sectoral approach (which involves private and public sector participation) to the management of urban drainage to provide sustainable benefits.

Case Study: The Metropolitan Glasgow Strategic Plan

This project is a national planning priorty to replace the ageing Glasgow drainage system which failed during the heavy rains of 2002 resulting in huge flooding problems in the city.The Metropolitan Glasgow Strategic Drainage Partnership (MGSDP) comprising of major stakeholders such as Scottish Water, Glasgow City Council (and other seven city councils surrounding Glasgow), Scottish Environmental Protection Agency and the Scottish Enterprise were tasked with the responsibility of working out strategies to reduce flood risk and evaluate Glasgow's complex drainage network with a view to finding lasting and sustainable solutions to the drainage problems. "*The five key objectives of the MGSDP are:*

- *Flood risk protection*
- *River water quality improvement*
- *Enabling economic development*
- *Habitat improvement*
- *Integrated investment planning*" (MGSDP 2008)

SUDS techniques have been identified by MGSDP as the best approach to reducing flood risk in Glasgow city and improving the water quality of river Cylde, improvement of economic growth and infrastructural development, improvement of natural habitat and the quality of life of the inhabitants of Glasgow. While this work is still on-going, it shows a clear application of SUDS as an IWRM management startegy. Further information on this project can be obtained from Metropolitan Glasgow Strategic Drainage Partners briefing Notes.

2.3 The Concept of Low Impact Development (LID)

There is no doubt that when conventional drainage systems linked to urbanization replaces open land with impervious surfaces, it alters the water balance and encourages pollution of run-off at the detriment of infiltration (EPA 2000a). Studies have shown that changes can occur in the stream ecology even when the ratio of impervious area is small; with major reduction in habitat and water quality occurring at just a proportion of 10-30% (EPA 2000a, Monk 2006). The reader is referred again to Table 2.1

The concept of Low Impact Development (LID) is said to have started in 1990 in Prince George’s County in Maryland, USA (DER, Prince George’s County 1999a,b) as an alternative to the traditional Best Management Practices (BMP) in controlling stormwater and maintaining predevelopment hydrological characteristics of the urban and suburban catchments (EPA 2006). The basic objective of LID is to copy the pre-development site hydrology by the use of design techniques that can ensure stormwater storage, detention, evaporation and infiltration (DER, Prince George’s County 1999a,b). LID is also described as an attempt to apply pollution control and waste reduction concepts to land development (NAHB Research Center 2003, EPA 2000a). Some of the LID practices and designs are sometimes referred to as environmentally friendly designs; resource efficient designs; better site designs (NAHB Research Center 2003) and environmentally sensitive designs (DER, Prince Georges County 1999a,b). LID approach has been shown to be efficient in dealing with stormwater pollution and protecting watersheds undergoing development and those already developed (EPA 2000a).

Source control and micro-scale integrated management practices which are among the practices of LID that have the capability to function effectively as stormwater retrofits in urban areas where large scale development has already taken place (Clar 2000, Clar and Coffman 2001). It also said to contribute to achieving beautiful neighbourhoods, thermal pollution reduction, wildlife habitat, increased property value and re-development potential, energy savings, smog reductions, decreased flooding and wetland protection (DER, Prince George’s County 1999b).

Clearly, the relationship between LID and SUDS is that LID is a Best Management Practice (BMP) or Sustainable Urban Drainage System (SUDS) strategy which seeks to utilize a development sites natural hydrologic property in dealing with stormwater runoff and meeting the requirements of environmental regulators (IOWA Stormwater Manual 2008). SUDS techniques that are employed in LID include: bioretention, filter/buffer strips, grassed swales, dry swales, wet swales, infiltration trenches, etc (IOWA Stormwater Manual 2008).

2.4 Use of Pervious Pavements in Urban Drainage

Pervious pavement systems (also referred to as permeable or porous pavement systems) are important part of the Sustainable Urban Drainage System (SUDS) approach to urban drainage (Newman *et al.* 2004b, Collins, Hunt and Hathaway 2006). Ferguson (2005) identified nine categories of porous surfacing options: decks, open-celled paving grids, open-graded aggregate, open-jointed paving blocks, plastic geocells, porous asphalt, pervious concrete, porous turf, and soft paving. These pavements have found much use in car parks and pedestrian walkways as a sustainable and effective replacement for the conventional system which involved the use of impervious surfaces (Newman *et al.* 2003, Newman *et al.* 2004b, Collins, Hunt and Hathaway 2006). The ability of pervious pavements to control drainage at source makes it an important approach to SUDS (EPA 1999, Pratt 1999, Pratt, Newman and Bond 1999, Newman *et al.* 2003, Newman *et al.* 2004b). This recognition as an effective tool for source control is as a result of its capability to infiltrate stormwater into hard surfaces and gradually attenuates it into the soil or a drainage outlet (Newman *et al.* 2003). Their use as car park surfaces among others has attracted attention from many researchers (Pratt 1995, Booth and Leavitt 1999; Newman *et al.* 2002a,b, Pratt, Wilson and Coope 2002, Brattebo and Booth 2004, Newman *et al.* 2003, Newman *et al.* 2004b, Ferguson 2005, Ping and Fang 2005) and some environmental institutions (CIRIA 2007a,b, EPA 2001, EPA 2006). The increasing use of pervious pavements in the UK, New Zealand, Canada (Newman *et al.* 2004b) and the USA (Ferguson, 2005, Collins, Hunt and Hathaway 2006) indicates the acceptance of this SUDS technique as an effective replacement for conventional impervious surfaces.

About 5 years ago, over 500,000 m^2 of pervious pavements were installed in the United Kingdom alone (Newman *et al.* 2004b) and about 30% of these installed pervious pavements were under sealed, thus having the potential of being used as a stormwater storage device (Newman *et al.* 2004b). Hence, it would be logical to use the water storage capacity of the pervious pavement system instead of separate water tanks in places where their installation is specified (Coupe and Nnadi 2007). The pervious pavement system has been shown to be capable of removing stormwater pollution especially hydrocarbons through filtration, sorption and biodegradation (Pratt 1995, Bond 1999, Pratt, Newman and Bond 1999, Coupe 2004, Newman *et al.* 2002a,b, Newman *et al.* 2002c, Brattebo and Booth 2004, Newman *et al.* 2006a,b). Hence, permeable pavements offer a solution to urban drainage problems as well as pollution of downstream and underground aquifer especially with increased use of cars (Brattebo and Booth 2004). Recently, research has shown (Hanson-Formpave combined SUDS building at BRE Watford, UK) that a ground source heat pump (GSHP) system can be incorporated in the pervious pavement system with the capability of providing cooling and heating in the linked building; hence saving up to 80% domestic heating and cooling costs (Coupe and Nnadi 2007).

Pratt *et al.* (2002) observed that the design of the pervious pavement system affects its performance. The pervious pavement system often consists of the natural stone base layer which serves both as a load bearing structure and a water storage reservoir, gravel layer sometimes separated from the sub-base by geotextile material and matrix of concrete blocks with voids necessary for stormwater infiltration (Pratt 1995, Brattebo and Booth 2004).

The geotextile material is considered by some as an important component of the pervious pavements system design which is effective in trapping pollutants in stormwater and serves as the site for biodegradation process within the system (Bond, 1999; Newman *et al.* 2006a). On the other hand, Yong *et al.* (2008) observed in a tanked laboratory based study in Australia that the installation of geotextiles in pervious pavement system encouraged clogging which affected the overall performance of the system. However, this material has been shown to encourage the growth of oil degrading microbes (Bond 1999, Pratt, Newman and Bond 1999, Coupe 2004, Newman *et al.* 2006a,b). Some researchers have demonstrated the efficiency of the geotextile layer in the pervious pavement system in filtering out heavy metals and adsorbing hydrocarbons in stormwater (Pratt, 1995, Bond 1999, Newman *et al.* 2003, Culleton *et al.* 2005).

Since Pratt (1999) recognized that the pervious pavement system has the capability to store water for reuse, the possibility of using the SUDS device simultaneously in source control and water recycling applications did not seem to have been holistically investigated. In the light of the foregoing, the author’s attempt to conduct this work was boosted by progressive research work in the porous pavement research group (currently known as the Sustainable Urban Drainage Research Group). Consequently, the author carried out a brief review of completed PhD work in this research group which had laid the foundation for the research work presented in this thesis.

2.5 A Brief Review of Completed PhD Work in Porous Pavement Research Group

Berry (1995) laid the foundation of PhD research on porous pavement in Coventry University. Her work determined the structure of laboratory PPS models. She tested the suitability of blast furnace slag, granite, limestone as sub base materials for the construction of the porous pavement system and established that granite is the best construction material for the sub base of the PPS. Granite was shown to have good load bearing capability as well as best water holding quality within the void ratio of the granite pieces. Her work also established the need for a geotextile within the porous pavement system and the effectiveness of Terram 1000 (Terram, Ltd UK) polypropylene geotextile in retaining pollutants and improving water quality. Berry’s work created an understanding of the geological and hydrological properties of porous pavement systems. Her design of a rainfall simulator which she used for testing infiltration and water holding capability of the porous pavement models paved the way for the use of rainfall simulator on porous pavement models and established the potential of system as a source control system for urban drainage.

Brownstein (1998) identified the capability of the porous pavement to retain hydrocarbons by simulating the catastrophic leaking of a crank –case of a vehicle engine on a porous pavement model. He established test systems and protocols by the research group. He did preliminary work identifying geotextile as the main component of the porous pavement system and established the maximum hydrocarbon load bearing capability of the system; hence identified the break-through point at which the system would fail to retain hydrocarbons. His work established the possibility of biodegradation within the porous pavement system and the possibility of oil treatment in-situ. He analyzed carbon dioxide and oxygen gases within the porous pavement system and asserted that the increased levels of carbon dioxide and decreased levels of oxygen were as a result of biodegradation of oil. Furthermore; he identified nutrients and degrading microbes as the factors necessary for simulation of biodegradation in the system. He also demonstrated the effect of temperature on biodegradation in such system. Brownstein's work changed the focus of the porous pavement research into a multidisciplinary research effort at Coventry

Bond (1999) analyzed the hydrological and chemical processes within the pervious pavement system. He successfully identified some of the hydrological properties of the geotextile in the system. He studied metabolic indicators in the system after addition of slow- release NPK and trace elements for 400 days and concluded that these nutrients facilitated the biodegradation process. He demonstrated through water quality tests that majority of pollutants were retained within the porous pavement system. Bond's work showed that a large and stable bacterial community thrived within the system. He commenced field based study in the research group by constructing a PPS car park in Coventry University which he monitored and tested with simulated rainfall regimes.

Coupe (2004), studied the structure and characteristics of the oil degrading microbes within the porous pavement system using scanning and transmission electron microscopy. He looked at the microbial diversity within the system and studied the effects of fungi and protozoa on the biodegradation process. He successfully identified some of the consumers of the primary decomposers such as: protozoa, testate amoeba, micoflagellates, gymnamoeba, ciliates and even metazoans including nematodes and rotifers. Coupe's work showed that the protozoan diversity came from some of the components of the PPS especially the granite sub- base material. His work showed the importance of the protozoan community in the biodegradation process within the pervious pavement system. He demonstrated this by removing the prokaryotic community by dilution, filtration and anti-microbial agents which resulted in a reduction in the biodegradation rate within the PPS. He compared recycled concrete and granite as sub base materials. He observed that granite supported a more complex protozoan community than concrete; while concrete supported more metazoans. On analysis of effluent after oil addition, he also discovered that concrete sub base system retained more oil than granite system. However, work by Newman *et al.* (2007) has shown that concrete is not universally good as a sub base material because of downstream deposition of calcium salts in the pipe wall of tanked systems. Coupe (2004) also did preliminary analysis of effluent from field based PPS for water quality. His work raised up a lot of side issues for further research. However, he was the first researcher to identify other microbial communities apart from bacteria within the PPS and their importance in the biodegradation process.

NPK and trace elements are important the biodegradation process within the pervious pavement system (Bond 1999). Spicer (2006) used this information to develop a self – fertilizing geotextile mat to provide a sustained release of these nutrients to the microbial community that requires it for effective biodegradation process within the PPS. She produced a geotextile mat spun from polymer fibers. These fibers contained phosphated polymer beads that released a sustained volume of phosphate required for biodegradation as soon as it makes contact with water. She observed an increased microbial growth with the use of this mats within the PPS through gas analysis. A comparison between a PPS with the phosphate mat and one with ordinary geotextile showed increased bacterial presence and activities in the phosphated mat. Her analytical results also indicated increased microbial diversity including protozoans in the system containing the phosphate mat. This result is in agreement with work done by Steve Coupe in 2004.

Puehmeier's (2008) work provided initial information on the ecology of oil degrading pervious pavements using molecular techniques. His work showed that it is possible to study bacterial diversity within the pervious pavement system with biological molecular techniques. These molecular techniques showed for the first time, that despite mainly a single carbon source (hydrocarbons) being available in the PPS, the microbial diversity of the system increases with time (Newman *et al.* 2002b). His work also demonstrated the ability of the PPS to retain pollutants long enough for them to be degraded which is one of the main factors necessary for effective biodegradation to take place (Newman *et al.* 2002b,c). He jointly developed an oil interceptor system incorporated within pervious surface construction which he experimentally showed to effectively retain pollutants capable to deal with worse case scenarios of credible pollution and rainfall events, i.e. crank case or fuel tank failure (Newman *et al.* 2003, Wilson *et al.* 2003, Newman *et al.* 2004a,b). The device also supports effective biodegradation of pollutants (Puehmeier *et al.* 2005).

Puehmeier also developed an effective sampling device for sampling oil from pervious pavement models for use in concrete chambers of field installations (Puehmeier *et al.* 2004b). This device allows the collection of a representative oily sample from experimental pervious pavement system by the tipping bucket system (Puehmeier *et al.* 2004b). He also compared oil retention capability of traditional PPS using granite sub - base to those using recycled concrete and plastics. He showed that the recycled concrete and plastic sub-bases retained more oil relative to the granite ones, though all the systems failed to retain oil satisfactorily under simulated sudden and extreme oil loadings (Puehmeier *et al.* 2005).

Conclusively, the review of literature:

- Explored some of the issues that related to this research work and contributed to my understanding of research work already conducted in this area.
- Showed that since Pratt (1999) and Newman *et al.* (2003) observed that the pervious pavement system posseses the capability for water storage, there is no evidence from literature before this work of investigation of this capability
- Showed that there is no evidence of investigation of the suitability of waters stored in the pervious pavement system for agricultural irrigation
- Indicated that the potential effect of nutrient addition to pervious pavement structures in order to simulate biodegradation (in cases where water from pervious pavement system was to be channeled to receiving natural waters) was underplayed by previous researchers

The author found these conclusions useful in the design and conduction of the experiments presented in this thesis.

The next chapter can be considered as both a contribution to the wider understanding of the pollution retaining performance of a wide range of pervious pavement surfaces, but more importantly as providing the author with an initial data set on how the system deals with pollution. This data set informed, particularly the irrigation water quality and plant irrigation experiments reported in Chapters 4 and 5 of this thesis.

Chapter 3: Water Quality of Waters Derived From a Range of Pervious Pavement Systems

3.1 Introduction

There is no doubt that urban run-off is often polluted with contaminants. The type and level of pollutant present in a particular run-off is dependent on the environment, speed of flow, etc. (Dechesne, Barraud and Bardin 2004, Eriksson *et al.* 2007). However, the common stormwater pollutants are hydrocarbons, metals, dust, microbes, pesticides and herbicides (Park and Stenstrom 2005, Weiss, Gulliver and Erickson 2007, Coupe *et al.* 2006a). Pervious pavements and its pollutant removal capability were discussed in Chapter 2 of this thesis. Also, research on microbiological component of stormwater pollution is presented at Chapter 6.

Pervious paving systems have been shown to posses the capability to remove pollutants from stormwater through attenuation and biodegradation *in situ.* Coupe (2004) had earlier reported 99.49% oil retaining capability of the pervious pavement system without bacterial inoculation. However, under higher oil loading over a shorter period of time, an oil retaining efficiency of 95.59% without bacterial inoculation (reported in pages 154-155) for the stone based PPS model that Coupe had earlier studied. The ability of the pervious pavement system to deal with particulate pollution has also been reported (Forsberg *et al.* 2009).

In this chapter, the pollution retaining performance of a wide range of pervious pavement surface was investigated and compared to the well-studied blocked paved surfaces. Furthermore, the waters from these wide range pervious pavement systems were examined using international irrigation water quality standards.

3.1.1 Irrigation Water Quality Standards

Whilst PPS effluents in both lab and field systems have, as we have seen, been widely studied from the point of view of the effluent as a pollutant, little work seems to have been done from the perspective of using the water as a resource for irrigating plants. It is obvious that stormwater treated and stored in pervious pavement system has to meet various quality standards in order to be considered for reuse as credible irrigation water. These standards will differ from the standards applicable to both simple disposals to a watercourse and for drinking water use. Irrigation water quality is determined based on the measurement of various parameters. Some of these include:

- Electric Conductivity (Tarchitzky *et al.* 2007)
- pH (Tarchitzky *et al.* 2007, Heidarpour *et al.* 2007)
- Total dissolved solids (TDS) (Tarchitzky *et al.* 2007)
- Elements in water (Chen *et al*. 2002, Heidarpour *et al.* 2007)
- Heavy or trace metals in water (Solis *et al.* 2006, Toze 2006, AbdEl-Hardy 2007)
- Sodium adsorption ratio (SAR) (Tarchitzky *et al.* 2007, Heidarpour *et al.* 2007)
- Carbonate (CO_3) and Hydrogen Carbonate (HCO_3) (Al-Shammiri *et al.* 2005)
- Microbial water quality (Solis *et al.* 2006, Toze 2006, Heidarpour *et al.* 2007)
- Total oil or /mineral oil in water (Tarchitzky *et al.* 2007)

Table 3.1 shows the threshold levels of some elements in standards set by some regulatory agencies and countries. It also shows results obtained after the use of mircofiltration (MF) technology in filtration of waste water for irrigation reuse in Kuwait (Al-Shammiri *et al.* 2005).

Table 3.1 Different Trace Metal Standards of Treated Wastewater for Irrigation

Element	Wastewater used in Pakistan for Irrigation	Standard Concentration	MF filtrate Water	FAO Standards	Canada Standards	Nigeria Standards
Aluminium	-	5.0	0.3-0.4	5.0	5.0	5.0
Arsenic		0.1	-	0.1	0.1	0.1
Beryllium	-	0.1	-	-	-	-
Boron	-	0.75	<0.3	-	-	-
Cadmium	0.01	0.01	<0.01	0.01	0.01	0.01
Potassium	34.7	-	9.6-10	-	-	-
Magnesium	67.6	-	8.26	-	-	-
Chromium	0.23	0.1	<0.05	0.1	0.1	0.1
Cobalt	0.06	0.05	-	-	-	-
Copper	0.35	0.2	<0.05	0.2	0.2-1.0	0.2-1.0
Iron	0.22	5.0	<0.05	-	-	-
Lead	0.04	1.5	<0.05	-	-	-
Lithium	-	2.5	-	-	-	-
Manganese	0.07	0.2	<0.05	-	-	-
Molybdenum	-	0.01	-	-	-	-
Nickel	0.14	0.2	-	0.2	0.2	0.2
Selenium	-	0.02	<0.05			
Vanadium	-	0.1	-			
Zinc	-	2.0	<0.05	2.0	1.0-5.0	0-5.0

Adapted from Al-Shammiri *et al.* 2005

Table 3.2 below shows the pH and acceptable levels of elements and compounds that could be present in irrigation water

Table 3.2 The Status of pH, Nutrient Elements and Compounds Found in Acceptable Irrigation Water

RELATIVE STATUS							
Element	Application	Units	V. Low	Low	Medium	High	V High
pH	All, 5.0-7.0 is normally acceptable. Some species benefit from more acidic conditions						
pH	Micro-irrigation. blockage		<6.5	6.5-7.2	7.2-7.6	7.7-8.0	>8.0
Nitrogen -Total N	All	ppm	<18	19-36	37-54	55-90	>90
Nitrate-N(NO_3-N)	All	ppm	<15	16-30	31-45	46-75	>75
Ammonium-N (NH_4-N)	All	ppm	<3	4-6	7-9	10-15	>15
NH_4-N +NO_3-N	Hydroponics	ppm	<5	6-13	14-21	22-30	>30
Phosphorus (P)	All	ppm	<1	1-1.9	2-2.9	3-5	>5
Potassium (K)	All	ppm	<3	3.1-4.5	4.6-6.0	6.1-10.0	>10
Calcium (Ca)	All	ppm	<40	41-80	81-120	121-150	>150
Magnesium (Mg)	All	ppm	<8	9-16	17-24	25-30	>30
Sulphate-S (SO_{4-}-S)	All	ppm	<24	25-50	51-240	241-300	>300
Boron (B)	Greenhouse, Nursery	ppm	<0.25	0.26-0.5	0.51-0.8	0.81-2.0	>2.0
Boron (B)	Field Crops	ppm	<.075	0.76-1.17	1.18-1.6	1.61-2.0	>2.0
Boron (B)	Hydroponics	ppm	<1.0	1.1-1.25	1.26-1.6	1.61-2.0	>2.0
Copper (Cu)	All	ppm	<0.05	0.06-0.10	0.11-1.2	0.21-0.30	>0.30
Iron (Fe)	All	ppm	<0.20	0.21-0.30	0.31-0.4	0.41-0.50	>0.50
Iron (Fe)	Micro-irrig. blockage	ppm	<0.20	0.21-0.63	0.64-1.0	1.1-1.5	>1.5
Manganese (Mn)	All	ppm	<0.50	0.51-0.75	0.76-1.0	1.1-2.0	>2.0
Manganese (Mn)	Micro-irrig. blockage	ppm	<0.10	0.11-0.57	0.58-1.0	1.1-1.5	>1.5
Molybdenum (Mo)	All	ppm	<0.005	.006-0.01	0.11-0.2	0.21-0.05	>0.05

Adapted from Spectrum Analytical Incorporated 2008b

Furthermore, Table 3.3 below shows various elements that may be toxic to plants when in excessive concentrations in irrigation water.

Table 3.3 Toxicity Hazard of Elements

TOXICITY HAZARD							
Element	Application	Unit	None	Increasing	Significant	High	Severe
Sodium	Foliar	ppm	<69	No specific calibration			
Sodium	others	-----	-----	Use SAR or SAR adj			
Sodium	Woody ornamentals	ppm	<30	31-35	36-45	46-50	>50
Aluminium	Long term irrigation	ppm	<1	1.1-3.0	3.1-4.0	4.1-5.0	>5.0
Chloride	Foliar	ppm	<40	41-60	61-80	81-100	>100
Chloride	Soil	ppm	<70	71-140	141-240	241-345	>345
Arsenic	Long term irrigation	ppm	<0.1	No specific information available			
Cadmium	Long term irrigation	ppm	<0.01	No specific information available			
Lead	Long term irrigation	ppm	<5	No specific information available			
Lithium	Long term irrigation	ppm	<2.5	No specific information available			
Nickel	Long term irrigation	ppm	<0.2	No specific information available			
Vanadium	Long term irrigation	ppm	<0.1	No specific information available			
Cobalt	Long term irrigation	ppm	<0.05	No specific information available			
Chromium	Long term irrigation	ppm	<0.1	No specific information available			
Selenium	Long term irrigation	ppm	<0.02	No specific information available			

Adapted from Spectrum Analytical Incorporated 2008a,b

Clearly, specific criteria for different levels of toxicity hazard for most of the elements are dependent on the type of plant. However, there are concentrations of non–toxicity as shown in the table above. This highlights the need for caution in the use of reclaimed water for irrigation because of the chance of over reliance on data on non-toxicity concentration and unavailability of data on increasing, significant, high and severe levels of the hazard of toxicity of these elements.

Table 3.3 shows the status of pH, some elements and compounds found in acceptable irrigation water as published by Spectrum Analytical Incorporated, USA. However, these statuses are only related to the levels of the elements in typical irrigation water and not their sufficiency for crop growth because elemental requirements as well as tolerance of plant species differs (Spectrum Analytical Inc. 2008).

Table 3.4 shows the relative toxicity of some elements to crops and animals that may forage on the crops when present solution over long and short terms respectively. This highlights the need to carry out elemental analysis on any water intended to be used for irrigation especially when this water is reclaimed.

Table 3.4 Recommended Limits for Constituents in Reclaimed Water for Irrigation

Constituent	Long-term use (mg/L)	Short-term use (mg/L)	Remarks
Aluminium(Al)	5.0	20	Can cause non-productivity in acid soils, but soils at pH 5.5 to 8.0 will precipitate the ion and eliminate toxicity
Arsenic (As)	0.10	2.0	Toxicity to plants varies widely, ranging from 12mg/L for Sudan grass to less than 0.05 mg/L for rice
Beryllium(Be)	0.10	0.5	Toxicity to plants varies widely, ranging from 5mg/L for kale to 0.5 mg/L for bush beans
Boron(B)	0.75	2.0	Essential to plant growth, with optimum yields for many obtained at a few tenths mg/L in nutrient solutions. Toxic to many sensitive plants (e.g. citrus) at 1mg/L. Most grasses relatively tolerant at 2.0 to 10 mg/L
Cadmium (Cd)	0.01	0.05	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/L in nutrient solution. Conservative limits recommended.
Chromium (Cr)	0.1	1.0	Not generally recognised as essential growth element. Conservative limits recommended due to lack of knowledge on toxicity to plants
Cobalt (Co)	0.05	5.0	Toxicity to tomato plants at 0.1 mg/L in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Copper (Cu)	0.2	5.0	Toxic to a number of plants at 0.1mg/L in nutrient solution
Fluoride (Fl)	1.0	15.0	Inactivated by neutral and alkaline soils.
Iron (Fe)	5.0	10.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of essential phosphorus and molybdenum.
Lead (Pb)	5.0	10.0	Can inhibit plant cell growth at very high concentrations
Lithium (Li)	2.5	2.5	Tolerated by most crops at up to 5 mg/L; mobile in soil. Toxic to citrus at low doses recommended limit is 0.075 mg/L.
Manganese(Mg)	0.2	10.0	Toxic to a number of crops at few mg/L in acid soils.
Molybdenum(Mo)	0.01	0.05	Non-toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high levels of available molybdenum.
Nickel (Ni)	0.2	2.0	Toxic to a number of plants at 0.5 to 1.0 mg/L; reduced toxicity at neutral or alkaline pH
Selenium (Se)	0.02	0.02	Toxic to plants at low concentrations and to livestock if forage is grown in soils with low concentrations of added selenium.
Vanadium (V)	0.1	1.0	Toxic to many plants at relatively low concentrations
Zinc (Zn)	2.0	10.0	Toxic to many plants at widely varying concentrations; reduced toxicity at increased pH (6or above) and in fine-textured or organic soils.

Adapted from Rowe and Abdel-Magid 1995 in A & M University Texas 2008

3.1.2 Alternative Paving Surfaces

Most of the previous work especially in Coventry University was on block paving surfaces. Porous asphalt and concrete are also attractive types of pervious pavement system and have been shown to be effective in stormwater management especially in car parks and roads (Ray 2008, Potier 2008). They are installed in the car parks of many major supermarkets in the UK and also used extensively in sidewalks, airport runways, air sides and car parks as well as in hotel complexes. A recent study published by the University of New Hampshire USA, shows that porous asphalt could reduce the application of salt on roads by 70% as well as remove stormwater pollutants such as heavy metals, sediments and petroleum products (Potier 2008). This indicates the enormous potential for the use of porous asphalt and concrete systems in stormwater recycling application. Consequently, the author initially proposed to carry out a small scale laboratory study to investigate the capability of the porous asphalt and concrete to retain pollutants such as oil and suspended solids. Due to resource constraints the author had intended to carry out only an initial scoping experiment on water quality from very small scale models and was therefore excited to learn about a proposal from Tarmac UK Ltd for a collaborative study with Sustainable Urban Drainage Applied Research Group (SUDSARG), Coventry University to evaluate the pollutant retention capability of the Tarmac Aquifer Pervious pavements in comparison to the “well studied” block paving system. Tarmac UK Ltd has a wide range of pervious paving products which have been installed on roads, car parks, sidewalks, airports, even in housing areas and the Tarmac Aquifer pervious pavements is among the range of paving products the company regularly installs on roads, car parks, airports and even sidewalks. Hence, the author was delighted to utilize this opportunity to study these products in a larger laboratory scale when his proposal was accepted for participation in this project and when he had the agreement of his supervisor at that time.

The part of the programme reported here was thus conducted within the Sustainable Urban Drainage Applied Research Group (SUDSARG), Coventry University. The author of this thesis carried out the day-to-day research activities involved in this study, except for the laboratory analysis. In this part of the work, the author was able to take advantage of support from the Coventry University Analytical Laboratory Consultancy. Given the large number of determinations required within the timeframe, it was not considered practical for the author to carry out the analytical work at this time. However as part of this process author was able to get important training and experience of these analytical processes and applied them in other studies reported in Chapters 4 and 5 of this thesis.

3.2 Materials and Methods

The broad outline of the experiment was to apply oil and street dust to a cross section of Pervious Pavement system models. Simulated rainfall was applied and the effluent was captured and analyzed for a number of determinands. Whilst the results would have great relevance to broader issues of pollutant retention and biodegradation in PPS, the author's personal interest was to consider the results in relation to water quality as applied to irrigation and other forms of re-use. Strictly speaking this would be only directly comparable to a situation in which water was collected from a pervious pavement system and stored off line prior to re-use, but the situation was considered sufficiently relevant to the situation where water is stored directly in the structure for it to inform further work later in the programme.

3.2.1 *Test Model Design*

Nine (9) test models were constructed and used for this study. Six (6) of the models were asphalt paved models; two (2) were porous concrete paved and one (1) Hanson-Formpave Aquaflow block paving model which was used as control (as it was the model used for previous studies). All were flushed with clean water after construction.

3.2.2 *Box Used for Models*

In previous laboratory model studies carried out at Coventry University most models had either been constructed using either glass tanks supported in steel frames or Perspex constructions held together by solvent welding. Given that a reasonable sized model was required to minimize edge effects and the large number of models required these approaches would be both expensive and susceptible to damage in the very busy and crowded laboratory. Attempts had been made by both Coupe (2004) and Puehmeier (2008) to use plastic dustbins as the basis for model pavement cross sections but there had been at least one serious failure with the plastic bins in the past and, given the need to vibrate various layers into place these were not considered practicable.

Following a review of materials available these models (9) were constructed within strong polypropylene box type stillages of dimensions 120cm × 100cm × 60cm (manufactured by George Utz Ltd Derbyshire, UK). These stillages were designed to be lifted on a fork lift truck and were supplied with appropriate blanked spigots for attachment of a tap. A plastic tap (supplied by Wilkinson, UK Ltd) was installed at one of these spigots which were located adjacent to the base; and connected with a slotted plastic pipe of 300m long and 15mm stand-off from the interior of the base of the box. The pipe was covered with Formpave standard geotextile (supplied by Hanson-Formpave Ltd, UK) cut to the size of 350mm × 350mm.

3.2.3 *Porous Asphalt Models*

Type 3 stone from Edwin Richards Quarry, Warley West Midlands UK was used as sub base for all the six (6) asphalt models. The asphalt used for the construction of the models was laboratory mixed using aggregate from Bayston Hill gritstone, Shewsbury, UK and Nynas bitumen, modified with 3% Sasobit and cellulose fibre. This was a proprietary mix developed by Tarmac. The models were labelled 1a, 1b, 2a and 2b as shown in figure 3.1 below. The depth of the sub base of test models 1a and 1b was 350mm while that of 2a and 2b was 300mm. In models 1a and 1 b, the binder layer had a thickness of 70mm and the thickness of the asphalt coating was 30mm as shown in Figure 3.1. Formpave standard geotextile (supplied by Hanson-Formpave, UK) was placed on top of the sub base and protected with a 50mm granular before the binder of 70mm was installed in test models 2a and 2b (Figure 3.1). Asphalt coating thickness in models 2a and 2b was the same as in models 1a and 1b. Test model 3 was same as models 1a and 1b except that the thickness of the binder layer was reduced by 20mm (Figure 3.1).

3.2.4 ***Matured Porous Asphalt Model***

During the design of this experiment, it was considered important to compare the performance these newly constructed pervious pavement models with porous asphalt that is already installed and has been in use. Therefore, a further test model (5) was constructed by digging out a Tarmac asphalt slab laid in 1999 at Stancombe, Quarry Car park Bristol, UK with mechanical digger and carefully placing the slab on 300 mm sub base layer (supplied by Richards Quarry, Warley West Midlands UK) already in the box after trimming all sides in other to fit into the box. Once in the box, the sides were then sealed with bitumen in order to avoid leakage at the edges and flushed through with clean water. This model was not replicated because of lack of availability of further cut out sections of suitable size.

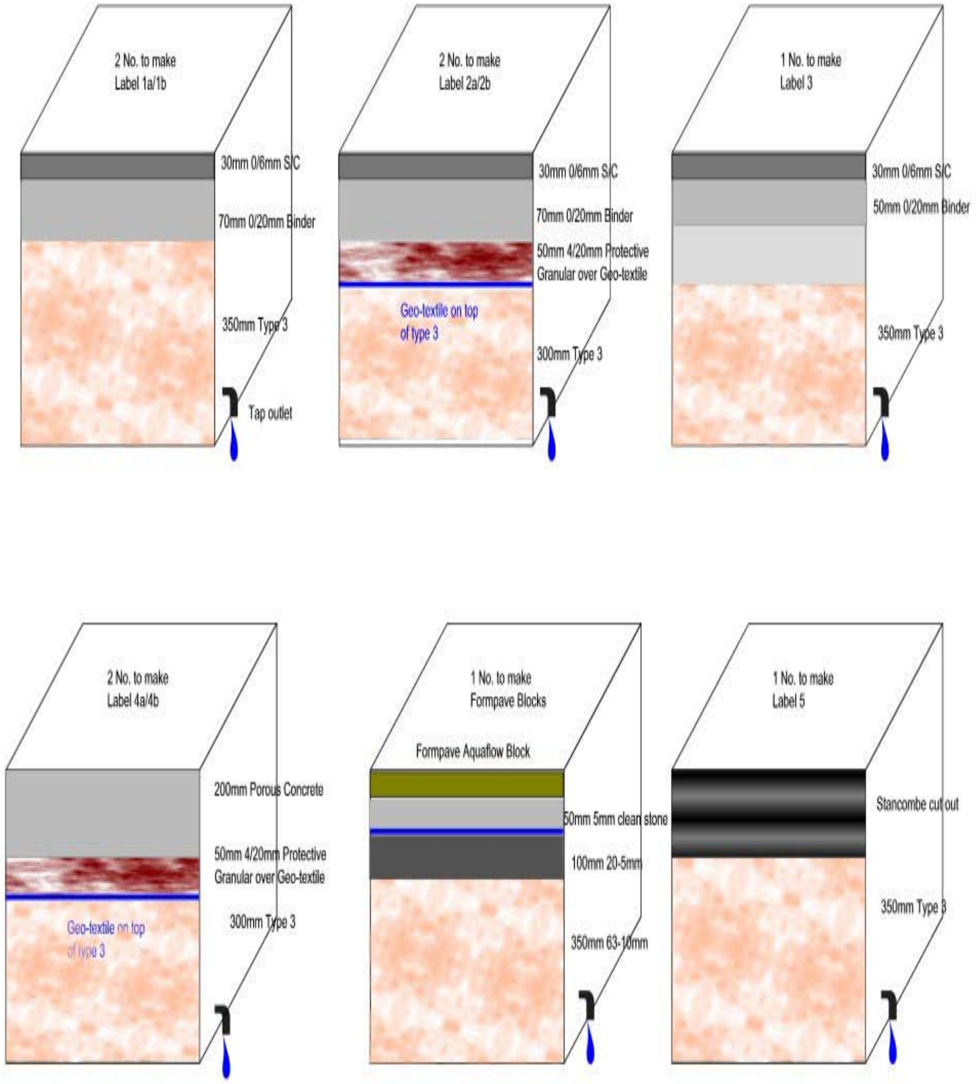

Figure 3.1 Schematic Diagram of the Test Models Used for the Experiment

3.2.5 *Concrete Model*

Two porous concrete paved models were constructed and labeled 4a and 4b.The sub base of the concrete models was the same used in the construction of the asphalt models and the thickness was 300mm. The sub base was laid at the same time as the asphalt models. Geotextile (same supplier as in the asphalt model) was placed on the sub base and a 4/20mm protective granular of 50mm thickness was laid between the geotextile layer and the 200mm porous concrete as shown in Figure 3.1 above. The concrete was laboratory mixed using Tarmac’s aggregate from Bayston Hill gritstone, Shewsbury, UK.

Figure 3.2 Test Models Arranged in the Laboratory in Coventry University-Plastic Barrels to the Rear Contain the Laboratory’s Effluent Treatment System for Treatment of Excess Effluent

3.2.6 *Block Paved Model*

Since considerable experience had already been obtained with block paved pervious pavement system models at Coventry University, it was considered suitable to utilize a single example of a model which utilized block paving.

The model was constructed using a blended aggregate of 63-10mm from Cliffe Hill Quarry Leicestershire, UK. The sub base was laid to a thickness of 350mm. Aggregates of 20-5mm (also supplied by Cliffe Hill Quarry Leicestershire, UK) were installed on the sub base to a thickness of 100mm and Formpave standard geotextile (supplied by Hanson–Formpave Ltd UK) was laid on it. Clean stone of 5mm (also sourced from Cliffe Hill Quarry was installed on the geotextile as bedding layer according to Hanson-Formpave standard at a thickness of 50mm. Formpave Aquaflow blocks were then laid on the bedding layer . The construction of this model was based on the Hanson-Formpave standard as obtained from the Hanson-Formpave manual (2007).

3.2.7 *Rainfall Simulation*

3.2.7.1 *Rainfall Regimes*

There is no satisfactory single simulated rainfall regime from literature that provides rainfall simulation that suits all situations and researches. Over the years, various researchers had adopted various rainfall simulation practices to fit their specific needs and it is not possible to compare the pollutant retaining capability of the pervious pavement system to any standard as a standard does not exist. In order to choose working intensities and rainfall regime that would be realistic and allow for the evaluation of pollutant retention capability of the models, it was decided that the 13mm would be effective since a “rain event” is typically considered by most researchers in this field to require a minimum of 13mm. More so, it was considered reasonable in the selection of rainfall volume not to extend beyond the “minimum rain event” as this might lead to extensive dilution in the system which may introduce a favourable bias to the retention data. Hence, 13 mm was used as the standard for this study.

The time frame over which this rain takes place was also considered important in this study. The range of rainfall intensities and total event volumes used in this area of research has often included a generally gentle rainfall regime of 13-15mm/hour to represent a “reasonable storm”. However higher rates have been used to simulate higher flow rates: Newman *et al.* (2007) had used a rate of 80mm/hour applied as sheet flow over 4 hours and Dierkes *et al.* (2002) used 144mm/hour on the pervious pavement system in Germany. Therefore, the author decided that for practical reasons, that values between 25 and 35mm/hour over 1 hour would be a typical and realistic “high rainfall rate” for indoor previous models in this study.

Hence, “normal rainfall events” was applied in the form of droplets from a rainfall simulator (described below) at a rate which delivered an equivalent of 13mm rain over the rain event at 15mm/hour (52 minutes rain events) twice monthly; a day before and after application of oil and dust (see details of oil and dust application below).

3.2.7.2 *Rainfall Simulator*

It was initially proposed to build a new simulator that would cover the entire surface area of the box, but funds were not made available for the construction of the proposed simulator. In order to continue the research, the author had to make use of the rainfall simulator available in the University. This rainfall simulator used in this study was originally built by Professor Ian Foster at Coventry University for geographical studies. This simulator was modified by shortening of the stand to 20cm. 100mm un-brake swivel castors with nylon wheel (supplied by Keystone Castor company, Birmingham UK) were also fixed on the stand to enable the free movement of the simulator from one test model to another. The modification to the simulator also included water supply which was from a regulated mains supply in Coventry University via a needle valve and a rotameter type flow meter (supplied by Techniquip, Somerset, UK). The rainfall simulator was calibrated before the start of the experiment to establish the relationship between the rotameter reading and the flow rate. Figure 3.3 shows the rainfall simulator mounted on one of the test models. The calibration protocol is presented below.

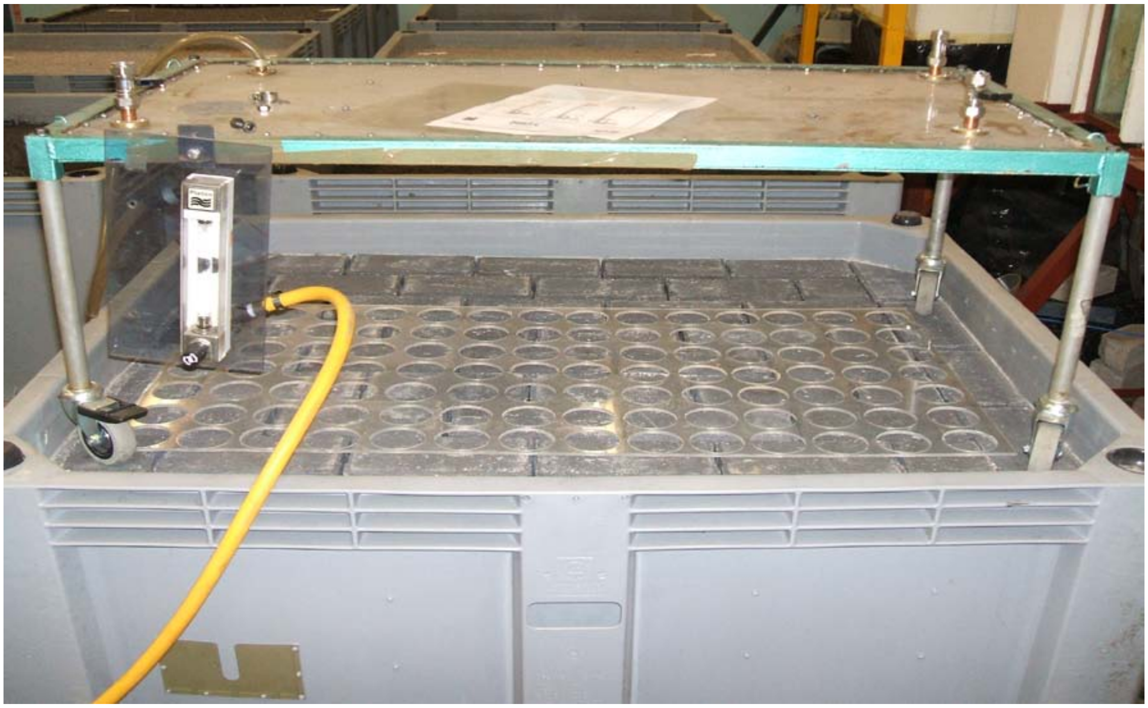

Figure 3.3 Showing Rainfall Simulator on a Test Model and Perspex Quadrat

3.2.7.3 *Calibration of Rainfall Simulator*

The rainfall simulator was set over a steel tray of 120cm × 100cm × 25cm with an overflow outlet pipe of 10cm diameter close to the base in the side wall (same tray constructed and used in calibration of test rig for high infiltration studies (Chapter 7)).

The tray was filled with water to the overflow level.

The rainfall was then simulated at a nominal 5mm/hour and was allowed to rain into the tray for 10 minutes.

The discharge from the pipe in the tray was then collected in a pre-weighed measuring cylinder.

The weight of the measuring cylinder was determined on a weighing balance (Supplied by Sartorius, UK Ltd)

Displaced water was collected in the measuring cylinder to 1 litre volume

Measuring cylinder was re-weighed with water inside (care taken to avoid spillage) to obtain weight of water plus weight of measuring cylinder (Z)

Original weight of the measuring cylinder was subtracted from Z to obtain the mass of water in the measuring cylinder

This protocol was repeated for simulated flow rates of 10mm, 15mm, 20mm and 30mm and calibration graph of flow rate Vs mass of water plotted to calibrate the rainfall simulator

3.2.7.4 *Area of Rainfall Simulation and Contaminant Application*

Due to the fact that the rainfall simulator could only cover $0.5m^2$ of the total surface area of the test model effectively, it was decided that the area covered by the rainfall simulator would be used for the experiment. This area was carefully marked out; and it was ensured that contaminant addition and rainfall simulation were carried within this area. Although this was forced upon the author by availability of rainfall simulator and the commercial availability of a suitable box, it had the advantage of avoiding edge effects caused by water running rapidly between the pavement cross section and the plastic box.

3.2.8 *Quadrat*

A quadrat frame was constructed with a Perspex sheet (Perspex Distribution Ltd, UK) of $0.5m^2$ to ensure that contaminant application was conducted randomly without been concentrated at one point. 14 × 7 circular holes of 10mm diameter were made on the Perspex sheet. The holes made on the quadrant were selected randomly for contaminant application within the marked out area of $0.5m^2$ on the surface of the model as shown in Figure 3.4 below. The quadrat is shown in Figure 3.3 above placed on the marked out area of the test model.

3.2.9 *Calibration of Syringe*

The plastic syringe used in this experiment was PLASTIPAK® (supplied by Becton Dickinson, Ireland). The same calibration method was used as in the irrigation experiment (Chapter 4, Page 94).

In this case, 5ml volume of the syringe used delivered an average of 4.46g throughout the study (see Page 94 for syringe calibration).

3.3.0 Pollutant Addition

3.3.0.1 *Oil*

Clean Shell Helix Super® engine oil 15W- 40 (supplied Shell UK) was applied once every 4 weeks as a single dose to each model at the 25 ml/m^2 to the marked out area of the test rigs (12.5ml/0.5m^2) with the calibrated syringe. Oil was applied in 2.5 ml aliquots at randomly spaced intervals across the marked out surface of the test rig using the rolling of the dice to select application points via the quadrat placed on the rigs as described earlier in page 51.

It was proposed that the oil loading would increase to maximum levels expected of a sump failure towards the end of 12 months.

The oil application rate was chosen for the following reasons:

1. In outdoor tests conducted in a car park at Coventry University, UK by Coupe (2004), a Formpave car park retained 50 ml/m^2, but when oil loading reached 100ml/m^2, detectable levels of oil were found.
2. After an extensive literature review, Bond (1999) proposed that about 0.2ml/m^2/week was the typical daily input of oil to a car parking area.

Hence, the proposed addition rate of 6.25 ml/m^2/week which was also applied in the irrigation experiment reported in this thesis was in excess of the 0.2ml/m^2/week without the risk of quickly overloading point areas.

3.3.1 Methods of Oil Addition

3.3.1.1 Slow Cumulative Addition

The quadrat (described above in page 51) was placed on the surfaces of the test models and the sites of oil application chosen with the 12 sided dice (as described in page 51). In an event that the same site was chosen twice during the same application event, another throw of the dice was made to select a different circle in the quadrant.

The centre of each circle in the quadrat was the application point of the oil to the test rig in each model. An injection of 2.5 ml of oil was made at the centre of five chosen circles in the quadrant using the calibrated syringe (described in pages 51 & 94). The nozzle of the syringe was held approximately 10 mm from the surface of the pavements in the test models as the oil was injected. The same syringe was used for all the models at each oil application event and discarded afterwards. Unused syringe from the same supplier was calibrated and used for each 4 weekly application. Each oil application was conducted a day prior to a scheduled rain event.

Figure 3.4 Showing Applied Oil Drops on Some Rig Surfaces

3.3.2 *Addition of Sediment*

The sediment used in this experiment was street dust collected during routine street sweeping activities and supplied by Coventry City Council. The sediment was dried, homogenized and sieved through a 0.5mm mesh. It was also thoroughly mixed such that 8 out of 10 times i.e. 0.6g aliquots (removed at random) had metal concentrations within +/- 15% of the mean value for metals in street dust according to ICRCL or CLEA SGV limits (Table 3.5 below) for domestic gardens or phototoxicity as appropriate.

Table 3.5 Metal Guideline Values (mg kg^{-1})   ND = No Data

	Cd	Cu	Pb	Ni	Zn
CLEA SGVs	30	ND	450	75	ND
ICRCL Trigger Values	3-15	130	500-2000	70	300

The method used in analysis of the samples by the Coventry University laboratory consultancy is presented in Appendix 21.

3.3.2.1 *Sediment Application Rate*

The sediment was applied at the rate of 21g/m^2, based on Wilson *et al*. (2003). Since the area of simulated rainfall was 0.5 m^2, therefore 10.5g of sediment was applied weekly to the test models.

3.3.3 *Collection of Water Samples for Oil Analysis*

Samples were collected directly from the outlet tap of the models in 100 ml (nominal) amber glass screw capped bottles. The samples were collected immediately the effluents started to flow, approximately halfway through the drainage period and during the last 10minutes of drainage. Background samples of tap water were not collected as background analysis of tap water was not conducted in this study. The author considered that oil would not be in tap water above detection limits.

The collected samples from the test models were refrigerated and analyzed within 28 days.

3.3.4 *Collection of Water Samples for Analysis of Suspended Solids*

During the collection of each oil analysis sample, a composite sample of approximately the first 300 ml was collected directly from models through the outlet tap. These samples were placed in amber glass bottles, refrigerated and analyzed within 14 days after collection.

Samples of tap water was not analyzed for suspended solids as it was considered that suspended solids would not be present in tap water above detection limits for the method used for analysis. Hence, a background analysis of tap water for suspended solids was not conducted. The method used for this analysis is presented in the Appendix.

3.3.5 *Collection of Water Samples for Analysis of Metals*

A composite sample was collected from approximately 300 ml after the collection of samples for the analysis of suspended solids. These samples were collected from the model via the outlet tap and placed in bottles washed and dried in a Lancer 1400 UP glassware washer and dryer (supplied by Lancer USA); using 25% acetic acid and de-ionized water to rinse.

After sample collection, the samples were acidified by addition of 2 ml of conc. Nitric acid (supplied by Fisher Scientific UK) in order to adjust the pH of the samples to less than 2. The samples were refrigerated and analyzed before 6 months after collection. The ICP analysis method was as described in page 97 (chapter 4).

3.3.6 *Collection of Background Sample for Analysis of Metals in Tap Water*

Due to the likelihood of metals being present in tap water, it was considered necessary to carry out a background analysis of tap water used in this experiment.

The background sample (1litre) was collected from the tap water via the connecting pipe to the rainfall simulator. The sample was placed in an acid washed glass bottle, acidified and stored as was conducted in the collection of samples from models above. The background sample was also analyzed using ICP as described in page 97 (chapter 4).

3.4 Results and Discussions

The results of research work on this project for the 8 month period of the experiment are presented below

3.4.1 *Metals in Sediment Extractable using DI Water, Tap Water and Rainwater*

The results of the extraction of metals from street dust experiments using tap water, De-ionized water and rainwater is presented in Figure 3.5 below.

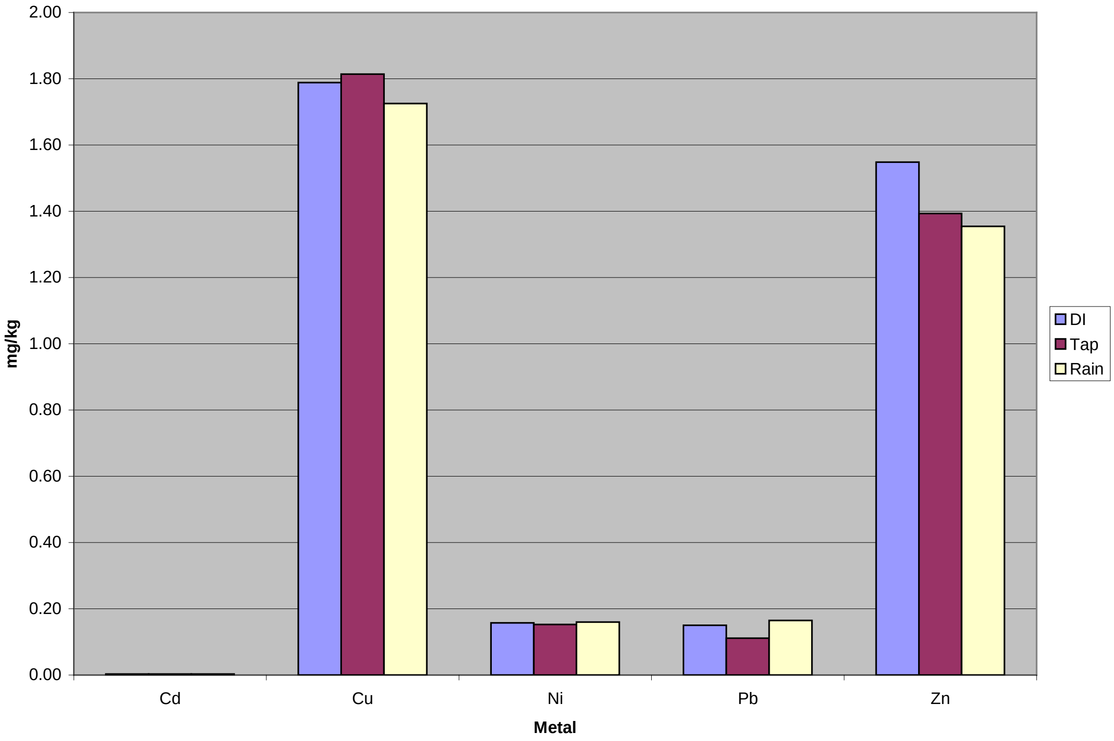

Figure 3.5 Extraction of Metals from Sediment

There is no significant difference between the rate of extraction of metals with De-ionized water, tap water and rainwater (ANOVA $p > 0.05$ (Appendix 4)). This shows that the results obtained in this experiments would not have been different if rain or de-ionized water was used and therefore consistent with what is obtainable in field conditions where rainfall is the extracting liquid.

3.4.2 *Metal Analysis of Effluent from Test Models*

The result of analysis of metals in the effluent from test models 1a ,1b, 2a, 2b, 3, 4a, 4b, 5 and Pavement are presented in Figures 3.6 to 3.14 below.

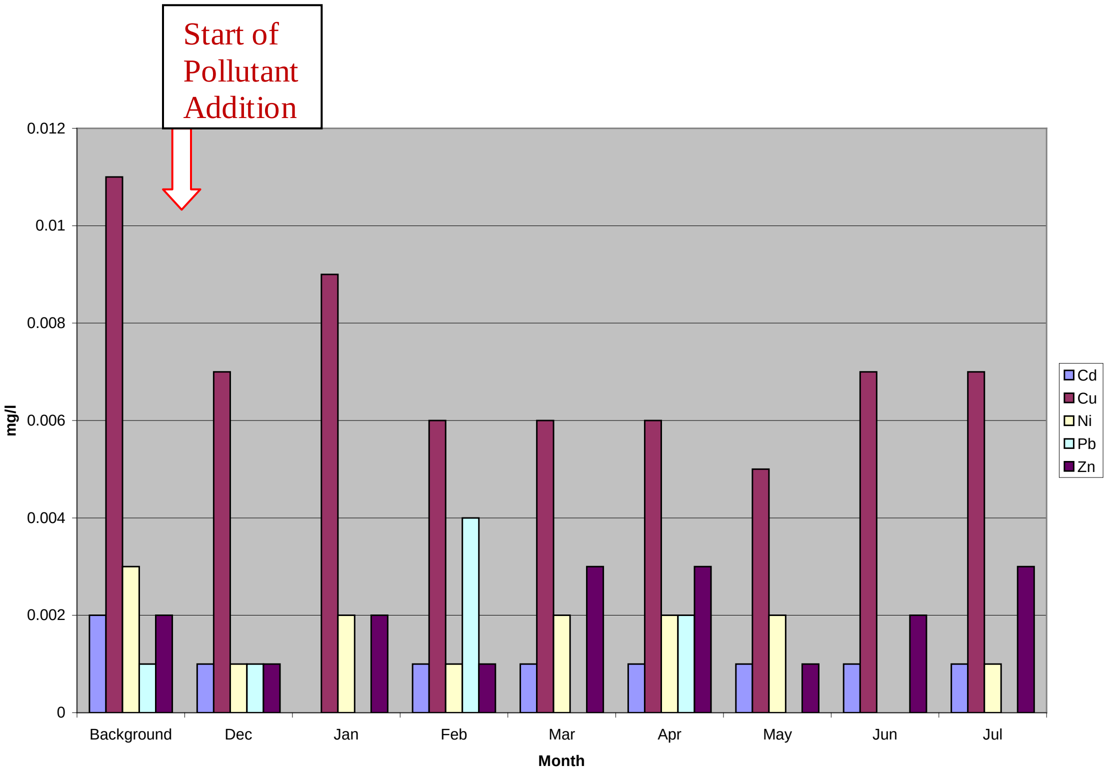

Figure 3.6 Metals in Effluent from Asphalt Test Model 1a (Porous Asphalt Model)

It can be seen from Figure 3.6 above that the metals in the sediment that was added to test rig 1a were not present in the effluent from the test model after 8 months of sediment application in which 84g was applied. The metal concentration in the sediment is as shown in Table 3.6. The level of metals in test rig 1a remained at background level (defined by the author as the level/concentration before addition of pollutants) after 8 months of sediment application except Cu which came down below the background level and Pb which became non-detectable at the 8th month (July).

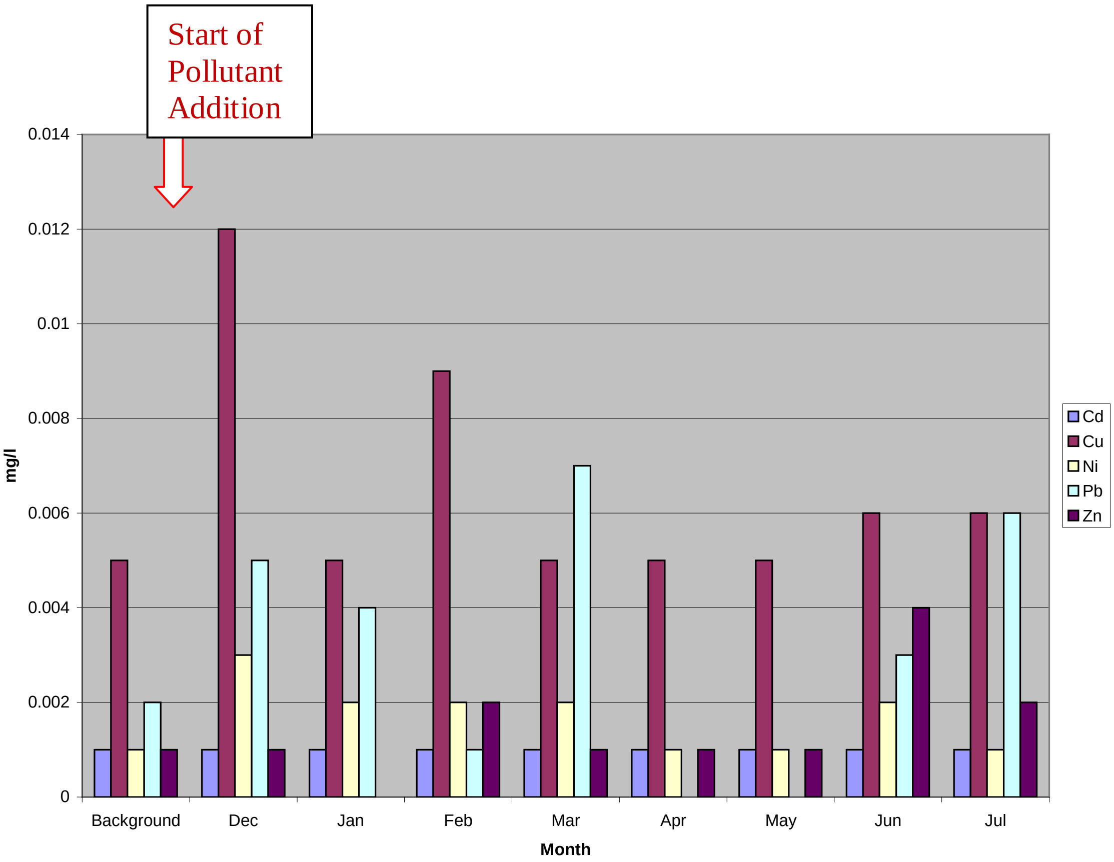

Figure 3.7 Metals in Effluent from Test Model 1b (Porous Asphalt Model)

The concentration of Cu in 1b, 2a, 3, 4b and 5 test models was above background level at the month of December (i.e. a month after background measurements), reduced to almost background level afterwards in all test models. However, the Cu level was lower than background level in December.

Also, the concentration of Pb in the effluent from the test models was within or below the background level except in the case of test models 2a, 2b, 5 and Pavement. In the case of 2a, Pb was non-detectable in February, March, April and June in the effluent. This is different from the case of 2b where Pb was non-detectable at the background level, December, April, May and June despite the fact that the two models are replicates (2a and 2b). However, these observed levels of Pb were low (<0.005 mg/l).

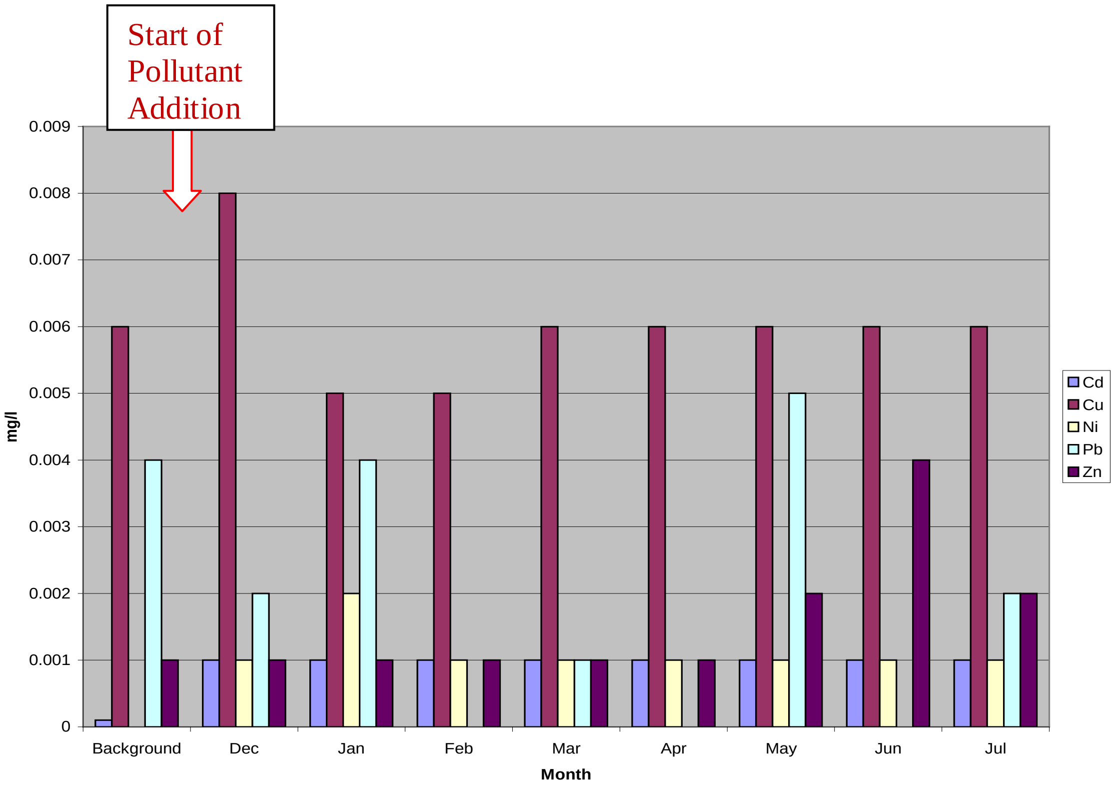

Figure 3.8 Metals in Effluent from Test Model 2a (Porous Asphalt Model)

Pb was not detected in test model 5 until March and in the pavement test model, a relatively higher level of Pb was observed though it was non-detectable in April. The concentration of Zn was within or below background levels in all the test models except in the case of test model 4b where the level of Zn in the effluent was 0.01 mg/l in the month of July and that of test model 3 where Zn was absent in the background test.

Ni and Cd were also within or below background levels in the test models up to the end of period of study. However, it should be noted that the ICP was working close to the limit of detection and the concentrations discussed above are very small. Hence, it is possible that any trends could be artifacts of the analysis.

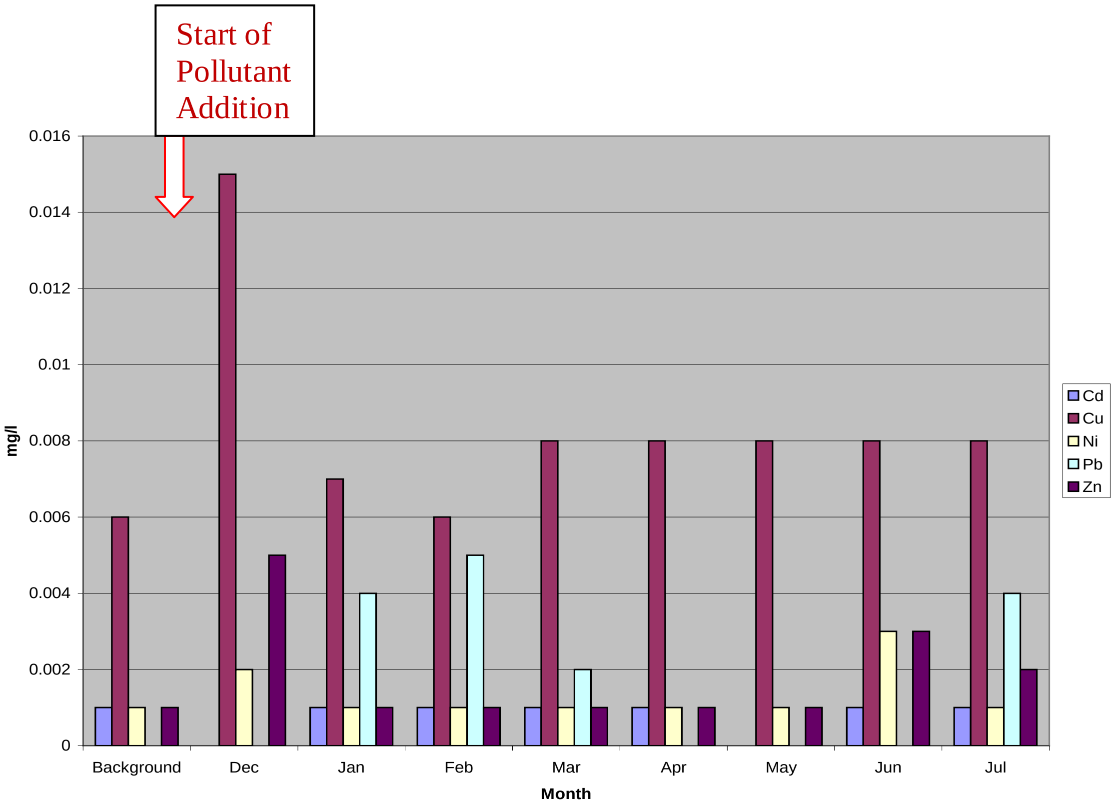

Figure 3.9 Metals in Effluent from Test Model 2b (Porous Asphalt Model)

The heavy metals analyzed from effluents from the test models are well below the concentrations specified by World Health Organization (WHO) for portable water as presented in Table 3.7 below and reclaimed wastewater for irrigation guidelines as presented in Tables 3.1, 3.2, and 3.4.

A comparison of the concentration of analyzed heavy metals in the effluent from the test rigs to the concentration of dissolved heavy metals in fresh water (Förstner and Wittmann, 1983) showed that the concentration of metals from the test rig effluents are within the limits of concentration of heavy metals dissolved in fresh water as shown in Table 3.11 below

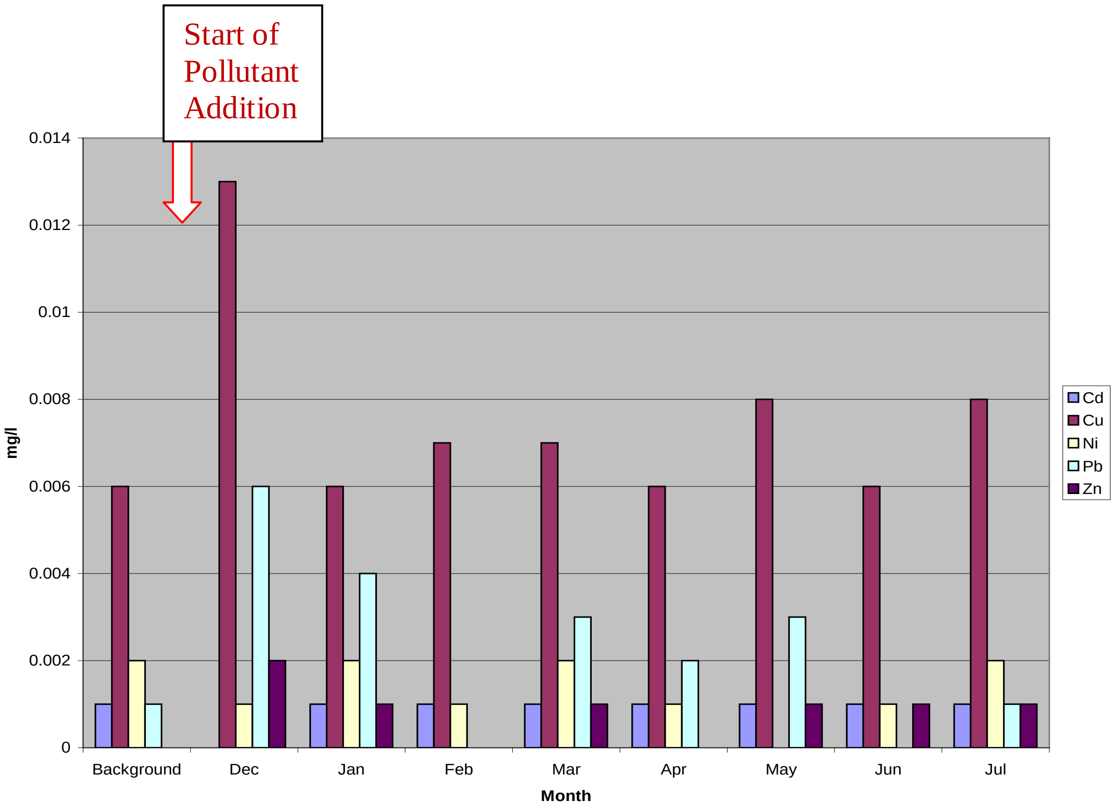

Figure 3.10 Metals in Effluent from Test Model 3 (porous Asphalt Model)

The concentration and availability of metals from the effluents from porous concrete models 4a and 4b appears different from each other contrary to expectations. There is no clear explanation for this difference. However, the author suggested that the difference in behaviour could be attributed to the $CaCO_3$ chemistry of the two porous concrete models which may have affected the mobility of some of the metals especially Lead. This theory was based on research carried out by Stead-Dexter and Ward (2004), Codling and Dao (2007).

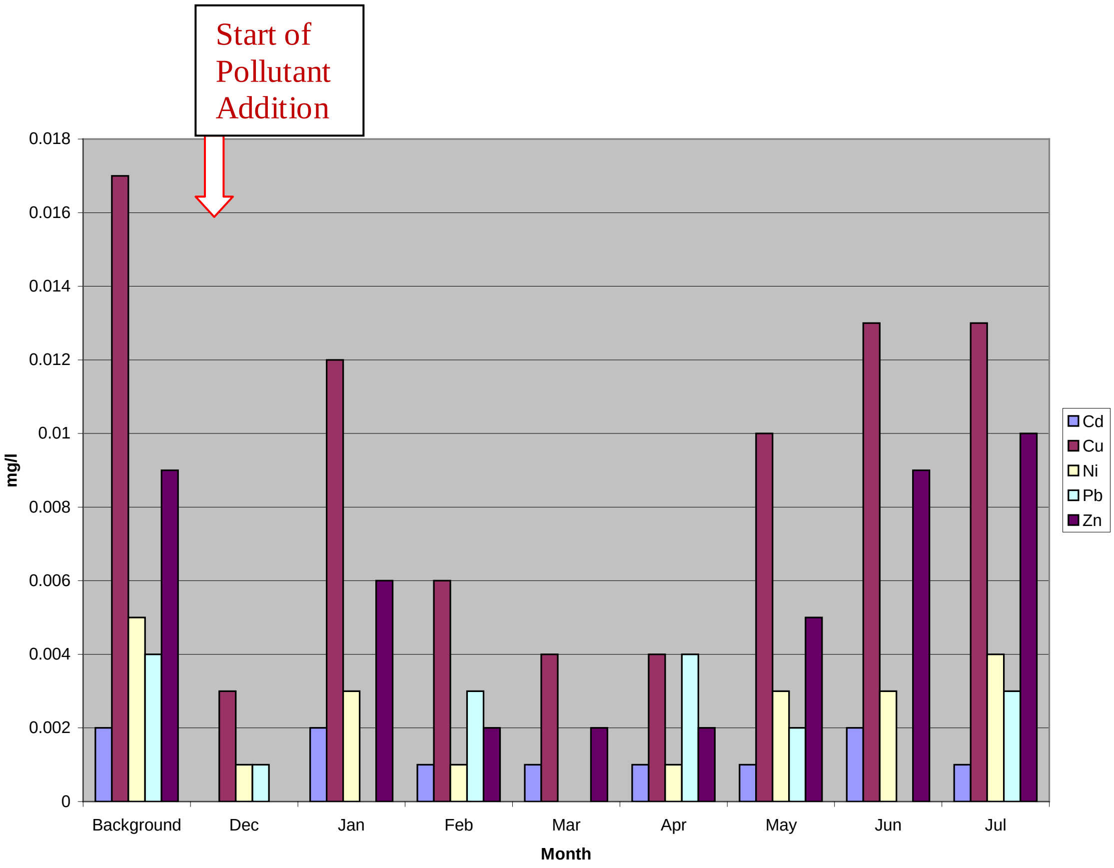

Figure 3.11 Metals in Effluent from Test Model 4a (Porous Concrete Model)

Stead-Dexter and Ward (2004) observed significant association of heavy metals with $CaCO_3$ and residual fraction in sediments taken from an unmanaged motorway detention pond. This study also showed that Lead amongst other metals has the strongest association with $CaCO_3$ (72%). Also, Work by Codling and Dao (2007) demonstrated that the solubility of Lead and other heavy metals can be controlled by pH through the addition of $CaCO_3$ amongst other factors.

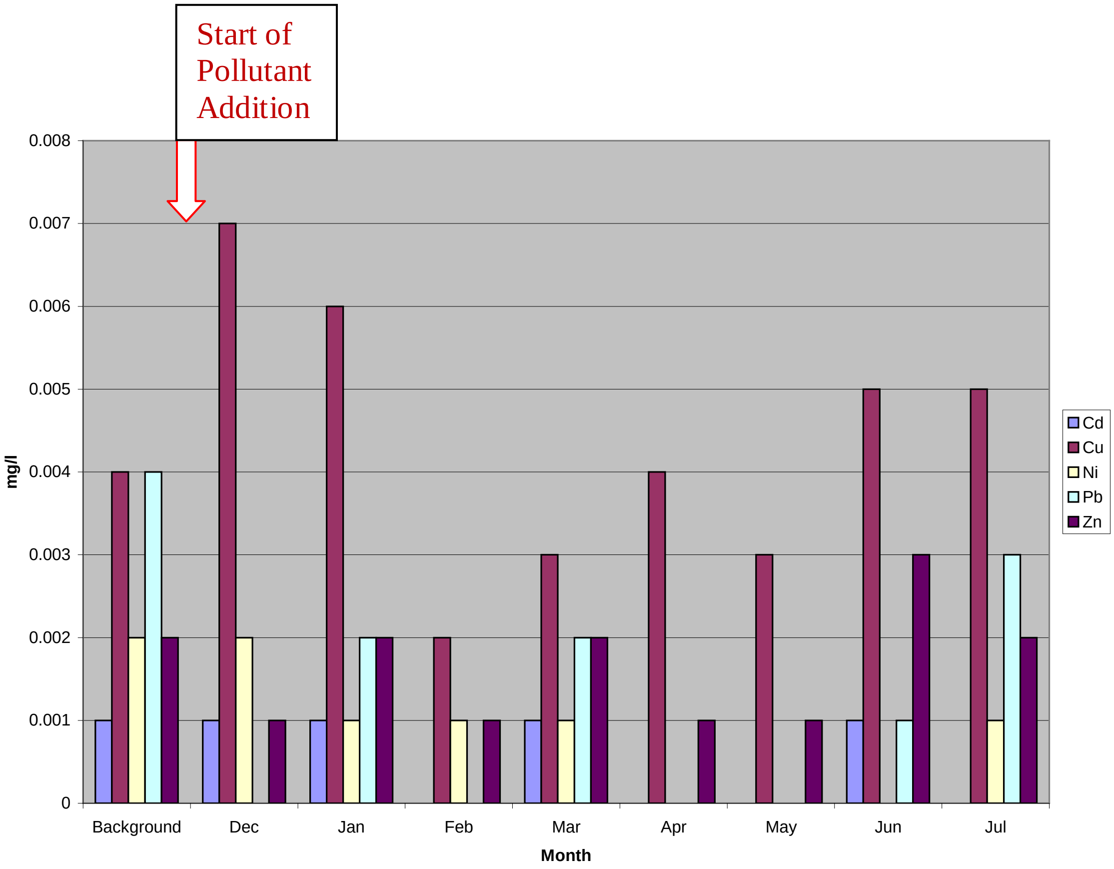

Figure 3.12 Metals in Effluent from Test Model 4b (Porous Concrete Model)

The porous concrete models (4a and 4b), like other models are mainly composed of materials (sub base, bedding and surface layers) that are rich in $CaCO_3$. However, unlike other models, the porous concrete surfacing was mixed in Tarmac's laboratory (as stated in methodology) and porous concrete mixture contains cementitious materials (NRMCA, 2008) which is rich in $CaCO_3$ (Matschei, Lothenbach and Glasser 2007) which can easily leach when in solution. The author suggests that this relatively high level of $CaCO_3$ may have associated with the metals in the effluent from the porous concrete test models (4a and 4b).

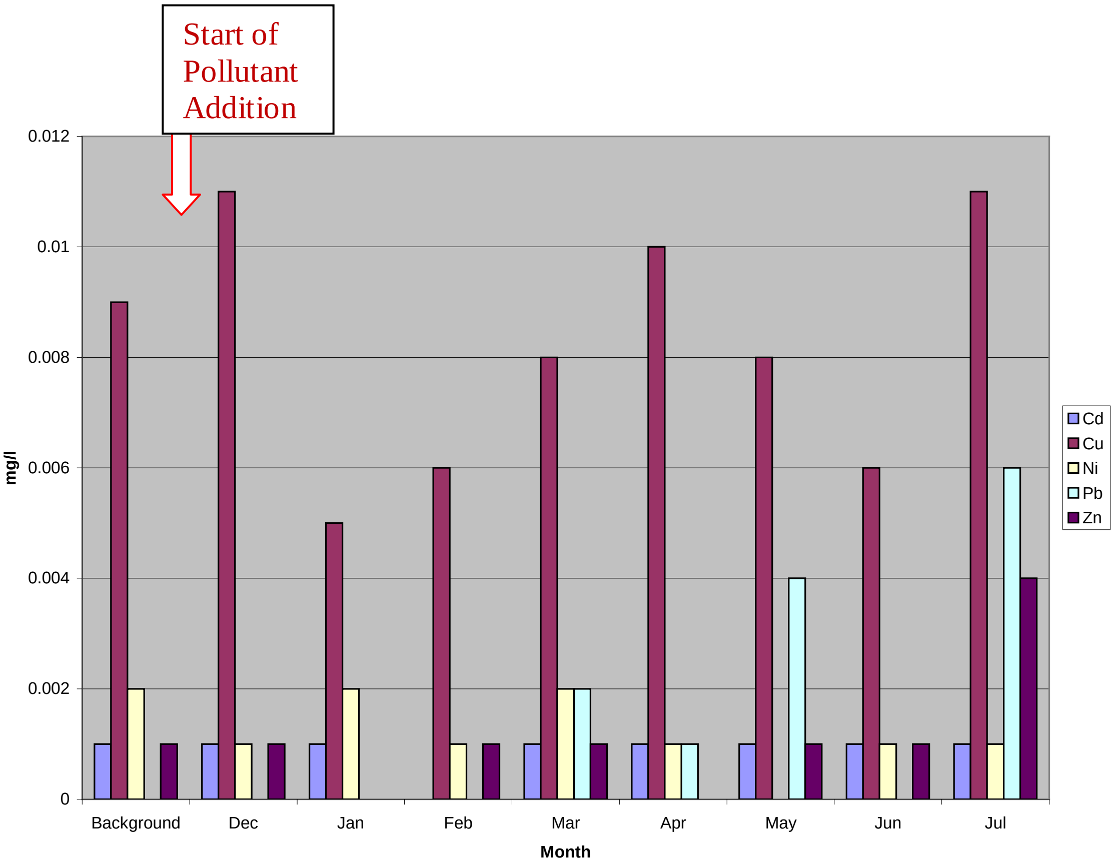

Figure 3.13 Metals in Effluent from Test Model 5 (Matured Porous Asphalt Model)

Test model 5 displayed distinctive characteristics from other test models as regards the concentration of heavy metals from the effluent. Lead was non-detectable even in the background until March while relatively high concentration of copper was recorded (above 0.01mg/l) even up to July and the levels of Cadmium and Zinc remained below 0.002 mg/l. This result was considered significant considering the source of the contents of this test rig (page 43) and continued monitoring is expected to provide more information on the behaviour of this test rig.

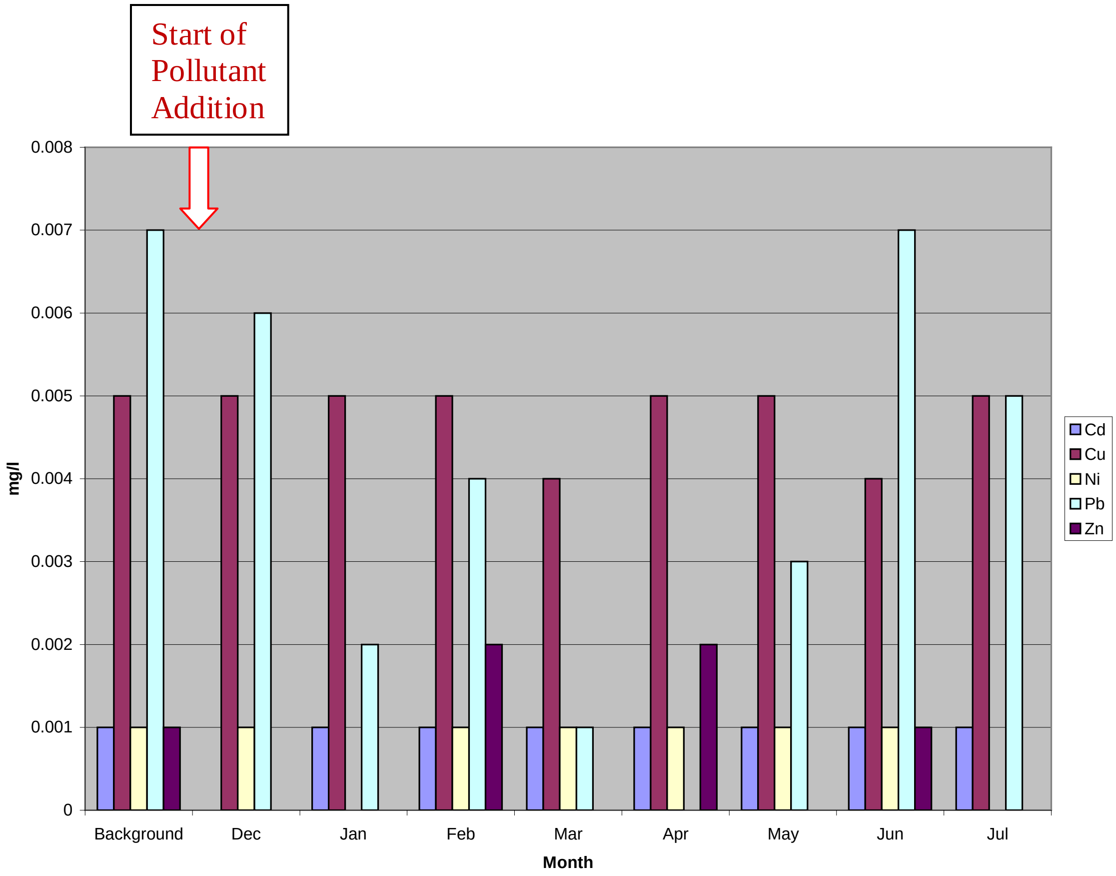

Figure 3.14 Metals in Effluent from Pavement Test Model (Paved Block Model)

Result from analysis of metals in the effluent from the “Pavement” test model showed relatively high concentration of lead in the background which reduced until May. Copper, Cadmium and Nickel remained at background level throughout the 8 month period of study. Zinc was non-detectable in the effluent from pavement in December, January, March, May and July.

However, it must be highlighted that this concentrations are less than 0.01mg/l and that the ICP was operating close to detection limit. It is true that results of further analysis will eventually determine the “breaking point” at which free product and high concentrations of metals would be present in effluent from each test rig, but already 100ml/0.5m^2 of oil and 84g/0.5m^2 of sediment had been added at this stage of the research. These results further demonstrate the high capacity and efficiency of the pervious system to remove metals from stormwater, and hence support previous research which had earlier demonstrated this capacity (Pratt 1995, Bond 1999, Newman et al. 2003, Culleton 2005).

Table 3.6 Background and Aquatic Environment Concentrations of Dissolved Heavy Metals in Fresh Water (µgl^{-1})

Förstner and Wittmann (1983)

Table 3.7 Comparison of WHO Heavy Metal Drinking Water Guidelines (µgl^{-1}) and Irrigation Water Limits with Effluent from Test Rigs (Suspended Solids (SS) is Reported in mgl^{-1}). Where BLD =Below the Limits of Detection; NG = No Guidelines; ND = No Data

	Cd	Cu	Pb	Ni	Zn	TSS
WHO (2008)	3.0	2000	10.0	70.0	3000	NG
Long-Term Irrigation Water Standard (Table 3.4)	10	200	5000	200	2.0	0 - 2.0×10^6 (Peterson 1999)
Short-Term Irrigation Water Standard (Table 3.4)	50	500	10000	200	10000	0 - 2.0×10^6 (Peterson 1999)
8 Months test Rig Monitoring						
Average	0.9	7.0	2.0	1.3	1.8	45.8
Maximum	2.0	15.0	7.0	4.0	10.0	343
Minimum	BLD	2.0	BLD	BLD	BLD	BLD
Background						
Average	1.0	7.4	2.4	1.8	2.0	140.2
Maximum	2.0	17.0	7.0	5.0	9.0	440.4
Minimum	BLD	4.0	BLD	BLD	BLD	6.2
Dissolution						
DI	BLD	1790	150	160	1550	ND
Tap	BLD	1810	110	150	1390	ND
Rain	BLD	1730	170	160	1350	ND

Furthermore, these results demonstrate the potential use of waters stored in the pervious pavement system for irrigation (Chapter 5).

3.4.3 *Total Petroleum Hydrocarbon (TPH)*

The result of total hydrocarbon analysis is presented in Figure 3.15 below. The average TPH recovered from the effluents of the test models in descending order was as follows:

Rig1a > Rig1b > Rig2a > Rig2b > Rig Pavement > Rig5 >Rig3 >Rig4a >Rig4b

0.28 > 0.23 > 0.22 > 0.17 > 0.14 > 0.13 > 0.11 > 0.10 > 0.08

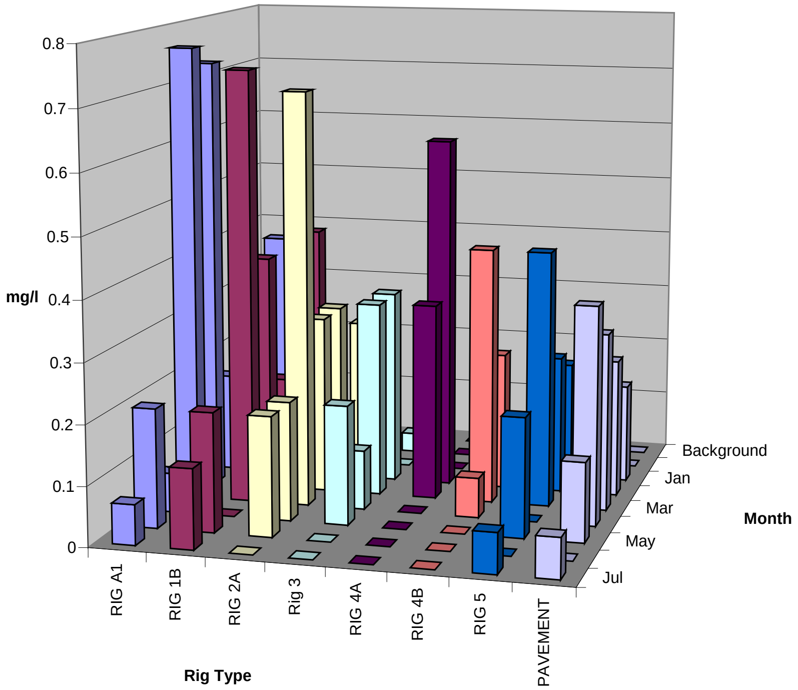

Figure 3.15 Total Petroleum Hydrocarbon in Effluent from Test Models

Also, the hydrocarbon retaining efficiency of the test models (area: 0.5m^2) in ascending order is as follows:

Rig1a < Rig1b < Rig2a < Rig2b < Rig Pavement < Rig5 < Rig3 < Rig4a < Rig4b
99.72% < 99.77% < 99.78% < 99.83% < 99.86% < 99.87% <99.89% <99.90% < 99.92%

The above result shows high hydrocarbon retention efficiency of the test models despite high oil loadings simulating worst case scenario. This result is consistent with that obtained by Bond (1999), Coupe (2004) as well as the results the author obtained from further irrigation quality experiments presented in the next chapter (Chapter 8). These results clearly demonstrated the capability of the pervious pavement system to trap hydrocarbons within the system which makes the system an important sustainable drainage device that not only controls drainage at source, but also removes pollutant in stormwater. Also, it shows the potential re-use of stormwater treated by, and stored within the pervious pavement system for irrigation of plants (see Chapter 5).

3.4.4 *Total Suspended Solids (TSS)*

Blockage of pipes and nozzles used for conveying irrigation water to plants by suspended materials may hamper irrigation efficiency. The severity of this problem is largely dependent on the type of irrigation system employed.

The result of Total Suspended Solids (TSS) analysis of effluents from the pervious pavement models are presented in Figures 3.16 to 3.24 below.

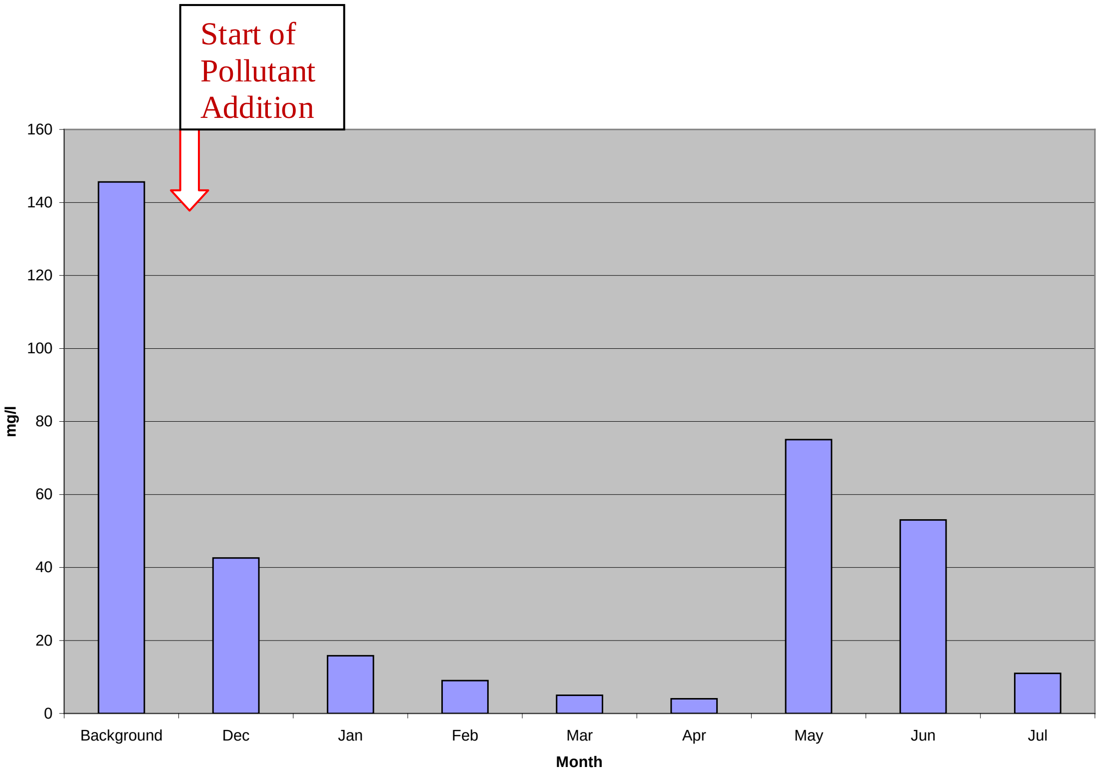

Figure 3.16 Total Suspended Solids from Test Model 1a (Porous Asphalt Model)

The TSS recovered from effluents from test rigs 1a, 1b, 2a and 5 remained below the background level which indicated that the sediments administered monthly for 8 months of this study was trapped within the study. However, the level of TSS recovered from effluents from test rig 3 remained lower than background level until at the month of July when a sharp increase from 94 mgl^{-1}(in June) to 343 mgl^{-1}(in July) was observed.

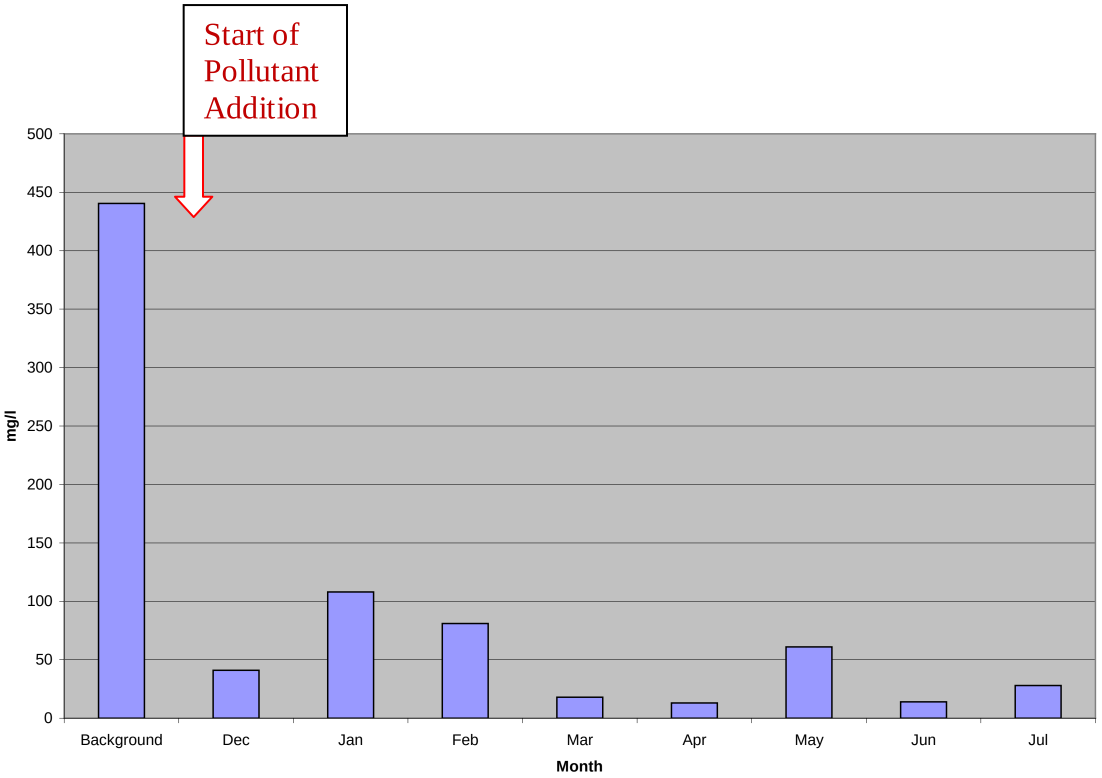

Figure 3.17 Suspended Solids from Test Model 1b (Porous Asphalt Model)

TSS recovered from effluent from test rig 4a was higher than the background level from January to February but reduced in March and remained below the background level until July.

Also, TSS levels in effluent from test rig 2b was above background level from December to January, but reduced to below background level from March to July.

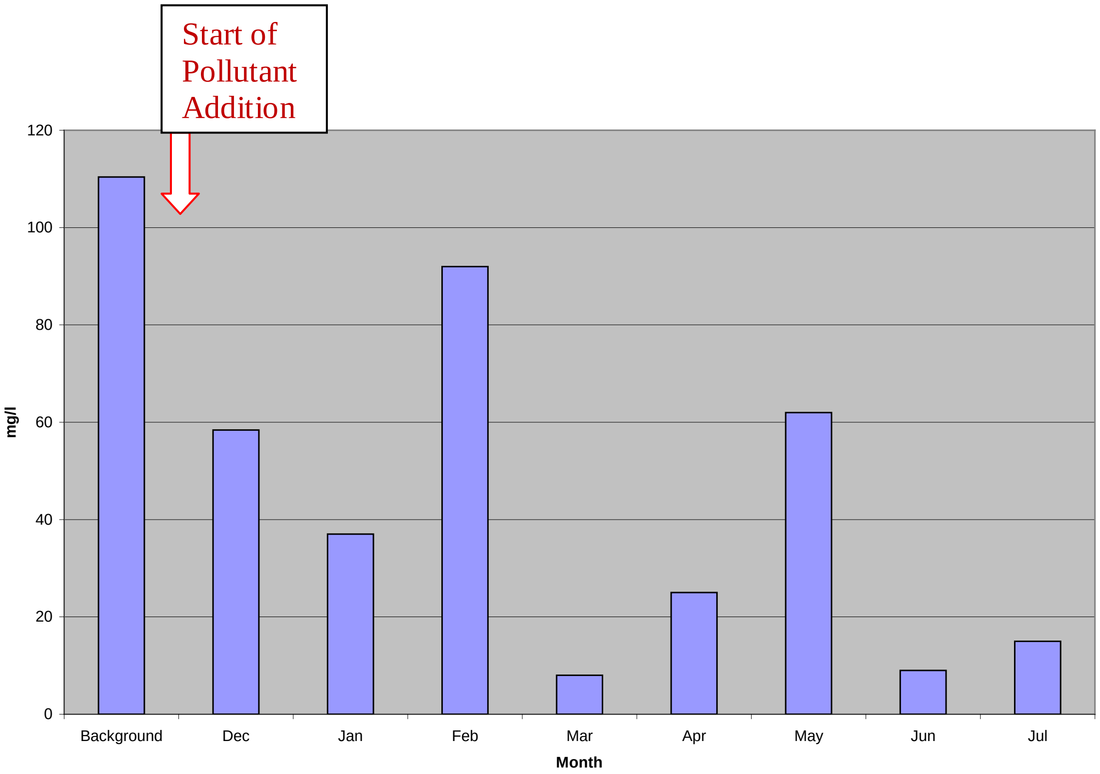

Figure 3.18 Suspended Solids from Test Model 2a (Porous Asphalt Model)

Similarly, TSS obtained from effluents from Test rig 4b was higher than background level in February. However, TSS level reduced to below background level from March to July.

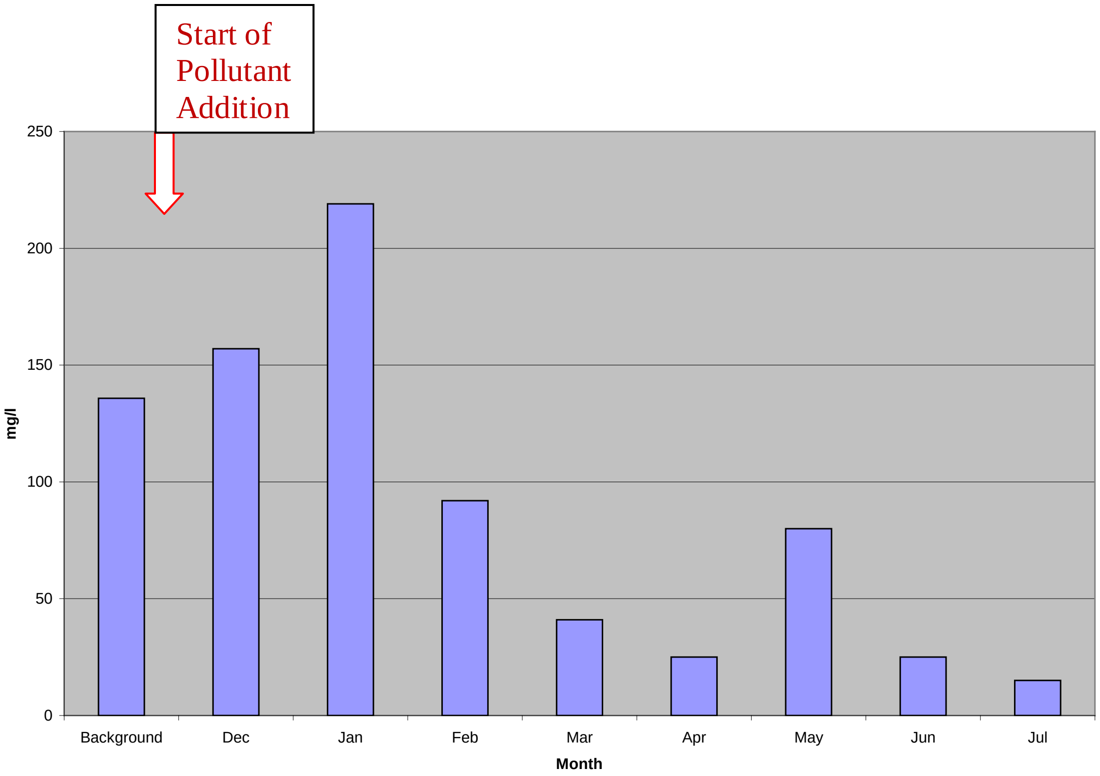

Figure 3.19 Suspended Solids from Test Model 2b (Porous Asphalt Model)

A sharp increase from 2 mgl^{-1} (in January) to 121 mgl^{-1} (in February) in TSS level was observed in the effluents from Pavement test rig. However, this TSS level was not sustained in effluent from pavement test rig as the TSS was non-detectable in March.

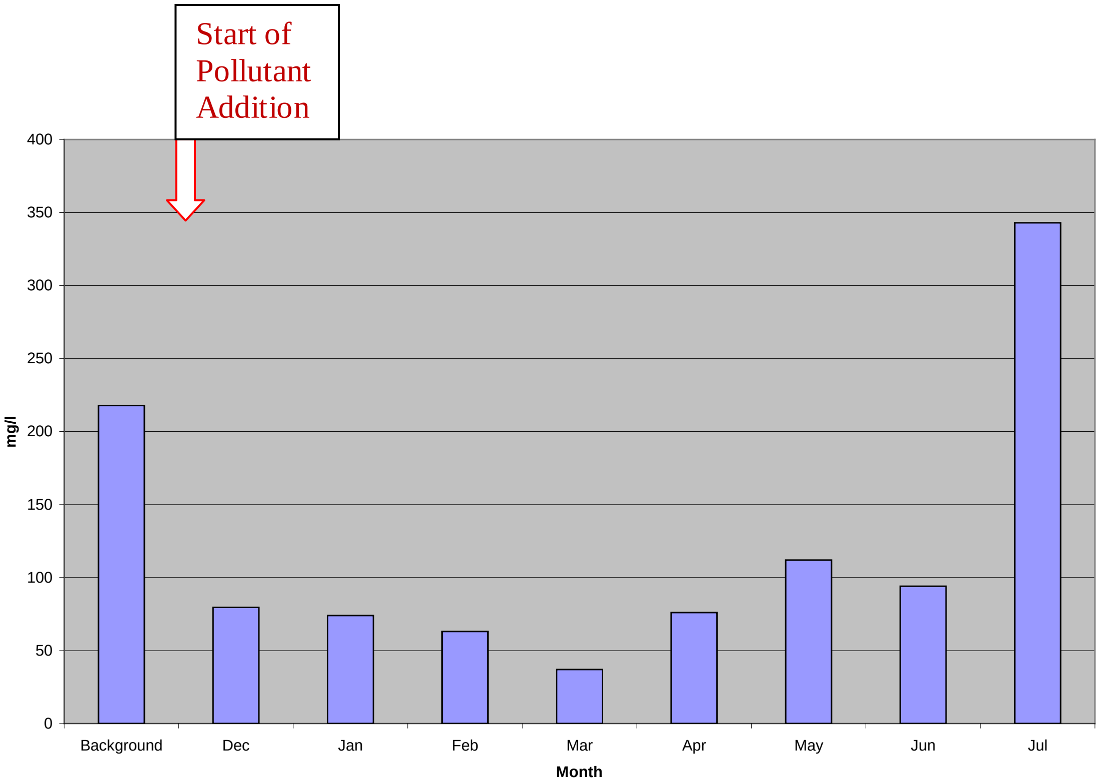

Figure 3.20 Suspended Solids from Test Model 3 (Porous Asphalt Model)

It was concluded that the TSS levels which were higher than the background level observed in effluents from test rigs 2b, 4a, 4b and Pavement in December, January and February was as a result of an "overshoot" of the TSS at background level which was retained within the system after the collection of the background sample (i.e. suspended solids that were retained in the models even after the initial wash-off prior to background sample collection). This conclusion was made considering that the increase was observed only in the months (1-2 months after background sample collection) following the collection of background sample and was not sustained afterwards as the TSS levels decreased to below background levels.

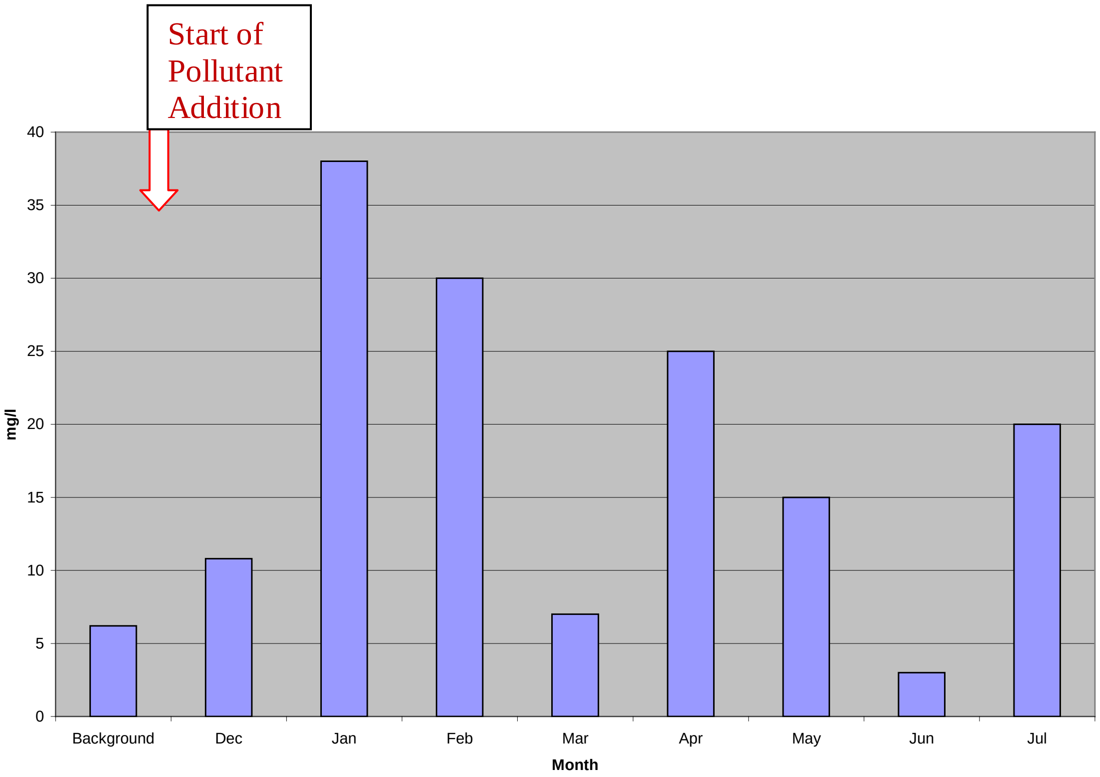

Figure 3.21 Suspended Solids from Test Model 4a (Porous Concrete Model)

The results reported in this chapter were obtained after monitoring of the test rigs for nine (9) months (December – July). The author hoped that when the monitoring resumes, it will provide more information on the capability of the pervious pavement system to deal with suspended solids and hydrocarbon pollutant constituents of stormwater. It is also expected to provide information on the "break-through" stage i.e. the point at which the test rigs can no longer retain hydrocarbons and sediments. As a result high levels of free-products and TSS are expected to be observed in the effluent at this stage.

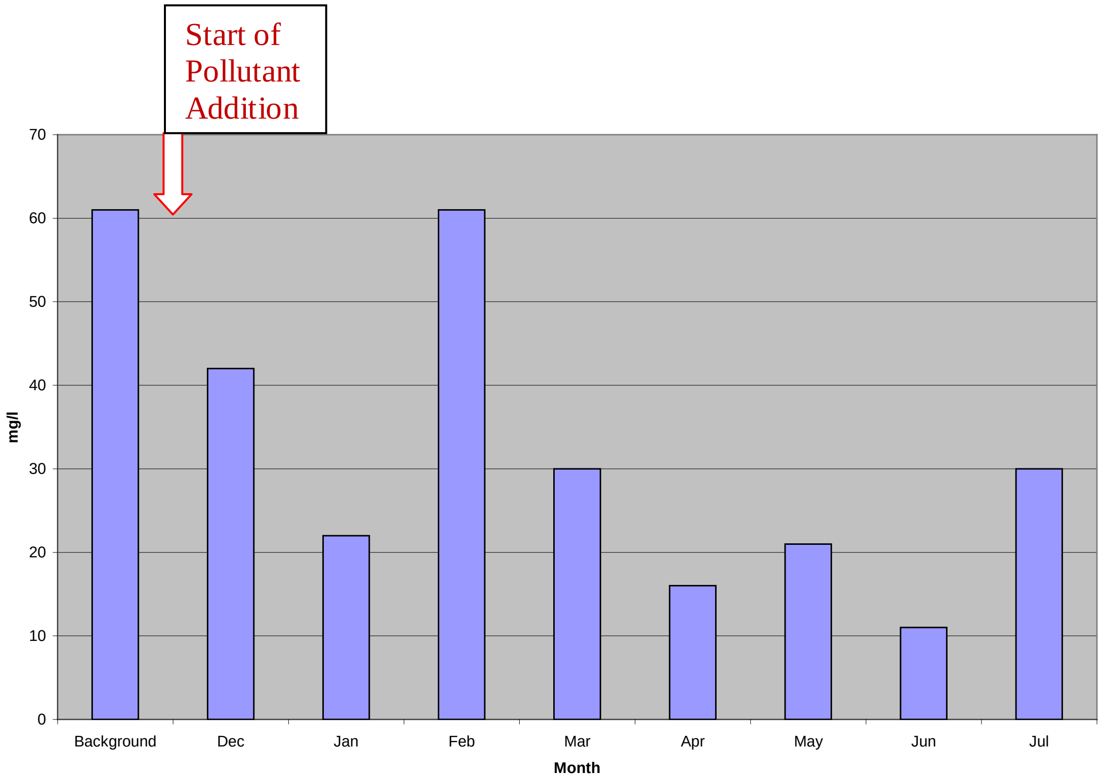

Figure 3.22 Suspended Solids from Test Model 4b (Porous Concrete Model)

It is also expected that this study (when it resumes) will provide information on the progress of the hydrocarbon and sediments added to the test rigs when the test rigs are cut open laterally. This data is also expected to provide additional information on the role of each layer of the pervious pavement system and microbiology of the system on which determines the efficiency of biodegradation of retained pollutants in conditions where nutrients usually added to encourage biodegrading microbial community was not added (in this case).

However, the results obtained during the 9 months period of monitoring of the test rig models provided important information on the capability of the pervious pavement system to deal with suspended solids, metals and hydrocarbons which are present in urban runoff.

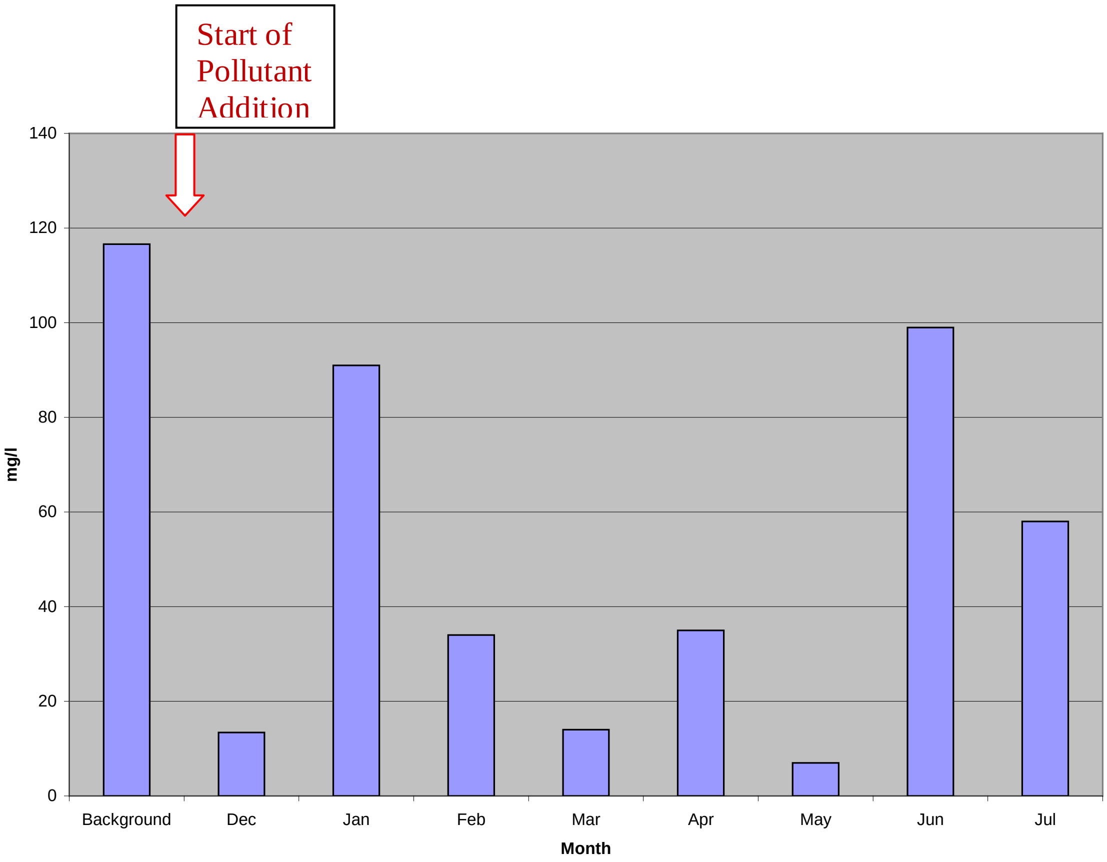

Figure 3.23 Suspended Solids from Test Model 5 (Matured Asphalt Model)

Furthermore, it provided useful data on the hydrocarbon retention efficiency of the pervious pavement system which is consistent with the result obtained in another experiment presented in page 154 (Figure 4.25) of the next chapter. It is also consistent with earlier research work carried out by Bond (1999), Coupe (2004) and Puehmeier (2008) in Coventry University.

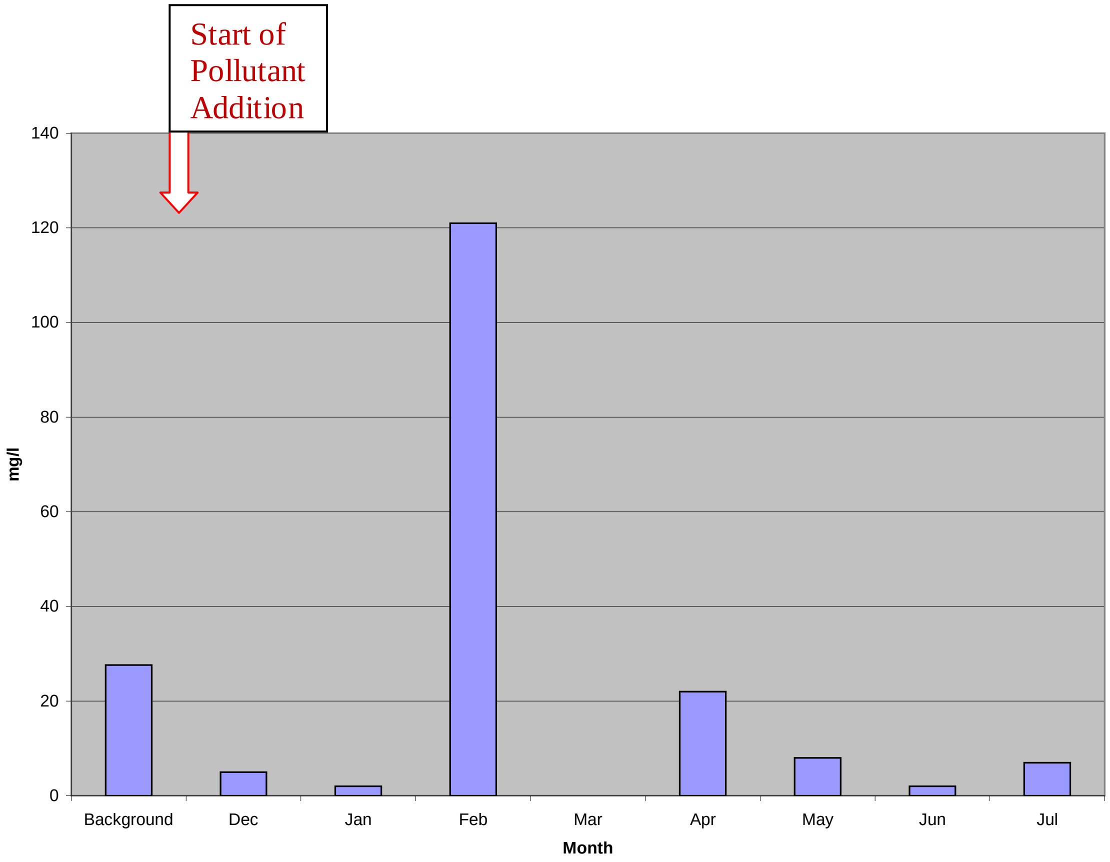

Figure 3.24 Suspended Solids from Pavement Test Model

Preliminary results presented in this chapter indicated the possibility of recycling water within the pervious pavement system for agricultural irrigation. The author decided to follow the practice of earlier researchers at Coventry by investigating further these important information obtained from the results in laboratory pervious pavement models where oil and nutrient were introduced to enhance biodegradation. The author considered that this further study (presented in Chapter 4) would provide information on the quality of waters stored in such systems as described above, and the potential effects of the added nutrients on the irrigation water quality. This study is presented in the next chapter.

Chapter 4: The Chemical Quality of Water Stored In Pervious Pavement System - Effects of Sub-base Type and Enhancement of Oil Biodegradation Using Inorganic Nutrients

4.1 Introduction

Results from chapter 3 have shown that it is possible to produce reclaimed stormwater using the pervious pavement system has chemical properties which, at first sight are favourable for irrigation. In this chapter, reports of further experiments to investigate the quality of water stored within the pervious pavement system for potential use for irrigation are presented. This work differs from Chapter 3 in that the experimental operation of the models followed the practice of Bond (1999), Coupe (2004) and Puehmeier (2008) in that microbial degradation of simulated mineral oil spillages was encouraged by the addition of slow release fertilizer pellet. It also utilized two different types of sub-base, the traditional stone sub-base and one based on the Permavoid plastic crate system. These sub-bases have a higher void ratio and thus an increased storage volume for a given excavation depth. They are also capable of storing the water at shallower depths than both stone systems with the same volume and other types of plastic crate void formers which all require a considerable depth of stone cover to provide the required load bearing capability. This can have important energy/physical effort advantages because of a reduced lift requirement when the water is recovered for reuse at the surface.

The main source of the world's food supply is agriculture and according to UNESCO (2007), about 70% of world water supply is used for agricultural irrigation and UNESCO also reported that this statistic is expected to increase by 14% in the next 30 years with the ever increasing world population and increase in irrigated land by 20%. It is also expected that by the year 2030, about 60% land with irrigation potential will be put to agricultural use, hence increasing the demand for water for irrigation (UNESCO 2007). According to a report released by the Organisation for Economic Co-operation and Development on the 5th of March, 2008, agricultural land use is expected to increase by 10% in 2030. This is expected to result in increased demand for water for irrigation especially with the high projection of climatic change over the same period. The OECD also estimated that about half of the world population (47%) will experience severe water scarcity in 2030 if no new water management policies are introduced (OECD 2008). This threat of global water shortage is increased by global warming which is expected to make summer droughts more frequent and cause water scarcity even in developed countries.

This study provides data on the potential use of harvested stormwater for agricultural irrigation. Furthermore, such technology will also be in line with the objectives of sustainable urban drainage by achieving source control and water reuse.

There are many studies on the use of water derived from “alternative” sources to high quality water, but sustainable sources for irrigation such as sewage (Sinha 1996, Paliwal, Karunaichamy and Ananthavalli 1998, Krishnamoorthi *et al.* 1996, Amahmid and Bouhoum 2000; Yadav *et al.* 2002, Debasish *et al.* 2003, Butt *et al.* 2005, Wallach, Ben-Arie and Graber 2005) and wastewater (Al-Jamal *et al.* 2002, Al-Shammiri *et al.* 2005). There are also reports that both treated and untreated wastewater have been used in many countries such as Ghana (Raschid-Sally, Carr and Buechler 2005), Pakistan, Mexico, Vietnam, Greece, Saudi-Arabia, Jordan and Israel for irrigation with Israel leading the way and expected to use treated wastewater to meet 70% of irrigation water requirement by 2040 (Al-Shammiri *et al.* 2005). In India, there are reports of additional benefit of higher crop yields from the use of waste water for irrigation (Bradford, Brook and Hunshal 2003).

As early as 1999, Pratt (1999) proposed that the pervious pavement system could be used as a reservoir for stormwater treatment and storage for re-use. Three years later, in the University of Florida, USA, Chen *et al.* (2002) carried out a two year comparison study on the potential of use of stormwater or rainwater collected from the roof of greenhouse, irrigation run-off from landscaped plant production bed and pond water for greenhouse production of bedding and foliage crops. At the end of their study, Chen and his team produced high quality and market yields of the crops irrespective of the sources of the irrigation water they used in the experiment.

It is becoming clearer, that with the application of innovative and sustainable construction methods and technologies, stormwater can become a resource which can be harnessed by various levels of governments, private enterprises, and even individuals in their homes (Madison and Emond 2007, Nnadi, Newman and Puehmeier 2008). The sustainable use of stormwater for irrigation is now viewed in many cities as the way forward for providing sustainable irrigation to golf courses (Schwecke, Simmons and Maheshwari 2007), recreational parks (e.g. Melbourne's Albert Park in Australia) , sports fields and providing year round recreation in lakes (ADEWHA 2007). In the city of Salisbury, South Australia, stormwater is captured in winter and treated by passing it through wetlands for ten days and then stored in limestone aquifers for use in summer (Midcoast Water 2008). The state of Hawaii in the United States of America is utilizing small lot re-use, source re-use, stormwater capture, stormwater storage and distribution technologies in the Island of Hawaii for irrigation distribution system and deep infiltration trench to capture stormwater for irrigation reuse on Oahu (Madison and Emond 2007, DAH 2008). In 2006, the North Sydney Council in Australia installed permeable pavements with sub-terrace water storage tanks in Raleigh, Street Cammeray in order to reduce the flow of polluted stormwater from car parks and busy shopping plazas in the street into the Sydney harbour and at the same time provide clean water for re-use by the council for other activities such as irrigation, street cleaning, etc (NSCA 2006).

Due to the high volume of water used annually for irrigation proposes and the projected increase in the agricultural water requirements as indicated above, reuse of stormwater for irrigation is an attractive option in sustainable stormwater management. But unavailability or irregular supply of irrigation water is not the only reason for the increasing use of alternative sources of irrigation water. High concentrations of nutrients such as nitrogen, phosphorus and potassium present in wastewater and other alternative sources of irrigation water as well as their relative continuous availability makes them more attractive to farmers as it enables them to grow crops all year round (especially vegetables) hence generating more income for them (Ensink and Hoek 2007).

Irrigation water quality standards (Tables 3.1 to 3.4) are presented in Chapter 3 of this thesis; and the waters collected and stored in the pervious pavement models were compared to these standards. These waters were used for irrigation in the plant experiment reported in the next chapter (Chapter 5).

4.1.1 Aim

This novel experiment was intended to further study the chemical suitability of stored water within pervious pavement systems. As mentioned above in this case, they comprised of stone and plastic sub bases. The focus here was specifically on irrigation and the experiment was intended to provide information on the effects of hydrocarbons and nutrients application on the irrigation water quality of the stored water.

This experiment was divided into two parts and reported for the sake of clarity to the reader in separate chapters: the 1st part investigated whether water stored within the pervious pavement system met irrigation water quality standards for reuse as irrigation liquid (presented here in Chapter 4). The 2nd part was pot trial experiments in the green house designed to investigate the effects of using water stored in the previous pavement system on plant growth, development, soil structure as well as the effects of the nutrients added to kick start biodegradation process and hydrocarbon application (simulation of pollution) on metal accumulation on plant parts and soil. The 2nd part of this experiment is presented in the next chapter (Chapter 5).

4.2 Materials and Methods

This experiment was originally designed to compare the performance of plants (this part of the experiment is presented in the next chapter (Chapter 5) using irrigation water derived from oil degrading pervious pavement models representing a proprietary plastic box water storage/sub base layer and stone-based sub layers used in more traditional pervious pavement systems. It was proposed that that the two systems might show varied performances due to differences in hydrocarbon (and hydrocarbon degradation product) contamination in the irrigation water and in the utilization or sorption of the slow release nutrients added to the pavements to encourage biodegradation. The controls used in this experiment could be said to have represented pedestrian paved areas not subjected to oil contamination and thus with no requirement for inorganic nutrient application.

The pervious pavement studied in this work was designed in accordance with those studied by previous researchers in Coventry Porous Pavement Research Group (see page 26) and originally designed by Chris Pratt in 1999. The pervious surfaces are based on non porous concrete blocks in which water is allowed to percolate through the surface through a block design which provides infiltration channels of one type or another .The structure on which these had been laid in research works within the research group invariably utilized a geotextile between the load bearing/water storage layer (either a stone sub–base or a plastic void forming sub-base) and the upper bedding layer (10mm pea gravel). This geotextile layer has been shown in earlier studies to play important role in retention and biodegradation of hydrocarbons (Bond 1999, Newman *et al.* 2002a,c). Although the oil retention capability under heavy loadings has been shown to be limited

(Newman *et al.* 2002c; Puehmeier 2008), under loadings simulating day to day oil drippings in car parks, the geotextiles have been shown to support the establishment , growth and development of biofilms of oil degrading microbes (Newman *et al.* 2002b; Coupe *et al.* 2003). It has also been shown to possess the capability to retain a high proportion of added oil provided it is added over a long period (Bond 1999).

4.2.1 ***Geotextile Material***

A new geotextile product known as Inbitex Composite® produced by Hanson Formpave UK Ltd was used for this study. The fabric of this geotextile is manufactured from polypropylene and polyethylene. Because of the process used, small pits are created in the geotextile during the manufacture which encourages microbial growth and development (Newman *et al.* 2002, Coupe *et al.* 2003a,b, Paving Expert 2008, Puehmeier 2008). A picture of Inbitex Composite® geotextile used in this experiment is shown in Figure 7.0a and 7.0b (page 265), while the principle by which the manufacturers claims it works is also presented in page 265.

4.2.2 ***Construction of the Pervious Pavement Model Used in Experiment***

The experimental pavement models were built into welded HDPE containers equipped with a system to allow withdrawal of irrigation water by siphon from the base of the models as shown in Figure 4.1 Care was taken to ensure that the models were never fully emptied and thus any free product would not have been withdrawn as part of the irrigation waters. In effect, this replicates the action of a Permaceptor® which could be incorporated into the pervious pavement system to remove hydrocarbon and silts from stormwater before it is channeled to watercourses (Puehmeier 2004a, 2005). Thus any negative effects would be limited to dissolved contaminants and this was considered as a reasonable approach to the management of the pervious pavement structures.

The cross sections of the models are shown in Figures 4.2 and 4.3. The depth of the stone sub- bases was 150mm which is equal to the depth of the Permavoid units (supplied by Permavoid (UK) Ltd). A 50mm bedding of 10mm pea gravel was used to support the layer of Formpave Aquaflow ® Paving (supplied by Hanson-Formpave (UK) Ltd). The stone aggregates used for the stone base and bedding layer were seived to 50mm and 10mm respectively. The aggregates were washed with clean water in order to remove dusts and silts before they were used in the experiment.

The geotextile used was Inbitex Composite® (supplied by Hanson-Formpave (UK) Ltd) (see page 87-88). The Inbitex Composite® was sandwiched between the sub base and the bedding layer in all the models. Figures 4.1 to 4.4 show the design and arrangement of different layers of the pervious pavement models used in this experiment. For more information on the design and arrangement of pervious pavement system, see Bond (1999) and Coupe (2004).

Figure 4.1 Schematic Diagram of the Rig Model Types: Top-Permavoid, Bottom-Stone Sub-base (Nnadi *et al*. 2008)

Figure 4.2 Experimental Rig Showing Permavoid Sub-Base

Figure 4.3 Experimental Rig Showing Stone Sub-Base

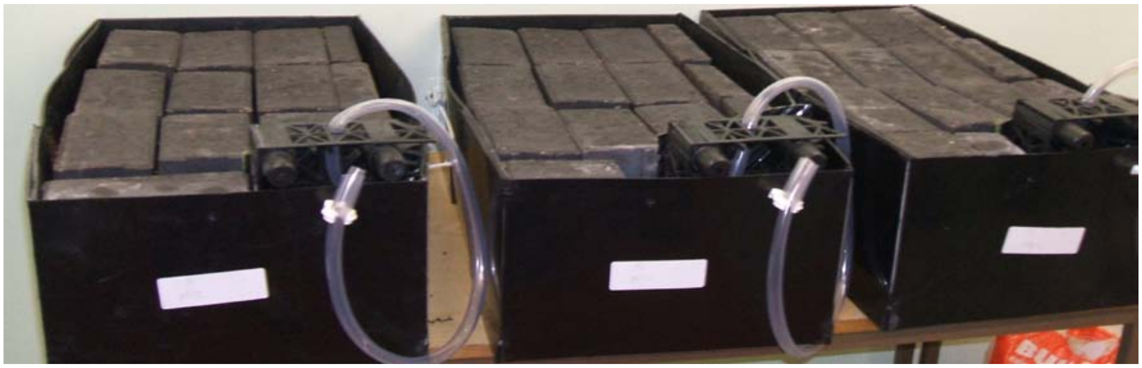

Figure 4.4 Three Out of the Eight Units of PPS Models Used in Experiment

Eight (8) of these specially designed experimental test models were constructed as described earlier (page 88 to 91).

One (1) test model with Permavoid Ltd plastic sub base replicated twice. Another test model with granite sub base also replicated twice.

Control test models with Permavoid Ltd and granite sub-bases respectively without oil and nutrient additions were set up to represent sidewalks as stated above in page 87. Table 4.1 shows the treatments applied to the test models.

Table 4.1 Showing Experimental Test Rigs Set up and Treatments Applied

TEST MODEL	ADDITIONS	TYPE OF SUB-BASE	NO. OF REPLICATE(S)
1	+ Oil and + NPK	Permavoid Plastic	3
2	+ Oil and + NPK	Stone	3
Control 1	- Oil and - NPK	Permavoid Plastic	Control 1
Control 2	- Oil and - NPK	Stone	Control 1

4.2.3 *Rainfall Simulation*

Rainfall was simulated using a watering can fitted with a shower rose (supplied by Wilkinson UK Ltd) suspended above the test models at a target intensity of 7.4mm/h over 1hour and applied at three events per week. Although minor variations in rate were obtained, the total volume at each rain event was constant. Rainfall was simulated a day before and after oil application.

4.2.4 *Oil Application*

Used oil was considered ideal for this experiment in order to effectively replicate realistic conditions of oil dripping from cars parked on a PPS car park. However, the author was faced with the problem of oil selection vis-à-vis: type of car, type oil; length of stay of oil in the car, whether there was regular addition of same /different type of oil to car, e.t.c. Coupe *et al.* (2006b) observed that although used oil was rich in minerals relative to clean oil, their release in effluent from pervious pavement system was < 50 mg/L and metals in oil found in effluent was < 0.2 mg/L. Coupe *et al.* (2006b) also observed that the microbiology of the pervious pavement system does not significantly change as a result of the use of clean or used oil. This study further stated that assumptions obtained from previous PPS studies where clean oil was used could be applied to field studies where used oil might form the main source of hydrocarbon pollution. However, Dange (2008) in a study carried out in Coventry University applied 2.7g of used and clean motor oil to two separate test rigs of $0.27m^2$ each at simulated rainfall of 1000mL. He recovered $3.5mgL^{-1}$ and $2.9mgL^{-1}$ in the effluent from the test rigs dosed with used and clean oil, respectively. However, in effluent from two other test rigs of the same area ($0.27\ m^2$) dosed with 0.3g of used and clean oil, Dange (2008) recovered $0.5mgL^{-1}$ and $2.6mgL^{-1}$ of the applied used and clean oil respectively after application of 500mL simulated rainfall. This result highlights variability which could occur with the use of used and clean oil under different conditions in laboratory simulation experiments. Consequently, the author decided to proceed with clean oil at this time since this is a novel work, and to leave the evaluation of the difference the use of used oil would make to another study.

Hence, a weekly dose of 6.23ml of unused Castrol GTX ®, 15w- 40w, specification: API SJ ACEA A2/B2 lubricating oil (supplied by Castrol (UK) Ltd., Swindon, UK) which was successfully used by Bond (1999) in pervious pavement research in Coventry University, UK was applied to the series of 710mm × 360mm model pervious pavement structure except the controls. This dose of oil was arrived at after considering the postulations of Bond (1999) and Newman et al. (2006b) that only a small portion of oil on urban surfaces could be observed in urban run-off, hence they applied 100 times of the derived average to the large test rig of pavement area of 0.3721m^2 (which amounted to 6.62g of oil per week) in other to replicate worst case scenario.

Oil was applied weekly and was carried out from the day before the first rainfall application. The oil application was conducted randomly into infiltration slots of the pervious pavement models by the means of a 10mL syringe (PLASTIPAK® supplied by Becton Dickinson, Dublin Ireland) to mimic oil drippings from vehicles parked in a car park constructed with pervious pavements. Bond (1999) had earlier used this method to replicate worst case scenario whereby almost all the oil was expected to enter the pervious pavement construction and limit oil absorption by the pavement blocks. The syringe was calibrated (as described below) and used throughout this study.

4.2.5 *Syringe Calibration*

The syringe was calibrated at the beginning and end of each oil application. According to UKAS (2002), the accuracy of syringes is +/- 5% of their capacity (i.e. +/- 0.5mL of 10mL syringe). The syringe used in this study delivered an average of 10.23mL. This was considered acceptable since it remained within +/- 0.5mL. This syringe was used to dispense a 10ml volume of unused oil (Castrol GTX) into a tarred beaker and weighed in a weighing balance (supplied by Cole-Palmer Instrument Co. Ltd, London, UK) to 2 decimal places. The mass dispensed by the syringe was recorded and used to calculate the volume of oil applied at each event. In this case, 10mL volume of the syringe used delivered an average of 8.89g throughout the study and the specific density of the clean oil used for this experiment was 0.89

4.2.6 *Nutrient Addition*

Osmocote® Plus controlled-release fertilizer granules (supplied by Grace-Sierra Horticultural Products Co. Milpitas, USA) were used for this experiment. This fertilizer is sold in the market as a garden fertilizer and was previously used in experiments involving the Pervious Pavement system in Coventry University by Bond (1999) and Coupe (2004). It contains trace elements and was reported to be able to supply nutrients for 6 months at an average soil temperature of 21°C (Bond 1999).

The elemental composition of Osmocote Plus® Controlled Release fertilizer is shown in Tables 4.2 while Table 4.3 below shows the mass of nutrient per application of Osmocote Plus ® controlled-release fertilizer based on the elemental composition of Osmocote Plus® Controlled- release fertilizer.

A single dose of 17.06 g of Osmocote® plus controlled - release fertilizer granules was administered to the surface of the pavement systems and brushed into the infiltration slots.

Table 4.2 Elemental Composition of Osmocote Plus Controlled- Release Fertilizer

(Scotts 1997 adapted from Bond 1999)

Table 4.3 Mass of Elements per Application of Osmocote-Plus Fertilizer

Nutrient	Mass per Application (mg/17.06g) approx.
N	1706
P	819
K	2542

The systems were maintained in the dark as much as possible throughout the experiment in other to discourage algal growth in the siphon arrangement which was a slight problem in a study carried out in University of Florida, USA (Chen *et al.* 2002).

4.2.7 ***Storage of Samples***

200mL of samples of water from test models were collected weekly and stored in the freezer at about -12 degrees Celsius. 100ml of these samples were acidified with HNO_3 before being stored.

4.2.8 ***Analysis of Water from Test Models***

The following analysis was carried out on the irrigation water from the Pervious Pavement System (PPS):

4.2.9 ***Elemental Analysis***

Analysis of the following elements were conducted: Calcium (Ca), Magnesium (Mg), Potassium (K), Phosphorus (P), Sodium (Na), Sulphur (S), Copper (Cu), Vanadium (V), Molybdenum (Mo), Aluminum (Al), Zinc (Zn), Iron (Fe), Cadmium (Cd), Arsenic (As), Boron (Bo), , Lead (Pb), Nickel (Ni), and Manganese (Mn) in the irrigation water was determined by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) Optima 5300DV© (supplied by Perkin Elmer , USA).

Calibration was achieved with standard concentrations which were prepared with analytical grade 1000ppm standards except in the case of calcium where 10,000ppm was used (supplied by Fischer Scientific, UK). Aliquots of these standards were taken with a micropipette (according to expected concentrations in elements in the sample) and dispensed into a 100mL volumetric flask and made up to the mark with distilled water. Distilled water was used as blank. Calibration for each element was achieved at minimum of R^2 0.9999 linearity before the samples were fed into the instrument. The samples were removed from the freezer, thawed and well shaken before analysis. Recalibration was carried out with the same working standards after the analysis of 20 samples. The result of the analysis was presented by the instrument in mg/L.

The elements were analyzed at the following wavelengths with the detector set in the axial mode:

Calcium (Ca) 315.887, Magnesium (Mg) 285.213nm, Potassium (K) 766.490nm, Phosphorus (P), Sodium (Na) 330.23nm, Sulphur (S) 180.734nm, Copper (Cu) 327.393nm, Vanadium (V) 292.402nm, Molybdenum (Mo) 202.031nm, Aluminum (Al) 396.153nm, Zinc (Zn) 206.200nm, Iron (Fe) 238.204nm, Cadmium (Cd) 228.802, Arsenic (As) 188.979nm, Boron (Bo)182.578nm, Lead (Pb) 220.353nm, Nickel (Ni) 231.604nm, and Manganese (Mn) 257.610nm.

4.3.0 *Electrical Conductivity (EC_w)*

The Electrical Conductivity of water (EC_w) was determined and these values were used to investigate the suitability of the water from pervious pavement systems for irrigation in view of the effects of irrigation water on soil structure, soil water infiltration and availability of nutrients for plant growth and development. Determination of Electrical Conductivity of soil (EC_e) used in plant experiment is presented in the next chapter (Chapter 5).

The Electrical Conductivity of water (EC_w) from the test rigs was determined by Conductivity meter (PTI-8 digital conductivity meter, Scientific Industries Intl. Inc. UK). ECw measurement was by dipping the electrodes of the Conductivity meter into a 100mL representative sample of water from each test model and the reading was displayed digitally on the screen. The measurement was repeated three times and the mean of the three values was determined and; used as the EC_w measurement.

4.3.1 *Potential Hydrogen (pH)*

The pH of water from the test models was determined by Corning M220 pH meter (supplied by Ciba Corning Diagnostics Ltd, Suffolk, England). The pH measurement was made by dipping the electrode of the pH meter into 100mL of water from each test rig and taking pH readings displayed digitally on the screen of the pH meter. Three measurements were made for water from each test model and the mean of these measurements were calculated as the pH reading.

4.3.2 *Analysis of Nitrate and Nitrite in Water*

The nitrate (NO_3) and nitrite (NO_2) in the stored irrigation water was determined using the principle of Flow Injection Analysis (FIA). The equipment used was Aquatec 5400 connected to Tecator 5027 auto sampler (manufactured by Tecator, Sweden). In this analysis, the water samples from the test models where injected into a stream of ammonium chloride which was then passed through a cadmium reducer to reduce nitrate to nitrite. The resulting compound was reacted with an acidic sulphanilamide solution to form a diazo compound. This compound was coupled with N-1-naphtyl-ethylene diamine dihydrochloride (NED) to form a purple azo dye which was measured at the wavelength of 540nm. A standard nitrate solution (1mL = 100µg N) for calibration was prepared by drying potassium nitrate in an oven by heating at the temperature of 105 degrees Celsius for 1 hour. Then 0.7218g +/- 0.0005g of the dried potassium nitrate was dissolved in distilled water and diluted to 1litre with distilled water in a graduated flask. Then a set of working standards were prepared by taking aliquots of 0, 10, 20, 30, and 40mL from the potassium nitrate solution were taking by pipette and put in 100mL volumetric flasks and made up to the mark with distilled water.

Injected volume: 30µL

Analysis time: 75seconds

Wavelength: 540nm

4.3.3 *Analysis of Total Hydrocarbons in Water Using the Horiba OCMA 310*

Determination of total hydrocarbons in the water from the test models (that were dosed with oil) was carried out by the principle of infra red spectroscopy using Horiba OCMA 310 oil analyzer (supplied by Horiba Co. Ltd, Japan). This automated instrument is capable of analyzing both low and high concentrations between 0mg/L to 200mg/L. Horiba OCMA 310 was previously and successfully used by Spicer (2006) at Coventry University. This instrument uses double chlorolotrifluoroethylene obtained from dimerization of chlorofluoroethylene monomer as a solvent (Trade name: S-316) (Horiba Ltd, 2001). The molecular weight of S-316 is 304 (boiling and freezing points are +134 and -143 respectively). Zero-calibration was achieved using the standard solution of clean S-316 solvent. 10mL of the solvent (S-316) and 20mL of the water from the test models were measured using a measuring syringe (for solvent and samples respectively); and inserted into the mixing chamber of the instrument. A drop of diluted Hydrochloric acid (HCL) which was poured through a glass rod into a glass flask containing pure water in a ratio of 1:1. The ‘extract’ button of the instrument was pressed and the contents of the vessel were thoroughly mixed by the instrument for 40 seconds and then separated into two layers with S-316 at the top (and the hydrocarbons in the water sample) and water (sample) at the bottom. The ‘extract’ cock was then opened to send the solvent layer into the measurement cell. This took about 30 seconds and the absorbance of the oil was measured using infra red absorbance spectroscopy within the range of 3.4 - 3.5 µm and digitally displayed in miligramme per litre (mg/L). After recording measurement result displayed on the screen, the drain cock was opened to release the mixture of sample and S-316 into the drain flask.

4.4. Results and Discussion

The results will be discussed under the following sub-headings:

- Elemental analysis
- Nitrate and Nitrite in water
- Analysis of potential hydrogen (pH)
- Analysis of Electric Conductivity (ECw)
- Analysis of oil and grease in water

Furthermore, the results of the analysis of the following parameters were also discussed

- Sodium Absorption Ratio (SAR)
- Soluble Sodium Percentage (SSP)
- Total Dissolved Solids (TDS)
- Exchangeable Sodium Percentage (ESP)
- Magnesium Hazards (MH)

4.4.1 *Elemental Analysis*

Analysis of the elements the following elements was carried out in the irrigation water from the test rigs: Calcium (Ca), Magnesium (Mg), Potassium (K), Phosphorus (P), Sodium (Na), Sulphur (S), Copper (Cu), Vanadium (V), Molybdenum (Mo), Aluminum (Al), Zinc (Zn), Iron (Fe), Cadmium (Cd), Arsenic (As), Boron (Bo), , Lead (Pb), Nickel (Ni) and Manganese (Mn)

4.4.1.1 *Calcium (Ca)*

This cation plays an important role in the determination of the salinity of irrigation water especially as it could also be available in the soil in significant quantity. The highest level of calcium (43.69 mg/L) was observed at 5th week in the water from the Permavoid base as shown in Figure 4.5. This concentration reduced in the 6th week to 18.89 mg/L. The concentration of calcium in water from the stone base test models remained fairly stable from week 1-5 within the range of 29.77mg/L - 30.38mg/L The average concentrations of calcium in water in the test rigs in descending order throughout the experiment were as follows: 25mg/L> 24.94 mg/L >16.52 mg/L >13.97 mg/L for Stone, Permavoid, Control stone and Permavoid bases respectively.

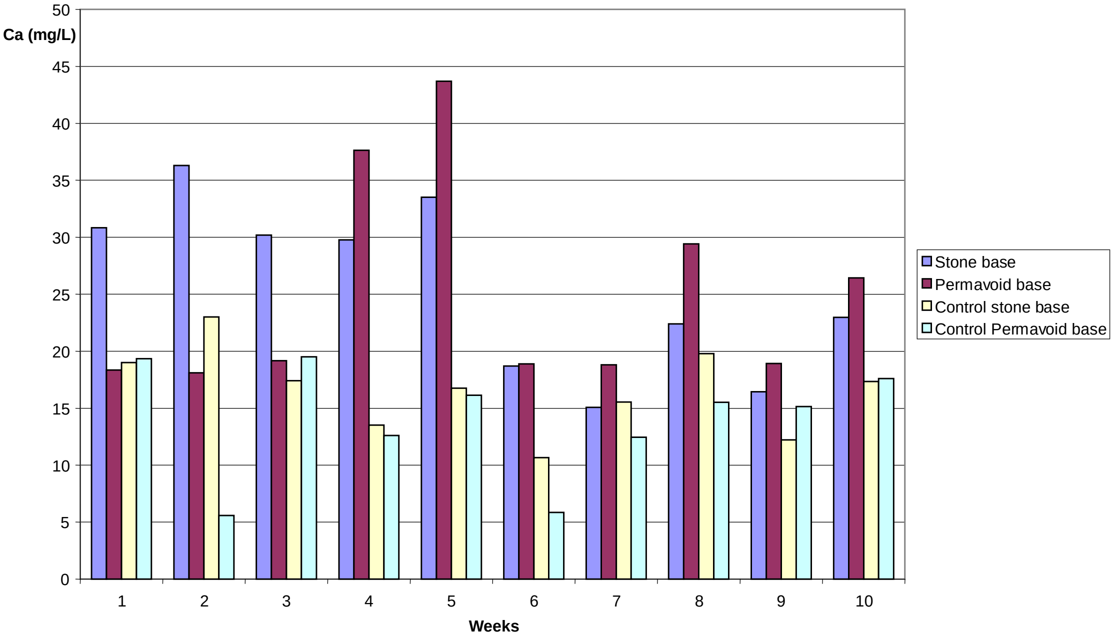

Figure 4.5 Calcium in Water from Test Models

Calcium concentration of < 40 ppm is regarded as very low and concentrations between 41 - 80ppm are regarded as low in irrigation water analysis as shown in Table 3.2 (page 30) (Spectrum Inc., 2008a,b). Based on this, the concentration of calcium in water from the test rigs is regarded as very low except at the 5th week when the concentration was 43.69 mg/L in water from Permavoid test rig.

4.4.1.2 *Magnesium (Mg)*

Magnesium cation is one of the important cations used in the determination of the suitability of any water for irrigation.

Figure 4.6 shows the level of magnesium in the irrigation water derived from the stone and Permavoid based test models as well as their control test rigs for 10 weeks.

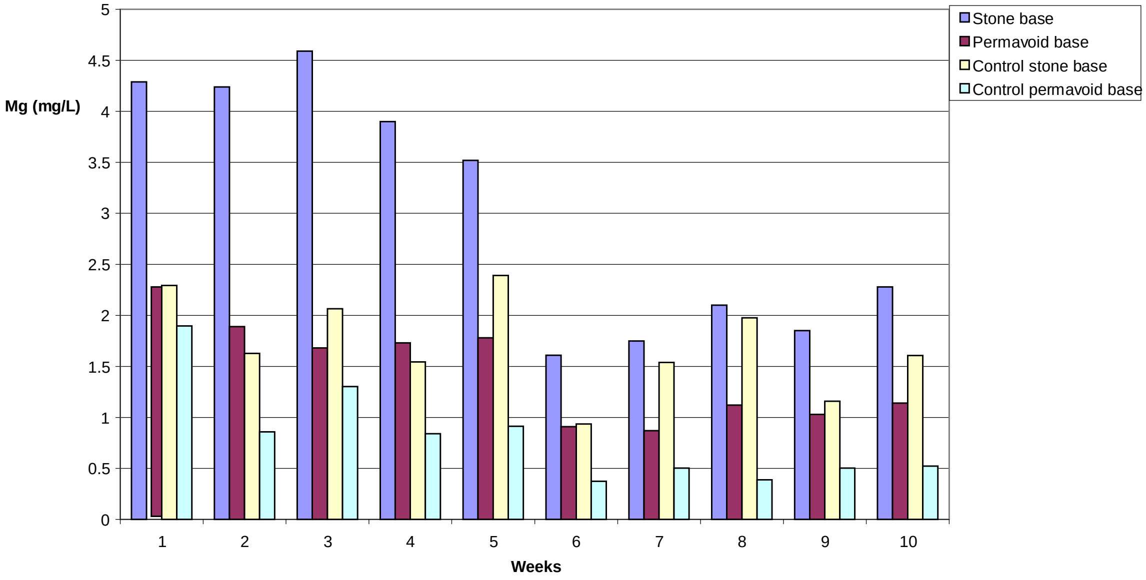

Figure 4.6 Magnesium in Irrigation Water

The highest concentration of magnesium observed in irrigation water from the test rigs was 4.59 mg/L which came from the stone base system at the 3rd week of the experiment and the lowest concentration from the same test rig was 1.6mg/L which was observed at the 6th week of the experiment as shown in Figure 4.6.

However, the highest and lowest levels of magnesium in water from the Permavoid test models was 2.25 mg/L and 0.87 mg/L which was observed at the 1st and 7th week of the experiment respectively. Also, 2.25 mg/L and 0.94 mg/L observed at the 1st and 6th week respectively was the highest and lowest concentrations of magnesium in water obtained from the control stone base test rig. Similarly, 1.9 mg/L and 0.37 mg/L observed at the 1st and 6th week of the experiment was the highest and lowest concentrations of magnesium in water respectively from the control Permavoid base test rig. The average concentration of magnesium in water from the test rigs in descending order is as follows: 3.01 mg/L > 1.44 mg/L > 1.72 mg/L > 0.81 mg/L for Stone, Permavoid , Control stone and Permavoid bases respectively.

According to Spectrum Inc. (2008a), and shown in Table 3.2 (page 35) any concentration of magnesium < 8.0 mg/L in water for irrigation is regarded as very low. It is clear that the highest average concentration of magnesium observed from the test rigs is less than even half of 8.0 mg/L; hence the concentration of magnesium can be regarded as very low especially when compared to the concentration of 8.26 mg/L obtained in treated wastewater after microfiltration as shown in Table 3.1 (page 34) (Al-Shammiri 2005). Supplementary addition of magnesium maybe required in order to augment the magnesium shortage depending on the type of plant and availability of magnesium in soil.

4.4.1.3 *Calculation of Magnesium Hazards (MH)*

Another method of determining the potential hazard from Magnesium in irrigation water is Magnesium Hazards (MH). MH looks at the level of magnesium in relation to the level of calcium in irrigation water and the Equation (4.1) for calculation of MH is shown below.

Magnesium Hazards (MH) = $\frac{[Mg^{2+}]}{\left(\left[Ca^{2+}\right].\left[Mg^{2+}\right]\right).100}$ *Equation 4.1*

(Al-Shammiri *et al.* 2005)

The conversion from mg/L to meq/L was carried out as follows:

Mass concentration = Molecular weight / Valency

Meq/L = x mg/L / mass concentration

Table 4.4 below shows average concentrations of Ca^{2+} and Mg^{2+} in meq/L

Table 4.4 Average Concentrations of Ca^{2+} and Mg^{2+} in meq/L

	Stone Base	Permavoid Base	Control Stone Base	Control Permavoid Base
Ca^{2+}	1.28 meq/L	1.25 meq/L	0.83 meq/L	0.7 meq/L
Mg^{2+}	0.25 meq/L	0.12 meq/L	0.14 meq/L	0.07 meq/L

The result of the computation of Magnesium Percentage Hazard (MH) according to Equation 4.1 is shown in Table 4.5 below.

Table 4.5 Magnesium Percentage Hazard (MH) of Water from Test Models

	Stone Base	Permavoid Base	Control Stone Base	Control Permavoid Base
MH	16.04%	9.44%	14.75 %	9.17 %

The Magnesium Percentage Hazard is used to determine the level of magnesium hazard in water for irrigation. If the hazard is < 50, the water would not pose a risk of magnesium toxicity if used for irrigation (Al-Shammiri *et al.* 2005). It is clear from the results presented in Table 4.5 above, that the average MH percentage was < 17% in the water from all the test rigs.

The Magnesium Hazard Percentage also remained < 20.5% in all the test models throughout the duration of the experiment. Consequently, the water from all the test rigs did not pose a risk of magnesium toxicity when used for irrigation. Furthermore, the MH value of water from the test models was better than 27.06% achieved by Al-Shammiri *et al.* (2005) after using microfiltration technology on wastewater in Kuwait.

4.4.1.4 *Phosphorus (P)*

Figure 4.7 below shows the concentrations of phosphorus in water stored in the test rigs for 10 weeks. The result indicates that the level of phosphorus was unsurprisingly high in water from those models to which nutrients were added, ranging between 1.6 mg/L to 2.97 mg/L between the 1st weeks to the 5th week of the study and remained below 1.5mg/L from the 6th week to the 10th week of the experiment. This is the highest level of phosphorus (2.97 mg/L) was recorded n the water from permavoid sub base models at the 3rd week of the experiment. However, the concentration of phosphorus in the water from the controls remained below 0.3 mg/L throughout the experiment.

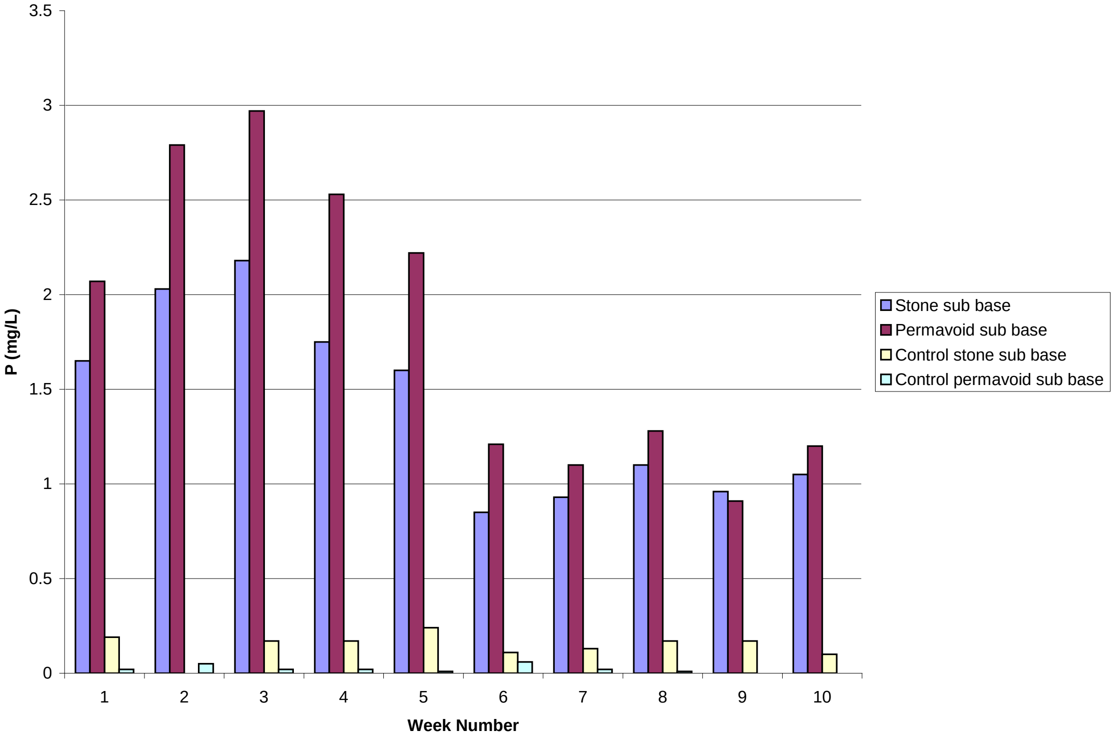

Figure 4.7 Phosphorus in Water from Test Models

The average concentration of phosphorus observed in water from the test rigs for the 10 weeks of the study in descending order is as follows:

1.83 mg/L > 1.41 mg/L > 0.15 mg/L > 0.02 mg/L

Permavoid base > Stone base > Control stone base > Control permavoid base

The higher concentration of phosphorus observed in the water from the stone and permavoid test models was expected as a single dose of Osmocote ® slow release fertilizer was applied to these models (see page 95). However, the maximum concentration of phosphorus that can be supplied by the applied nutrient is presented in Table 4.3 (page 97).

Concentration of phosphorus < 1 mg/L is very low, 1-1.9 mg/L is low and 2-2.9 mg/L is classified as medium (Spectrum Inc. 2008a,b) as shown in Table 3.2. Harivandi (1982) observed that the Nutrient content of reclaimed water for irrigation maybe low because they are supplied at regularly and frequently, but they are utilized by plants efficiently. Hence, the water from the test rigs dosed with nutrients can be used for *fertigation* - which is the application of nutrients and soil amendments through irrigation water (Hou *et al.* 2007).

4.4.1.5 *Copper (Cu)*

It was observed that the highest level of copper in water for all the systems was 0.01mg/L. The level of copper in the water from the stone based system between weeks 1-5 was 0.01mg/L and was non-detectable between weeks 6 -10. However, copper was not detected in the water from the Permavoid based system. 0.01mg/L of copper was also detected at the 1st, 3rd’ 5th, 8th, 9th and 10th weeks in the water from the control stone system, but was not detectable during weeks 2, 6 and 7. Also, the level of copper in water from the control Permavoid test rig remained at 0.01mg/L in weeks 1-2 and became non–detectable throughout the remaining eight (8) weeks of the experiment.

Hence, the highest level of copper recorded in the irrigation water from the different test rigs (i.e. 0.01 mg/L) is lower than the recommended limits of 0.2 mg/L and 5 mg/L for long-term and short-term uses of reclaimed water for irrigation (Rowe and Abel-Magid 1995) (as shown in Table 3.4 page 38). It is also lower than the levels set as standards for reuse of wastewater for irrigation by FAO (0.2 mg/L), Pakistan (0.35), Canada (0.2-1.0mg/L) and Nigeria (0.2-1.0 mg/L) (Al-Shammiri *et al.* 2005) and that of drinking water (2 mg/L) (WHO 2008). This very low level of copper (<0.05) was also observed after the microfiltration of wastewater in Kuwait for agricultural irrigation (Al-Shammiri *et al.* 2005).

The toxicity of copper when in nutrient solution to some plants starts from the concentration of 0.1 mg/L (Rowe and Abel-Magid 1995) as shown in Table 3.4 (page 38). Hence, the level of copper in the irrigation water from the test rigs was very low and non-toxic to both the tomato and ryegrass used in this experiment despite the fact that it was present in the nutrients applied to the test rigs (see page 95).

4.4.1.6 *Sodium (Na)*

Excess sodium in irrigation water might lead to salinity problems that might even affect the soil structure and limit infiltration of water (Warrence, Pearson and Bauder 2003). Accumulation of excessive sodium around the root zone may cause serious crop development problems as it might limit the availability of other nutrients and may even be directly toxic to the plant. Hence the level of available sodium in irrigation water relative to the concentration of magnesium and calcium is an important indication of the salinity level of the water (Nnadi, Newman and Puehmeier 2008). The parameter for measuring this relationship is known as Sodium Absorption Ratio (SAR). SAR is determined and discussed in this thesis on page 113, and the relationship between SAR and EC_W is presented in pages 150.

The highest level of sodium in water 39.95 mg/L was recorded at the 5th week in water from the control stone base test rig system and lowest concentration of 11.0 mg/L was observed in the water from the Permavoid system at the 7th week. The average concentrations of sodium in the systems in descending order are as follows:

26.30 mg/L > 26.10 mg/L > 23.81 mg/L > 16.60 mg/L

Stone base> Control Stone base > Control Permavoid base > Permavoid base

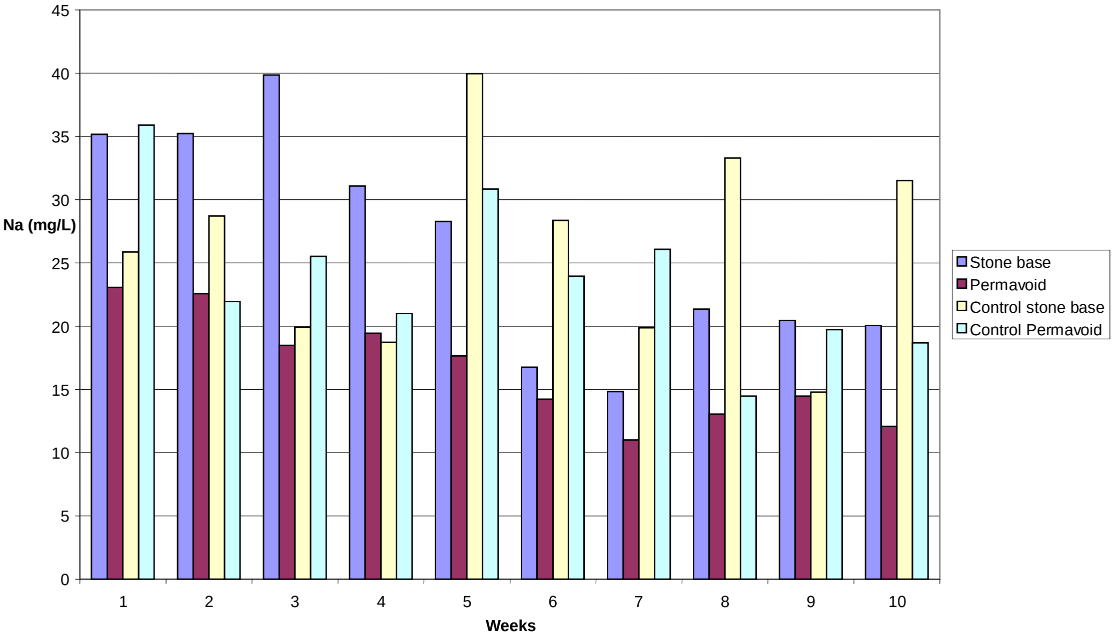

Figure 4.8 Sodium in Water from Test Models

It was observed that the concentration of sodium in water from the Permavoid system is less than that from the control stone and even control Permavoid based systems. However, the only difference between the Permavoid and the control Permavoid systems was the addition of oil and nutrients to the Permavoid system. This suggest that the oil and nutrient addition to the Permavoid system might have limited the availability of sodium in the system as the difference between the concentration of sodium in the control Permavoid system and the Permavoid system is 7.21 mg/L as shown in figure 4.8. However, it was observed that there was no significant difference (i.e. 0.2 mg/L) between the average concentrations of sodium from the stone base systems and that of the Control stone base system despite oil and nutrient addition to the stone base system (t-test, $p > 0.05$: Appendix 10). The methodology for oil and nutrient dosing on the test rigs was as stated in pages 93 & 95.

An investigation of the significance of these concentrations of sodium as regards the suitability of the water supplied by them for irrigation was further progressed by Sodium Absorption Ratio (SAR) as recommended by many researchers (Al-Shammiri *et al.* 2005; deHayr and Gordon 2006, A&M University Texas 2008, Nnadi, Newman and Puehmeier 2008). However, Colorado University recommends concentration of $Na^+ < 46$ in irrigation water for tomato plants (Bauder, Waskom, and Davis 2008).

4.4.1.7 *Sodium Absorption Ratio (SAR)*

Sodium Absorption Ratio (SAR) as stated above under Na^+ content of the water is the ratio of sodium to calcium and magnesium ion concentration calculated in miliequivalent. The conversion of mg/L to meq/L was carried out as shown in page 106.

The Sodium Absorption Ratio was calculated from the following equation:

$$\text{SAR} = \frac{Na^+ \text{ (meq/L)}}{\text{(Square root } (Ca^{2+} + Mg^{2+})/2) \text{ (Meq/L)}} \qquad \textit{Equation 4.2}$$

deHayr and Gordon, (2006)

Where, Na, Ca and Mg are expressed in miliequivalent.

The concentrations of Ca^{2+}, Mg^{2+} and Na^+ in miliequivalent for test rigs are presented in Tables 4.6, 4.7 and 4.8 below

Table 4.6 Concentrations of Ca^{2+}, Mg^{2+} and Na^{+} in Water from Stone Base Test Model in meq/L

Week Number	Na^{+} (meq/L)	Ca^{2+} (meq/L)	Mg^{2+} (meq/L)	K^{+} (meq/L)
1	1.53	1.54	0.36	0.34
2	1.53	1.81	0.35	0.27
3	1.73	1.51	0.38	0.35
4	1.35	1.49	0.33	0.41
5	1.23	1.68	0.29	0.33
6	0.73	0.94	0.13	0.69
7	0.64	0.75	0.15	0.24
8	0.93	1.12	0.18	0.30
9	0.89	0.82	0.15	0.48
10	0.87	1.15	0.19	0.46

Table 4.7 Concentrations of Ca^{2+}, Mg^{2+} and Na^{+} in Water from Permavoid Base Test Model in meq/L

Week Number	Na^{+} (meq/L)	Ca^{2+} (meq/L)	Mg^{2+} (meq/L)	K^{+} (meq/L)
1	1	0.92	0.19	0.56
2	0.98	0.91	0.91	0.74
3	0.8	0.96	0.96	0.69
4	0.85	1.88	1.88	0.79
5	0.77	2.18	2.18	0.77
6	0.62	0.94	0.94	0.44
7	0.48	0.94	0.94	0.43
8	0.57	1.47	1.47	0.57
9	0.63	0.95	0.95	0.54
10	0.53	1.32	1.32	0.61

Table 4.8 Concentrations of Ca^{2+}, Mg^{2+} and Na^{+} in Water from Control Stone Base Test Model in meq/L

Week Number	Na^{+} (meq/L)	Ca^{2+} (meq/L)	Mg^{2+} (meq/L)	K^{+} (meq/L)
1	1.12	0.95	0.19	0.21
2	1.25	1.15	0.14	0.41
3	0.87	0.87	0.17	0.14
4	0.81	0.68	0.13	0.11
5	1.74	0.84	0.2	0.06
6	1.23	0.53	0.08	0.31
7	0.86	0.78	0.13	0.08
8	1.45	0.99	0.16	0.09
9	0.64	0.61	0.1	0.07
10	1.37	0.87	0.13	0.11

The Sodium Absorption Ratio (SAR) of the water from the test rigs for 10 weeks duration of the experiment is presented in Figure 4.9 above. When SAR value is < 9, it is an indication of soil permeability problems (Harivandi 1982). However, effective evaluation of potential soil structure, infiltration and permeability problems arising from irrigation water is determined by SAR and Electric Conductivity because for any given SAR value of water, an increase in Electric Conductivity (EC) will result in soil infiltration and permeability problems (Harivandi 1982, deHayr and Gordon 2006, FAO 2008).

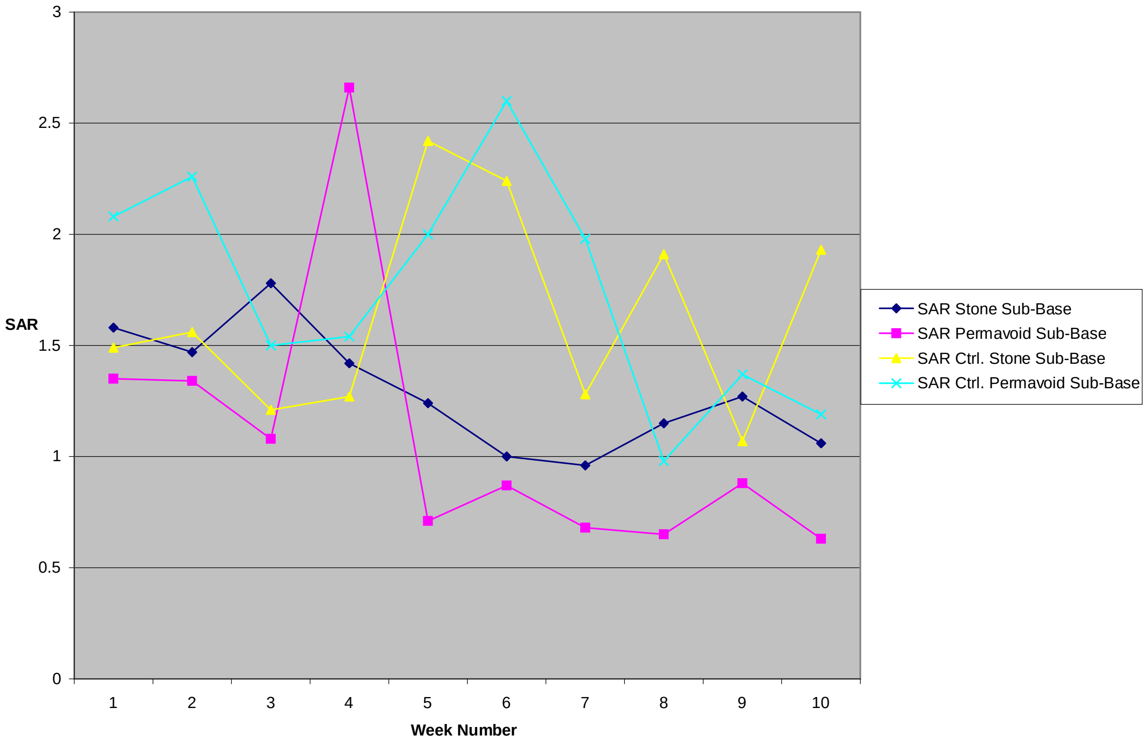

Figure 4.9 Sodium Absorption Ratio (SAR) of Water from Test Rigs for 10 Weeks

Table 4.9 Concentrations of Ca^{2+}, Mg^{2+} and Na^{+} in Water from Control Permavoid Base Test Model in meq/L

Week Number	Na^{+} (meq/L)	Ca^{2+} (meq/L)	Mg^{2+} (meq/L)	K^{+} (meq/L)
1	1.56	0.97	0.16	0.34
2	0.95	0.28	0.07	0.39
3	1.11	0.98	0.11	0.39
4	0.91	0.63	0.07	0.37
5	1.34	0.81	0.08	0.39
6	1.04	0.29	0.03	0.26
7	1.13	0.62	0.04	0.36
8	0.63	0.78	0.03	0.27
9	0.86	0.76	0.04	0.38
10	0.81	0.88	0.04	0.38

Hence, this relationship between SAR and EC of irrigation water is an effective tool in the prediction of potential soil structure stability problems resulting from application of irrigation water (deHayr and Gordon 2006). This relationship as regards water from the test models is investigated in page151.

The effect that salt application on pervious pavement system during winter may have on the stored water in the system (including the levels of SAR and EC_w) is a subject of further studies (Chapter 8). However, the potential reduction in salt application during winter (gritting) by the use of the pervious pavement system was highlighted earlier as an outcome of research work in University of New Hampshire, USA by Potier (2008) (see page 39).

4.4.1.8 *Soluble Sodium Percentage (SSP)*

SSP is another method of measuring potential of sodium hazard in irrigation. It is the ratio of sodium to calcium, magnesium, potassium and then sodium in miliequivalent. It measures the percentage of solubility of sodium ions relative to other positive ions present in the water.

The Equation 4.3 for calculation is as follows:

$$SSP = \frac{Na^{+}\ (meq/L)}{(Ca^{2+} + Mg^{2+} + K^{+} + Na^{+})\ (meq/L)} \qquad \textit{Equation 4.3}$$

(Al-Shammiri *et al.* 2005)

The Soluble Sodium Percentage of water from the test models used in this experiment for 10 weeks is presented in Figure 4.10 below. The average SSP of water from the test models for the same period in descending order was as follows:

49.4% > 48% > 37% > 27.2%
Control Stone Base > Control Permavoid Base > Stone Base > Permavoid Base

It is clear from the average SSP result shown above, that the SSP of water from the control sub base models was higher than that of the Stone and Permavoid systems which were dosed with oil and nutrients (see pages 93 and 95 respectively).

Water that has SSP > 60%, is considered to pose a potential risk to soil structure if used for irrigation as it may result in the accumulation of sodium in the soil (A&M University Texas 2008). According to Al-Shammiri *et al.* (2005), this threshold of 60% was raised by Green (1948) to 80%; with the condition that the total dissolved solids (TDS) in the water should be < 10 meq/L (the TDS of water from the test models is presented in this in page 150).

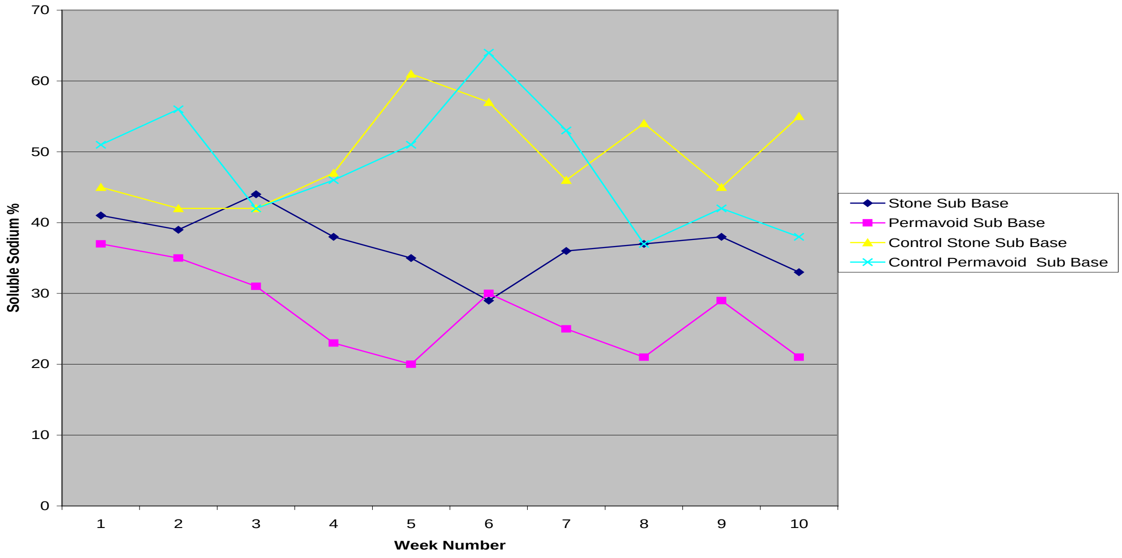

Figure 4.10 Soluble Sodium Percentage (SSP) of Water from Test Model

Hence, it is clear from the average SSP results shown above that the waters from the all the models did not pose a sodium hazard as the average SSP values were < 60%. It is necessary to highlight that the average SSP for waters from the Permavoid and Stone base models (27.2% and 37% respectively) were even lower than that of the controls (48% and 49.4% respectively) despite the cumulative application of oil and single heavy dose of nutrients to the systems (result of TPH analysis is presented in pages 154). Again, these SSP values from the test rigs were better, when compared to 59.265% (indication of moderate risk for irrigation purpose) obtained after the application of microfiltration technology to wastewater (Al-Shammiri *et al.* 2005).

4.4.1.9 ***Exchangeable Sodium Percentage (ESP)***

The ESP is another important indicator of potential sodium hazard from irrigation water. It is a tool for the evaluation of the potential effects of sodium on the soil's physical properties and has a relationship with other indicators of sodium (Al-Shammiri et al. 2005). Like other indicators of sodium, a low ESP value is desirable for irrigation water and a higher value is a sign of potential sodium hazard and consequently, a potential hazard to soil structure. One of the effects of soil sodicity (a condition of high ESP) is development of a relatively impervious layer to air and water on the surface of the soil known as soil seal (Hillel 2000). The relationship between ESP and SAR was determined after measurements in western United States by United States Salinity Laboratory (USSL) as shown in Equation 4.4.

$$ESP = 100(- a + b (SAR)) \div (1+ (-a + b (SAR)) \qquad \textit{Equation 4.4}$$

Where a = 0.0126 and b = 0.01475 (Hillel, 2000)

This relationship is also shown in Equation 4.5 used for the calculation of ESP.

$$ESP = \frac{100.(-0.0126 + 0.01475.SAR)}{1 + (-0.0126 + 0.01475.SAR)} \qquad \textit{Equation 4.5}$$

Al-Shammiri *et al.* (2005)

The Exchangeable Sodium Percentage (ESP) of water from the test models for 10 weeks duration of the experiment is shown in Figure 4.11 below.

The recommended value for ESP is ≤ 5 ; and values between 6 and 9 is an indication of increasing soil structure problems; while ESP values above 15 is an indication of serious soil problems (Al-Shammiri *et al.* 2005). This is similar to the classification of ESP presented by UNSW (2008) and shown in Table 4.10 below:

Table 4.10 Classification of Exchangeable Sodium Percentage

ESP	Classification	Non Sodic	Sodic	Moderately Sodic	Strongly Sodic	Very Strongly Sodic
	%	< 6	6 - 10	10 - 15	15 - 25	25

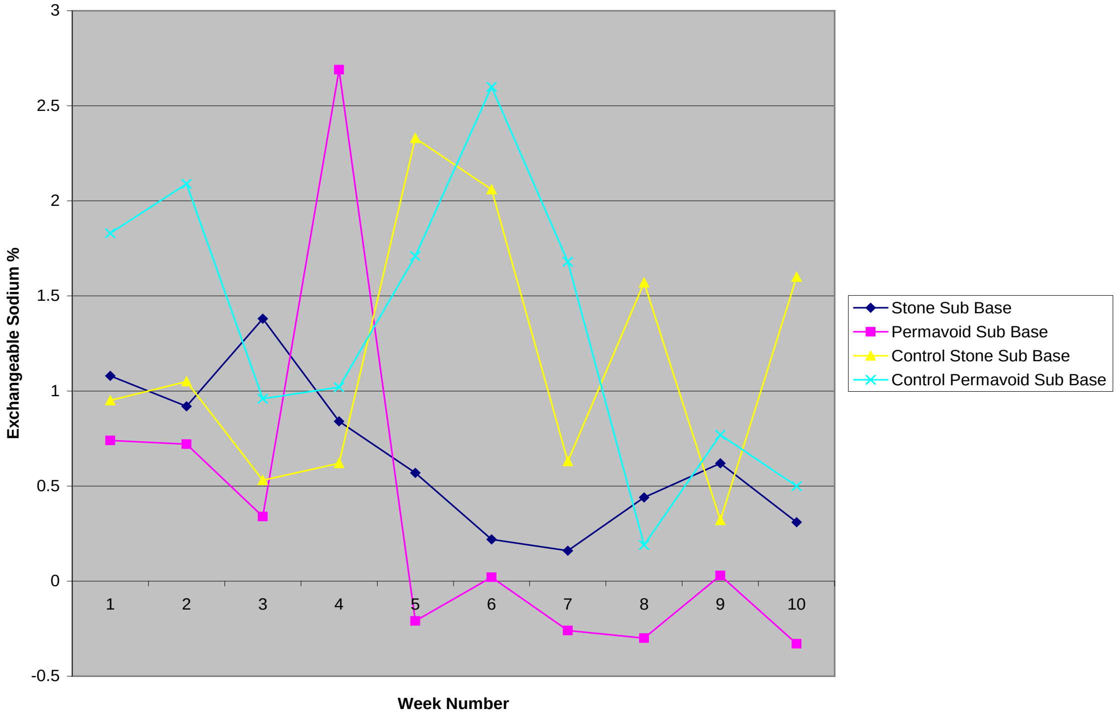

Figure 4.11Exchangeable Sodium Percentage of Water from Test Models

In theory, irrigated soils maybe “sodic” without being “saline” or vice versa and in some cases may even become both sodic and saline as reported in some arid in arid region (Hillel 2000).

The average ESP values from the test models in descending order are as follows:

1.34 > 1.17 > 0.65 > 0.34
Control plastic Base > Control Stone Base > Stone Base > Plastic Base

The average ESP values (shown above) and ESP values for the duration of the experiment (Figure 4.11) clearly shows the ESP values of the water from the test models was non – sodic and would not pose soil infiltration and permeability problems if used for irrigation.

4.4.1.10 *Sulphur (S)/ Sulphate (SO_4^{2-})*

Total sulphur was determined in accordance with Methods for the Examination of Waters and Associated Materials, Sulphate in waters, Effluents and Solids, 2nd Ed, 1988, C, pages 21-23. Hence, the concentrations represent sulphate (SO_4^{2-}) $^-$ in water. This is considered reasonable especially as the experimental test rigs were left open in an environment with unlimited air flow. Sulphate in water is another important parameter that is considered in determining the suitability of water for irrigation. It is recognized as a major contributor to salinity problems in irrigation water in Colorado, USA , but rarely toxic and may hinder the uptake of essential nutrients if excessively present in irrigation water (Bauder, Waskom, and Davis 2008). Figure 4.12 shows the concentrations of sulphur/sulphate in the water from the test rigs. The highest concentration of 6.41mg/L was observed from the Permavoid system at the 1st week and the lowest concentration of 1.29 mg/L was recorded from the control Stone system at the 7th week. It is clear from Figure 4.12 that the concentration of sulphur/ sulphate reduced after the 5th week of the experiment .The average concentrations for the 10 weeks of the experiment are shown below in descending order:

3.92 mg/L > 3.66 mg/L > 2.88 mg/L > 2.15 mg/L
Permavoid base > Stone base > Control Stone base > Control Permavoid base

The water from Permavoid and stone bases which were dosed with oil and nutrients contained more sulphur/sulphate than their control test systems. Sulphate concentration of <10 mg/L in irrigation water is regarded as insufficient for maximum production of most crops because it enhances crop fertility (Bauder, Waskom, and Davis 2008)

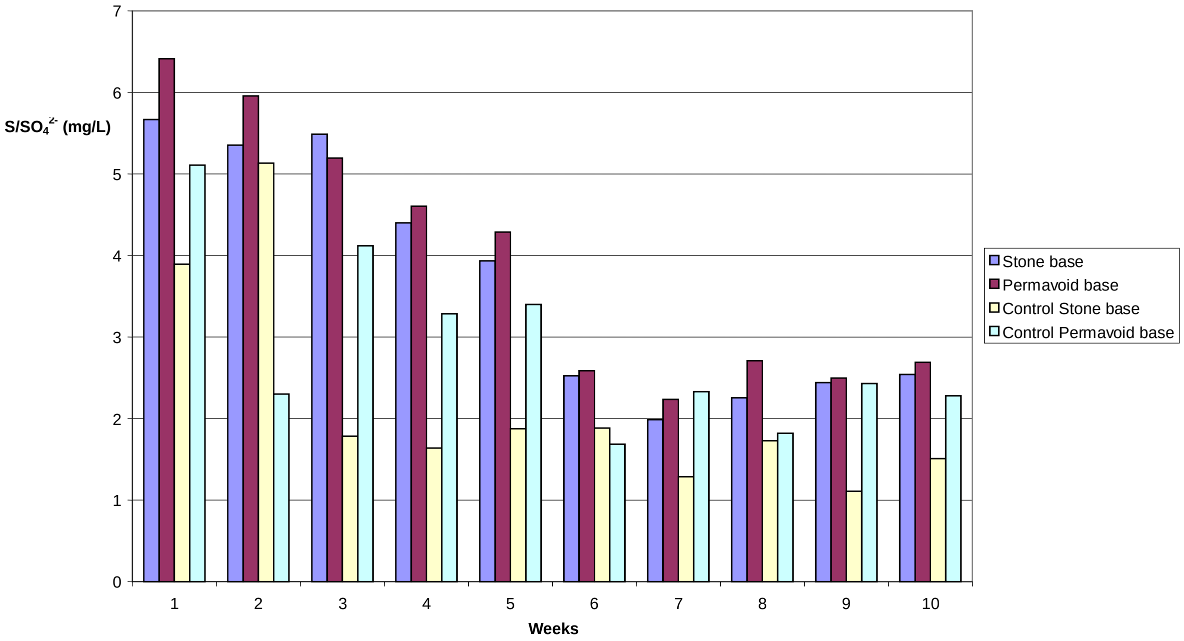

Figure 4.12 Sulphur/ Sulphate in Irrigation Water

Also, Spectrum Inc. (2008a) considers any concentration < 24ppm in irrigation water as very low (see Table 3.2 page 35). Consequently, the concentration of sulphate in the irrigation water from all the test rigs is very low and the author advises that sulphate addition maybe necessary in order to meet plant's sulphate requirements. The author is aware that this is dependent on the level of sulphur (SO_2 and H_2S) in the atmosphere as sulphur maybe supplied through rain in rich sulphur environments (e.g. industrial and coal producing areas).

4.4.1.11 *Iron (Fe)*

Figure 4.13 shows the concentration of iron in the water from the test rigs. The average concentrations over ten weeks of the experiment in descending order are as follows:

0.07 mg/L > 0.05 mg/L > 0.02 mg/L > 0.01mg/L
Control Stone base > Control Permavoid > Stone base > Permavoid

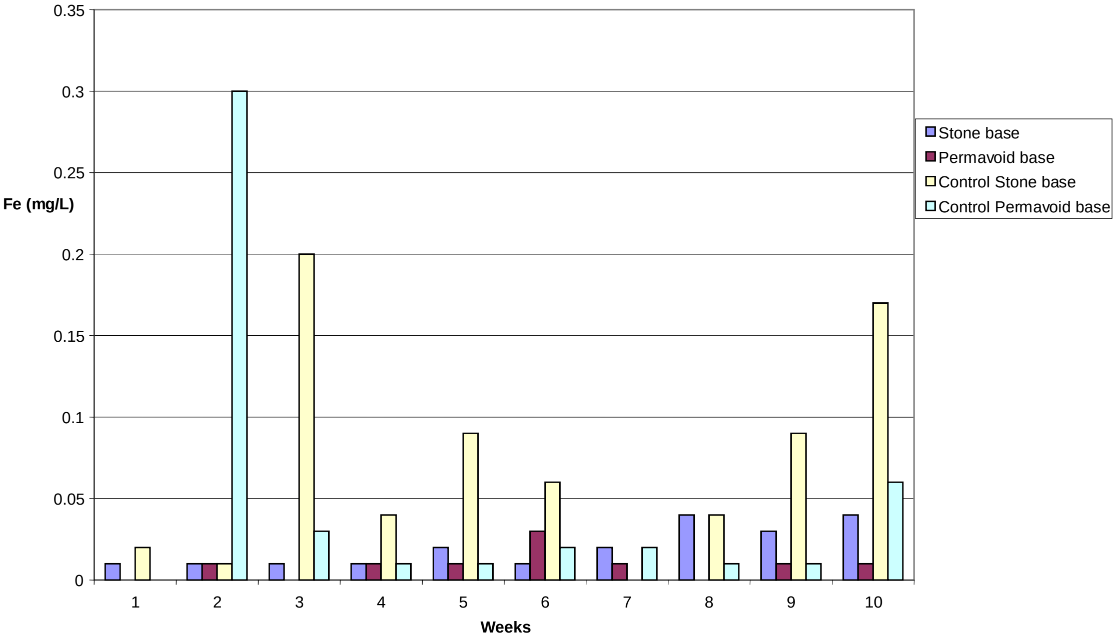

Figure 4.13 Iron in Water from Test Models

The control models contain more iron than the test models treated with oil and nutrients. However, it is obvious that the difference between the concentrations is not high. The recommended concentration for Iron in reclaimed water is 10 mg/L and 5.0 mg/L for short and long term uses respectively as shown in Table 3.4 (page 38). Spectrum Inc., (2008a) categorized any concentration of iron < 0.2 mg/L as very low (see Table 3.2 on page 35). Since the highest average concentration of iron in water from the test models is 0.07 mg/L, then, the concentration of iron in the water from the test rigs is very low. This result is below the standard concentration of 5.0mg/L for iron and consistent with the concentration observed after wastewater treatment with microfiltration technology to make it suitable for irrigation in Kuwait as shown in Table 3.1 (page 34).

4.4.1.12 *Cadmium (Cd)*

At wavelength of 228.802nm, the concentration of cadmium was not detectable in water from all the test models. The recommended limits for cadmium in irrigation water is 0.01mg/L and 0.05 mg/L for long and short term respectively (Table 3.4 page 38) and the standard concentrations in Canada, Nigeria and FAO is 0.01 mg/L as shown in Table 3.1 (page 34). Also, the concentration of non-toxicity hazard of cadmium in water is <0.01 (Spectrum Inc., 2008) as show in Table 3.4 (page 38). The non detection of cadmium in the water from the test rigs in ten weeks is an indication of good irrigation water quality considering that cadmium toxicity in crops can occur at concentrations as low as 0.02 mg/L (A&M University Texas, 2008). This result is consistent with, but better than <0.01 observed after application of microfiltration technology to wastewater for irrigation purposes (Al-Shammiri *et al*. 2005).

4.4.1.13 *Arsenic (As)*

The average concentrations of arsenic from each test rig are as follows in descending order:

0.005 mg/L > 0.004 mg/L > 0.003 mg/L > 0.002 mg/L

Permavoid base > Stone base > Control Permavoid base > Control Stone base

These concentrations are lower than the limits set for reclaimed water for irrigation of 0.10 mg/L and 2.0 mg/L for long and short term applications respectively (A&M University Texas 2008). Al-Shammiri *et al.* (2005) also reported the standard concentration of 0.1 mg/L for Arsenic, but failed to show the concentration observed after microfiltration of wastewater for irrigation application. However, Spectrum Inc. (2008a), reported that a concentration of < 0.1 mg/L of arsenic is the level of non - toxicity hazard to crops. Also, A&M University, Texas (2008) noted variations in the toxicity of arsenic relative to the type of crop; that arsenic could be toxic to some plants (e.g. rice) at even a low concentration of 0.05 mg/L and others at concentration as high as 12.0 mg/L (e.g. Sudan grass)

4.4.1.14 *Boron (B)*

Boron was non-detectable at the wavelength of 182.578nm in the water from all the rigs throughout 10 weeks of the experiment. This result is expected as the slow release fertilizer contained only 0.01% Boron by weight as shown in Table 4.2 (page 96) above. This is a significant indication of good irrigation water quality as boron toxicity is a major problem in irrigation water especially in the use of reclaimed water for irrigation (Nable *et al.* 1997, Sotiropoulos, Therios and Dimassi 2003, Bauder, Waskom, and Davis 2008). Nable *et al.* (1997) identified irrigation water as the most significant source of excess Boron. Although Boron is required by some plants at very low concentrations, the element may become toxic if available in excess and an excess concentration may be as low as 1.0mg/L to sensitive crops (Bauder, Waskom, and Davis 2008). Rowe and Magid (1995) as reported in A&M University Texas (2008) observed that citrus is sensitive to Boron at 1 mg/L and that most grasses are tolerant to the element at 2.0-10 mg/L. Mass (1990), as reported in (Bauder, Waskom, and Davis 2008), also observed in a study carried out in Colorado, USA, tomato was tolerant to Boron at the concentration of between 4.1- 6.0 mg/L. However, Rowe and Abdel-Magid (1995) as reported in A&M University Texas (2008) recommended Boron concentrations of 0.75 mg/L and 2.0 mg/L in reclaimed water for irrigation on long-term and short-term basis respectively. Also, the Canadian Council of Ministers (1987) as reported by Peterson, (1999) recommended the threshold level of 0.5mg/L as the maximum Concentration of Boron in irrigation water in Canada.

4.4.1.15 *Vanadium (V)*

Vanadium is a rare element and exists in many oxidation states; the most common is the pentavalent vanadium pentoxide (Fiorentino *et al*. 2007). However, vanadium is also a toxic element to plants, animals and man even at relatively low concentrations (Peterson, 1999, Fiorentino *et al.* 2007). Vanadium was observed to have a significant correlative relationship with boron, arsenic and fluoride (Fiorentino *et al.* 2007) and have been reported to be the most abundant metallic element present in all crude or residual oils (Mastoi *et al.* 2006, Amorim *et al.* 2007) in the concentration of between 0.1mg/kg – 1500 mg/kg (Amorim *et al.* 2007).

Results of tests for vanadium concentration in water from the test models were below the mean concentration of 0.01mg/L. This observed concentration is below the recommended maximum concentration of 0.1 mg/L in irrigation water (Fiorentino *et al.* 2007), treated wastewater for irrigation (Al-Shammiri *et al.* 2007) and reclaimed water for irrigation (A&M University Texas, 2008). Spectrum Analytical Inc., (2008a) stated that it is only when the concentration of vanadium is < 0.1ppm, in irrigation water that there would pose a toxicity hazard to plants. Hence, there was no risk of vanadium toxicity hazard from the water stored in the PPS test models and used for irrigation.

4.4.1.16 Lead (Pb)

The concentration of 0.01 mg/L Lead was observed in the water from the control stone sub base, stone sub base and control permavoid sub base at the 1st, 2nd and 10th week respectively of the study.

Lead can reduce the growth and development of plants if present in high concentration (Peterson 1999). The standard concentration of lead in treated wastewater for irrigation purposes is 1.5mg/L (Al-Shammiri *et al.* 2005). The Canadian Council of Ministers of the Environment recommended the maximum concentration of 0.01mg/L of lead in irrigation water (Peterson 1999). However, Rowe and Abdel-Magid (1995) as reported in A&M University, Texas (2008) recommended the concentrations of 10.0 mg/L and 5.0 mg/L as limits for lead in reclaimed water for irrigation for short and long term uses respectively. According to Spectrum Inc. (2008a), the risk of lead toxicity hazard from irrigation water is non-existent only at concentration of < 5.0 mg/L for long term irrigation purposes.

It is clear from above that the level of lead in the water from the test models was below the standards and the hazard threshold levels; hence the water from all the test models did not pose a risk of lead toxicity when used for irrigation.

4.4.1.17 *Zinc (Zn)*

The concentrations of zinc observed in water from the test models are shown in Figure 4.14 below.

The average concentrations of zinc from all the test models in descending order are as shown below:

0.016 mg/L > 0.014 mg/L > 0.007 mg/L = 0.007 mg/L
Stone base > permavoid base > Control stone base = Control permavoid base

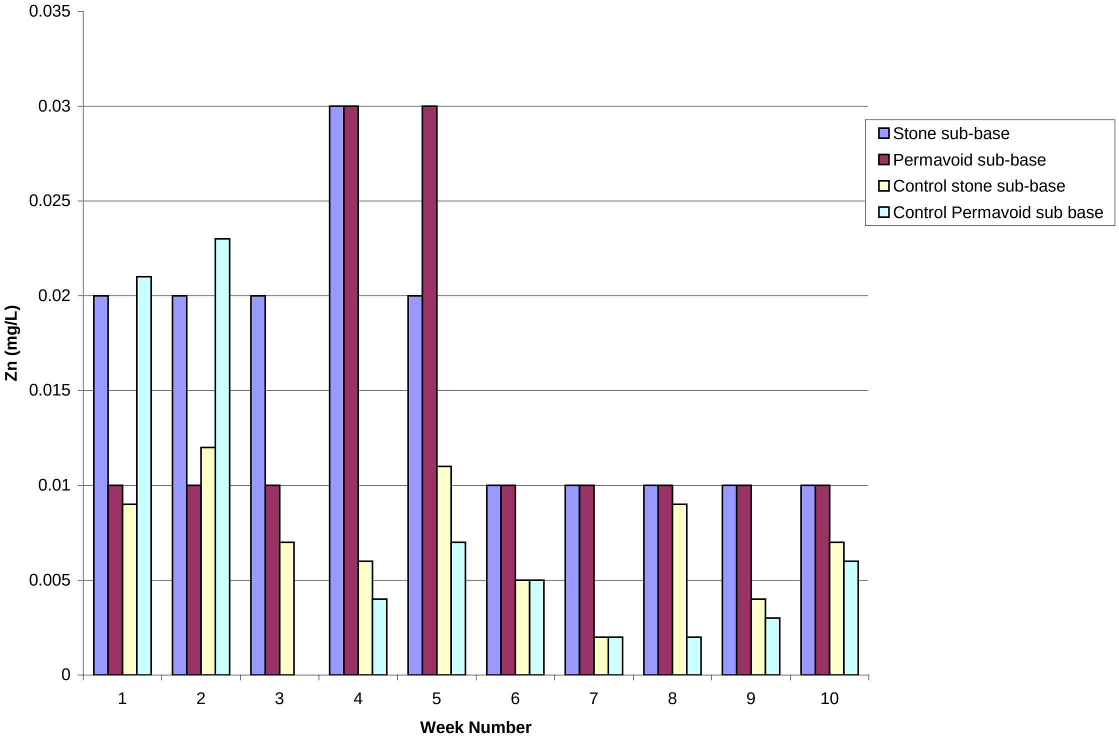

Figure 4.14 Zinc in Water from Test Models

The toxicity of zinc to plants varies at different concentrations and is dependent on the pH (toxicity reduces at pH > 6) and soil texture (A&M University, Texas 2008).

The National Academy of Sciences of the United States of America recommended the maximum concentration of 5.0 mg/L of zinc before any effluent could be used as irrigation fluid in the USA (Harivandi 1982). Rowe and Abdel-Magid (1995) as reported in A&M University, Texas (2008), recommend the maximum concentrations of 10.0 and 2.0 mg/L of lead in reclaimed water for irrigation for short and long term uses respectively. Al-Shammiri *et al.* (2005), reported standard concentrations of 2.0 mg/L, 1.0 - 5.0 mg/L, and 0 - 5.0 mg/L of zinc in wastewater for irrigation of FAO, Canada and Nigeria respectively. Since the highest concentration of zinc in water from the test models was 0.016 mg/L, hence there was no risk of zinc toxicity when the water from the models was used for irrigation as the levels of zinc observed was lower than the recommended maximum concentrations.

4.4.1.18 Aluminium (Al)

The trend of aluminium concentration throughout the duration of the study is as shown below in Figure 4.15. Average concentrations of aluminium in water from the test rigs in descending order are as follows:

0.1 mg/L = 0.1 mg/L > 0.03 mg/L > 0.02 mg/L
Control stone base = Control permavoid base > Stone base > Permavoid base

High concentration of aluminium may lead to non-productivity especially in acid soils (pH <5.5), but aluminium toxicity is eliminated if the pH is raised above neutrality level (i.e. pH >7.0) because of the precipitation of aluminium ions (Peterson 1999, A&M University Texas 2008).

The recommended standard concentration of aluminium in wastewater for irrigation purposes of FAO, Canada and Nigeria is 5.0 mg/L. Rowe and Abdel-Magid (1995) as reported in A&M University Texas, (2008), recommended the concentrations of 20 mg/L and 5.0 mg/L of aluminium in reclaimed water for irrigation for short and long term purposes respectively.

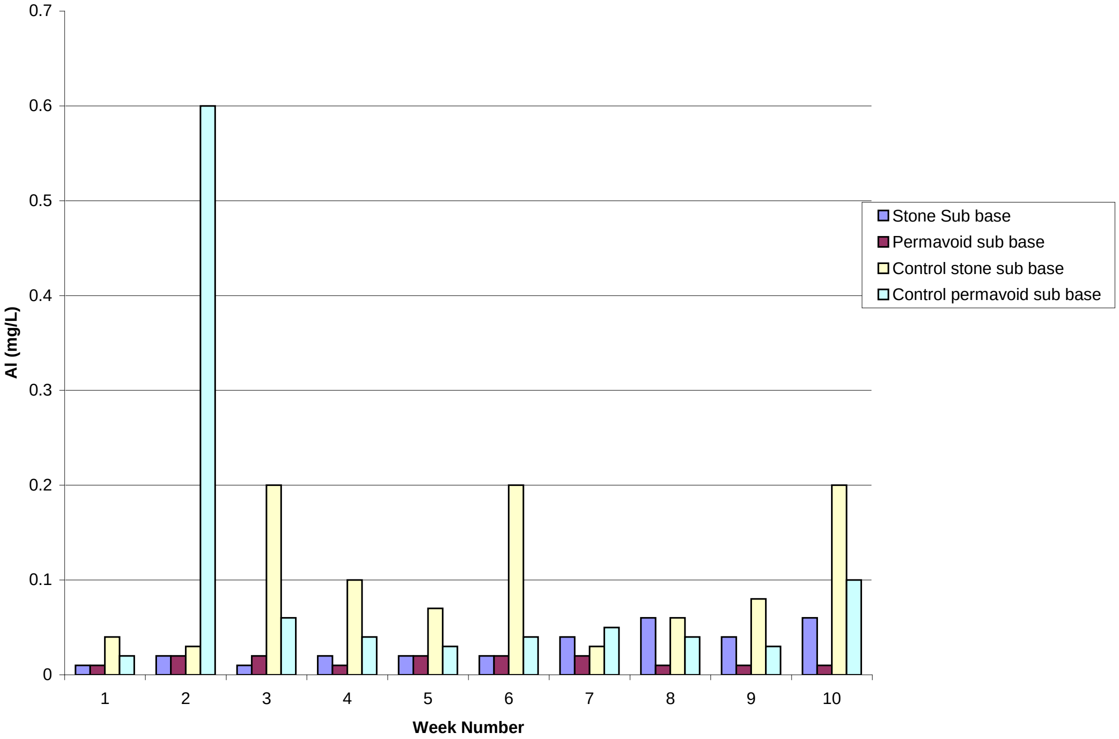

Figure 4.15 Aluminium in Water from Test Models

According to Spectrum Inc. (2008a), aluminium toxicity hazard to plants from irrigation water does not exist if the concentration of aluminium is > 1 mg/L (Table 3.3 page 36). Since the highest concentration of aluminium from the test models was 0.6 mg/L, hence the concentration of aluminium in water from the test models was below the maximum standard concentrations and within the non-toxicity level.

4.4.1.19 *Nickel (Ni)*

The concentration of nickel in water from the test models is presented in Figure 4.16 below. The average concentration of nickel in all the test rigs throughout the experiment was 0.002 mg/L.

Nickel is toxic to most plants at concentrations of between 0.5 to 1.0 mg/L especially with low soil pH (increasing acidity), but toxicity decreases from neutral (pH 7.0) as the pH increases (Peterson 1999, A&M University Texas 2008).

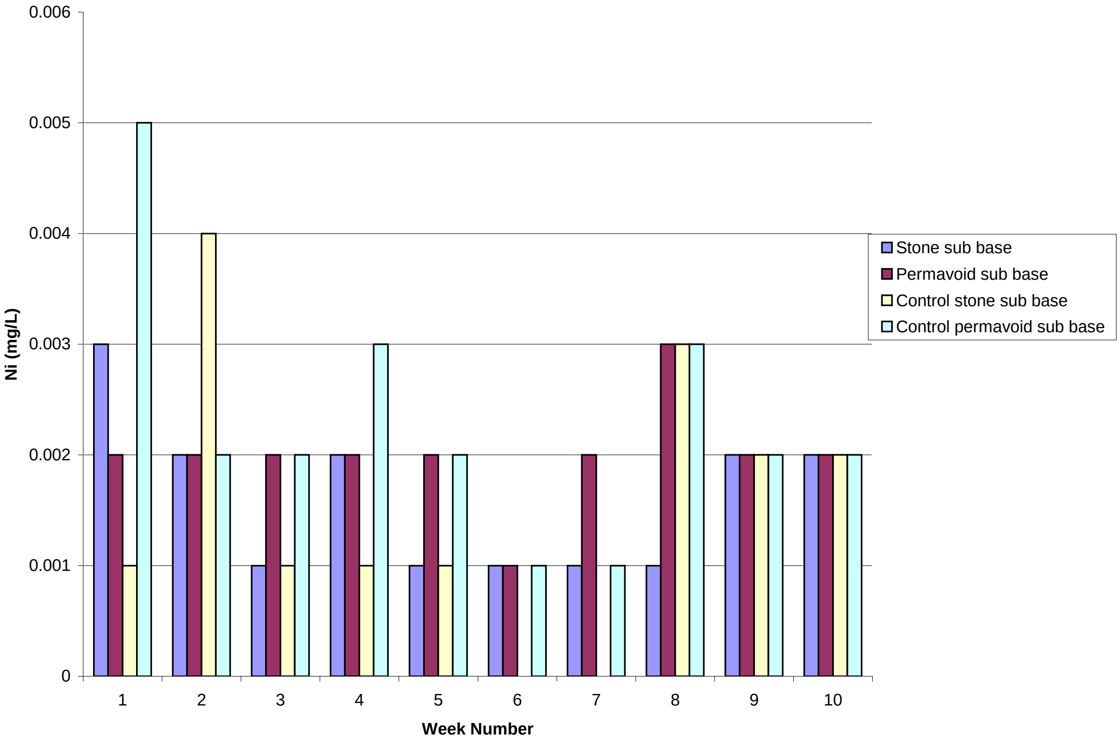

Figure 4.16 Nickel in Water from Test Models

The National Academy of Sciences of the USA recommended the maximum concentration of 0.5 mg/L of nickel in any effluent to be used as irrigation fluid (Harivandi, 1982). Also, Al-Shammiri *et al.* (2005) and Canadian Council of Ministers of the Environment recommended the standard concentration of 2.5mg/L of Nickel in wastewater intended for use in irrigation (Peterson 1999). However, Spectrum inc. (2008a) recognised the level of non-toxicity of nickel in irrigation water as < 2.0mg/L (see Table 3.4 page 38). Rowe and Abdel-Magid (1999) reported in A&M University Texas (2008) recommended the maximum concentrations of 0.2 mg/L of nickel in reclaimed water for irrigation for both short term and long term uses.

Due to the low concentration of nickel observed in the water from the test rigs (average of 0.002 mg/L); the author concluded that the water from the test models did not pose a risk of toxicity from nickel when used for irrigation.

4.4.1.20 *Molybdenum (Mo)*

Molybdenum is used as an additive to oil and grease used in cars in the form the compound molybdenum disulphide (GlobalSpec 2009, IHS 2008). The concentration of molybdenum during the 10 weeks of the study is shown in Figure 4.17 below.

The average concentration for the test models is as follows:

0.007 mg/L > 0.006 mg/L = 0.005 mg/L > 0.004 mg/L
Permavoid base > Stone base = Control permavoid base > Control stone base

Molybdenum is a micro nutrient to plants and usually non toxic to plants if present at normal concentrations, but maybe toxic to animals that feed on the crops if the crops are grown under high concentrations of the element (Peterson 1999). This should be taken in consideration when applying irrigation water that contains high concentration of molybdenum on pastures. However, the standard concentration of molybdenum in irrigation water is 0.01mg/L (Peterson 1999, Al-Shammiri *et al*. 2008) and 0.5 mg/L for short term application (A&M University Texas 2008).

The concentration of Molybdenum in irrigation water is classified as low if within the range of 0.006 – 0.01 (Spectrum Inc. 2008a) as shown in Table 3.2 page 35.

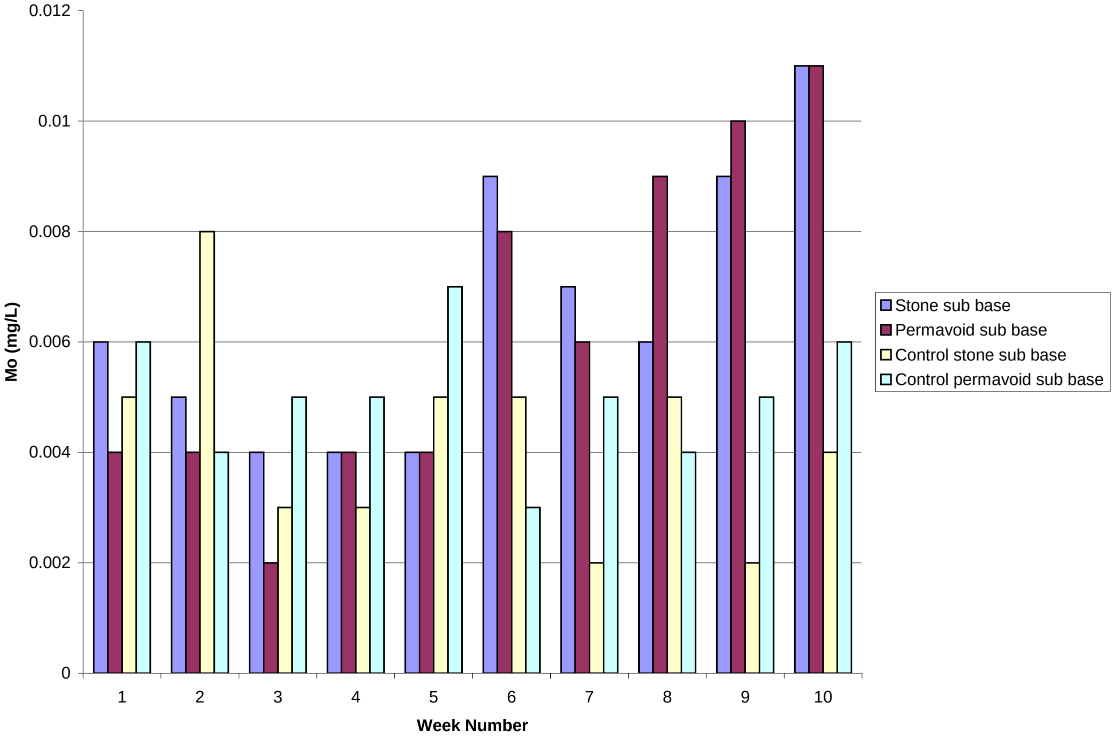

Figure 4.17 Molybdenum in Water from Test Models

Hence the concentration of molybdenum in water from the test models was low and did not pose a toxicity threat to both plants and animals when used for irrigation.

4.4.1.21 Manganese (Mn)

Manganese is an important micronutrient required by plants, but maybe toxic if present in high levels especially when the pH of the soil or medium is $\leq$5.5 (Whipker 1999). Toxicity levels is dependent on type of plant, but ranges from 0.2 to 10 mg/L for long and short term irrigation respectively (A&M University, Texas 2008). High concentrations of manganese in irrigation water may result in brown or black deposit on leaves of crops especially if foliage irrigation was conducted (Whipker 1999).

The concentration of manganese in water from all the models was < 0.01mg/L throughout the 10 weeks of the experiment. Hence, there was no risk of manganese toxicity from water from the test models.

4.4.1.23 ***Potassium (K)***

Potassium is another important nutrient which is essential for plant growth and development. K was one of the major nutrients supplied by the added nutrient (Table 4.3 page 97). Figure 4.18 shows the levels of potassium in the water from the test models for 10 weeks. The average concentrations in descending order are as follows:

23.97 mg/L > 15.02 mg/L > 13.72 mg/L > 6.21 mg/L
Permavoid base > Stone base > Control Permavoid base > Control stone base

It is evident from Figure 4.18 and the average concentrations presented in descending order (above) that higher concentration of potassium was observed in water stored in the Permavoid sub base systems. Also, water stored in the control Permavoid sub base system clearly showed high concentration (average concentration of 13.72 mg/L) of potassium although the system was not dosed with NPK compared to the control stone sub base system with an average of 6.21 mg/L of potassium under similar conditions. It is difficult to attribute this to any reason in particular considering that the only difference between the systems is the sub base; and the plastic (Permavoid) sub base cannot be considered as

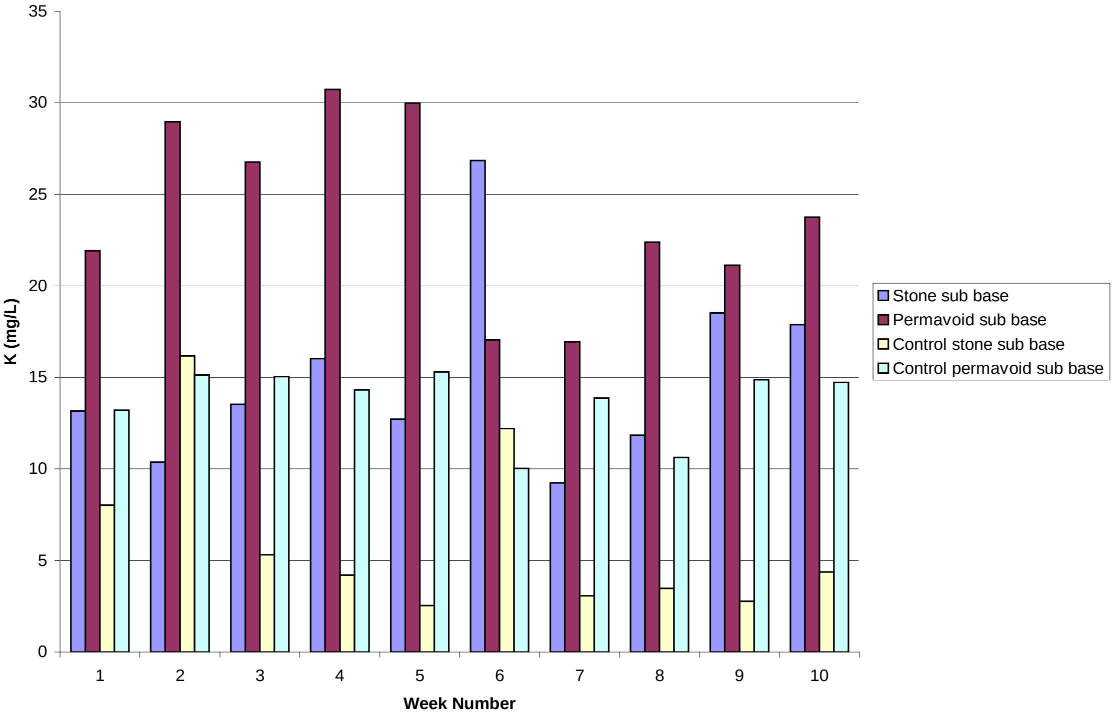

Figure 4.18 Potassium in Water from Test Models

a credible source of potassium. The author suggests that the reason for relatively low potassium in water from stone based systems could be that potassium released from the upper layers of the test rig was re-absorbed by the stone sub-base layer. However, this suggestion requires verification to be made through further studies with more replication to provide more information as regards to this observation.

Furthermore, the concentration of potassium between 6.1 – 10.0 mg/L is regarded as high, while concentrations > 10 mg/L are classified as very high (Spectrum Inc. 2008a,b) as shown in Table 3.2 (page 35). However, Vallentin (2006), proposed the concentration limit of < 80 mg/L for potassium in irrigation water. The levels of potassium observed in the water from all the test models for the study period of 10 weeks are below this limit and hence will be a credible source of the essential element (potassium) to the crops if used as irrigation fluid without posing a toxicity hazard. This result is in agreement with the observation that the potential of harnessing inorganic nutrients which could serve as a source of fertilizer exits in recycled water (Heidarpour *et al.* 2007). However, the question is: How long will the supplies of potassium from the pervious pavement system last? Potassium is an essential element and reduction in the supply of this element may have serious effects on the growth and development of the plants. Therefore, the author suggests that the continued monitoring of the level of the elements and in the case of K, alternative source of K could be applied to the plants in order to meet the K need of the plants if the need arises.

Potassium Absorption Ratio (PAR) was considered as a more viable measurement of potassium in water especially where nutrient leaching through soil media (or systems such as the pervious pavement) is being considered. PAR is discussed below.

4.4.1.23 *Potassium Absorption Ratio (PAR)*

Many soils have a high affinity for potassium even higher than for sodium, calcium and magnesium (Oster 2008). Levy and Torrento (1995) reported a particular soils high affinity of potassium ten times more than the soils affinity for sodium. The mobility of potassium in the underground water is governed by the cation-exchange which usually occurs on the clay matrix (Griffioen, 2001). It is possible that the re-use of urban wastewater could lead to higher levels of exchangeable potassium in the soil (Oster 2008) especially when water softening was carried out as this could increase the potassium and decrease the sodium levels in wastewater (Avnimelech *et al.* 1992 as cited by Oster 2008). Furthermore, increases in the concentration of potassium have been reported in areas where land is used for agricultural purposes due to nutrient leaching (Griffioen 2001). It was also reported that the effects of exchangeable potassium percentage of 20-30 improved the hydraulic conductivity of two Israeli soils, but had a negative effect on the 3rd soil (Chen *et al.* 1983). Levy and Torrento (1995); and Levy and Feigenbaum (1996) observed that for a given SAR, an increase in PAR resulted in a decrease of exchangeable sodium.

However, it was also recognized that an increase in the concentration of K (sometimes temporarily) maybe caused by desorption due to infiltration of hard water (Griffioen 2001). This observation was also supported by Oster (2008). Hence, it is clear from above, that both leaching (from nutrients) and desorption (inflow of hard water) are responsible for increases in the concentration of K in groundwater. However, despite the fact that both phenomena may lead to increases in the concentration of K, the PAR only increases in the case of nutrient leaching and decreases in the case of desorption (Griffioen 2001). Consequently, the author concluded that PAR is a more suitable parameter for measuring potassium in groundwater and, hence water from systems such as the pervious pavement than only looking at the potassium concentration.

Hence it is considered necessary in this work to look at what might be the fate of nutrient potassium in the pervious pavement system if increased nutrients containing NPK are added and recycled water from the system is stored and; used for irrigation using the PAR (which was determined by Equation 4.6).

$$\text{PAR} = {K^{+}(meq/L)} \Big/ \sqrt{\frac{(Ca^{+} + Mg^{2+})(meq/L)}{2}} \qquad \textit{Equation 4.6}$$

(Oster, 2008; Griffioen, 2001; Sarah, 2004)

The concentrations of cations in miliequivalent per liter (meq/L) in the water from different models of the pervious pavement system used in this study are presented in Tables 4.6, 4.7 and 4.8.

Figure 4.19 shows the PAR of water from the test models. There is a clear indication of different processes in the models especially between the stone and Permavoid based systems. It can be suggested that the points at which PAR increases suggests, there was a release of K from Osmocote or /and the stone aggregates. The K was subsequently leached from the surface of the pervious pavement models to the stored water in systems where oil was nutrients were applied.

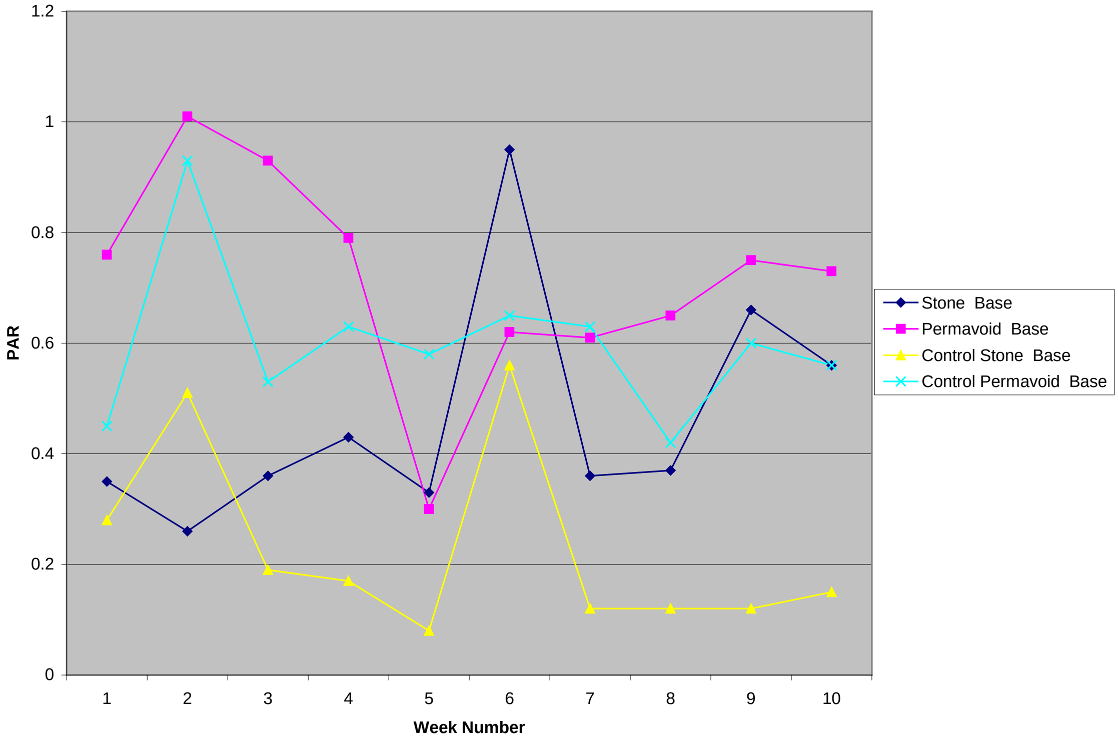

Figure 4.19 Potassium Absorption Ratio (PAR) in Water from Test Models

Higher levels of PAR in the Permavoid systems could be as a result of the pronounced voids in the plastic sub base which makes it easier for K to leach into the stored water than in the case of the stone sub base where the voids between the stones are less than in the plastics. This situation was also noticed in the controls where the PAR of the control plastic was even higher than that of the stone models dosed with oil and nutrients (as shown in Figure 4.19 above). The source of K could be attributed to the bedding layer which is made up of stone aggregates. Since the bedding layer was present in all the test models, the author suggested that the leached K from the bedding layer in the control Permavoid system was getting to the stored water faster and easier than the total of K from the fertilizer added and the bedding layer in the stone based systems (in the case of the models dosed with oil and nutrients).

4.4.2 *Nitrate and Nitrite (NO_3 + NO_2) in Water*

Nitrogen usually occurs in the form of nitrate (NO_3^-) in water although; it may also exist as nitrite (NO_2^-), ammonium (NH_4^+), nitrous oxide (N_2O) and organic nitrogen. Chemical and biological processes control the form, behaviour and concentration of nitrogen; that forms the nitrogen cycle (NERC, 2003). The speciation of nitrogen in aqueous systems is governed by redox reactions; hence in aerobic aqueous environments (such as in the test rigs used in this experiment), nitrogen occurs in the forms of nitrate and nitrite (NERC 2003).

The result of analysis of nitrate and nitrite in the water from the test rigs is presented below in Figure 4.20. The range of the concentration of NO_3+NO_2 for 10 weeks of the study was 15.53 - 52.15 mg/L, 17.99 – 62.58 mg/L, 1.72 – 9.8 mg/L and 0.16 – 0.83 mg/L for water from the stone sub base, Permavoid sub base, control stone sub base and control Permavoid sub base respectively. The average concentrations are as follows in descending order:

37.43 mg/L > 33.06 mg/L > 3.41 mg/L > 0.53 mg/L
Permavoid base > Stone base > Control stone base > Control Permavoid base

The highest concentration of 62.58 mg/l was observed in the water from the Permavoid sub base test rig at the 4th week of the experiment. It is obvious that there is difference between the concentration of NO_3+NO_2 in the water from the stone sub base and that of the control stone base systems as well as that of the Permavoid sub base and the control Permavoid sub base systems However, there is relative similarity between the concentration of NO_3+NO_2 in water from the stone and the Permavoid base system. It is obvious that the test rigs that were dosed with NPK to enhance biodegradation produced waters with higher concentrations of NO_3+NO_2 than the test rigs that were not.

The average concentration of nitrate in wastewater ranges from 0-30mgN-NO_3/L (Lazarova. and Asano 2005). Stark *et al.* (1983) recommended the maximum concentration of nitrogen for continuous fertigation of tomatoes using surface drip irrigation system as 75 mg/L. However, Badr and AbouEl-Yazied (2007) observed that the yield of tomato was significantly affected by the rate of application of N in fertigation, method and the frequency of application. Also, Lazarova and Asano (2005) concluded that the concentration of 30 mg/L of total N applied regularly to plants may lead to development problems and yield losses during flowering and fruiting stages.

Earlier work by Bond (1999) on the porous pavement system indicated that the release of inorganic nutrients from the rigs would be minimal other than after just after the first application of the fertilizer. Hence, this leads to the consideration that whilst these waters would be suitable for plant irrigation and release through infiltration where soil attenuation mechanisms would be in operation (and the effects would be little different from using the fertilizer in horticultural applications directly to soil), the release of effluent from pavements fertilized to give enhanced rates of biodegradation into a watercourse may cause eutrophication.

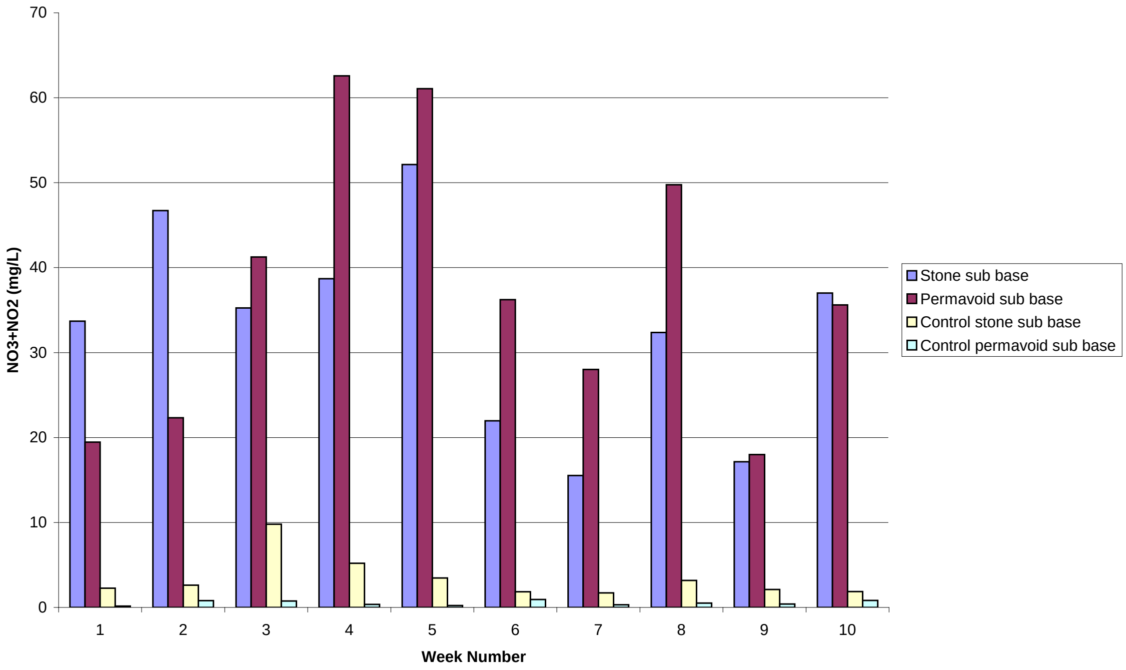

Figure 4.20 Nitrate and Nitrite in Water from Test Models

This illustrates perhaps that the use of normal slow release fertilizers should not be encouraged in systems where the stormwater is collected in a subsurface tank for release to the surface water network of a surface drainage system (Nnadi, Newman and Puehmeier 2008). In such circumstances, two approaches would seem to offer a solution. The first of these is the very slow release system reported by Spicer *et al.* (2006), but this system is not available commercially yet. The second might be to use a system capable of holding greater amounts of oil before saturation (Nnadi, Newman and Puehmeier 2008).

Earlier Work within the porous pavement research group has shown (Puehmeier *et al.* 2005, Puehmeier 2008) that even without enhancing the biofilm with outside supply of fertilizer; microbial activity (as measured by ATP determinations) is still present. Thus perhaps the key would be to hold the oil in the system long enough for natural attenuation process to take place, indicating perhaps a need for a geotextile with very high oil retention capacity (Nnadi, Newman and Puehmeier 2008). Thus, negating the need to encourage rapid biodegradation.

4.4.3 *pH of Water Stored in the Pervious Pavement System*

pH is one of the important physicochemical parameters that determine the availability of essential nutrients for absorption by plants (Almeida *et al.* 2007, Dysko, Kaniszewski and Kowalczyk 2008). The pH range is logarithm and measures the relative acidity and alkalinity of the water. The scale ranges from 0 – 14, with 0 – 6.9 (acidic), 7.1 – 14 (alkaline) and 7 (neutral).

The pH of water from the system is presented in Figure 4.21 below. The pH range is as follows: Stone sub base: 6.58 – 7.98, Permavoid Sub base: 6.29 – 8.26, Control stone sub base: 6.29 – 8.23, Control Permavoid sub base: 6.67- 8.33.

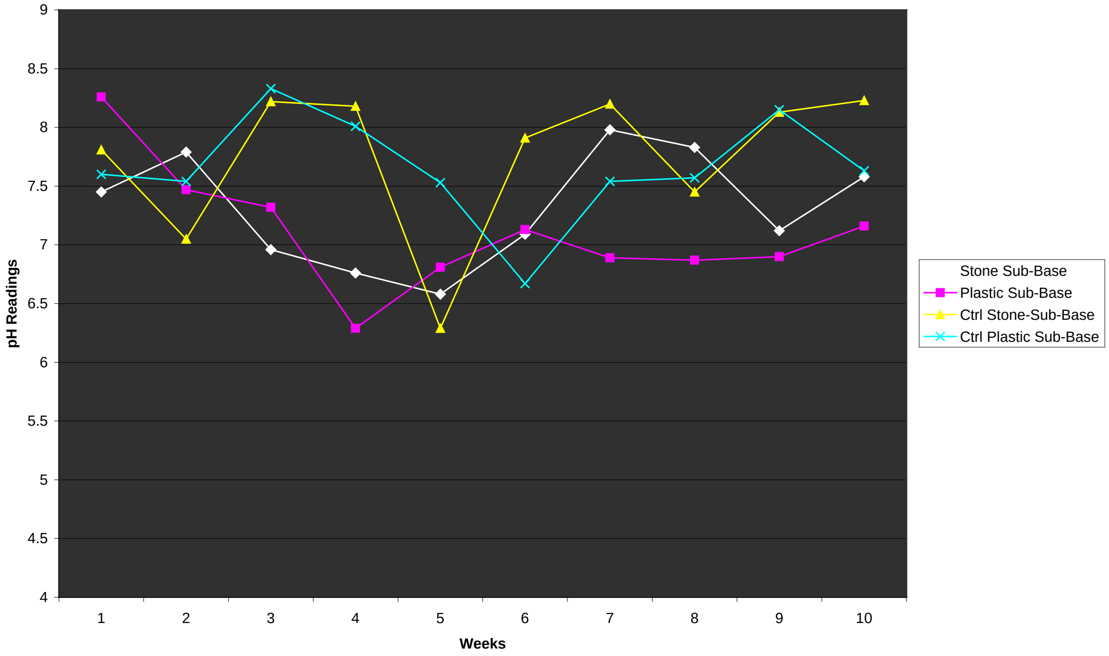

Figure 4.21 pH of Irrigation Water from the Test Models

The FAO (2008), recommended the pH range of 6.5 – 8.0. According to (Bauder, Waskom, and Davis 2008) and Harivandi (2008), the normal range for pH of irrigation water is 6.5 - 8.4. Peterson, (1999) recommended a pH range of 6.0 – 8.5 as appropriate pH for irrigation water, while Wu, Guo and Brown (2000), reported the successful use of reclaimed water of pH of 8.0 for irrigation of landscape plants. This shows that the pH of the waters from the test models is within the range of recommended range of 6.0 – 8.5. However, if pH reduction is required, it could conveniently achieved by the addition of gypsum (Nnadi, Newman and Puehmeier 2008), which would add sulphur to the system.

4.4.4 *Electrical Conductivity of Water Stored in Pervious Pavement System (ECw)*

Electrical Conductivity of water (ECw) is sometimes referred to as specific conductance or salinity of irrigation water is an indirect measure of ions or charged particles present in the water by an electrode (Bauder, Waskom, and Davis 2008). The Electrical Conductivity of water from the test rigs is presented below in Figure 4.22. The average Electrical Conductivity of water from the test rigs in descending order is as follows:

341.40 µS/cm > 293.97 µS/cm > 253.10 µS/cm > 242.50 µS/cm
Plastic Base > Stone Base > Control Stone Base > Control Plastic Base

The classification of irrigation water based on electrical conductivity is presented in Table 4.11 below

Table 4.11 Classification of Irrigation Water Based on Electrical Conductivity

Bauder, Waskom, and Davis 2008

The range of the average EC_w of water from the test rigs is 242.50 – 341 µS/cm throughout the duration of the experiment. This within the region of ‘excellent’ and ‘good’ based on the classification shown on Table 4.11 above. It is obvious from the average EC_w result presented above that the test models dosed with oil and nutrient generated stored water with good electrical conductivity for irrigation purposes despite the high oil and nutrient loadings to simulate worst case scenario.

In temperate regions, one would have to take into account de-icing salts in winter and in coastal communities, “wind blown” salts would also be considered.

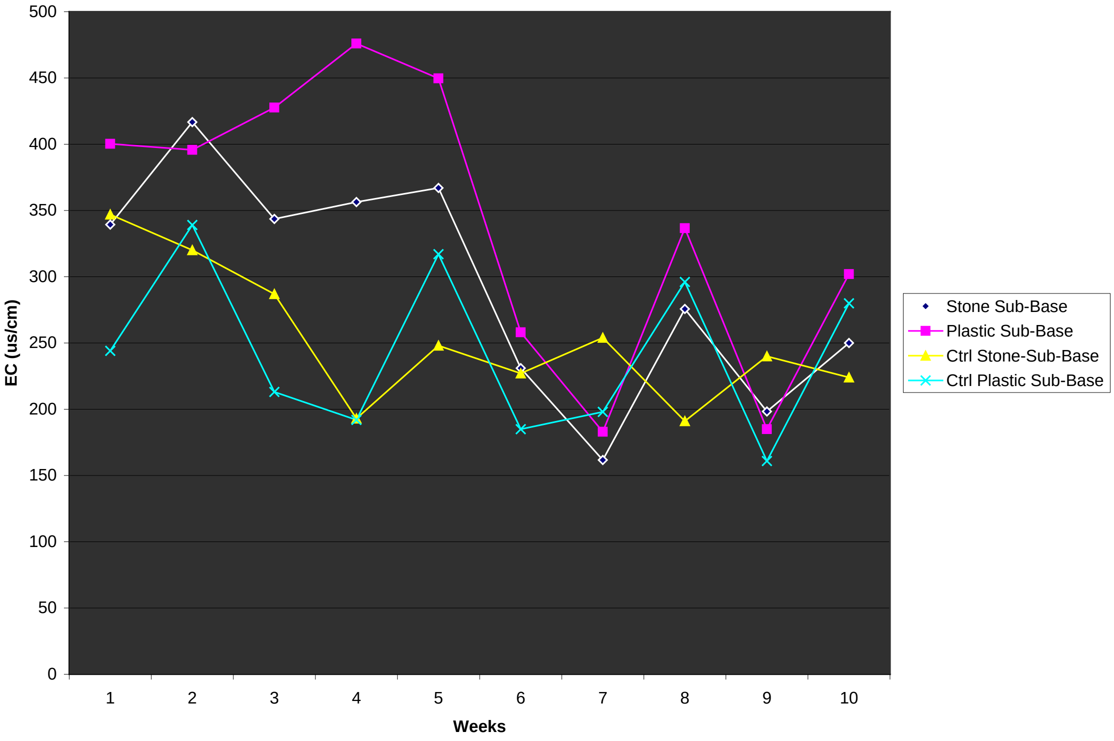

Figure 4.22 Electric Conductivity of Water from Test Models (ECw)

Relationship between Electrical Conductivity of water (ECw) and other parameters such as Sodium Absorption Ratio (SAR) (deHayr and Gordon 2006); Potential Hydrogen (pH) (Shu *et al.* 2001); Leaching Fraction (LF) (Hill and Koenig 1999, A&M University Texas (2008), Spectrum Analytic Inc. 2008b); Electrical Conductivity of soil at the root zone (EC_i) (deHayr and Gordon 2006) and Crop Yield (deHayr and Gordon 2006, Bauder, Waskom, and Davis 2008) have been recognized by many researchers. In view of the aim of this study two of these relationships are discussed below.

4.4.5 *Relationship between Electrical Conductivity (EC_w) and Total Dissolved Solids (TDS)*

TDS can be derived from EC_w. An increase in EC_w results in a corresponding increase in TDS values. The unit of TDS is miligramme per litre (mg/L) or miliequivalent units per litre (meq/L) or parts per million (ppm) and it is often defined as total salinity (A&M University Texas 2008). TDS is a direct determination of dissolved ions in water (Bauder, Waskom, and Davis 2008). The Total dissolved solids (TDS) in water from the test rigs were determined from the Electrical Conductivity values (EC_w) by Equations 4.7 and 4.8 below:

TDS (mg/L) = 640EC_w iff EC_w < 5 dS/m *Equation 4.7*

TDS (mg/L) = 800ECw iff ECw > 5 dS/m (1dS/m = 1000μS/cm) *Equation 4.8*

(Bauder, Waskom, and Davis 2008).

The average TDS values in descending order are as follows:

219.52 > 88.80 > 161.92 > 155.52
Permavoid Base > Stone Base > Control Stone Base > Control Permavoid Base

According to Peterson (1999), the normal range of TDS in irrigation water is 0 – 2000 mg/L. Table 4.12 below shows the classification of TDS ranges in irrigation water. The TDS of water from all the test models is within the range of 'none degree of restriction of use' for irrigation as shown in Table 4.12 below.

Hence, the TDS of the waters are within the range of normal irrigation water.

Table 4.12 Classification of Total Dissolved Solids (TDS) of Irrigation Water

FAO (1985) cited in FAO (2008).

4.4.6 *Relationship between Electric Conductivity (ECw) and Sodium Absorption Ratio (SAR)*

deHayr and Gordon (2006), presented a chart which indicate how the relationship between Electrical Conductivity (ECw) (deHayr and Gordon 2006) (designated as EC_i in Figures 4.23 and 4.24) and SAR of water can be used to predict the possibility of soil structure problems if the water is used for irrigation. This chart is shown in Figure 4.23 below. If the water quality (EC_w and SAR relationship) falls within the solid line, it is considered suitable for use for irrigation as it would not pose a problem to soil structure. However, quality that falls outside the solid line but within the dotted lines and within the green region indicate that the water should be used with caution and considerations made of the soil characteristics before used for irrigation. Furthermore, water quality outside the two lines is considered unsuitable for use for irrigation.

The determination of the suitability of the water from the test models for irrigation using the dehayr and Gordon’s (2006) chart described above is presented in Figure 4.24 below.

The average values of EC and SAR of water from the test rigs and their potential effects on soil structure are (SAR and EC of water are presented in pages 113 and 147 respectively) shown in Table 4.13 (page 153)

Figure 4.23 EC, SAR and Soil Structure (deHayr and Gordon 2006)

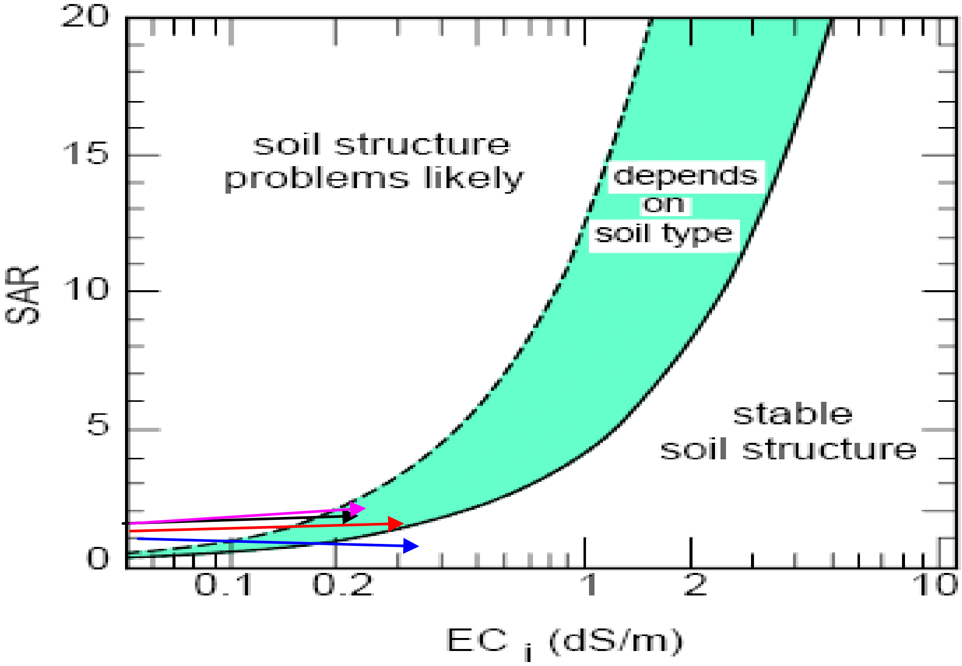

Figure 4.24 Effects of EC and SAR of Water from Test Models on Soil Structure

Table 4.13 Potential Effects of Average EC and SAR of Water from Test Models on Soil Structure

	Stone Base	Permavoid Base	Control Stone Base	Control Permavoid Base
SAR	1.3	1.09	1.64	1.75
EC	0.3	0.34	0.23	0.24
Arrow Colour (Chart)	Red	Blue	Black	Orange
Soil Structure	Stable	Stable	Depends on soil Type	Depends on Soil Type

It can be deduced from the chart in Figure 4.24 and Table 4.13 that the waters from the stone and Permavoid Sub bases would not pose a problem to soil structure and are suitable for irrigation on all types of soil without additional water management processes. It is necessary to highlight that this water quality was achieved despite high cumulative oil loadings and nutrient addition to replicate worst case scenario. However the waters from the control test models which were not treated with oil and nutrient would require consideration of soil characteristics to see if management is required before application as irrigation fluid due to the relatively low nutrient content of waters of these systems as shown in Table 4.13.

4.4.7 *Total Petroleum Hydrocarbon (TPH)*

The results of analysis of Total Petroleum Hydrocarbon (TPH) in the water from the test models is presented in Figure 4.25 below

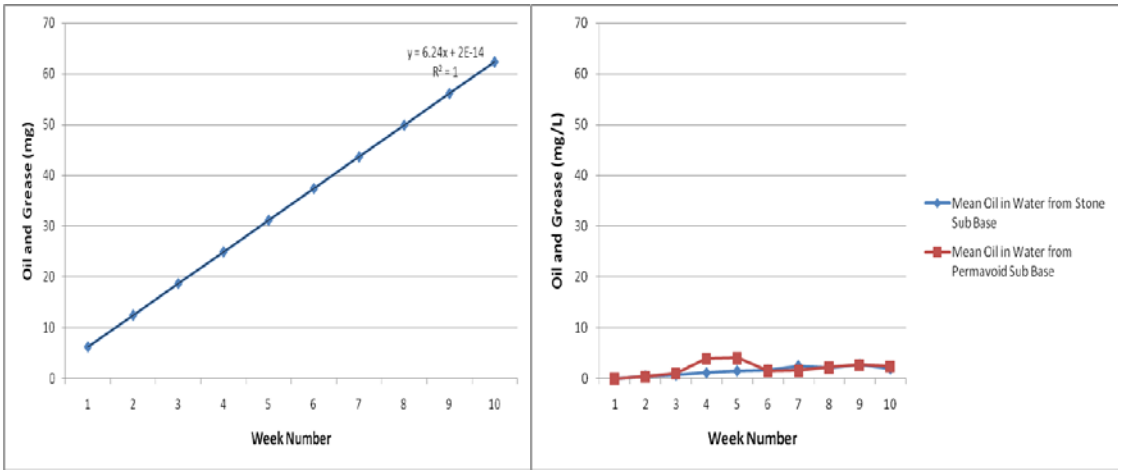

Figure 4.25 Oil Addition to and Recovery from Stone and Permavoid Test Models

The chart shows that despite high cumulative weekly oil addition to the models to simulate worst case scenario, high removal rate of hydrocarbons was achieved by both the stone and Permavoid based systems.

The mean efficiency to retain oil of 95.59% and 94.16% was observed in the stone and Permavoid based systems respectively. Out of 343.20 g/m^2 of oil added in 10 weeks to the test models, a mean of 15.13g and 20.03g were recovered in water from the stone and Permavoid sub base systems respectively.

4.4.7.1 *Calculation of Oil Retention Efficiency*

Mass of oil applied in 10 weeks = 343.20g/m^2

Oil recovered from Stone sub base system = 15.13g

Oil retained in Stone sub base system = (343.20 – 15.13)g = 328.07g

Therefore, oil retention efficiency = (328.07/343.20) ×100 = 95.59%

Similarly, Oil recovered from Permavoid sub base system = 20.03g

Oil retained in Permavoid sub base system = (343.20 – 20.03)g = 323.17g

Therefore, oil retention efficiency = (323.17/343.20) ×100 = 94.16%

This further highlights the high rate of efficiency of removal of pollutants by the system which was reported by earlier researchers (Bond 1999, Coupe 2004, Newman *et al.* 2002). Coupe (2004) observed that efficiency of the PPS to retain mineral oil was 99.49% in non-inoculated models. However, Coupe (2004) applied less mineral oil (92.05g) over a longer period of 61 weeks. It could be suggested that the reduction in the level of hydrocarbon reaching the stored water in the system towards the end of this study despite increased cumulative loading from week 8 was as a result of establishment of biofilm by microbial communities in the geotextile.

Brownstein (1998) and Bond (1999) had earlier explained how the hydraulic and chemical properties of the geotextile under simulated rainfall traps hydrocarbons carried by water on the surface of the geotextile. Coupe (2004) highlighted the importance of the biological process of biodegradation of the accumulated oil by micro organisms which utilize the oil as a nutrient source in the maintenance of the system. However, it can be suggested based on the result shown in Figure 4.25 that the establishment of a viable microbial community in the system is essential for the enhancement of the ‘hydrocarbon trapping’ efficiency of the geotextile upon which the efficiency of the PPS is based. Coupe (2004) in support of this, observed that even partial removal of the trapped oil on the surface of the geotextile could alter the oil removal efficiency of the pervious pavement system.

Summarily, the result of experiments reported in this chapter indicated that the

- Waters stored in the pervious pavement system met the chemical and electrochemical requirements for use for agricultural irrigation. However, the author recognizes the limitations of this study which was that road dust was not applied and clean oil was used to simulate hydrocarbon pollution in the field (see Chapter 8).

The experiments reported in the next chapter takes the above conclusion even further, and practically demonstrated the use of these waters in pot trials to grow plants in the green house. Chemical analysis would show that the edible parts of one of the plants grown with waters stored in the pervious pavement system were good enough for human and animal consumption.

Chapter 5: Effects of Stored Water in the Pervious Pavement Used For Irrigation on Plant Growth and Development

5.1 Introduction

The work reported in this chapter represents an extension of the work on the chemical qualities of stored water reported in Chapters 3 and 4. These chapters concentrated largely on the parameters which would be most relevant to the use of the stored water as irrigation water. The work reported here now takes the experimental work further looking at the effects on growing plants in two randomized block design experiments with waters stored in the pervious pavement system.

Both experiments involved cultivation of plants for 10 weeks in the greenhouse of Coventry University. These experiments were designed to provide data on the practical use of water stored in this manner for irrigation. Chemical analysis was carried out to provide information on the level of heavy metals in soil and plant as well as the suitability of this irrigation strategy for cultivation of edible crops. Finally, a comparison analysis between the edible crop products cultivated with water from the pervious pavement system and similar crop product sold in the market was carried out in order to establish whether the plants cultivated with water stored in the pervious pavement system was fit for human consumption.

5.2 Methodology

This section covers the methodology used for this experiment and is reported under two main parts namely: tomato and ryegrass experiments.

5.2.1 *Plant Selection*

Two (2) types of plants were selected for the greenhouse experiments representing both landscaping (ryegrass) and horticultural (tomato) applications of irrigation water from the pervious pavement system.

The test plant species were tomato *(Lycopersicon esculentum* (Fantasio F1 hybrid*))* and ryegrass (*Lolium perenne* L.cv Profit).

5.2.1.1 ***Lycopersicon esculentum (***Fantasio F1 hybrid***)***

The tomato variety used for this experiment was the Fantasio F1 hybrid from Suttons UK. This variety is ideal for both outdoor and greenhouse growing. It is a variety which produces rounded fruits of up to 200g in weight per plant (Suttons UK 2008). It also has a good blight tolerance which helps to ensure that the leaves remain green and healthy which enhances effective food production. The F1 variety is also know for being resistant to tobacco mosaic virus, verticilium, fusarium wilts and nematodes. These qualities made the Fantasio F1 hybrid ideal for this experiment as a representative for horticultural application of irrigation water from the pervious pavement system.

5.2.1.2 ***Lolium perenne L.cv profit***

Perennial ryegrass (*Lolium perenne*) is grass from the family Poaceae and widely grown around the world. *Lolium perenne* is one of the quickest grasses to cultivate from seed with seed germination occurring within 5-8 days after sowing in favourable conditions (Richardson and McCalla 2007). Germination usually occurs near the soil/compost surface. It is a low growing grass with green leaves cultivated as a pastural and forage plant. It is also used for lawns and sports pitches because of its ability to resist wear, survive extreme climatic conditions, adapt to wide variety of soils and regenerate quickly. These qualities make *Lolium perenne* ideal representative for landscaping use irrigation water. The perennial ryegrass seeds used in this experiment were obtained from Rolawn Ltd, York, UK.

5. 2.2 *Tomato Experiments*

A total of thirty-six (36) plastic plant pots (120mm high, 14mm diameter) were filled with 200g of John Innes seed compost. The filled pots were placed on saucers and were arranged in a randomized block design as shown in figure 5.1 the pots were maintained in an unheated green house with a temperature of 19-22 degrees Celsius in Coventry University with a daylight and supplementary light from 400W high pressure sodium Son/T lamps providing a minimum of 16hour photoperiod and a photon flux of 180-210µmol $m^{-1}s^{-1}$ at bench level. Each pot was planted with two (2) tomato seeds (*Lycopersicon esculentum* Fantasio F1 hybrid). Three (3) pots were assigned to each of the models and four (4) pots were designated for watering with de-ionised (DI) water.

The pots were watered to saturation on each occasion with water from the experimental rigs using a watering can fitted with rose shower head, with a watering can allocated specifically for each of the test rigs. The watering of pots using with water from the test rigs was carried out three (3) times per week and at other times, de-ionised (DI) water was applied to the pots representing times of abundance of rainwater for the plants and hence, irrigation was not required. Conversely, other pots received de-ionised (DI) water at the same time throughout the experiment. Any leachate was retained in the saucers after watering on each occasion.

Table 5.1 Randomized Block for Tomato Irrigation Experiments

TOMATO *(Lycopersicon esculentum (*Fantasio F1 hybrid*))*

Permavoid Sub-Base 16 Pots Block 3

ROW 1	B1	CB	B3	B2
ROW 2	CB	B3	B1	B2
ROW 3	CB	B1	B3	B2
ROW 4	B3	B2	CB	B1

Stone Sub-Base 16 pots Block 4

ROW 1	A1	CA	A3	A2
ROW 2	CA	A3	A1	A2
ROW 3	CA	A1	A3	A2
ROW 4	A3	A2	CA	A1

Di-ionised Water Row for Tomato DI Block

ROW 1	DI1	DI2	DI3	DI4

TOTAL NO. OF POTS FOR TOMATO = 36.
NOTE: BLOCKS 3, 4 & DI WERE TOGETHER IN PRACTICE FORMING ROWS 1-9

Where,
A1, A2, A3 = Stone Sub base replicates
B1, B2, B3 = Permavoid (plastic) Sub base replicates
CA = Control Stone Sub base
CB = Control Permavoid Sub base

Figure 5.1 Layout of Plants in Randomized Block Design in the Greenhouse

As indicated above, each model had three (3) replicates assigned to it. 100% germination was achieved after 7 days and after 4 weeks, the weakest seedling in each pot was removed. The plants were inspected daily, except for most Sundays, with the first detectable flowering and fruiting dates recorded for each plant. Where necessary, bamboo canes were used to support the growing plants. After 70 days, when the first plants had reached a height of around 1meter, the above-soil parts of the plants were harvested by cutting with a pair of scissors and the fruits were hand plucked. The fruits were not allowed to ripen and clearly considerably more fruit would have been produced had the growth been allowed to continue.

The fresh (wet) weights of the stems, leaves and fruit were recorded separately during the day of harvest. These plant materials were then dried in a forced-air oven at 80°C for 3 days after which dry weights were also recorded.

Figures 5.2, 5.3 and 5.4 shows the tomato plants 2 weeks, 4 weeks and 10 weeks after planting.

Figure 5.2 Tomato (Fantasio F1 hybrid) 2 Weeks Post Planting

Figure 5.3 Tomato (Fantasio F1 hybrid) 1 Month Post Planting

Figure 5.4 Tomato (Fantasio F1 hybrid) 10 Weeks Post Planting

5.2.3 *Ryegrass Experiments*

The ryegrass experiment was also carried out using three (3) pots per model and four (4) pots for de-ionised (DI) water (identical to tomato experiment). A total of 36 pots were sown with 0.5g of ryegrass (*Lolium perenne*) seed into the same compost as was used in the tomato experiment. An identical randomized block design to the tomato experiment was adopted for the ryegrass and the outline is shown in Table 5.2 below. The same watering regime was used as in the tomato experiment. In this experiment, the ryegrass was harvested at 55 days and 93 days by cutting with scissors at 2cm above the compost surface which allowed the grass to re-grow. Wet and dry weights were determined after harvest. No formal germination rate was determined, but there seemed to be little difference in initial sward production between plots.

Figures 5.5, 5.6 and 5.7 show the ryegrass 4 weeks after planting; 1 day after 1st harvesting and 2 weeks after 1st harvesting respectively.

Figure 5.5 Ryegrass 4 Weeks Post Planting

Table 5.2 Randomized Block Design for Ryegrass Experiment

Ryegrass
Permavoid Sub-Base 16 Pots Block 1

ROW 1	B1	CB	B3	B2
ROW 2	CB	B3	B1	B2
ROW 3	CB	B1	B3	B2
ROW 4	B3	B2	CB	B1

Stone Sub-Base 16 Pots Block 2

ROW 1	A1	CA	A3	A2
ROW 2	CA	A3	A1	A2
ROW 3	CA	A1	A3	A2
ROW 4	A3	A2	CA	A1

Di-ionised Water Row for Ryegrass DI Block

ROW 1	DI1	DI2	DI3	DI4

TOTAL NO. OF POTS FOR RYEGRASS = 36.
NOTE: BLOCKS 1, 2 & DI WERE TOGETHER IN PRACTICE FORMING ROWS 1-9

Where,
A1, A2, A3 = Stone Sub base replicates
B1, B2, B3 = Permavoid (plastic) Sub base replicates
CA = Control Stone Sub base
CB = Control Permavoid Sub base

Figure 5.6 Ryegrass 1Day after 1st Harvest Showing Rapid Re-growth

Figure 5.7 Ryegrass 14 Days after 1st Harvest Showing Re-growth

5.2.4 *Heavy Metal Analysis of Plant Parts*

Analysis for the following metals shown in Table 5.3 was carried out on the harvested and dried parts of the plants (tomato and ryegrass). The method used for these analyses is discussed in detail below.

Table 5.3 Heavy Metals Analyzed in Plant Parts and Soil

Metals	Wavelength
Cadmium (Cd)	214.440nm
Copper (Cu)	324.752nm
Iron (Fe)	238.204nm
Nickel (Ni)	231.604nm
Lead (Pb)	217.000nm
Zinc (Zn)	213.857nm

5.2.5 *Plant Parts Preparation for Metal Analysis - Tomato*

The harvested tomato plant parts (stem, leaves and fruits) were cut into pieces of less than 2cm with a laboratory stainless knife and placed in paper bags labeled according to the set up of the planting pots in randomized block design (as shown in Table 5.1 above) .These plant parts were then dried in a forced-air oven at 80°C for 3days after which they were homogenized according to irrigation water treatments as follows:

Stone sub base (A1-A3); Plastic sub base (B1-B3); Control Stone sub base (CA); Control Plastic sub base (CB) and De-ionized water (DI)

(Please see the randomized block design arrangement on Table 5.1).

The homogenized samples were ground to powder separately in a laboratory ceramic mortar using a laboratory ceramic pestle. Care was taken to avoid cross contamination of the samples during preparation. Each ground sample was then put in a paper bag which was carefully sealed and labeled for analysis.

5.2.6 *Plant Parts Preparation for Metal Analysis – Ryegrass*

The harvested ryegrass (1st and 2nd harvest) was kept separate from each other, placed in paper bag, labeled and dried in a forced air oven at 80°C for 3 days. The dried plant parts were homogenized as in the tomato samples (see page 169 above), crushed with a lab mortar and pestle avoiding cross contamination in the process. Each ground sample was then put in a paper bag which was carefully sealed and labeled for analysis.

5.2.7 *Acid Digestion of Plant Parts (Tomato and Ryegrass): Wet Dissolution Method*

- 1 g (+/-0.0001g) of each sample was weighed out in a measuring boat using the weighing balance (Sartorius BP110S supplied by Sartorius AG Germany) and transferred to Pyrex digestion glass tubes (1 tube per sample) which was appropriately labeled
- 3 Spikes were prepared by using micro pipette to measure out 0.1ml of Cu, Cd, Pb, Zn, Fe and Ni (for each spike) from 1000ppm analytical reagent standard (supplied by Fisher Scientific, UK) into 3 Pyrex digestion tubes (1 tube for each spike)

- 3ml of 70% analytical grade HNO_3 (supplied by Fisher Scientific, UK) was added to the digestion tubes using glass pipette. 2ml analytical grade H_2O_2 (supplied by Fisher Scientific, UK) was also added to each of the digestion tubes including the "spike tubes" with a glass pipette (HNO_3 : H_2O_2 ratio = 3ml:2ml) in a fume cupboard
- 3 Blanks were prepared by measuring out 3ml of 70% analytical grade HNO_3 (supplied by Fisher Scientific, UK) using glass pipette into 3 digestion tubes. 2ml analytical grade H_2O_2 (supplied by Fisher Scientific, UK) was also added to each of the 3 tubes in a fume cupboard to complete blank preparation (HNO_3 : H_2O_2 ratio = 3ml:2ml)
- Digestion tube condensers were place on each tube and the tubes were left in the fume cupboard overnight (method used by Huang *et al.* 2004)
- The following day, the tubes were electrically heated for approximately 7hrs in the fume cupboard at 130-140°C by inserting them into pots in the electric heater (supplied by Hoskin Scientific, Canada) until the brown fumes disappeared.
- The tubes were then allowed to cool and the contents were filtered with a 90mm Whatman filter paper Cat N0.1001090 (Whatman Intl. Maidston, England) through a glass funnel into a 100ml volumetric flask using de-ionized water to wash the tubes thoroughly into the tubes ensuring that each volumetric flask was made up to the mark for ICP-AES analysis

5.2.8 *ICP-AES Analysis*

Method of ICP –AES analysis of samples is as described in page 97 of this thesis.

5.2.9 *Analysis of Heavy Metals in Soil*

The soil was also analyzed for the heavy metals listed in Table 5.3 (page 169) before planting (of tomato and ryegrass) and at the end of the experiment. The method used for these analyses is presented below:

5.2.10 *Soil Preparation-Pre-Planting of Tomato and Ryegrass*

- 20g sample each was collected from three bags of John Innes seed compost used as soil in this pot trial experiment.
- The samples were mixed thoroughly in a tray, transferred into a paper bag, labeled and dried in the forced air oven (supplied by Hoskin Scientific, Canada) at 80°C for 3 days and passed through 2mm sieve
- The oven was then switched off in other for samples to cool for acid digestion

5.2.11 *Soil Preparation-Post-Planting of Tomato and Ryegrass*

- At the end of the pot trial experiment in the greenhouse, the soil content of the pots was homogenized keeping the tomato and rye-grass pots separately as follows: ***Stone sub base (A1-A3); Plastic sub base (B1-B3); Control Stone sub base (CA); Control Plastic sub base (CB) and De-ionized water (DI)***
- 20g from each homogenized sample was put into a paper bag, labeled and dried in a forced –air oven (supplied by Hoskin Scientific, Canada) at 80°C for three days and passed through 2mm sieve.
- The oven was then switched off in other for samples to cool for acid digestion

5.2.12 *Acid Digestion of Soil: Wet Dissolution Method*

The method of Acid digestion of the dried soil samples (pre and post harvesting) was same as that of the plant parts (as described above in page170)

5.2.13 *ICP-AES Analysis*

Method of ICP –AES analysis of samples is as described in page 97 of this thesis.

5.2.14 *pH of Soil*

- The weighing balance (Sartorius BP110S supplied by Sartorius AG Germany) was used to measure 15g (+/- 0.0001g) of each homogenized and dried soil sample into a 100ml conical flask.
- 15ml of distilled water was added to the flask containing the soil sample in a ratio of 1:1 (Buol *et al*, 2003; Walker and Lin, 2008)
- The resulting mixture (soil and water) in the flask was stirred with a spatula and the flask was then covered with a cork
- The flask was then mounted on an orbital shaker (supplied by Weiss Gallenkamp, UK) at 160rpm for 30minutes
- After shaking, the mixture was filtered using Whatman filter paper through a funnel into a clean 100ml conical flask
- Measurement of pH was by Corning M220 pH meter (supplied by Ciba Corning Diagnostics Ltd, Suffolk, England) and standardization was conducted against reference buffer solutions according to manufacturer’s manual, and the glass electrode was adequately solvated prior to measurement.
- The mean of three readings was recorded for each sample and it was ensured that the solution was manually shaken before each measurement

5.2.15 *Electrical Conductivity of Soil (EC_e)*

The method used for the measurement of Electric Conductivity (EC_e) of soil samples is same as that of pH except that in the case of Electric Conductivity (EC_e), measurement was conducted by Conductivity meter (PTI-8 digital conductivity meter, Scientific Industries Intl. Inc. UK).

5.3 Results and Discussion

The result obtained from the plant experiment is presented below in 4 sections namely: Soil analysis, growth parameter for tomato and ryegrass, analysis of tomato and ryegrass.

5.3.1 *Soil Analysis*

The results of analysis conducted on the soil pre-and post harvesting of tomato and ryegrass are presented below.

5.3.2 *Electrical Conductivity and pH of Soil- Tomato*

Electrical Conductivity (EC_e) and pH of soil on which tomato and ryegrass were planted (pre and post-harvesting) is shown below in Figures 5.8 and 5.9 while that of pH is

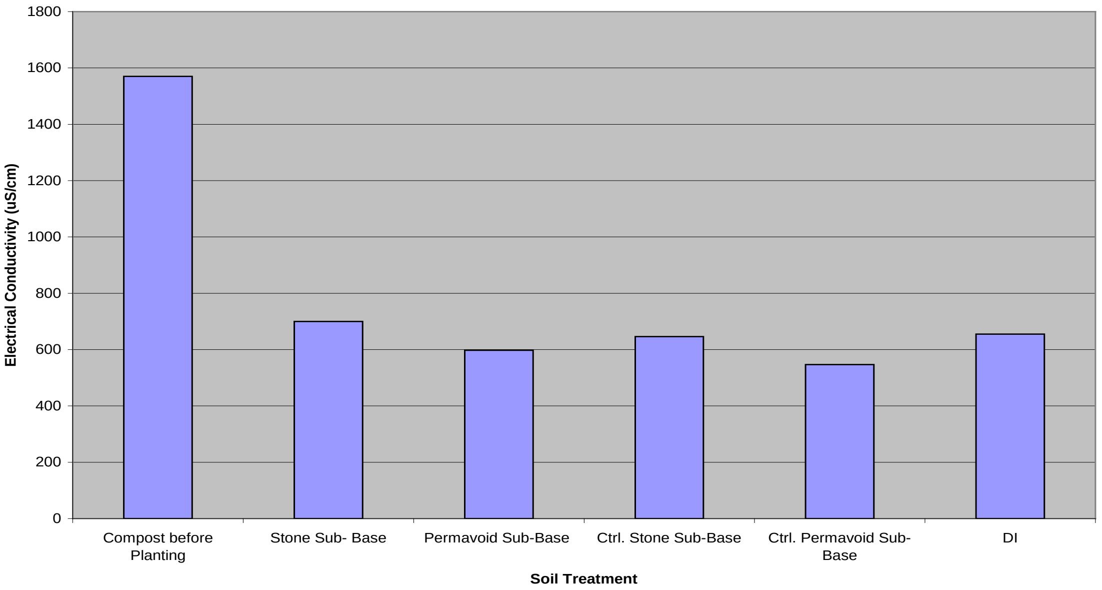

Figure 5.8 Electrical Conductivity of Soil Pre-Planting and Post-Planting of Tomato

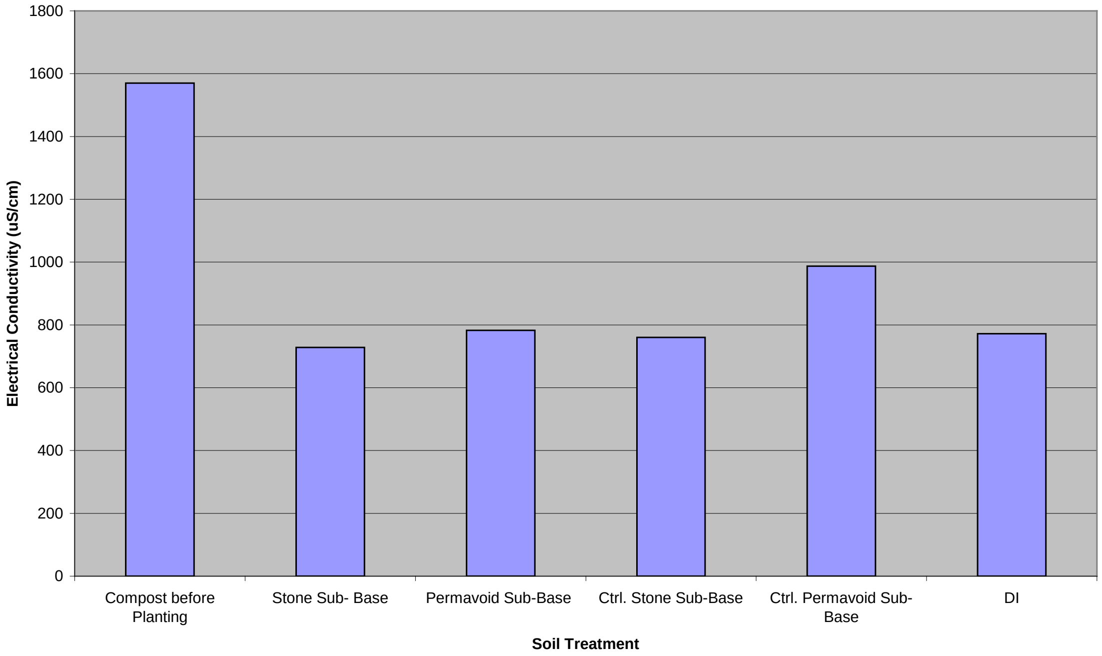

Figure 5.9 Electrical Conductivity of Soil Pre–Planting and Post-Planting of Ryegrass

presented in Figures 5.10 and 5.11. It can be seen from Figure 5.8 that the EC_e of the soil reduced from 1570µS/cm before planting of tomato to 700µS/cm in the soil irrigated with water from the Stone Sub-base test rig, 597.67µS/cm Permavoid Sub-base test rig, 646µS/cm Control Stone Sub-base test rig, 547µS/cm Control Permavoid Sub-base test rig and 655µS/cm De-ionized water after 10 weeks. Similarly, Figure 5.9 shows that the Ec_e also decreased in the case of ryegrass from 1570µS/cm pre-planting to 728µS/cm in the soil irrigated with water from the Stone Sub-base test rig, 728.67µS/cm Permavoid Sub-base test rig, 760µS/cm Control Stone Sub-base test rig, 987µS/cm Control Permavoid Sub-base test rig and 772µS/cm De-ionized water. This reduction in EC_e is not surprising considering that the tomato and ryegrass plants were expected to make use of some the available salts in the soil for growth and development. Also it was proposed that the reduction in EC_e could be partly attributed to leaching of some of the nutrients from the pots.

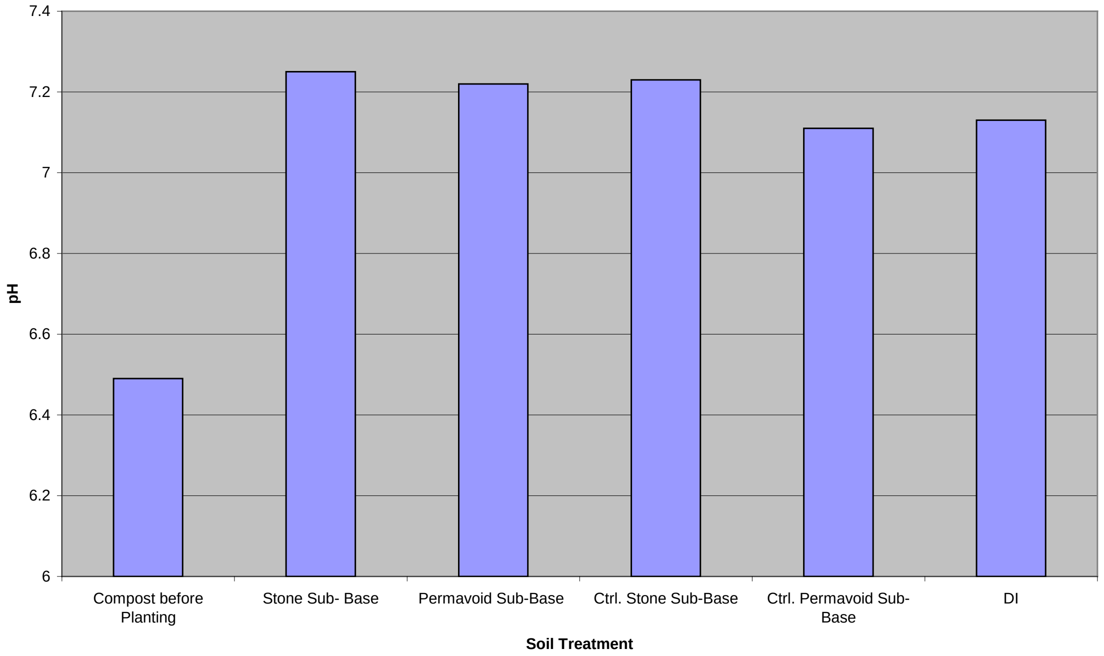

Figure 5.10 pH of Soil Pre –Planting and Post-Planting of Tomato

The soil pH increased from 6.49 pre-planting (slightly acidic) to the range of 7.11-7.25 and 7.25-7.40 (slightly alkaline) in the case of tomato and ryegrass in all the soil samples treated with irrigation water from different test rigs and de-ionized water as shown in Figure 5.10 and Fgure 5.11. This increased pH range is still within the normal pH range (6.5-8.0) for most soils for agriculture uses (Peacock 1998, Buol *et al.* 2003).

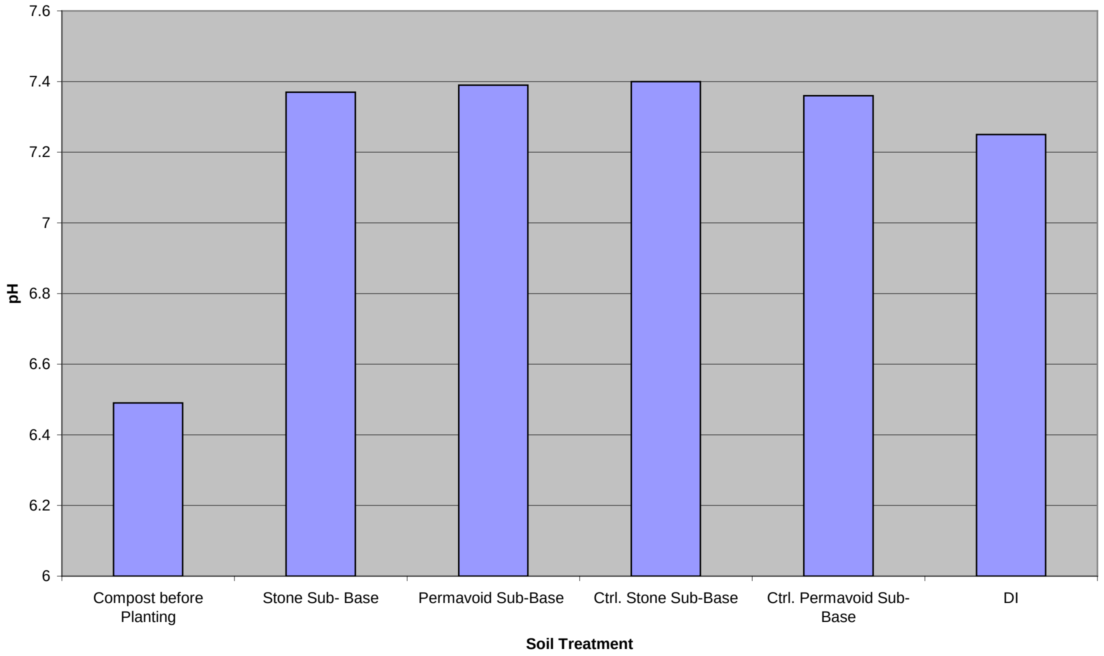

Figure 5.11 pH of Soil Pre-Planting and Post-Planting of Ryegrass

This result increase in pH is in agreement with results obtained by Al-Lahham, El Assi, and Fayyad (2007). These authors concluded that the application of wastewater as irrigation fluid will increase the soil pH especially post harvesting.

5.3.3 *Analysis of Metals in Soil*

The result of analysis of metals in the soil pre-and post-planting of tomato and ryegrass is presented below.

5.3.4 *Metals in Soil- Post- Planting of Tomato and Ryegrass*

The result of the analysis of heavy metals (Cd, Cu, Ni, Pb, Zn and Fe) in the soil sample used in the plant experiment before planting of tomato and ryegrass is presented in Figures 5.12 to 5.15.

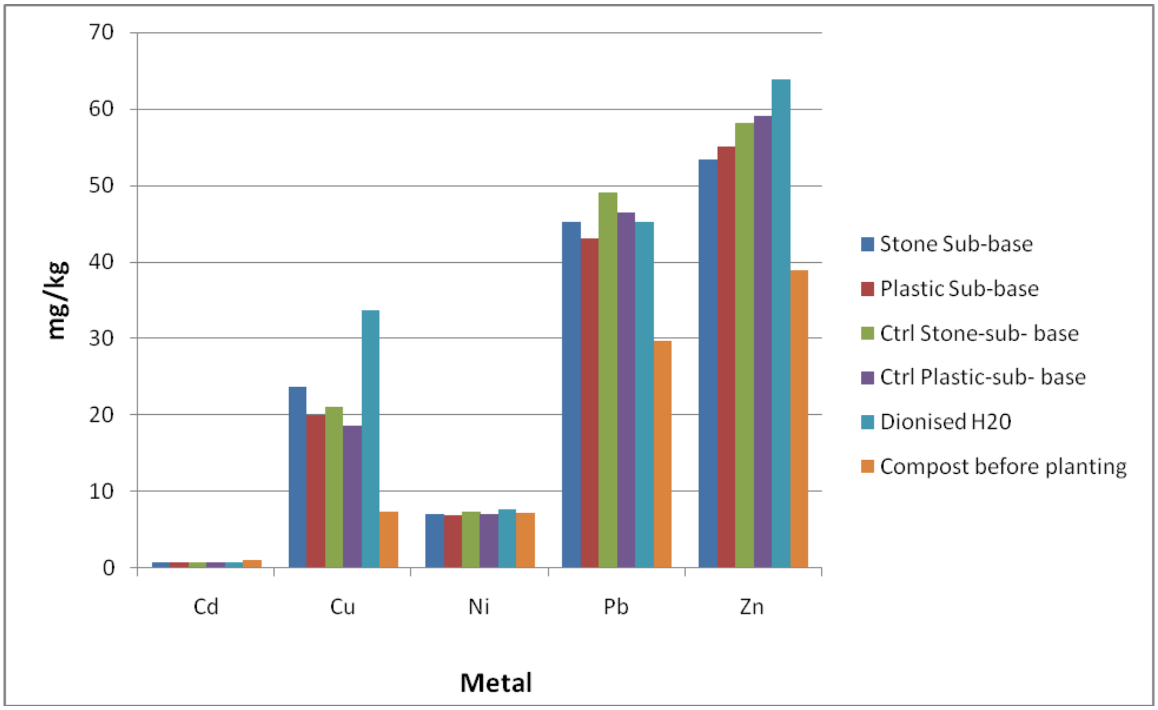

Figure 5.12 Metals in Soil Pre- and Post Planting of Tomato

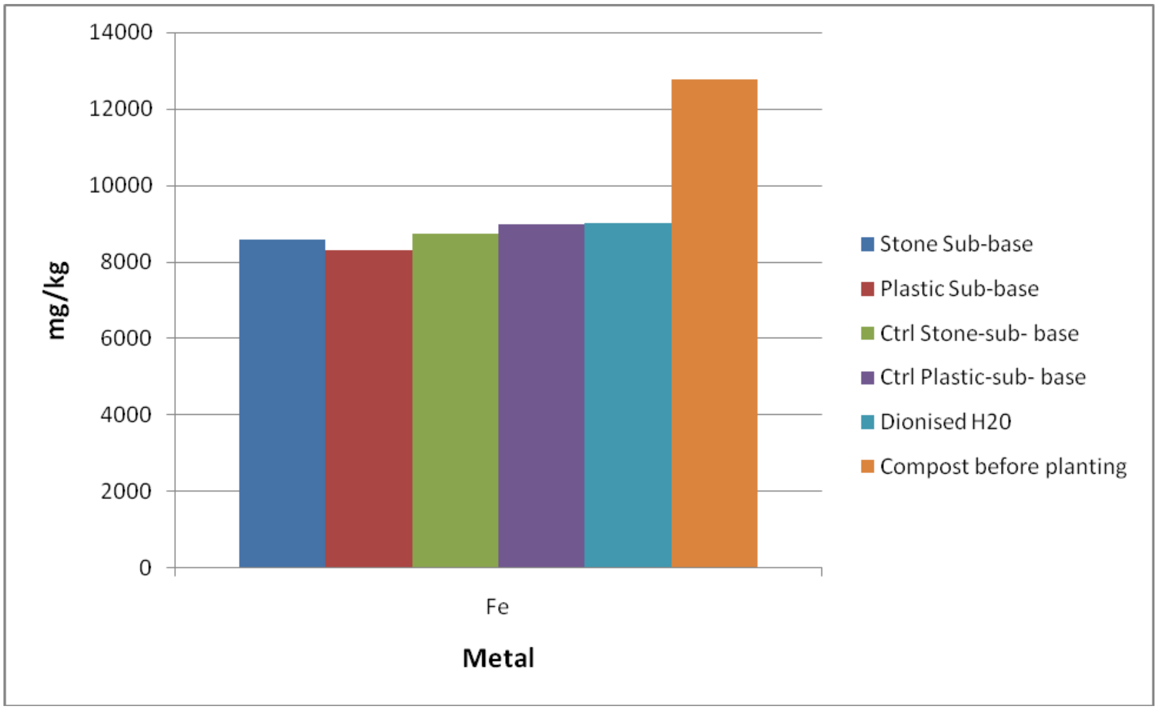

Figure 5.13 Iron in Soil Pre and Post-Planting of Ryegrass

The concentrations of the heavy metals were below maximum permissible limits for Potentially Toxic Elements (PTES) in the soil as can be seen from Table 5.4 below for both tomato and ryegrass at the pH of > 7.0. The BIO-GRO New Zealand (2001) limits for heavy metals in soils and composts are presented in Table 5.6 below. The reader should note that BIO-GRO is the major organic certification agency in New Zealand; hence these limits were set as part of requirements for certification of organic products in New Zealand and do not apply to soils for cultivated of non-organic crops. These limits are usually raised for soils that are used for cultivation of non-organic crops. It is important to highlight that the level of heavy metals in the soil cultivated with non-organic soil, but irrigated with water from the test rigs was below the limits set for soils used for cultivation of organic crops. This implies that the soils irrigated with water from the test rigs met the standard for the cultivation of organic crops. However, the author is aware that the application of nutrients cannot be said to be ‘organic’, but the criteria for determination of suitability of irrigation water for cultivation of organic crops is dependent on the levels of the parameters shown in Figure 5.4.

After harvesting of tomato and ryegrass, the concentrations of Cu, Pb and Zn were higher in the soil samples treated with water from the test rigs and with de-ionized water than in the soil before planting of the plants except in the case of Cu in soils post planted with ryegrass and treated with DI water, where the level of Cu in the soil was slightly lower than that of the soil before planting. In the case of soil post-planted with tomato, a relatively higher level of Cu (>30mg/kg) was recorded for the soil treated with DI water compared to the Cu level of < 10mg/kg recorded for soils that received water from the test rigs. Different result was obtained in the case of ryegrass, where the level of Cu was lower in the DI treated soil than in the soils treated with water from the test rigs. Furthermore, higher level of Cu (>20mg/kg) was noticed in the soils post planted with ryegrass and irrigated with water from Permavoid sub-base test rig relative to <15mg/kg recorded for soil samples that received water from the Stone sub base and control test rigs.

Higher level of Zn (>60mg/kg) was recorded for soil sample treated with DI water in the case of tomato relative to < 35mg/kg recorded in the case of soil post planted with ryegrass. This result could be attributed to the higher trace metal uptake capability of the perennial ryegrass, since relatively higher levels of Zn (>50mg/kg but < 60mg/kg) was also recorded for soils that received water from the test rigs compared to >40mg/kg but <50mg/kg for the same treatments in the case of ryegrass. However, this is not clear from these results as the trend was not observed in other metals such as Pb, Ni, and Cd. Consequently, the author proposed the possibility that this trend could be as a result one or a combination of one or more of the following mechanisms:

- Microbial degradation of the peat content of the compost used as soil in this experiment which resulted in higher concentrations of Zn in soil
- Leaching of soluble salts which resulted in a relative increase in the mobility and availability of Zn for plant uptake
- De-ionized water increased the mobility and availability Zn for uptake by the plants or
- The trend was as a result of sampling error

Gray and Mclaren (2005) highlighted the potential of using ryegrass varieties for phyto-remediation of pasture soils in New Zealand but also called for further research on this issue.

High concentration of iron (> 8000mg/kg) in the soil was recorded for both tomato and ryegrass after the experiment as shown in Figures 5.13 and 5.15. It is obvious from these Figures that there is great similarity in the levels of iron in the soil planted with tomato and ryegrass. There are no trigger values and/or maximum permissible concentrations for iron as the element is regarded as an essential element for plant growth and development (Table 5.5).

Table 5.4 Maximum Permissible and Advisable Concentrations of Potentially Toxic Elements (PTES) in Soil after Application of Sewage Sludge to Agricultural Land

DEFRA 1998

However, the high concentration of iron recorded in the soils after harvesting of tomato and ryegrass was attributed to the concentration of iron (> 1200mg/kg) in the seed compost used as soil in this experiment as can be seen from Figures 5.13 and 5.15 as <0.5mg/l of Fe was observed in the irrigation water applied for 10 weeks (as shown in Figure 4.13, page 124). It is obvious from Figure 5.13 and 5.15 that there is no difference in the level of iron in the soils treated with water from different test rigs apart from that of the fresh compost. It can be deduced from the data that about 400mg/kg of the Fe in the seed compost before planting was used /and leached out during the experiment. However, an attempt to calculate a mass balance of Fe (shown in pages 201-204) shows a loss of about 835mg and 890mg (stone and permavoid test rigs respectively) of Fe from each of the pots planted with tomatoes which may be attributed to leaching. Similarly, that of ryegrass was about 897mg and 835mg for stone and permavoid respectively (pages 203-204).

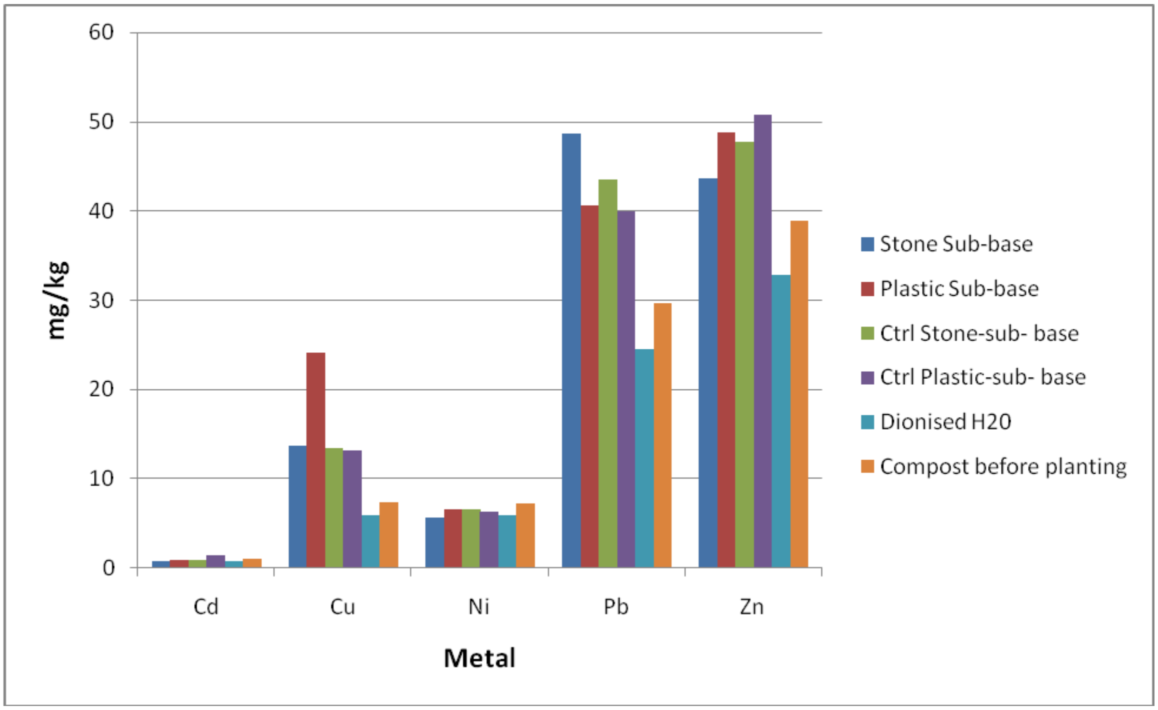

Figure 5.14 Metals in Soil Pre- and Post-Planting of Ryegrass

The role of the compost in the remediation process and the mobility of metals is not clear, especially where recycled water from non-conventional water storage systems such as the pervious pavement is used as the source of irrigation water in composted soils. In situations where compost is used for plant cultivation instead of soil as in the plant experiment reported in this thesis. The Permaculture Research Institute of Australia

(PRIA, 2006) in a publication on 22nd April, 2006 reported the removal of total hydrocarbon in contaminated soil by compost within 70 days by 98%.

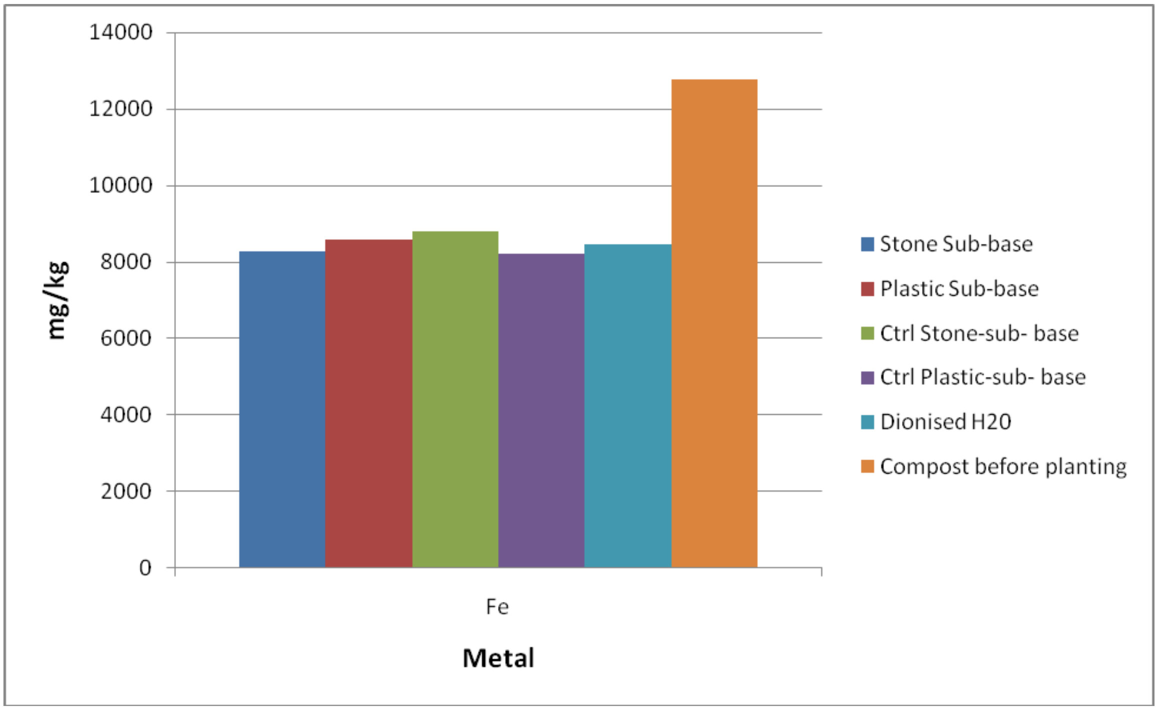

Figure 5.15 Iron in Soil Pre- and Post-Planting of Ryegrass

Table 5.5 ICRCL 59/83 Trigger Concentrations for Agricultural Use

Source: Contaminated Land UK 2008

The same report cited USEPA (1997) where it was reported that the fungi in compost was responsible for the breakdown of the hydrocarbon which makes it available as food for bacteria. It also cited USEPA (1998), where it reported that composts have the capability to prevent the uptake of metals by plants and animals and hence preventing the mobility of these metals in the food chain by binding. The author is aware that composts can be defined differently as natural materials converted to compost and a medium for planting crops or both.

In the light of the information provided above, it was not possible to ascertain the role of the compost as regards metal mobility and bio-availability in this experiment. Also, it is not clear, if the levels of metals in the soil after harvesting of tomato and ryegrass would have been different if normal soil was used instead of compost and/or if the experiment was carried out using other type of compost(s). The seed compost was used throughout this experiment in other to reduce the level of variation in soil type as well as to provide information on how far the nutrients in the water from the test rigs which was used for irrigation can go in supporting the growth and development of the plants.

Table 5.6 Limits for Heavy Metals in Soil and Compost

Source: BIO-GRO (2001)

5.3.5 *Growth Parameters – Ryegrass*

The quantitative growth parameter results obtained from this experiment for ryegrass are presented in Table 5.7

Table 5.7 Growth parameters –Ryegrass

Parameter	Source of Irrigation Water				
	DI	Control		Treated	
	Water	Permavoid	Stone	Permavoid	Stone
Wet Weight 1st Harvest (g/pot)	4.32	8.92	8.75	11.18	11.23
Wet Weight 2nd Harvest (g/pot)	2.53	3.71	4.63	11.57	8.52
Dry Weight 1st Harvest (g/pot)	0.79	1.61	1.33	1.98	1.85
Dry Weight 2nd Harvest (g/pot)	0.50	0.85	0.90	2.02	1.62

5.3.6 *Growth Parameters – Tomato*

The growth parameters for the tomato and rye-grass experiments are shown in table 5.8

Table 5.8 Growth Parameters -Tomato

Parameter	**Source of Irrigation Water**				
	DI	**Control**		**Treated**	
	Water	Stone	Permavoid	Stone	Permavoid
Mean Height After 10 Weeks (m)	0.85	0.82	0.92	1.01	1.12
Max. Height After 10 Weeks (m)	0.74	0.80	0.80	0.81	0.87
Leaf Biomass -Wet Wt. (Mean) (g)	7.4	14.7	13.6	27.3	19.3
Stem Biomass-Wet Wt. (Mean) (g)	7.8	17.3	16.4	22.5	23.3
Fruit Biomass-Wet Wt (Mean) (g)	0.0	0.0	5.3	26.2	33.6
Mean Non-Root Biomass-Wet (g)	15.2	32.0	33.3	76.0	76.2
Leaf Biomass -Dry Wt. (Mean) (g)	2.1	3.0	3.7	4.3	3.0
Stem Biomass-Dry Wt.(Mean) (g)	2.5	3.5	4.3	4.2	3.6
Fruit Biomass-Dry Wt. (Mean) (g)	0.0	0.0	0.5	1.9	2.4
Mean Non-Root Biomass-Dry (g)	4.6	6.5	8.5	10.4	9.0
First Flowering Days from Sowing	51	55	49	48	51
First Fruit Set Days from Sowing	NA	NA	68	60	61

It is clear from these Tables (5.7 and 5.8) that there is little difference in the performance between the plants watered with water from the two treated sub-base rig types. However, there is considerable difference between the plants irrigated with water from treated and control rigs and between the treated rig irrigated plants and DI water irrigated plants. These differences were all found to be significant at the 5% level (Anova: appendix11). This result is almost certainly due to the excess nutrients released from the oiled rigs which enhanced the growth of both sets of plants (Nnadi, Newman and Puehmeier 2008). Hence, it could be deduced that the water from the treated test rigs provided additional benefit by supplying nutrients which supported the growth and development of the plants.

It is however pertinent to mention here that this experiment was conceived as one to compare the performance of the two rig types in water recycling and potential use of recycled water for irrigation. Hence, the tremendous difference in the performance of plants irrigated with water from the test rigs treated with oil and nutrients compared to the untreated controls was unexpected. Earlier work by Barrett (2005) had indicated that that the hydrocarbons would be expected to inhibit the growth and development of the plants and work by Bond (1999) indicated that the release of inorganic nutrients from the rigs would be minimal other than just the first application of the fertilizer.

5.3.7 *Metal Analysis-Tomato*

Accumulation of heavy metals in soils and plant tissues after irrigation with reclaimed water is a major concern (Okoronkwo, Igwe and Onwuchekwa 2005, Al-Lahham *et al.* 2007). The accumulation of these metals in the roots, stem, leaves (Okoronkwo, Igwe and Onwuchekwa 2005, Islam *et al.* 2007) and fruits (Al-Lahham *et al.* 2007, Islam *et al.* 2007) of different types of crops from contaminated soils have been reported in literature. Heavy metals maybe toxic to plants and if bio-accumulated in edible parts of the crops, these metals may pose a health risk to humans and animals (Butt *et al.* 2005, Islam *et al.* 2007, Clemens 2006, Murtaza, Ghafoor and Qadir (2008). Partial translocation of heavy metals to tomato fruit from wastewater irrigation was recorded by Al-Lahham, El Assi, and Fayyad (2007).

However, the rate of uptake of metals varies from plants to plants and sometimes depends on pH, the concentration and availability of other metals (Murtaza *et al.* 2008). Also, the accumulation levels of metals in a particular plant differs in the roots, leaves, stem and fruits example Cd is reported to be more present in the leaves than in the stem and roots (Murtaza, Ghafoor and Qadir 2008).

With the fore-going in mind, the result of metal analysis of tomato of stems, leaves and fruits of the tomato plants after harvesting in this plant experiment section is presented below.

5.3.8 *Metal Analysis-Tomato Stem*

The result of analysis of analysis of Cd, Cu, Fe, Ni, Pb and Zn in the stems of tomato plants is shown below in Figures 5.16 below. A relatively higher level of Ni (20.8mg/kg) was observed in the stem of the tomato plants treated with water from the Permavoid sub-base test rig compared to a range of 0.4 - 0.9mg/kg observed in the stem of tomato plants that was treated with water from other test rigs including DI water.

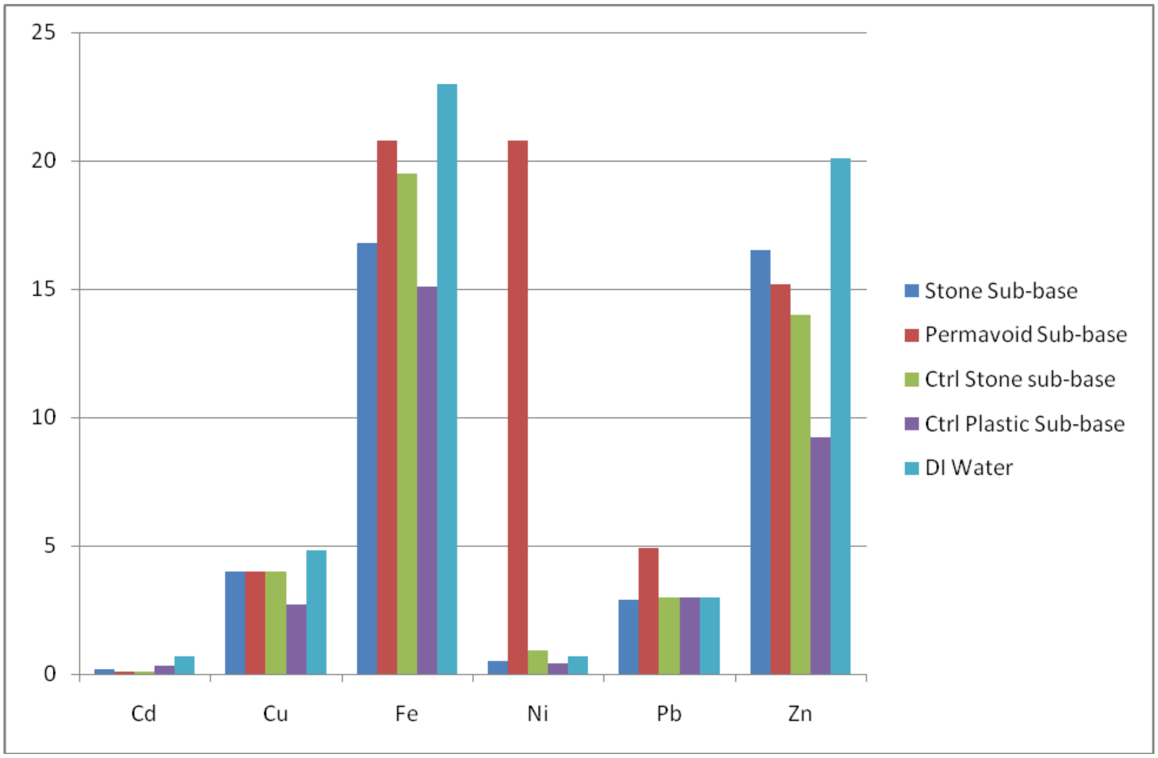

Figure 5.16 Metals in Tomato Stem

The level of Cd in the stem of tomato plants varied from 0.1 - 0.7mg/kg. The highest level of Cd of 0.7mg/kg in stem was observed in the stem of tomato plants treated with DI water and other treatments ranged from 0.1 - 0. 3mg/kg.

A relatively higher concentration of 20.1mg/kg of Zn was also observed in the stem of tomato plants irrigated with DI water and the lowest level of 9.2mg/kg was observed in the stem of tomato plants treated with water from control Permavoid test rig. However, there was no significant difference (ANOVA: $p>0.05$, Appendix12) between the levels of Zn in the stem of tomato plants that were treated with water from the Stone, Permavoid and control Stone sub-Base test rigs with Zn concentration range of between 14-16.5mg/kg.

The concentration of Fe in the tomato stems varied from 15.1 – 23mg/kg with the highest concentration of 23mg/kg observed in the tomato stems that were treated with DI water and the lowest level of 15.1 observed in the stem of tomato plants that were irrigated with water from control Permavoid test rig.

The concentration of Cu in all the tomato stem samples ranged from 2.7 – 4.8 with the lowest concentration of 2.7mg/kg observed in the stem of tomato plants irrigated with water from Control Permavoid Sub-Base relative to the range of 4.0 – 4.8mg/kg observed in the stems of tomato plants that were irrigated with water from other test rigs including DI water.

Pb concentration in all the stem samples varied from 2.9 - 4.9mg/kg. However the level of Pb in the stem of samples of tomato plants irrigated with water from the Permavoid sub base test rig observed was twice (4.9mg/kg) the range of 2.9 - 3.0 observed in the stem of tomato plants that were irrigated with water from other test rigs including DI water. This observed level of Pb in the stem of tomato plants irrigated with water from Permavoid test rig was however inconsistent with levels found in the soil after the experiment as can be seen from Figure 5.12 (page180) and the levels in the water from the test rig which was 0.001mg/l as can be seen in page129.

5.3.9 *Metal Analysis-Tomato Leaves*

Figure 5.17 shows the levels of metals in the leaves of tomatoes obtained from this experiment.

Boon and Soltanpour (1992) as cited in Murtaza, Ghafoor and Qadir (2008), reported higher levels of Cd in the leaves of vegetables such as tomato, carrot, lettuce and radish than in their fruits and roots. This was not observed in the results of this experiment as the Cd levels were undetectable in all leaf and fruit samples (Figure 5.17 below) that were irrigated with water from the test rigs including DI water relative to 0.1 – 0.7mg/kg observed in stem of the same plants as shown in Figure 5.16 (page193). This was considered a good result since Cd was not detected in the edible part of the plant-fruits in all the samples analyzed.

There was no significant difference (ANOVA: $p > 0.05$: Appendix 21) between the levels of Cu, Ni, Pb, and Zn in all the leaf samples analyzed including those irrigated with DI water. The level of Cu, Ni, Pb and Zn in all the tomato leaves was within the normal range as shown in Table 5.17 below.

The observed concentration of iron in the tomato leaves was as follows:

51.2mg/kg <66.6mg/kg < 69mg/kg < 79.6mg/kg < 82.5mg/kg for Stone, Control Permavoid, Permavoid, Control Stone and DI water respectively. This result indicates that Fe was accumulated in the leaves more than in the stem and the highest concentration of the metal in the leaves and stem was found in the tomato plants irrigated with DI water.

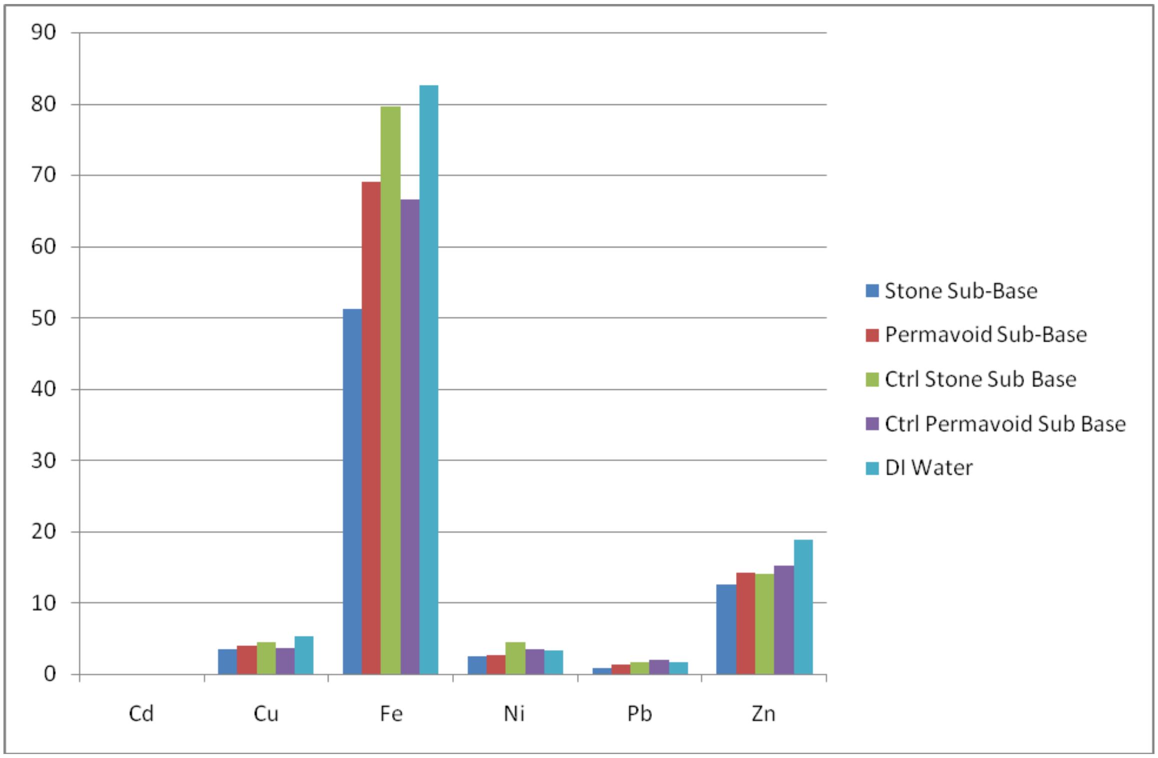

Figure 5.17 Metals in Tomato Leaves

Table 5.9 Normal and phytotoxic Level for Trace Metals in Plant Leaves

Source: Abdullahi *et al.* 2007

However, the concentration of Fe in the Tomato leaves is less than the toxic doses to man and plants as shown in Table 5.9 above.

5.3.10 *Metal Analysis-Tomato Fruit*

The result of analysis of metals in the tomato fruits is presented in Figure 5.18 below. There were no fruits from the tomato plants irrigated with water from control stone sub-base test rig and de-ionized water.

It was observed that Cd and Pb were undetectable in all the fruit samples analyzed. This was considered as an indication of good fruit quality achieved even after high dosing of pollutant on the stone and Permavoid sub-base test rigs to simulate worst case scenario on the water quality of water from test rigs used in the irrigation for this plant experiment).

Table 5.10 Concentration Range for Trace Metals in Edible Vegetables and Fruits (mg/kg)

	Cd	**Cu**	**Pb**	**Fe**	**Ni**	**Zn**
FAO/WHO[a]	0.02 - 0.2	-	0.5 - 1.0	-	-	-
Australian and New Zealand Limit[b]	0.05	-	0.01	-	-	-
EU Limit[c]	0.05	-	0.1	-	-	-
South African Limit[d]	0.1	30	1.0	-	-	40
Ramadan, 2007 (Tomato only)	0.1	4 - 40	-	25 - 300	-	-

Sources: [a]Abdullahi 2007;
[b]Food Standard of Australia New Zealand, 2003
[c] EU, 2006
[d]South African Dept. of Health, 2003

Maclean *et al.* (1987) as cited by Murtaza, Ghafoor and Qadir, (2008) considered the Cd level of 0.1mg/kg in edible part of plant material on dry weight basis as critical. The limit and normal range of Cd in vegetables and fruits is presented in Table 5.10 above.

However, the levels of Cu, Zn and Ni remained at similar levels found in the leaves of the tomato plants (see Figure 5.17 above) and below the limits as shown in Table 5.10 above.

Fe concentration was < 40mg/kg in the fruits from tomato plants irrigated with water from the Stone and Permavoid test rigs, but high accumulation of Fe was observed (>120mg/kg) in tomato fruits from plants irrigated with water from Control Permavoid test models. However, these concentrations were within the normal range found in plant organs (Ramadan and Al-Ashkar 2007).

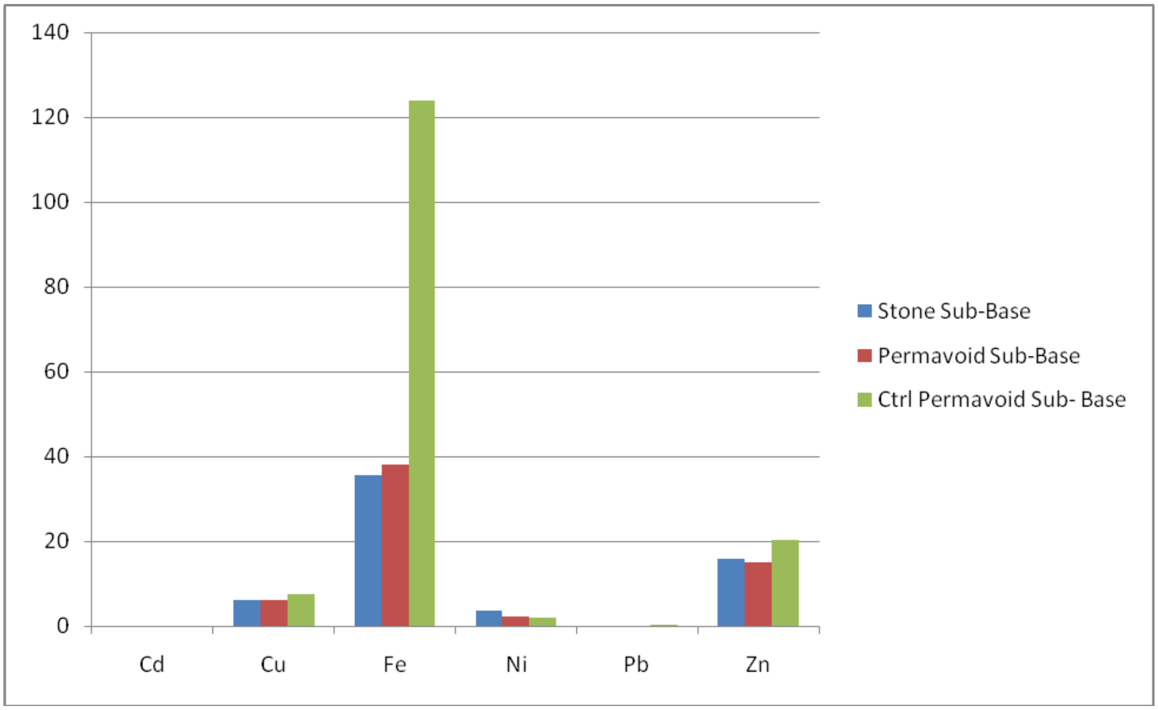

Figure 5.18 Metals in Tomato Fruit Treated with Water from Control Permavoid Sub-Base Rig

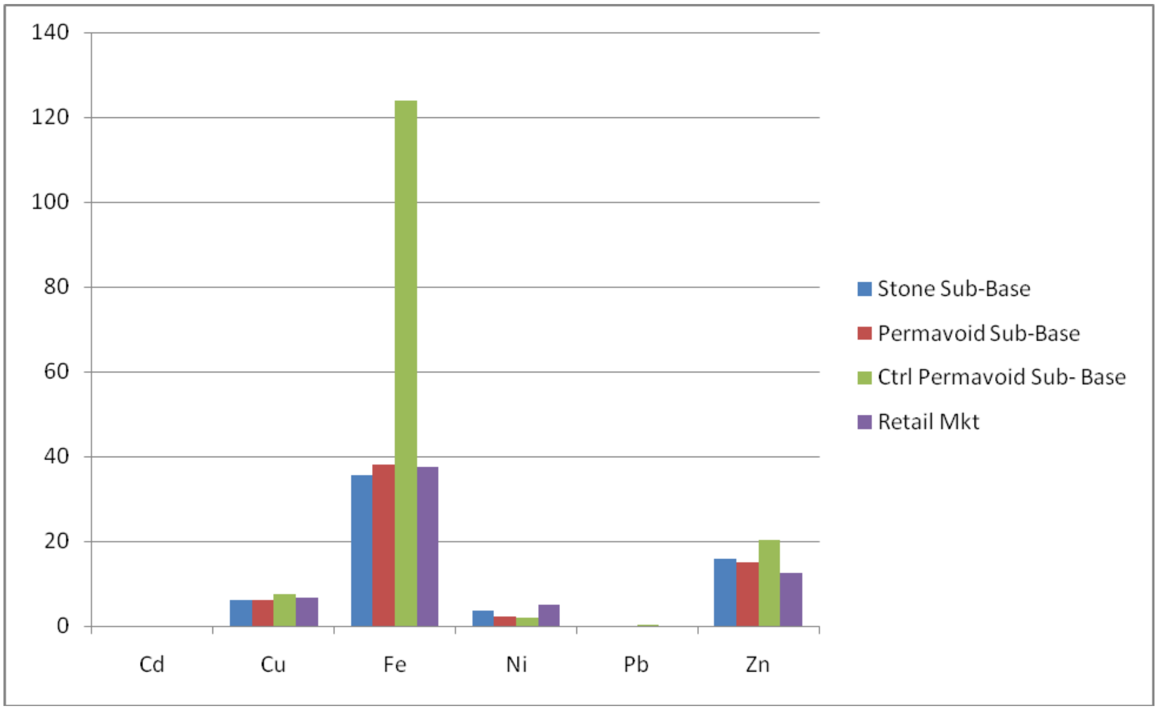

Figure 5.19 Comparison between Tomato Fruit irrigated with Water from Stone, Permavoid and Control Permavoid Test Rigs Treated with Oil/Fertilizer (PPS) and Tomato from Retail Market

Comparison between the concentration of metals in the tomato fruits irrigated with water from the test rigs (note: there were no fruits from Control Stone Sub- Base and DI water irrigated plants) and tomato fruits obtained from retail markets is presented in Figure 5.19 above. There is no significant difference between tomato fruits irrigated with water from Stone Sub Base, Permavoid Sub Base and the fruits obtained from retail market (Anova p>0.05: Appendix13) . However, there is difference between the fruits from tomato plants irrigated with water from Control Permavoid Sub Base test rigs and the tomato fruits from retail market due to the relatively high level of Fe (>124mg/kg) in the fruits from the plants irrigated with water from Control Permavoid Sub Base test rig. However this concentration of Fe (124mg/kg) observed in the fruits from tomato plants irrigated with water from Control Permavoid Sub Base test rig was within the normal range (25 - 300mg/kg) of concentration of Fe in organs of tomato plants (Ramadan and Al-Ashkar 2007). This shows that the fruits from tomato plants irrigated with water from the test models were fit for human consumption and highlights the great potential of the Pervious Pavement System (PPS) for water storage and recycling especially for irrigation purposes.

5.3.11 *Attempted Mass Balance of Iron (Fe) in the Tomato Experiment*

The following is an attempt by the author to compute the mass balance for iron in the tomato experiment.

5.3.11.1 *Stone Sub-Base*

Total Dry Mass of Plant (Stem + Leaves + Fruit) = 10.36g = 0.0104kg

Total Conc. of Fe in Plant = 103.6mg/kg (non-root parts)

Mass of Fe in tomato = (0.0104kg × 103.6mg/kg) = 1.077mg--------------------- (z)

Soil Mass = 200g = 0.2kg

Conc. of Fe in Soil before Planting = 12755.4mg/kg

Mass of Fe in Soil before Planting = (12755.4mg/kg × 0.2kg) = 2551.08mg -----(x)

Conc. of Fe in Soil Post Harvesting = 8571.54mg/kg

Mass of Fe in Soil Post Harvesting = (8571.54mg/kg × 0.2kg) = 1714.31mg--------(y)

Difference in Mass of Fe Pre- and Post Harvest =

(x) – (y + z) = (2551.08 – (1714.31 + 1.077)) mg = 835.69mg

Then difference in Mass of = 835.69mg

5.3.11.2 *Permavoid Sub-Base*

Total Dry Mass of Plant (Stem + Leaves + Fruit) = 10.80g = 0.0108kg

Total Conc. of Fe in Plant = 127.80mg/kg (non-root parts)

Mass of Fe in tomato = (0.0108kg × 127.80mg/kg) = 1.380mg--------------------- (z)

Soil Mass = 200g = 0.2kg

Conc. of Fe in Soil before Planting = 12755.4mg/kg

Mass of Fe in Soil before Planting = (12755.4mg/kg × 0.2kg) = 2551.08mg-----(x)

Conc. of Fe in Soil Post Harvesting = 8299.21mg/kg

Mass of Fe in Soil Post Harvesting = (8299.21mg/kg × 0.2kg) = 1659.84mg--------(y)

Difference in Mass of Fe Pre- and Post Harvest =

(x) – (y + z) = (2551.08 – (1659.84 + 1.380)) mg = 889.86mg

Then difference in Mass of = 889.86mg

This result shows that about >835.69mg and >889.86mg of Fe was lost from stone and permavoid sub base treated pots respectively in the tomato experiment except for Fe in the root of the plants (analysis of the roots was not conducted in this study). The author concluded that this loss occurred mainly through leaching because the dry root mass is not expected to account for more that 20% of the lost Fe.

5.3.12 *Attempted Mass Balance of Iron (Fe) in the Ryegrass Experiment*

This is an attempt by the author to compute the mass balance for iron in the Ryegrass experiment.

5.2.12.1 *Stone Sub-Base*

Total Dry Mass of Plant (1st & 2nd harvests) = 3.47g = 0.00347kg

Conc. of Fe in Plant = 105mg/kg (non-root parts)

Mass of Fe in tomato = (0.00347kg × 105mg/kg) = 0.364mg--------------------------- (z)

Soil Mass = 200g = 0.2kg

Conc. of Fe in Soil before Planting = 12755.4mg/kg

Mass of Fe in Soil before Planting = (12755.4mg/kg × 0.2kg) = 2551.08mg-----------(x)

Conc. of Fe in Soil Post Harvesting = 8267.66mg/kg

Mass of Fe in Soil Post Harvesting = (8267.66mg/kg × 0.2kg) = 1653.53mg-----------(y)

Difference in Mass of Fe Pre- and Post Harvest =

(x) – (y + z) = (2551.08 – (1653.53 + 0.364)) mg = 897.19mg

Then difference in Mass = 897.19mg

5.3.12.2 *Permavoid Sub-Base*

Mean Dry Mass of Plant (1st & 2nd harvests) = 4.0g = 0.004kg

Mean Conc. of Fe in Plant = 94.98mg/kg (non-root parts)

Mass of Fe in tomato = (0.004kg × 94.98mg/kg) = 0.380mg--------------------------- (z)

Soil Mass = 200g = 0.2kg

Mean Conc. of Fe in Soil before Planting = 12755.4mg/kg

Mass of Fe in Soil before Planting = (12755.4mg/kg × 0.2kg) = 2551.08mg-----------(x)

Conc. of Fe in Soil Post Harvesting = 8578.99mg/kg

Mass of Fe in Soil Post Harvesting = (8578.99mg/kg × 0.2kg) = 1715.80mg-----------(y)

Difference in Mass of Fe Pre- and Post Harvest =

(x) – (y + z) = (2551.08 – (1715.80 + 0.380)) mg = 834.90mg

Then difference in Mass of = 834.90mg

This result shows that >897.19mg and >834.90mg of Fe was lost from stone and permavoid sub base treated pots respectively in the ryegrass experiment except for Fe in the root of the plants. Similarly, the author concluded that this loss occurred mainly through leaching.

5.3.13 *Metal Analysis-Ryegrass (1st Harvest)*

The result of analysis of metals in the 1st harvest of ryegrass (harvested 55 days after planting) is presented in figures 5.20 and 5.21 below.

In the 1st harvest, it was observed that the concentrations of Cd in ryegrass that was irrigated with water from all the test rigs including DI water was in the range of 0.33 – 0.43mg/kg which is within the normal range found in plant leaves (0.1-2.4mg/kg) as shown in Table 5.9 above, in dry foliage (0.1 – 1 mg/kg) (Table 5.11) and below the FAO toxicity level of Cd in animal feeds (10 mg/kg) (Aganga 2005) as well as the maximum tolerable concentration by animals in dry diet (0.5 mg/kg) (Table 5.11).

Also, Cu was in the range of 8.33 – 10.39mg/kg in all the test rigs in including DI water which is within the normal range found in plant leaves (5 – 20 mg/kg) as shown in table 5.9 above, in dry foliage (3 – 20 mg/kg) (Table 5.11) and below the FAO toxicity level of Cu in animal feeds (40 mg/kg) (Aganga 2005) as well as the maximum tolerable level by animals in dry diet (100 – 500 mg/kg) (Table 5.11).

The concentration of Ni was in the range of 1.4 – 3.69 mg/kg in all the test rigs including DI water with the highest concentration of 3.69 mg/kg observed in ryegrass plants that was irrigated with DI water. Ni in ryegrass irrigated with water from test rigs was in the range of 1.4 – 2.03 mg/kg, but the concentrations were within the normal range of Ni in plant leaves (0.02 – 5 mg/kg) as shown in Table 5.9 above, normal level in dry foliage

(0.1 -5 mg/kg) and below the maximum tolerable concentration by animals in dry diet (50 – 300) as well as the phytotoxic levels in plants (50 – 100 mg/kg) (Table 5.11) .

The level of Pb observed in ryegrass that was irrigated with water from the test rigs was in the range of 0.27 - 0.4 mg/kg while the concentration of Pb in ryegrass irrigated with DI water was 0.7mg/kg as shown in Figure 5.19. However, these concentrations of Pb observed were within the normal range of Pb in plant leaves (5 – 10 mg/kg) as shown in table 5.9 above, normal level in dry foliage (2 - 5 mg/kg) (Table 5.11) and below the FAO toxicity level of Pb in animal feed (40 mg/kg) (Aganga 2005) as well as the maximum level of Pb tolerated by livestock (30 mg/kg) (Table 5.11).

Higher concentration of Fe was observed in the ryegrass that was irrigated with DI water where the concentration was 91.96mg/kg compared to the range of 51.4 - 59.31 mg/kg of Fe observed in ryegrass that was irrigated with water from test rigs. However, these concentrations of Fe observed in ryegrass were below the FAO toxicity level of Fe in animal feed (1000 mg/kg) (Aganga 2005) and within the normal range of Fe in dry foliage (30 – 300 mg/kg) (Table 5.11). The level of Fe in ryegrass was also below the maximum level tolerated by livestock (500 – 5000 mg/kg) (Table 5.11)

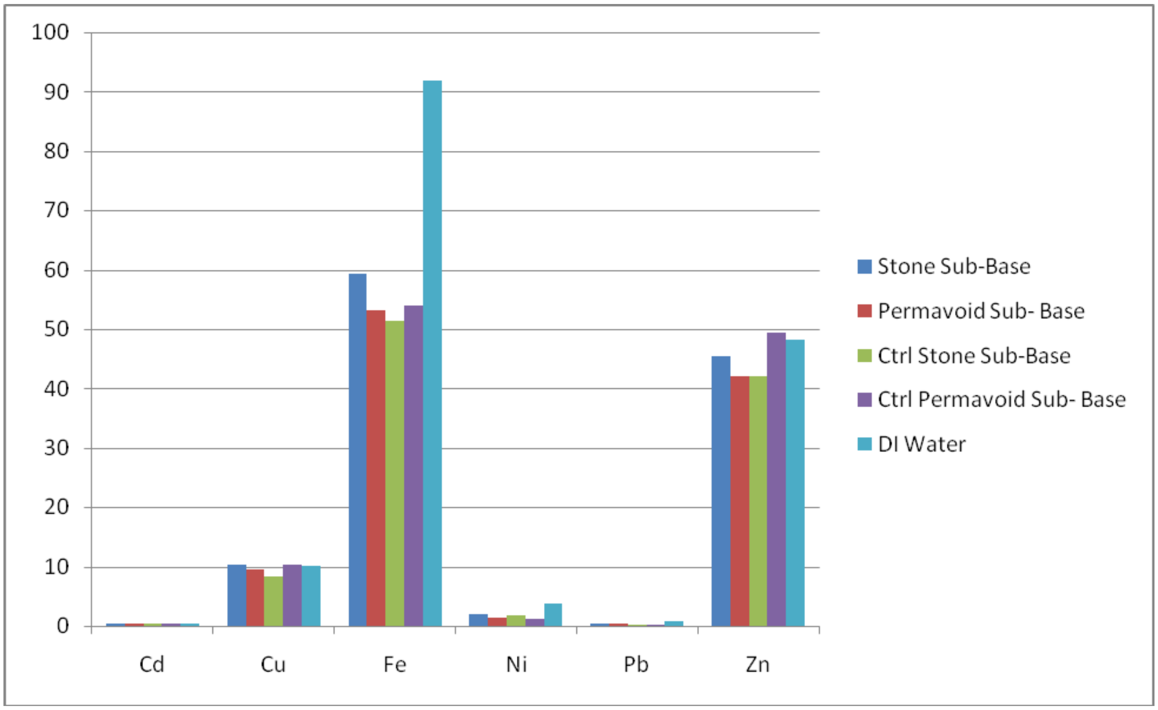

Figure 5.20 Metals in Ryegrass (1st Harvest)

The concentrations of Zn observed in ryegrass irrigated with water from the test rigs except Control Permavoid Sub-base test rig was in the range of 42.03 – 45.39 mg/kg. Zn concentration in ryegrass irrigated with water from Control Permavoid test rig and DI water was 49.33 mg/kg and 48.26 mg/kg respectively. However, the concentrations of Zn observed in all the ryegrass samples was within the normal range in plant leaves (1-400mg/kg), below the toxicity range (100 – 400 mg/kg) as shown in Table 5.9 and below the FAO toxicity level in animal feeds (1000 mg/kg) (Aganga 2005).

5.2.14 *Metal Analysis-Ryegrass (2nd Harvest)*

The result of metal analysis of the 2nd harvest of ryegrass (harvested 98 days after planting and 38 days after the 1st harvest) is presented in Figure 5.21 below.

The concentration of Cd in the ryegrass irrigated with water from the all the test rigs including DI water was in the range of 0.13 – 0.27 mg/kg which similar to the result of the 1st harvest was within the normal level of Cd in plant leaves (0.1- 2.4 mg/kg), dry foliage (0.1- 1mg/kg) (Tables 5.9 and 5.11 respectively) and below the maximum level tolerated by livestock (0.5 mg/kg dry diet) (Table 5.11).the concentration was also below the FAO toxicity level of Cd in animal feeds (Aganga 2005).

Cu level in the ryegrass irrigated with water from all the test rigs was in the range of 5.33 - 7.93mg/kg. The highest concentration of Cu (10.92 mg/kg) was observed in ryegrass irrigated with DI water. However, these Cu levels were within the normal range of Cu in plant leaves (5-20 mg/kg) (Table 5.9), normal level in dry foliage (3 -20 mg/kg) (Table 5.11.) and below the phytotoxic and maximum levels tolerated by livestock in dry foliage (25 – 40 mg/kg and 25 – 300 mg/kg respectively) (Table 5.11)

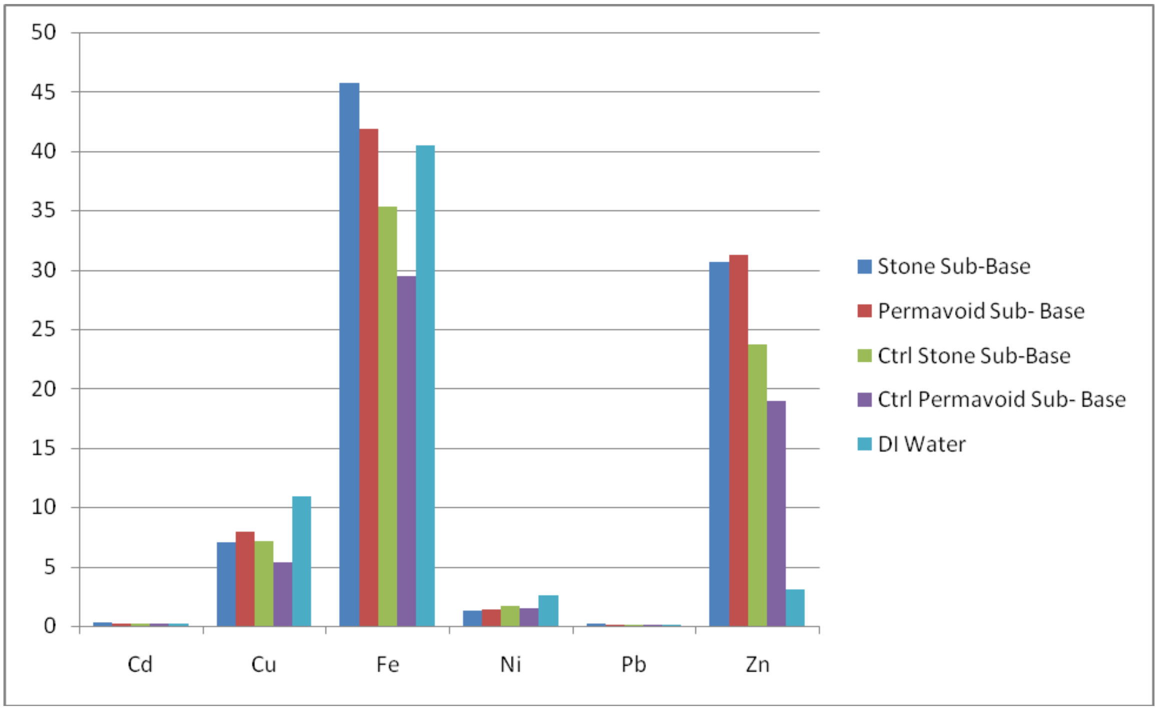

Figure 5.21 Metals in Ryegrass (2nd Harvest)

The concentration of Fe in ryegrass irrigated with water from all the test rigs including DI water was in the range of 29.46 – 45.69 mg/kg. The level of Fe observed in ryegrass irrigated with DI water was 40.46 mg/kg. Unlike the result obtained in the 1st harvest (91.96 mg/kg), the highest concentration of Fe was not the observed in ryegrass irrigated with DI water, but in ryegrass irrigated with water from Stone sub-base (45.69 mg/kg). However, the level of Fe observed in all ryegrass analyzed in this experiment was within the normal level of Fe in dry foliage (30 – 300 mg/kg), below the maximum level tolerated by livestock (500 – 5000 mg/kg) (Table 5.11) and the FAO toxicity level in animal feeds (1000 mg/kg) (Aganga 2005).

Table 5.11Normal Ranges in Plants, Phytotoxic Concentrations and Toxic Levels for Livestock for Analyzed Trace Metals

Source: Madejón *et al.* (2002)

The level of Pb in all the ryegrass analyzed was from 0.07 - 0.2 mg/kg. This level of Pb observed in the ryegrass is below the normal range in dry foliage (2 – 5 mg/kg) (table 5.11) and plant leaves (5 – 10 mg/kg) (Table 5.9) as well as maximum levels tolerated by livestock (30 mg/kg) (Table 5.11).the level of Pb was also below the FAO toxicity level in animal feed (40 mg/kg) (Agangu 2005).

The level of Zn in the ryegrass irrigated with water from Stone and Permavoid Sub Base test rigs was 30.64 mg/kg and 31.21 mg/kg respectively. 23.71 mg/kg and 18.91 mg/kg levels of Zn were observed in ryegrass irrigated with water from the Control Stone and Permavoid Sub Base test rigs respectively. The lowest level of Zn (3.1 mg/kg) was observed in ryegrass irrigated with DI water which is inconsistent with the result obtained in the 1st harvest (48.26 mg/kg). The level of Zn observed in all treatments was within the normal range found in plant leaves (1 – 400 mg/kg) (Table 5.9) and dry foliage (15 – 150mg/kg). The levels were also below maximum levels tolerated by livestock (500-1000mg/kg) (Table 5.11); plants (60 – 400 mg/kg) (Table 5.9) and man (150 – 600mg/kg) (Table 5.11).

The result of analysis obtained from this experiment clearly demonstrates the potential of the pervious pavement system to effectively recycle water for agricultural irrigation of plants for human and animal consumption. The concentration of all the metals analyzed were below toxicity levels and falls within even in some cases below (Pb in ryegrass: 2nd harvest) the normal concentration in plant organs for animal (ryegrass) and human (tomato fruits) consumption respectively. It should be highlighted that the results obtained from test rigs which where polluted with hydrocarbon in simulation of worst case scenario of oil pollution in a car park were able to recycle and store water (chemical water quality results in Chapter 4) which was used for irrigation of ryegrass and tomato plants. It is also clear that the water did not only support the germination, growth and development of these plants, but also produced fruits (in the case of tomato) and foliage which was considered fit for human and animal consumption respectively.

The author considers it necessary to highlight the following limitations:

I. Clean oil was applied in this experiment as a simulation of oil dripping from car parked in a park installed with the pervious pavement system (hydrocarbon pollution). The reason behind the choice of clean oil over used ones by the author was discussed in the previous chapter. The potential effect of the application of used oil on the outcome of this study could not be determined due to time constraints and hence, left for further studies (see Chapter 8).

II. The statistics applied in this chapter is limited by the number of replicate samples analyzed (samples were homogenized before analysis as stated in the methodology). However, the result show that the heavy metals analysed are well below the international limits and does not affect the summary conclusion presented below.

- Summarily, results from this chapter have demonstrated that it is possible to make practical use of waters from pervious pavement system for irrigation of plants that may be consumed by man and animals without compromising soil structure.

This study was taken further (in the next chapter) in order to investigate the biological safety of use of waters stored in such way for irrigation. This was considered necessary in view of the potential threat potential pathogenic organisms might pose in such water recycling and storage application.

Chapter 6: Microbiological Water Quality

6.1 Introduction

In previous chapters, the hydraulic potential and chemical quality of recycled water in the pervious pavement system has been investigated. Also, in Chapter 4, the study of potential use of recycled water in the pervious pavement system for irrigation is presented. However, the risks associated with microbial pollution of stormwater are normally considered to be higher than that from chemicals (Hamilton *et al.* 2005). Thus, microbial water quality needs to be investigated if pervious pavement water recovery/harvesting system are to become acceptable. Stormwater runoff contains small particles of about 2-20µm which includes microorganisms (Coupe, Nnadi, and Oyelola 2008a). Hoffman *et al.* (2002) reported that high level of bacteria in stormwater runoff to streams and rivers from agricultural and urban areas was the reason for the failure of about 40% of streams and rivers in the United States to meet the water quality criteria for use for fishing and swimming. *Escherichia coli* and other pathogenic organisms have also been identified in stormwater (Vieira *et al.* 2002, Casteel *et al.* 2005). These pathogens may originate primarily from pet or bird waste (Vieira *et al.* 2002, Coupe, Nnadi and Oyelola 2008a). In a study of two beaches in Toronto Canada, Edge *et al.* (2007) identified bird faeces as the primary source of *E.coli* as it accounted for 30-60% of the total load of the coliform bacteria in the beaches. EPA (2007) reports shows that beaches in the USA are closed down to the public for recreational activities if *E.coli* levels exceed 1,000 CFU/100mL. Illicit disposal of raw sewage to stormwater by connections of sewage pipes to stormwater carriage pipes as well as poorly constructed or collapsing septic systems which are over flooded during rainfall and fecal materials are carried by stormwater (Vieira *et al.* 2002, Melbourne Water 2005) are other potential sources of E.coli in stormwater. Freshly applied livestock manure is rich in microorganisms and these organisms (some of which are potentially pathogenic) could be carried by stormwater during rainfall events (Ritter and Shirmohammadi 2001). Therefore, it is clear from the potential sources of these pathogens in stormwater that the predictability of contamination episodes is difficult and this makes their study difficult (Coupe, Nnadi, and Oyelola 2008a). Some of these examples would not normally be a problem in a pervious pavement system, where the system is solely used as a source control device, but the potential use of the system for water recycling makes the study of the biological quality of the stored water necessary. There is limited information on the potential risk that pathogens could pose to humans and livestock when stormwater is stored and recycled in non–conventional water storage/recycling systems such as the pervious pavement system. Most available information is on the potential health hazards associated with reuse of wastewater (Srikanth and Naik 2004, Al-Shammiri *et al.* 2005, Toze, 2006, Ensink and Hoek 2007, Qadir *et al*. 2007). While these studies are very useful, they cannot be said to be completely relevant to the use of unconventional water treatment device (such as the pervious pavement system) as each study is specific and making generalizations about microbial hazards from specific circumstances could be considered careless (Hamilton *et al.* 2005). Since the possibility of occurrence of potentially pathogenic microbial contamination in recycled stormwater application exists, and the pervious pavement system is been considered as an important device in stormwater recycling and storage; the author considered it important to investigate the fate of these organisms within the pervious pavement system.

6.1.1 *Pathogenic Organisms in Harvested Water and Heath Effects*

The possibilities of occurrence of a number of potentially pathogenic organisms of various taxonomic descriptions exist in harvested stormwater (Grabiowiecki *et al.* 2008; Coupe, Nnadi and Oyelola 2008a). These organisms have the capability to increase in number under a range of conditions (Coupe, Nnadi, and Oyelola 2008a). Table 6.1 shows a list of some of pathogenic organisms that may pose a risk in harvested rainwater.

Most human microbial pathogens found in water recycling application are enteric in nature and enter into the environment through faecal and sewage contamination as runoff from agricultural soil and livestock manures (Toze 2006). These organisms include: bacteria, protozoa, helminthes and viruses.

Studies have shown that there is increased reuse of reclaimed water for agricultural irrigation (Ensink *et al.* 2002, Hamilton *et al.* 2005, Carr 2005, Qadir *et al.* 2007) and processing of harvested products (Gerba and Choi 2006). The potential health hazards that may arise from this practice could be enormous as contamination of agricultural products may result if the water was not well treated to remove potential pathogenic microbes. Table 6.2 shows the survival rate of some pathogenic microbes (viable) on some crops. Solomon, Pang and Matthews (2003) demonstrated that repeated exposure to the source of

Table 6.1 Some Potential Microbial Contaminants in Harvested Stormwater

Genus of Microbe	**Taxonomy**	**Source**	**Associated Illness**
Salmonella/ Salmonella typhi and Salmonella paratyphoid	*Bacterium*	Animal wastes	Diarrhoea/Typhoid
Shigella	*Bacterium*	Animal wastes	Dysentry
Faecal coliforms (e.g. *E.coli*)	*Bacterium*	Animal wastes	Diarrhoea/colitis
Enterococcus	*Bacterium*	Animal wastes	Urinary infections, secondary infections
Non-enteric*: Legionella spp., Mycobactrium, Leptospira*	*Bacterium*	Stagnant warm water	Legionellosis
Vibrio cholerae	*Bacterium*	Brackish rivers/inadequate drinking water treatment/sewage contamination	Cholera
Coccogoneae or Hormogoneae (Blue – Algae)	*Cynobacterium*	Poor treated drinking water/receiving surface waters e.g. lakes, ponds	Skin infection, diarrhoea, mouth blisters,liver damage, fever, stomach cramps, muscle and joint pains
Cryptosporidum	*Protist*	Animal wastes/sewage	Intestine infection/diarrhoea
Acanthamoeba spp.	*Protist*	Most fresh water bodies	Eye infections (*Keratitis*), encephalitis, cutaneous lesions and sinusitis
Ascaris lumbricoides; Ancylostoma duodenale or Necator americanus; Trichuris trichiura, Onchocerca volvulus	*Helminths*	Wastewater/rivers	Diarrhoea, rectal prolepses, Anaemia, *Ascariasis, river blindness*
Enteric viruses e.g Picornaviridae, Adenoviridae, Caliciviridae,Reoviridae	*Virus*	Sewage contaminated water/wastewater	Hepatitis,diarrhoea

contamination and not direct application of water to the plant (spray irrigation) increases the level of potential pathogenic organism (example *Escherichia coli* 0157:H7) on a plant such as lettuce.

Table 6.2 Survival of Some Pathogens Found in Reclaimed Water on Some Crops

Yates (2008)

The World Health Organization (WHO) guideline for use of wastewater in agriculture recommends that specific socio-cultural, environmental, local disease history should be taken into consideration and the guideline modified accordingly in order to accommodate these factors. The WHO guideline is presented in Table 6.3

Furthermore, there is also the risk of disease infection to maintenance workers of the pervious pavement system if they are repeatedly exposed to potential pathogenic organisms in the course of their job.

Table 6.3 WHO (1989) Microbiological Wastewater Quality Guidelines for Agricultural Use

The potential pathogenic waterborne micro-organisms can be divided into four main groups: bacteria, protozoa, viruses and helminthes. These groups are discussed below.

6.1.1.1 *Bacteria*

As discussed above, many classes of Bacterial pathogens and opportunistic pathogens can be found in wastewaters and harvested waters. According to Toze (1999), bacteria are the most commonly found microorganism capable of causing diseases in water recycling applications. Most potentially pathogenic bacteria are enteric in nature, but non-enteric pathogenic bacteria such as *Legionella* spp., *Mycobacterium* spp., and *Leptospira* have also been found in wastewater and are capable of self-replication (Toze 2006).

According to Reynolds (2003), coliform (*coli-aerogenes*) bacteria are defined by their gram-negative and non-spore forming nature as well as their ability to ferment lactose to produce acid and gas when exposed to a temperature of 35degrees Celsius for 24hours. The fecal coliforms are members of the total coliforms that posses the special ability to grow at the temperature of 44.5 degrees Celsius (Reynolds 2003). Also, Coliforms were defined in the *Standard Methods for the Examination of Water and Wastewater* (Part 9221 and 9222; APHA *et al.* 1998) as reported in Rompre *et al.* (2002) as follows:

- *"all aerobic and facultative anaerobic, Gram-negative, non-spore forming, rod-shaped bacteria that ferment lactose with gas and acid formation within 48h at 35^{o}C (multiple –tube fermentation technique; section 3.1 0) or*

- *All aerobic and many facultative anaerobic, Gram-negative, non-spore-forming, rod shaped bacteria that develop a red colony with a metallic sheen within 24h at 35^{o}C on an Endo-type medium containing lactose (membrane filter technique; Section 3.2)".*

These definitions are based on the method of detection of these microorganisms (Leclerc *et al.* 2001) and biochemical features (Rompre *et al.* 2002). The coliforms are grouped into *Escherichia*, *Citrobacter*, *Entrobacter* and *Klebsiella* (Nogueira *et al.* 2003) as above.

Over a century, microbial indicators such as total and faecal coliforms have been used for tests of microbial water quality (Stevens, Ashbolt and Cunliffe 2003, Reynolds 2003). *Escherichia Coli* (*E.coli*) and *Entercocci* are recommended by the United States Environmental Protection Agency (USEPA) (Kloot *et al.* 2006) and European Union (EU) (Stevens, Ashbolt and Cunliffe 2003) as indicators of presence of potentially pathogenic microorganism in freshwater and drinking water. However, According to Stevens, Ashbolt and Cunliffe (2003), "*…E.coli is regarded as the most sensitive indicator of faecal pollution"*. This is because of their existence in large densities in the faeces (Coupe, Nnadi and Oyelola 2008a) and intestines of man and other animals (concentration of about 10log 9 (-1)) as well as their low existence in other environments (Edberg *et al.* 2000; Rompre *et al.* 2002)). Hence, the presence of *E.coli* in an environment which is unnatural to them (such as drinking water) is regarded as an indication of poor microbial water quality which might be as a result of poor or ineffective water treatment process, breakthrough of pollutants or pollution of supply route as well as re-growth problems (Rompre *et al*. 2002). The World Health Organization (WHO) guideline for irrigation water is 1000 faecal coliforms (FC)/100ml (Fattal, Lampert and Shuval 2008).

Table 6.4 Coliform Bacteria in the Family Enterobacteriaceae

	-	-

Leclerc *et al*. 2001

This guideline is also used by USEPA in regulating the use of use of beaches for recreational activities (EPA 2007). Table 6.4 shows enteric bacteria and their occurrence in water. It can be seen from the Table 6.4 that most enteric coliform bacteria occur in water and the most common source of contamination is human and animal faeces.

6.1.1.2 *Protozoa*

Protozoa are a diverse and rich group of microorganisms that feed by engulfing other organisms. They live in wide range of habitats including aquatic environments and are divided into four major groups: flagellates, naked amoebae, testate amoebae and ciliates (Arnott 2001). Protozoa have long been used as indicators of water quality (Finlay 1997). Most enteric pathogenic protozoa are obligate eukaryotic parasites with one cell which exist as cysts or oocysts at dormant stage outside the host (Toze 2006). The most common pathogenic protozoans found in water includes: *Entamoeba histolytica* (Toze, 2006), *Giardia* spp., *Cryptosporidium* spp. (Finlay 1997, Toze 2006), *Acanthamoeba polyphaga* (Coupe, Nnadi, and Oyelola 2008a). A list of some of the diseases that could arise from protozoan infection is presented in Table 6.1

Acanthamoeba spp; *Giardia* spp. *and Cryptosporidium* spp. are ubiquitous in nature (Mattana *et al.* 2006, Jeong *et al.* 2007, Gómez-Couso, Paniagua-Crespo and Ares-Mazás 2007). This attribute and the formation of dormant cysts (especially the genus *Acanthamoeba*) enable them to survive conventional water treatments and disinfection. Hence, they can be found in chlorinated swimming pools, cooling towers, drinking water (even after treatment), natural thermal water, hospital water system, wastewater, recycled water and marine water (Mattana *et al.* 2006, Toze 2006). *Acathamoeba spp.* can be referred to as both "*opportunistic*" and "*non-opportunistic*" disease causing microorganism (Mattana *et al.* 2006). Table 6.1 shows some of the potential diseases caused by *Acanthamoeba spp.*

There are many reports of association of *Acanthamoeba* with other disease causing microbes such as: enhancement of growth and development of *Legionella pneumophila,* (Cirillo *et al.* 1994, Bozue and Johnson 1996, Bouyer *et al.* 2008, Mattana *et al.* 2006); encouragement of the existence and spread of *Coxsackieviruses* (Mattana *et al.* 2006); contribution to the spread of *Shigella sonnei* (Jeong *et al.* 2007); carriage and transmission of *Cryptosporidium* (Gómez-Couso *et al.* 2007); encouragement of the persistence of some endemic strains of MRSA (Huws *et al.* 2006) and act as a reservoir for *Campylobacter jejuni* (Axelsson-Olsson *et al.* 2005).

6.1.1.3 *Viruses*

Enteric viruses are the smallest single - stranded RNA pathogens found in water ranging from about 20nm to 30nm in diameter (Fong and Lipp 2005, Toze 2006). They usually occur in water through the contamination of water with sewage/feacal matter (Bosch 1998, Fong and Lipp 2005, Toze 2006), urban runoff and wastewater discharge (Fong and Lipp 2005). Viruses have low infectious doses and only a small quantity of viable particles is required to cause infection (Brassard *et al.* 2005). Enteric viruses have the capability to multiply within the gastrointestinal region of their hosts by giving instructions to the cells of their host (Fong *et al.* 2005, Toze 2006). The viral transmission is usually through the feacal – oral route, where the highly infectious stage of the virus is shed after replication through feacal matter of the host and hence, increasing the chance of infection (Brassard *et al.* 2005; Fong *et al.* 2005). Hence, it has been stated that the potential risk of infection by viruses when consumed in drinking water is about 10-to-10, 000 times greater than of pathogenic bacteria consumed at the same level in drinking water (Bosch 1998, Fong and Lipp 2005). High levels of persistent of enteric viruses in marine environment have been reported as increasing the risk of infection to humans who use this these environment for recreational activities and infection of shell fish which tends to build up this viruses in their tissues more than it may even be found in surrounding water environment (Lees *et al.* 1995, Myrmel *et al.* 2004, Fong and Lipp 2005). Table 6.1 shows some of the diseases caused by human enteric viruses. However, diseases caused by enteric viruses to man and animals are well reported by Fong and Lipp (2005).

A strong case has been made in literature against the sole use of total and feacal coliforms as indicators of microbial water quality as the persistence, characteristics and prevalence of viruses and protozoa in water cannot be effectively represented by coliforms (Bosch 1998, Toze 1999, Fong and Lipp 2005, Brassard *et al.* 2005, Fong *et al.* 2005).

Table 6.5 Suggested Guidelines for Potentially Pathogenic Protozoa and Viruses in Irrigation Water for Public Access Area (Focus on Residential)

Organism	Units	Suggested Guidelines	
		Average	Maximum
Giardia	Viable cysts/100L	1.4	5.0
Cryptosporidium	Viable oocysts/100L	5.8	22
Enterovirus	PFU/100L	0.044	0.165

Adapted from York *et al.* (2003)

Reports of viral disease outbreaks after the consumption of water that passed total and feacal coliform tests were presented by Bosch (1998), Fong and Lipp (2005). The review of the differences in persistence of viruses and coliform bacteria (Fong and Lipp 2005) as well as protozoa (York *et al.* 2003) has been done elsewhere. Yorke *et al.* (2003), reported the suggestion of protozoan and viral pathogens irrigation water guidelines developed by York and Walter-Coleman (2002) based on risk assessment methodology and assumption that all the protozoan oocysts/cysts and viruses were viable and potentially infections (Table 6.5). Fong and Lipp (2005) highlighted the potential of *Adenoviruses* and *enteroviruses* as indicators of microbial water as well as their transmission to animals.

The author could not study viruses because of time and funding constraints because analysis of viruses in water requires a lot of time as well special equipment due to their minute size and relationship with bacteria.

6.1.1.4 *Helminths*

Helminthes are parasitic worms which might constitute a health risk if found in recycling water applications, wastewater, irrigation water, aquatic environments, etc. The parasites commonly found in recycled water include: round worm (*Ascaris lumbricoides*), hook worm (*Ancyclostoma duodenale* or *Necator americanus*), and whip worm (*Trichuris trichiura*) (Toze 2006). Report of the existence of relationship between the consumption of raw vegetables (carrots, lettuce, cucumber and cauliflower) irrigated with untreated sewage effluent and the rate of infection by round worm was highlighted by Peasey *et al.* (2000), Toze (2006). There are also suspicions regarding possible infection of cereals irrigated with recycled water and bio-solids by helminthes (Crute *et al.* 2004; Toze *et al.* 2006). Ensink *et al.* (2007) observed relatively high level helminthes (0.7eggs/g) than *Escherichia coli* (1.9 *E.coli*/g) on harvested vegetables harvested from farms in Faisalabad, Pakistan.

Waterborne zoonotic helminthes are mostly opportunistic parasites that are transmitted from animals-man and vice versa through the fecal-oral route (Nithiuthai *et al.* 2004). *Schistosomes* is referred to as the most significant human infectious helminth in the world affecting over 200 million people in the world with about 80% in sub-Saharan Africa and over 600million at risk (Chitsulo *et al.* 2000).The author did not study helminths in water stored in the pervious pavement system due to time and funding limitations.

6.1.2 Aim

The aim of the experiment presented in this chapter was to determine some aspects of the level of water quality that the pervious pavement system has the potential of storing within the system in view of the threat that some potential pathogens (such as *Escherichia coli* and *Acanthamoeba spp.*) pose in stormwater recycling application and storage (as shown in literature review). Hence, assess the ability of the geotextile layer of the pervious pavement system to filter out chemical and particulate pollutants from storm water (Newman *et al.* 2002a,b, Coupe, Nnadi and Oyelola 2008a). This study also intends to determine the fate and persistence of this potentially pathogenic protist (*Acanthamoeba polyphaga*) in the pervious pavement system as the organism interacts with indigenous microbial community in the system. It was also the aim of this study to determine the levels of treatment of potentially pathogenic bacteria (using *Escherichia coli* as surrogate for other bacteria) by the pervious pavement system with and without geotextile particularly where faecal contaminant could occur in water recycling application through scenarios described in literature review (Chapter 2).

6.2.0 Methodology

This is a novel research work, consequently there appeared to be no methodology in literature for this study. However, the approach adopted for this study was to simulate a ‘worst-case’ scenario by application of two selected potential pathogenic microbes to a simulated pervious pavement system. The selected microbes were the gram-negative enteric bacterium *Escherichia coli* strain 418 and the protist, *Acanthamoeba polyphaga.* Viruses and helminths while been recognised as potential pathogenic organisms (see Chapter 2); they were not studied in this research due to time constraint. Hence, the author hopes that further studies would provide information on these important organisms.

6.2.1 *Escherichia coli strain 418*

Escherichia coli was chosen because is it is used as an indicator of feacal contamination and hence in the determination of microbial water quality as shown earlier in literature review (Chapter 2). Also, the organism can be manipulated safely in a category 2 Microbiology Laboratory (Coupe, Nnadi and Oyelola 2008a).

A culture of *Escherichia coli* strain 418 was obtained from culture collection of Faculty of Health and Life Sciences, Coventry University. It was presumed before addition of *E. coli* to the test rig, that the organism is not normally found at high concentration in pavement aggregates.

The organism was sub-cultured in Nutrient Broth from the Coventry University Nutrient Agar Streak stock before addition to the test rig.

6.2.2 *Acanthamoeba polyphaga*

Acanthamoeba polyphaga was selected as the model protist pathogen due to its ubiquitous existence in permeable pavement system at very low densities. Coupe *et al.* (2004) reported the highest density of 2.0 $\times 10^1$ organisms per millilitre in effluent from pervious pavement. Therefore, a simulated addition of *A. polyphaga* could be made with a low chance of that increase in density occurring unexpectedly from the indigenous microbial community of the pervious pavement rig rather than due to artificial contamination (Coupe, Nnadi and Oyelola 2008a). It has also been reported that the cell density of some protists especially the microflagellates or small ciliates may vary by at least two orders of magnitude in effluent from pervious paving within 7 days due to competition, presence of food or biotic and abiotic factors (Coupe *et al.* 2003, Coupe 2004, Coupe, Nnadi and Oyelola 2008a).

Also, *Acanthamoeba polyphaga* is relatively easy to culture and can be identified in its amoeboid/cyst state by the aid of microscope (Page 1976, Coupe, Nnadi and Oyelola 2008a). The organism can also be manipulated safely in a category 2 microbiology laboratory

A culture of *Acanthamoeba polyphaga* used in this experiment was obtained from culture collection of Algae and Protozoa (CCAP), SAMS Research Services Ltd, Scotland, UK.

6.2.3 *Test Rigs*

The pervious pavement test rigs used in these experiments were made of steel frame and glass walls enabling the researcher to view different components of the test model without taking the rig apart. These test rigs are scaled down versions of the pervious pavement system and followed the structural design of Pratt *et al.* (1989). These mini-test rigs of $0.27m^2$ area were described and effectively used as pervious pavement indoor models in previous research work in Coventry University by Spicer (2006). Two different sets of the test rigs used in this experiment for *E.coli* and *Acanthamoeba polyphaga* respectively. The test rig models contained free draining Inbitex® geotextile at the base and between the sub-base and bedding layers. This study did not investigate the response of a test rig system with impermeable geotextile (such as Inbitex composite®) to direct application of pathogens as the author was aware of on-going large – scale research using impermeable geotextile (Inbitex composite®) at Edinburgh University (Grabiowiecki *et al.* 2008). However, preliminary results on the capability of a test rig system containing impermeable geotextile to retain and support oil degrading microbes is presented in chapter 4 of this thesis. Figure 6.1 below shows the set-up of the test rig in the category 2 laboratory in Coventry University.

Figure 6.1 Set up of Test Rigs Used in the Experiment in Category 2 Laboratory

6.2.4 *Addition of Escherichia coli Experiment*

Four (4) test rig models were set up in the laboratory. Two (2) test rigs contained geotextile and the other two (2) test rigs were not installed with geotextile (Table 6.6). There was neither oil nor nutrient additions to the test rigs.

Table 6.6 Test Rig Models Used in Experiment

TEST MODEL	ADDITIONS	GEOTEXTILE	NO. OF REPLICATE(S)
1	- Oil and - NPK	Yes (inbitex)	2
2	- Oil and - NPK	No	2

Distilled water was applied using a measuring cylinder as simulated rainfall at the rate of 100ml/week on the test rigs and effluents were collected at the base of the test rigs in a sterilized 20ml universal laboratory bottles for each test rig at the 1st flush, middle flush (flush was defined in this case as the rush out of water after rainfall simulation) and at the end of outflow of effluent. McCarthy (2008) observed that the 1st flush mechanism for *E.coli* in urban run-off is inconsistent. After effluent collection, the samples were transferred from the 20ml bottles to sterilized centrifuge tubes which were sealed with foil and centrifuged at 1500rpm for 5 minutes at room temperature in order to concentrate particles in the samples. The centrifuged samples were then concentrated to 10ml by removing the excess water with disposable plastic pipette (one for each sample in order to avoid cross contamination).

6.2.4.1 *Serial Dilution of Samples*

9ml of distilled water was transferred to 10ml sterilized universal bottles (200/week) by hand pipettes. The universal bottles were then loosely closed with their lid (in order to avoid explosion during sterilization), wrapped with a foil, clearly labelled with sterilization tape and sterilized in Autoclave Sterilizer for 24 hours. After sterilization and cooling, six bottles containing 9ml sterilized distilled water were arranged behind each sample (labelled 10^{-0}) and labelled from 10^{-1} to 10^{-6}. Each sample was then diluted from 10^{-0} to 10^{-6} by taken out 1ml of sample from the bottle labelled 10^{-0} with micro pipette after the bottle was hand-shaken for about 1minute and transferred to the bottle labelled 10^{-1}. Similarly, 1ml was taken from 10^{-01} bottle into the bottle labelled 10^{-03}.This process continued until each sample was diluted to 10^{-06} .This process was used for all the samples collected weekly throughout the experiment.

6.2.4.2 *Addition of E.coli*

In order to determine the baseline of bacteria and protozoa before the addition of *E.coli*., the collected effluents were analyzed for total and enteric bacteria on Nutrient and MacConkey agar respectively. A description of media used in this study is presented in appendix. Method used in preparation of Nutrient and MacConkey agar is presented below (pages 235 - 236). Incubation of Nutrient and MacConkey agar plates was conducted at 25°C and 37°C respectively. Enumeration of live cells was conducted by spread plate count method (Coupe, Nnadi and Oyelola 2008a, Chigbu and Sobolev 2007). Also, the protists were enumerated and identified to genus level by light microscopy techniques.

It was originally expected that it would take about 2 weeks to achieve the baseline of the bacterial and protozoan community in the test rigs, but it surprisingly took 4 weeks to achieve a relatively stable baseline before the addition of *E.coli* to the test rigs.

After sampling at the 28th day of the experiment, *Escherichia coli* 418 was added in pure culture form to the surface of the test rig models at a density of 2.0×10^{8} cells/millilitre and a final volume of 10ml was applied through a hole of 10mm drilled through the paving block in each test rig in order to simulate worst case scenario. 15 minutes after the addition of *E.coli*, a 100ml rainfall event was simulated on top of the test models over 5 seconds ensuring even a wash through the hole at the centre of the paving blocks- simulating a ‘worst case’ situation. However, the protocol of rainfall application, sampling and analysis was repeated every week for 63 days for the bacteria and 70 days for the protozoa.

6.2.4.3 *Recovery of Total Coliform from Test Rig Materials*

After 70 days, different layers of the pervious pavement system in the test rigs were taken apart and soaked in 1litre 0.5% saline at 20°C. The solution was then manually agitated in order to extract and enumerate the total number of coliform bacteria on these materials. The resulting suspension was concentrated by centrifugation (see page 231) to increase the concentration of microbes by a factor of 10 and the efficiency of complete removal of the microbe by the pervious pavement system was determined by culturing the effluent in Eosin Methylene Blue Agar (EMBA) incubated at 37°C.

Similarly, un-used aggregate materials stored outside Hydrology laboratory, Coventry University for about 6 months and those stored indoors in the same laboratory for same length of time (sources of aggregates used in the experiment) were subjected to similar extraction process as the rig materials and used as *control* in the recovery of total coliforms from the test rig materials after the experiment.

The preparation of the agar powder for inoculation, inoculation process as well as incubation of these media are reported below. Description of Media (Nutrient, MacConkey and Eosin-Methyl-blue agar) used in this experiment is presented in Appendix 22.

6.2.4.4 *Preparation of Nutrient Agar Powder for Inoculation*

Nutrient agar powder (CM0003) was supplied by Oxoid Ltd, Basingstoke, Hampshire, England.

The constituents of nutrient agar powder (p^H 7.4 ± 2.0 at $25^{\circ}C$) according to manufacturers were as follows:

'Lab-Lemco' powder…….	1.0g/l
Yeast extract……………..	2.0g/l
Peptone………………..	5.0g/l
Sodium Chloride………	5.0g/l
Agar…………………...	15.0g/l

- 14g of Nutrient agar powder was weighed in a laboratory weighing boat from 500g container using a stainless spoon on a laboratory analytical weighing balance
- The weighed - out agar powder (14g) was then transferred into a sterilized calibrated 500ml bottle
- 500ml of distilled water was measured out in a volumetric flask and used to suspend the nutrient agar powder in the 500ml bottle
- The bottle was then hand-shaken in order for the powder to dissolve completely and labelled with autoclave tape

- The bottle containing the nutrient agar solution was then sterilized by autoclave (manufactured by LTE Scientific Ltd and supplied by Appleton Woods, UK) at 121°C for 15mins
- And transferred with the aid of leather gloves to a waiting (ready at 70°C) Clifton unstirred water bath (Nickel-Electro Ltd, Somerset, England)
- The molten nutrient agar was poured into sterile plates (supplied Bibby Sterilin Ltd, UK) in a fume cupboard (supplied by Microflow Pathfinder Ltd, Hampshire, UK); allowed to cool and solidify before inoculation.

6.2.4.5 *Preparation of MacConkey Agar Powder for Inoculation*

Nutrient agar powder (CM0007) was supplied by Oxoid Ltd, Basingstoke, Hampshire, England.

The constituents of nutrient agar powder (p^H 7.4 ± 0.2 at 25°C) according to manufacturers were as follows:

Peptone………………20.0g/l

Lactose………………10.0g/l

Bile Salts……………...5.0g/l

Sodium Chloride……..5.0g/l

Neutral Red………….0.075g/l

Agar…………………..12.0g/l

- 26g of MacConkey agar powder was weighed in a laboratory weighing boat from 500g container using a stainless spoon on a laboratory analytical weighing balance.
- Same steps as in Nutrient agar preparation (see page 235)
- The surface of the MacConkey agar gel was dried before inoculation

6.2.4.6 *Preparation of Eosin Methylene Blue Agar (EMBA) Powder for Inoculation*

EMBA powder (CM0069) was supplied by Oxoid Ltd, Basingstoke, Hampshire, England.

The constituents of nutrient agar powder (p^H 7.1 ± 0.2 at 25°C) according to manufacturers were as follows:

Peptone	10.0g/l
Lactose	10.0g/l
Di-Potassium Hydrogen phosphate	2.0g/l
Eosin Y	0.4g/l
Methylene Blue	0.06g/l
Agar	15.0g/l

- 37.5g of EMBA powder was weighed in a laboratory weighing boat from 500g container using a stainless spoon on a laboratory analytical weighing balance
- Same steps as in Nutrient agar preparation (see page 235)

- However, unlike the nutrient agar, the EMBA was cooled to 60°C in an unstirred water bath after autoclaving and hand-shaken before it was poured into plates in order to oxidize the methylene blue (i.e. bring back its blue colour), and suspend the precipitate.

6.2.4.7 *Inoculation of Agar Plates-Spread Plate Method*

The spread plate technique can be used to count the number of colonies.

The agar (Nutrient, MacConkey and EMBA) plates (Petri dishes containing the dry agar gel) were inoculated in the Fume Cupboard (Microflow Pathfinder Ltd, UK). The steps were as follows:

- Agar plates to be used were selected and appropriately labelled according to the dilutions made (see page 232)
- 4 replicates of agar plates was used to each dilution and labelled accordingly
- Burner was lighted in the fume cupboard and placed safely at one of the ends of the fume cupboard
- 20ml of 70% Methylated Spirit (highly inflammable alcohol for sterilization) was poured in a glass jar containing a bent glass rod and placed safely away from the burner in the fume cupboard
- 250μl aliquot of sample (10^{-0} to 10^{-6}) was taken with the aid of micropipette and dropped on the surface of the agar plate (ensuring that droplets of samples are not lost) in the fume cupboard

- The bent glass rod immersed in alcohol was lifted and rolled in the blue flame of the burner until the alcohol had burnt off in other to sterilize the rod
- The dropped inoculum was spread across the surface of the agar gel using the sterilized bent glass rod in order to create a dilution gradient which would form isolated bacterial colonies if active cells were present in the samples.
- The agar plates were left inside the fume cupboard for 5mins to dry after inoculation and then transferred to Incubator
- The inoculated agar plates were placed inverted in the Incubator and incubation was as follows: Nutrient 25°C/48hours; MacConkey 25°C/48hours and EMBA 37°C/48hours respectively.
- Bacterial Counts (CFU/mL) = $\frac{\text{Colony Count on Agar plate}}{\text{Total Dilution of Tube} \times \text{Amount Plated}}$

6.2.4.8 *Preparation of Nutrient Broth Used for Culturing of E.coli*

Nutrient Broth powder (CM0001) was supplied by Oxoid Ltd, Basingstoke, Hampshire, England.

The constituents of nutrient agar powder (p^H 7.4 ± 0.2 at 25°C) according to manufacturers were as follows:

Peptone	5.0g/l
‘Lab-Lemco’ Powder	10.0g/l
Yeast Extract	2.0g/l
NaCl	5.0g/l

- 13g of the nutrient broth powder was weighed out on an analytical weighing balance
- The power was transferred into a sterilized 1litre bottle and filled with 1litre of deionised water measured out in a volumetric flask
- The bottle was lightly covered with a cap and hand-shaken for 1 minute in order to dissolve the suspended powder
- The cap on the bottle was then slightly loosened and the bottle was appropriately labelled with autoclave tape
- And autoclaved at 121^{o}C for 15 minutes

6.2.4.9 *Sub-culture of Nutrient Agar Plate culture of E.coli in Nutrient Broth*

The source of *E.coli* used in this experiment was a Nutrient Agar plate culture obtained from Coventry University as earlier reported (page 228). Therefore, the author considered it necessary to sub-culture *E.coli* in Nutrient Broth in order to achieve luxuriant growth of the organism and achieve the required concentration of the organism in the appropriate media for subsequent transfer into the test rigs.

The technique used for the sub-culture of *E.coli* in a Nutrient Broth was as follows:

- This procedure was performed in the Microflow fume cupboard
- The *E.coli* Nutrient Agar Plate was removed from the fridge where it was stored and placed in the fume cupboard with air flow and burner lighted.

- 100ml prepared Nutrient Broth (see page 239) was poured into 10 conical flasks (100ml/flask) placed in the fume cupboard
- The wire of an inoculating loop was heated to red hot in the burner in order to sterilize it
- Then the lid of the Nutrient Agar plate was gradually lifted without taking the entire lid off and the inoculum of *E.coli* was picked up off on the top of the slant like a scraping motion with the sterilized loop; and the lid immediately closed
- The inoculum was knocked around in the Nutrient Broth and against the sides of the flask
- The flask was then covered with a foam bong and metallic foil
- The loop was re-sterilized by placing it in the fire to red hot
- This process was used for all the flasks (10)
- Incubation of the inoculated nutrient broth was at 30°C

6.2.5 *Addition of Acanthamoeba polyphaga Experiment*

This experiment was conceived out of the need to provide guidance to the end user of the pervious pavement systems as well as regulators on the survival of potential pathogenic microorganisms especially where water recycling and storage within the system is being considered as stated earlier in the introduction. However, free living heterotrophic protests such as *Acanthamoeba polyphaga* are not related to contamination episodes in the same way as *E.coli* is usually linked to faecal contamination (Coupe, Nnadi and Oyelola 2008a).

Therefore, the *Acanthamoeba polyphaga* addition experiment reported here was set up to simulate what would happen if a large number of these potentially pathogenic protests were to be introduced to the pervious pavement system from adjoining areas or grew to higher than usual concentrations. Coupe, Nnadi and Oyelola (2008a) observed in a complementary experiment in Coventry University, that *Acanthamoeba polyphaga* introduced into a mixed culture of bacteria and other protists from pervious pavement test rig was reduced in density from 4.0×10^4 cysts/ml to 6.0×10^2 active cells/ml after 3 weeks. The same authors reported a successful growth of *Acanthamoeba polyphaga* in a liquid culture with *Escherichia coli* 418 as the source of food to the density of 3.2×10^4 active cells/ ml in 5 days.

Thus, the objectives of this phase of experiment were:

- determination of the attenuation of *Acanthamoeba polyphaga* by the pervious pavement system when added to the surface of the pavement and attenuation rate measured through effluent released from bottom of test rig
- Analysis of the persistence of *Acanthamoeba polyphaga* in the pervious pavement system was through the extraction process as described earlier in page 234. However, in this case, identification and enumeration of the protist, *Acanthamoeba polyphaga* was carried out by light microscopy.

6.2.5.1 *Acanthamoeba polyphaga*

A culture of Acanthamoeba polyphaga was received from the Culture Collection of Algae and Protozoa (CCAP, UK) and transferred to seven conical flasks containing Page's Amoeba Saline Solution (PAS) (Figure 6.2) which was prepared according to the guideline on page 204 of the catalogue of the UK National Culture Collection (UKNCC, 2001) as follows:

- 2 stock solutions were prepared and then mixed with DI water to form the PAS medium
- Stock Solution 1 & 2 were prepared in 2 different sterilized 500ml bottles as follows:

Stock Solution 1:

The following compounds were weighed out on analytical weighing balance and put in a 500ml bottle:

NaCl………………………12.0g

$MgSO_4.7H_2O$………………0.4g

$CaCl_2.6H_2O$………………..0.60g

- 500ml distilled water was then added to the bottle containing the compounds in order to make the stock solution 1.

Stock Solution 2:

The following compounds were weighed out on analytical weighing balance and put in a 500ml bottle:

Na_2HPO_4……………………14.20g

KH_2PO_4……………………..13.60g

- 500ml distilled water was then added to the bottle containing the compounds in order to make the stock solution 2.

PAS Medium

- 5ml was taken out of each stock solution (1 & 2) with glass pipette and transferred to 7 conical flasks (100ml)
- The conical flasks were labelled with autoclave tapes, covered with foams and wrapped with metallic foils (figure 6.2)
- The bottles containing stock solutions (1&2) were loosely covered with corks and labelled with autoclave tapes
- The flasks and stock solutions were autoclaved at 121^{o}C for 15 min.

Figure 6.2 Amoeba Saline Solutions

6.2.5.2 *Incubation of Acanthamoeba polphaga*

Acanthamoeba polyphaga was incubated by inserting the conical flasks containing the micro-organism in a shaking incubator (JELO TEC SI-900, supplied by Medline Scientific Ltd, UK) at 24^{o}C and 1500rmp for 5 min.

6.2.5.3 *Experimental Set-up*

Eight (8) pervious pavements test models (described earlier in page 230-231) were set up in the laboratory (Table 6.7).

Table 6.7 Laboratory Test Models for Microbiology Experiments

TEST MODEL	ADDITIONS	NO. OF REPLICATE(S)
1	- oil and - NPK	1
2	+ oil and - NPK	1
3	- oil and + NPK	1
4	+ oil and + NPK	1

Effluents from pervious pavement models were collected for analysis in other to determine the base line of bacteria and protozoa present in these test rigs and their variability before the addition of *Acanthamoeba polyphaga* as was done before the addition of *E.coli* (page 233).

The baseline of the test rigs was achieved in 4 weeks as in the *E.coli* experiment (see pages 233-234) before the addition of oil and NPK fertilizer.

6.2.5.4 *Oil and NPK Addition*

On the 28th day, a clean motor lubricating oil and NPK slow release fertilizer were used in this experiment to simulate pollution and encourage bacterial activities respectively (as used in Chapter 4).

Oil was added at the rate of 600mg/week with a calibrated syringe (type of oil and addition to pervious pavement models is described in Chapter 4) and 2.2 g of Osmocote NPK fertilizer was added once at the beginning of experiment (fertilizer and addition to pervious pavement model is presented in Chapter 4).

6.2.5.5 *Rainfall Simulation*

100ml of simulated rainfall was applied weekly (as described in E.coli experiment) throughout the duration of this project.

6.2.5.6 Introduction of *Acanthamoeba polyphaga* to PPS Test Rigs

Acanthamoeba polyphaga inoculum density of 2.4 × 10^4cells/ml was added to the test rigs in the same way as *E.coli* (see page 233) and washed through with 100ml of distilled water as simulating rainfall after protozoan contamination episode-hence, simulating worst case scenario.

6.2.5.7 Investigation of Persistence of *Acanthamoeba polyphaga* in PPS Test Rigs

After the addition of *A.polyphaga* to the test rigs, analysis of the persistence of the microbe within the pervious pavement test rigs was conducted through the effluent collected at the bottom of the test rigs by light microscopy. Preparation of the effluent for microscopy was by centrifugation in order to increase the concentration of the microbes by a factor of 10 (same as the *E.coli* experiment reported on page 232-233).

6.2.5.8 *Recovery of A. polyphaga from Test Rig Materials*

4weeks after the addidtion of *A. polyphaga*, the rigs were taken apart and extraction process was conducted as was earlier reported in the case of *E.coli* addition experiment (page 233)

6.5 Results and Discussion

The results from the experiments are presented under *E.coli* and *Acanthameoba polyphaga* addition experiments.

6.5.1 *E.coli* Addition Experiment

It was observed that each test rig used in this experiment presented its own variability or range of species as well as number of individual organisms. This random and unpredictable behaviour is usually observed in studies concerning living things (Camazine *et al*. 2003, Gilmore 2005) - in this case, micro-organisms. Thus, it was considered that a presentation of the mean of observed results would not clearly show this independence of test rigs. Consequently, the author chose to present the results of each test rig in the charts even when they are replicates.

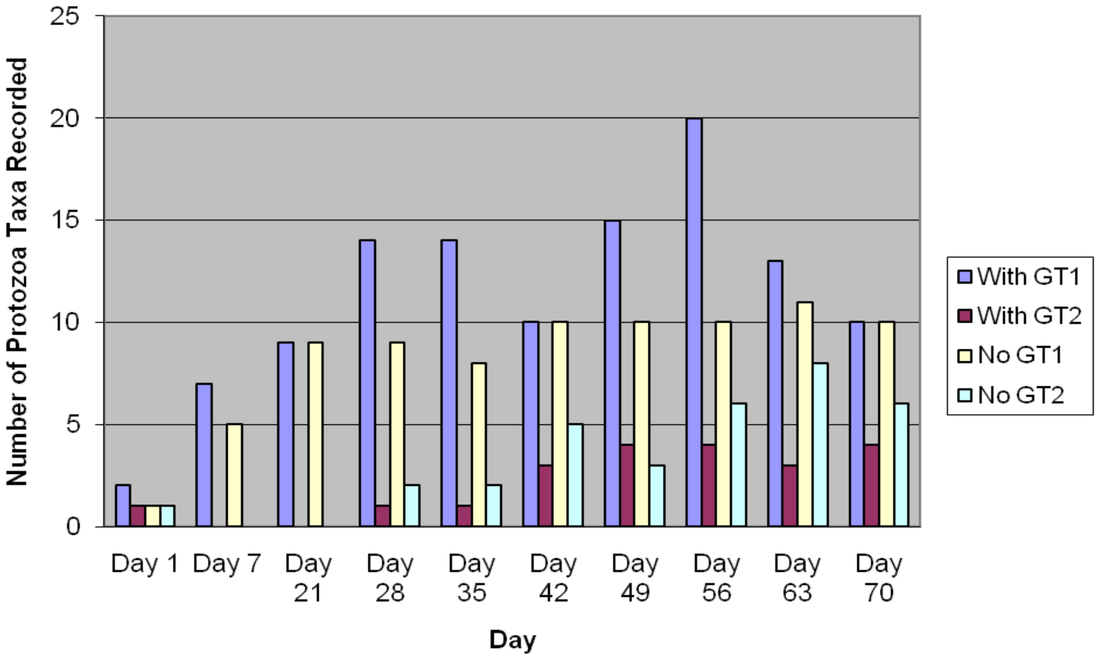

Figure 6.3 Mean No. of Protozoan Spp. Detected in Effluent from Test Rigs in *E.coli* Addition Experiment

The Protozoan spp. detected in the test rigs for 70 days are presented in Figure 6.3 above. The variability of the protozoan community present in the test rig was observed to have increased with increase in the bacterial community (Figures 6.3 and 6.4) which is their source of food by addition of 2.0×10^8 density of *E.coli* at the 35th day. This was also observed in Figure 6.5 where the number of protists per mL increased with the addition of *E.coli*. This observed increase in number and variability of the protozoan community in response to increases in food sources was observed to have occurred in all the test rigs irrespective of whether geotextile material was incorporated in the systems or not. The author concluded that the available food sources were the introduced *E.coli* and existing indigenous micro-organisms (e.g. bacteria) in the pervious pavement system that became active as a result of the presence of nutrients in solution due to the addition of water and from the broth solution introduced during the addition of *E.coli*.

Furthermore, the number and variability of protozoa was observed to be relatively higher in one of the test rigs incorporated with geotextile (GT1); increasing to about 6.9×10^3 protists per mL and 20 protozoan spp. respectively in the 56th day of the experiment (and 21 days after the addition of *E.coli* to the test rigs). However, a marked decrease in the level of protists was observed after the 56th day following the pattern of decrease observed in the level of bacteria (see Figures 6.4 and 6.5).

This observed increase in the number of protists (as stated earlier) in GT1 could be attributed to the presence of geotextile material because this result was not consistent with what was observed in GT2 which was a replicate of GT1 (Figures 6.5). This was also the case in the number of bacterial colonies observed. Hence, the author concluded that the incorporation of geotextile material in some test rigs did not have any effect in the results as can be observed from Figures 6.3, 6.4 and 6.5.

The total number of colonies of heterotrophic bacteria in effluent from the test rig models was observed to be relatively constant at an average of between 6.0×10^4 and 1.1×10^5 cells per mL, with average decrease in cells over time (see Figure 6.6).

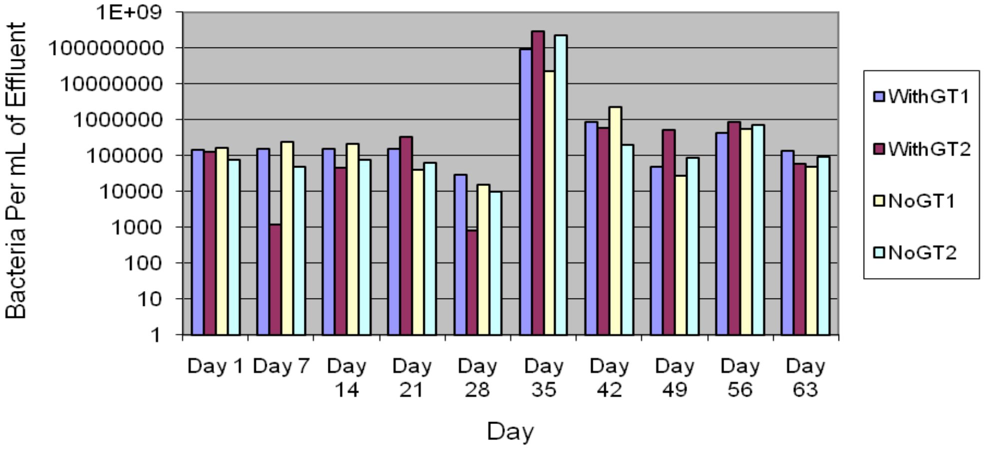

Figure 6.4 Bacterial Colonies Counted on Nutrient Agar in Effluent from Test Rigs in *E.coli* Addition Experiment

However, this result changed following the addition of *E.coli* at the density of 2.0×10^8 per mL (with the total number of bacteria added being 2.0×10^9) and the simulated rainfall of 100ml as the average number of heterotrophic bacteria colonies recovered from effluent from test rigs increased to 4.0×10^6 per mL independent of addition geotextile to test rigs.

This result showed almost 85% efficiency of removal of the *E.coli* that was added to the test rigs 15min after addition and wash-off with 100ml simulated intense rainfall (as shown in the calculation below).

Subsequently, Figures 6.4 and 6.5 shows a rapid decrease in the number of colonies of heterotrophic bacteria from the 42nd day (i.e. a week after addition of *E.coli*) to the 63rd day when the bacterial density returned to the background or near background levels observed prior to the introduction of *E.coli* to the test rigs.

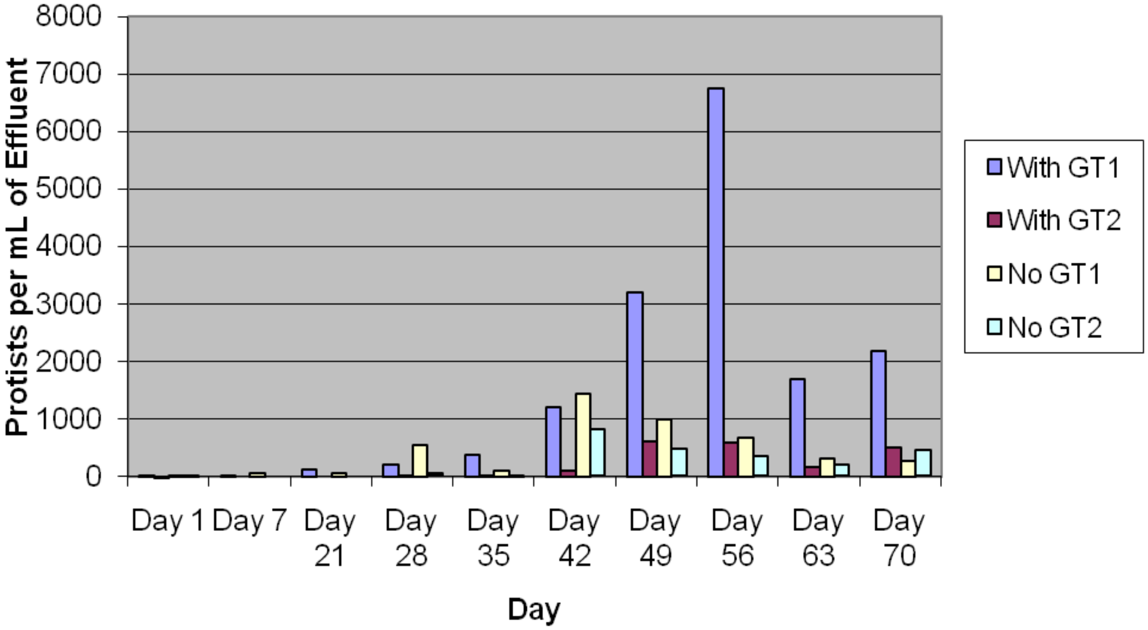

Figure 6.5 Protozoa Detected in Effluent from Test Rigs in *E.coli* Addition Experiment

Calculation of Average Decrease in Bacterial Density Observed in the Test Rigs after the Addition of *E.coli*

Number of *E.coli* Added = Concentration of *E.coli* × Volume of E.coli Added…..(a)

Number of *E.coli* washed - off = Concentration of *E.coli* × Volume of Rain……..(b)

Expected Number of *E.coli* Retained (No Addition) =

= Mean Concentration Just Before *E.coli* was Added × Volume of Rain…………(c)

Number of Added Bacteria Retained = (b) – (c) ………………………………….(d)

% of *E.coli* Retained = (d) / (a) ×100 ……………………………………………(e)

Hence,

(a) $= 2 \times 10^8$ per mL $\times 10$mL $= 2.0 \times 10^9$

(b) $= 4.0 \times 10^6$ per mL $\times 100$mL $= 4.0 \times 10^8$

(c) $= 10^6 \times 100$mL $= 10^8$

(d) $= (b) - (c) = 3.0 \times 10^8$

(e) $= (d) / (a) \times 100 = 15\%$

Therefore 15% of the added E.coli was retained in the test rig after the 1 week after addition (35-42 day) as shown in Figure 6.5. Consequently, 85% of *E.coli* was washed – off after 1 week as stated earlier in page 251 above.

The average decrease in bacterial density observed in the test rigs after addition of *E.coli* was over 8.0×10^5 cells per week, but was actually highest in the 1st week with a more than 10 times reduction observed when allowance was made for dilution effects.

The result of the comparison of number of total coliforms on the highly selective Eosin Methylene Blue Agar (EMBA) in a sample of aggregate stored outdoor and exposed to environmental conditions to the same type of aggregates in the test rigs used for experiment (after taking the test rigs apart) are presented in Table 6.6 below. Similarly, number of total coliforms on EMBA in geotextile stored indoor compared to geotextile in the test rigs (GT1 and GT2) used for the experiment.

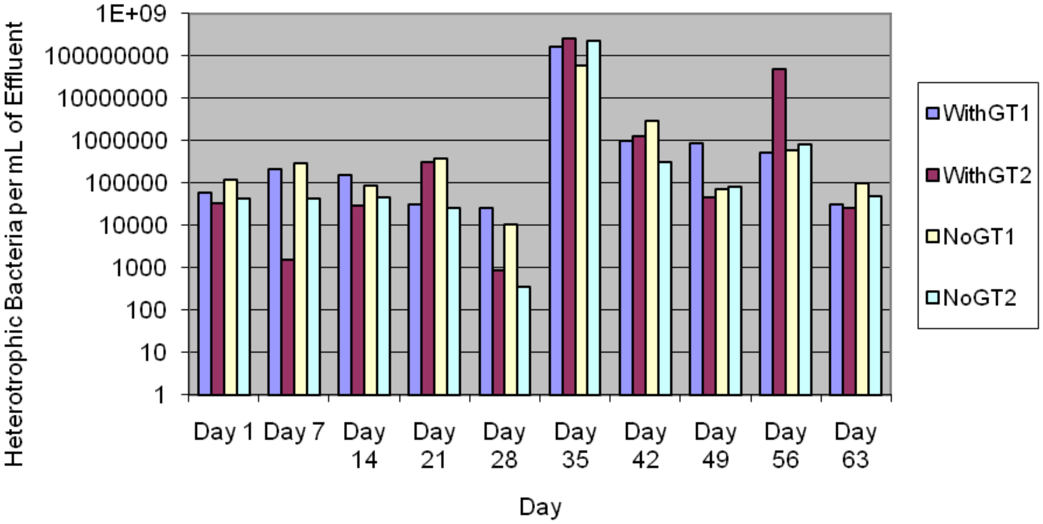

Figure 6.6 Heterotrophic Bacteria Colonies Counted on MacConkey Agar in Effluent from Test Rigs in *E.coli* Addition Experiment

It was observed that the concentration of coliforms on the aggregates stored outdoor were higher than the number of coliforms observed in the aggregates used for the experiment (Table 6.7).

Table 6.8 Total Coliforms Recovered From Permeable Paving Materials

Coliforms per gram of Control (outdoor stored) aggregate material	Coliforms per gram of aggregates obtained from Test Rig	Coliforms per gram of Control (indoor stored) Geotextile	Coliforms per gram of Geotextile obtained from Test Rig
0.3	ND	ND	0.3
37	ND	ND	0.7
27	ND	ND	ND

ND= Not Detectable

However, no coliform was detected on the geotextile material stored indoors, but a maximum of 0.9×10^1 coliforms per mL was recovered from the geotextile material from the test rigs, which confirms the effectiveness of the coliform removal process as the geotextile layer has been shown to be the most microbial active layer in the pervious pavement system (Coupe *et al.* 2003).

The removal of the introduced *E.coli* from the test rigs occurred relatively rapidly despite a significantly high contamination event of 2.0×10^9 per mL. *E.coli* 418 is a bacterium that exists in optimal conditions in mammalian intestines (page 220). This condition was different from what was obtainable inside the test rigs and may have contributed to the rapid removal of the *E.coli* population. However, the recorded persistence of *E.coli* in environmental samples indicates that with a consistent addition of the micro-organism (e.g. from a point source) without adequate control measures, the number of colonies of the microbe may not necessarily decrease (Byappanahalli *et al.* 2006, Coupe, Nnadi and Oyelola 2008a). It is also expected that the introduction of bacteria (*E.coli* in this case) in suspension to indigenous protozoan community in a dynamic biotic system (such as the interior of pervious pavement system) would lead to an increase in the number of their primary predators (protists) especially over the period of the addition of the bacteria. Although a complete investigation of the protozoan community was not conducted on this occasion due to time and resource constraints, an increase in the number of relatively large (>100µm) ciliated protists (about half the number of protists in a given effluent sample) in the weeks after the addition of *E.coli* was observed. These ciliated protists are known to ingest thousands of bacteria per hour and reproduce rapidly (Taylor 1986, Coupe, Nnadi and Oyelola 2008a). However, as mentioned earlier in this chapter, a rapid decrease in the number of protists was observed after the number of bacteria reduced. Hence, indicating another characteristic of the ciliate community – they quickly form cysts and reduce in numbers within samples as soon as the number of suspended bacteria (food source) reduces to a certain number that can no longer support the population of the eukaryotic community present in the sample (Coupe, Nnadi and Oyelola 2008a). It is necessary to point out that despite the observation of what appeared to be biological control (using the pervious pavement system), it still took significant time (28-30days) for the bacterial numbers to decrease to pre-inoculation or background levels (between 6.0×10^4 and 1.1×10^5 cells per mL). This could be partly attributed to the likelihood of stimulation of the entire microbial community by the addition of extra resources (especially Carbon, Nitrogen and Phosphorus) in the form of the introduced bacteria (*E.coli*). These resources even when ingested by the protists will eventually be used up by other heterotrophic bacteria (Nisbet 1984), and this may be a secondary reason why the total bacterial count was higher after the addition of the inoculum (*E.coli*) rather than just the persistence of the introduced bacteria (*E.coli*). Another important result was that the number of coliforms per gram of material from the used test rigs decreased relative even to an environmental control (the unused aggregates stored outdoor). The explanation for the relatively high level of coliforms in the environmental control sample could be that it received input from adjoining areas or feacal matter from animals (e.g. birds and dogs) in the area. While more research is required, it is encouraging that the result from this investigation shows that pervious pavement system does not provide a favourable environment for potential pathogenic bacteria (e.g. *E.coli*), if contamination episode were to occur.

6.5.2 *Acanthamoeba polyphaga* Addition Experiment

The variability of the protozoan community increased in all the test rigs used in the experiment up till the 63rd day of the experiment (Figure 6.7). This increase could not be attributed to the effect of added oil (to simulate pollution) and nutrients (to encourage establishment of microbes) as it occurred across all test rigs. Hence, the author postulated that the food source carried by the rig materials was made available to the microbial community in suspension by the simulated rainfall. Furthermore, *Acanthamoeba polyphaga* added to the test rigs at the density of 2.4×10^3 was non-detectable in concentrated 10ml volume of the effluent from the test rigs after the addition of 1000ml of simulated rainfall.

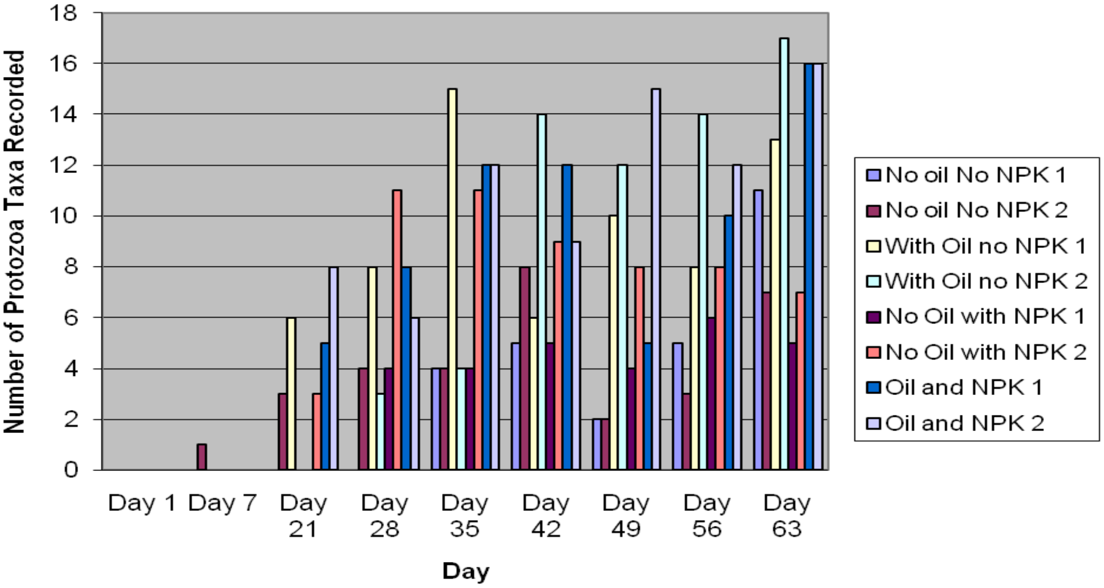

Figure 6.7 Protozoan Spp. Detected in Effluent from Test Rigs in *Acanthamoeba polyphaga* Addition Experiment

The complete removal of *Acanthamoeba polyphaga* demonstrated by its non-detectable in the effluent from the test rigs indicates the biological treatment capability of the pervious paving system. The absence of the organism (*A. polyphaga*) in the effluent after 1 week maybe attributed to predatory activities of other eukaryotes (Nisbet 1984). The indigenous eukaryotes may have taken advantage of the ‘new comer’ (*A. polyphaga*) before it had the chance to establish and stabilize in the test rig. It is also likely, that this was the reason why the number of *A. polyphaga* decreased in the initial complementary culture experiment conducted by Oyelola (2007) and reported in Coupe, Nnadi and Oyelola (2008a).

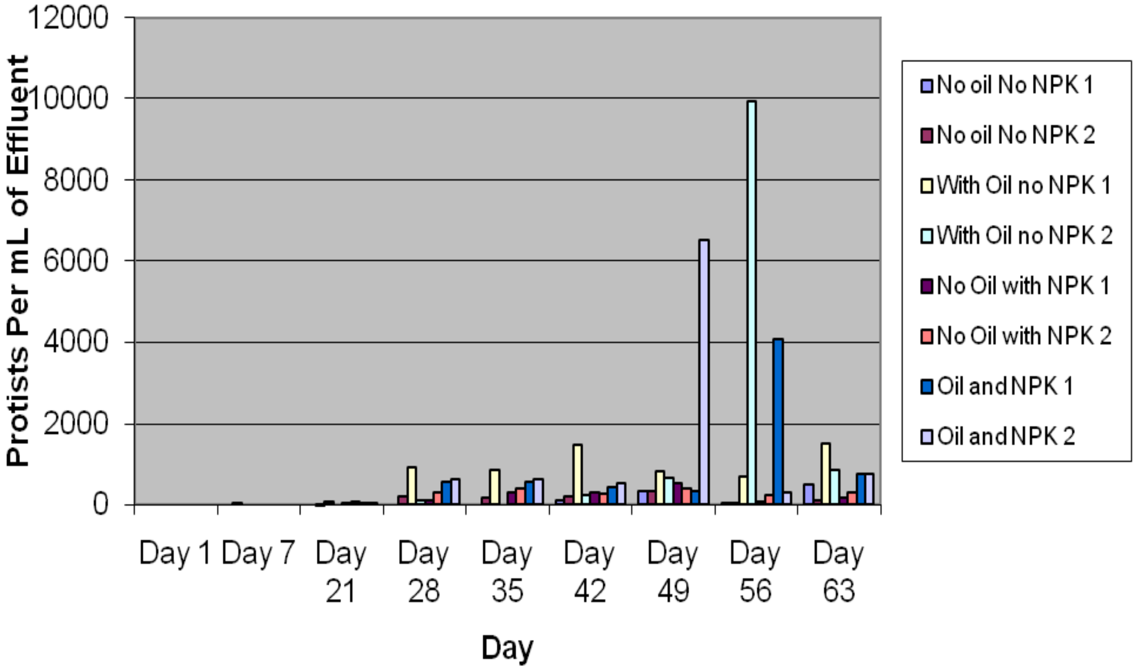

Figure 6.8 Protozoa Detected in Effluent from Test Rigs in *Acanthamoeba polyphaga* Addition Experiment

However, the author wishes to point out that the this feeding pattern was not directly observed in this study; and further studies to confirm this theory could not be conducted due to lack of resources and time constraints.

Earlier studies by Coupe (2004) showed that *Acanthamoeba polyphaga* is capable of dwelling in oligotrophic environments and occurs in low concentrations in the pervious pavement system. Also, the persistence of *Acanthamoeba polyphaga* in tap water is recognised as one of the reasons for the possibility of opportunistic ocular infections or *amoeboid keretitis* (see Table 6.1) and clearly demonstrates the persistence of

A.polyphaga even when faced with chemical treatment and low nutrient environment as that of tap water. Consequently, the removal of the added protist (*A.polyphaga*) further confirms that the pervious pavement system does not offer a suitable habitat for the microbe and also demonstrates the capability of the system to offer biological treatment should contamination of the system with potential pathogenic protists occur. Figures 6.9 and 6.10 shows active cell and cysts (respectively) recovered from test rig components.

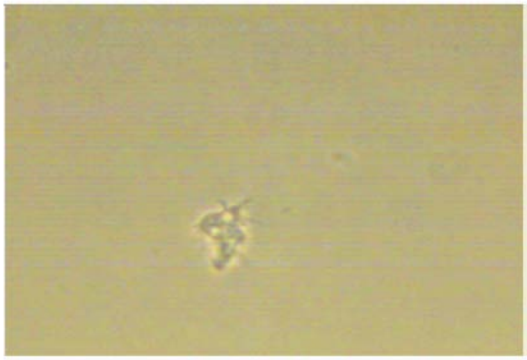

Figure 6.9 Active Cell of *A. polyphaga*

Figure 6.10 Cysts of *A.polyphaga*

The analysis of the components of the test rigs used in the experiment revealed a very low number of active *Acanthamoeba polyphaga* although the organism was detected on all the components of the rig materials from top to bottom (Figure 6.11), but more active cells were relatively found higher up in the pervious pavement system (Table 6.8). This showed that *A.polyphaga* was capable of moving through the rig components either by passive or active means enabled by its micro size and its ubiquitous characteristics. The highest number of active cells (mean: 7) was found in the bedding layer of test rig added with oil and nutrient addition (Table 6.8). Also, 2 cells and 2 cysts of *A. polphaga* were found in the top geotextile layer of the test rig that was dosed with oil and nutrients relative to 2 cysts found in the test rig dosed with nutrients only.

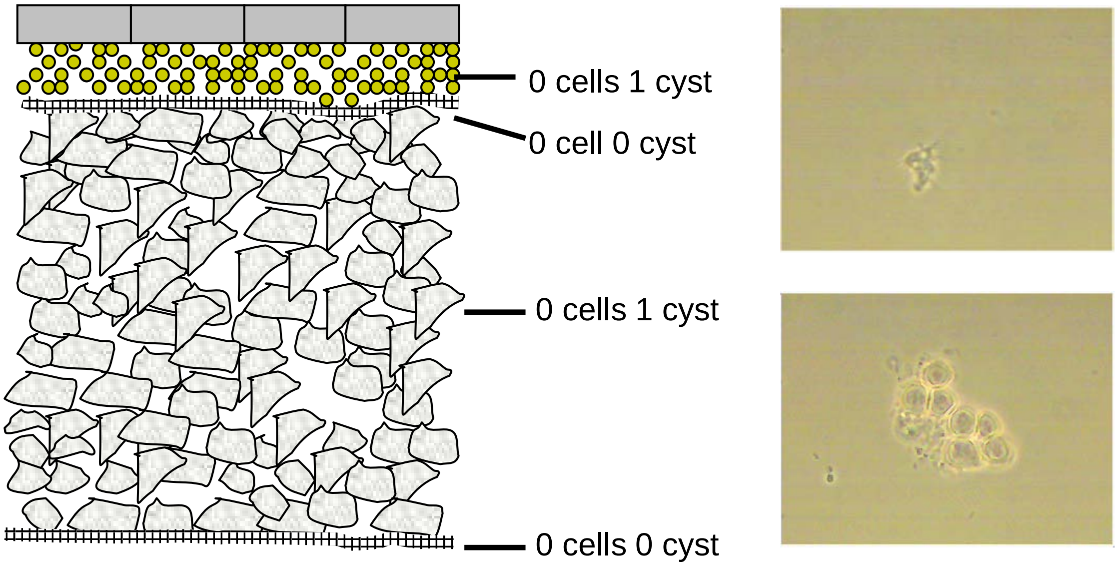

Figure 6.11 Schematic Diagrams of Different Layers of the PPS and *Acanthamoeba polyphaga* Recovered from a Test Rig Without Oil and Nutrient Addition after Direct Application of the Organism.

Table 6.9 Recovery of *Acanthamoeba polyphaga* from Test Rig Materials

Test Rig Component	Outdoor Stored aggregates	Outdoor Stored aggregates	Mean (+Oil, +NPK) Test Rig	Mean (+ Oil, -NPK) Test Rig	Mean (-Oil, +NPK) Test Rig	Mean (- Oil, -NPK) Test Rig
Gravel(Bedding Layer)	ND	ND	7 cells; 3cysts	2 cysts	10 cysts	1 cyst
Top Geotextile	ND	ND	2 cells; 2 cysts	2 cysts	ND	ND
Granite (Sub-base layer)	ND	ND	1 cyst	ND	ND	1 cyst
Bottom Geotextile	ND	ND	1 cell; 1 cyst	ND	1 cyst	ND

The organism was not detected at the top geotextile layer of test rigs subjected to other oil and NPK treatments (Table 6.8 and Figure 6.11). This indicates that the presence oil and nutrient was favourable for the organism as no active cell was found in other treatments (Table 6.8). Oil is a source of carbon when broken down and NPK supplied essential nutrients for the oil degrading microbes which in turn is a food source for the protists. The detection of 10cysts in the bedding layer of test rigs that were dosed with NPK only (Table 6.8) further demonstrated the effects of NPK on the persistence of the *A.polyphaga* in the pervious pavement system. *A.polyphaga* was not detected on the outdoor and indoor aggregates. This demonstrates that the risk of *A.polyphaga* contamination from test rig materials is very remote and any opportunistic contamination of the pervious pavement system by the organism system may only emanate from adjoining areas.

- Summarily, the removal of *A.polphaga* and *E.coli* demonstrates that the organisms do not have prolonged residence time within the pervious pavement system and shows that the pervious pavement system is effective in the removal of potential pathogenic pollutants such as *A.polyphaga* and *E.coli* should they find their way into the pervious pavement system.

- This result (stated above) is encouraging as it offers greater opportunities for the use of the pervious pavement system as water storage and recycling device. It also allays the fear of biological contamination should the system be used for water recycling.

The next chapter deviates from the ‘quality’ issues of the stored water in the PPS to the ‘quantity’ issue. It also investigates the water storage capability of the PPS and takes a brief look at some of the hydrologic issues involved in water storage using PPS.

CHAPTER 7: AN EVALUATION OF THE USE OF STORED WATER DERIVED FROM PERMEABLE PAVING SYSTEM FOR IRRIGATION PURPOSES

7.1 Introduction

The work reported in Chapters 3, 4, and 5 gave good indications that waters exiting from pervious pavement systems have qualities which would support the use of a pervious pavement system in the harvesting of water and Chapter 6 indicated that with appropriate precautions, potential microbial risks of this type of use were not great. This chapter takes a brief step aside from the quality issues to report work carried out to address an issue which is particularly relevant to applications in hotter climates: that of water storage.

As highlighted in Chapter 2, the large reservoir contained by the pervious pavement system below the sub-surface offers potential for use of the sub-base of such structures for longer-term water storage for re-use (Pratt 1999, Coupe *et al.* 2006a). However, there is always a potential for significant amounts of water loss in underground storage systems. This could include evaporation from water surfaces as well as seepage through the walls and floor of the structure. Whilst seepage losses can be controlled by means of close control of quality of waterproof membranes and their construction (Somerville 2005), alternative reservoir structures could be constructed from more substantial materials such as concrete or poly-plastics. Evaporation losses though, are not so effectively controlled because as seen in saturated soil systems, evaporation is dependent on the depth of the water beneath the surface and the suction potential (controlled by external conditions e.g. atmospheric conditions) at the surface (Hillel 1998). However, the suction alone does not determine the rate of extraction of water from the sub surface matrix of the strata, but it is also dependent on the water transmission capability of the soil profile (which also includes the depth of the water below the surface) (Hillel 1998). Hence, in the case of the pervious pavement system, the profile of the entire system (which is the combination of the layers of the system) can limit the evaporation of water from the system provided it is in an unsaturated condition for at least part of the profile. It has been recognized that about 25% of water is lost in the previous pavement system through evaporation (PavingExpert 2008). Consequently, potential changes/modifications of the design and construction of the pervious pavement system are capable of improving the water conservation capability of the system.

The characteristics and role of the geotextiles in the pervious pavement system are well recognized (see Chapter 2), but with the recent types of commercially available permeable geotextiles installed in the system, if the pervious pavement system is used for water recycling, it was proposed that a significant quantity of the conserved water would evaporate during a dry season at a time when it would be most needed, especially in arid and drought prone areas, (Coupe *et al.* 2006a). One of the potential options to enable a reduction in evaporation rate from a pervious pavement system is to modify the paving surface. However, the market strength of certain types of paving surface such as the Hanson-Formapave Aquaflow block® would indicate a need for different approach and it is perhaps obvious that the next potential part of the structure is the geotextile.

At the start of this study, a newly available product came to the author's attention. This seemed to offer great advantages in reducing evaporation provided that other properties (stormwater infiltration, pollution control capability and encouragement of formation biofilms) could be reconciled. The product consists of two layers, one permeable but able to attenuate contaminants and the other providing a barrier to water vapour (Coupe *et al.* 2006a, Gómez-Ullate *et al.* 2008) (shown in Figures 7.0a and 7.0b).

Figure 7.0a Inbitex Composite (Front)

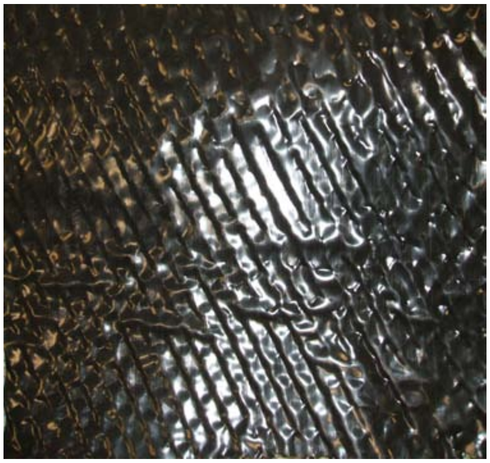

Figure 7.0b Inbitex Composite (Back)

The principle by which the manufacturers claimed it works was that the water would pass through the upper geotextile layer and the separating grid would laterally transmit water along the top of the impermeable membrane until it reached a slit or joint in the membrane, water would then be free to pass downwards. However, the pollutant retention efficiency, infiltration capability, water conservation efficiency and ability of this product to support microbial communities when installed in the pervious pavement system had not been previously studied before this work.

In order for the pervious pavement system to effectively perform the role in water harvesting and storage for reuse, the sustainable urban drainage device must not only be able to infiltrate as much stormwater as possible, but must also be able to have sufficient capacity to retain the infiltrated water as well as meet other required properties of a water storage system which includes:

a. Sufficient capacity to deal with the volume of water required to be stored for re-use and also sufficient storage to take account of additional requirements for flood attenuation purposes.
b. A structure which allows water to get into the reservoir. This should minimally have sufficient transmission capability to cope with the design storm which the pavement's flood protection performance is intended to deal with. Ideally it should also transmit water in such a way that after a rain event, as little as possible of the available volume of water is not held in the upper layers of the structure in a region where evaporative losses will be greater.
c. Evaporative loss potential should be as low as possible so that even in a situation where the soil temperature is elevated, the cooling structure of the system would ensure that any evaporated moisture is condensed within the system and gradually returned to the water storage layer.
d. Oil, metals and suspended solids retaining capability should be effective to ensure that pollutants are not transmitted with the water to the storage layer and that retained pollutants are effectively degraded within the system.

The high rate of infiltration of stormwater by the pervious pavement system is one of the main functions that make the device effective in source control which is one of the key objectives of sustainable urban drainage (SUDS). However, as opposed to an infiltration system where a pervious pavement system is designed to gradually attenuate the infiltrated stormwater through the sub base layer into the surrounding soil, a “tanked” pervious pavement system is designed to store water temporarily in the underground structure and then release it to a drain or surface water tank. Therefore, the author considered that in a case where the traditional pervious pavement system is modified for water harvesting and storage, and fitted with the two layer type of geotextile (described earlier) such as inbitex composite®, it would be necessary to determine the effectives of this new geotextile and how it would affect infiltration and potential water storage capacity of the pervious pavement system. Thus, the questions that needed to be answered were; if the pervious pavement system is to be adopted in developing countries such as Nigeria, where there is high annual rainfall in some cities such as Lagos and Port Harcourt (see page 3) and installed to provide the added benefit of water recycling, what would the water holding capacity of the system need to be? Furthermore, what hydrologic conditions would make the system easier to install?

The author had carried out some initial small scale experiments on reduction of evaporation loss when he became aware that Hanson Formpave was supporting an extensive trial at the University of Cantabria in Spain. Given that the work they were carrying out had the advantage of a much more appropriate climate the author decided that the time available for practical work in this programme would be much better spent in investigating the water throughput characteristics of the geotextile, leaving validation of evaporation losses to those better placed to do so.

In this chapter, experiments are reported which were designed to establish infiltration rate through the pervious pavement and the relationship between the modifications made on the geotextile material to increase infiltration of water through the system as well as water conservation capacity of the system are described and results presented. As a result of the development work carried out to achieve this, one of the major outcomes of the work described here was an experimental rig designed to reproducibly create very high and realistic rainfall events over model pavement structures. There is no evidence from literature, that a high flow test rig like this has been designed or used before in the world. Indeed, the design, construction and testing of this rig took significantly longer than the experiments carried out on it by the author. It does remain as a major resource for further studies. Experimental results reported here provided preliminary information on the potential capability of the pervious pavement system to support water recycling and hence, beneficial to other experiments reported in other chapters of this thesis. It is necessary to highlight that the number of data generated and presented in this thesis may not reflect series of repetition, time, resources and man-power expended to generate these results, especially the infiltration experiments.

7.2 Methodology

7.2.1 *Infiltration Studies*

- Preliminary infiltration experiment on the modified PPS
- Design and validation of a test for high rainfall infiltration studies
- Establish infiltration rate through the modified pervious pavement system
- Determine the relationship between type and size of slit made on inbitex composite and infiltration rate
- Determine the effects of ordinary inbitex overlap placed on the slits made on inbitex composite on the infiltration rate

7.2.2 *Preliminary Infiltration Experiments on Modified PPS with Inbitex Composite*

The aim of this experiment was to determine the flow rate at which infiltration through the pervious pavement system would be achieved and further increase in application rate of water would lead to flooding. Flooding in this case was defined by the author as the rise in the level of water above the pavement blocks on the surface of the pervious pavement system. Preliminary studies were carried out on a PPS modified with inbitex composite in a series of out-door test models of dimension 120cm x100cm x 60cm constructed from plastic stillages as shown in Figure 7.10 below. Previous researchers in Coventry University had made use of various models for laboratory experiments (Bond 1999, Coupe 2004, Spicer 2006, Puehmeier 2008); the size of this box offered the author the opportunity to study the PPS in a larger model. Initial single slits of 3.5cm and then 6.0cm was made at the centre of the material was tested with and without inbitex overlap.

Water was supplied through a hose pipe connected to the mains public water supply. The rate of flow of water over time from the hose pipe at a complete turn of the tap was measured three (3) times to determine an average flow rate before application to the test model. Water was applied to the model and the time was monitored by a stop clock until the system reached the saturation point at which infiltration stopped and additional application of water was observed to give rise to flooding of the system as water reached the top of the blocks. When application of water was slowed down, the height of water in the test rig started to fall from top of the blocks and subsequent little increase in application of water made water rise again above the blocks. This process was continued until the flow rate at which water held level with top of the blocks was achieved. This flow rate was then recorded.

Figure 7.1 Showing Construction of the PPS Model for Out-door Infiltration Experiments

7.2.3 *Design and Validation of Test Rig for High Rainfall Infiltration Studies*

The results obtained from preliminary infiltration experiment above showed relative poor reproducibility and variability (this result is presented in Figure 7.13). The possible reasons for these poor results were:

a. Poor reproducibility in water supply
b. Poor reproducibility in mode of application
c. The fact that huge amounts of water were being wasted, perhaps did not allow saturation to be determined accurately as there was no time for the application system to equilibrate and stabilize
d. Different sub-bases were used for different slit sizes instead of using same sub-base for same slit size. There was need for a more controlled experiment.

Consequently, it was proposed that the solution to these problems was a rainfall simulator with the capability of simulating high volume rainfall without depending on public water supply system. It was also considered that the new system would be able to prevent waste of water and provide sufficient space for testing of various rig models as well as provide solutions to other issues (raised above) that might have led to the failure of the preliminary tests.

The design of the test rig was based the theory that a constant head of water under gravitational force and stable conditions would supply water at flow rate that is proportional to the constant head of water. In the design of the test rig for high rainfall studies, the author considered it beneficial to test the practicability of this theory as well as the possibility of designing a test rig that would produce reproducible results by carrying out small scale tests before embarking on large scale design of the system. This was done using a small scale rig illustrated in Figure 7.2 but for the sake of brevity the detailed results are not reported.

It was observed that good reproducibility was achievable with the small scale test, but impractical to use thread (which was tried with in the small scale test) to form drips. There was need for a system that generated high flows and can provide good rain drop formation. Consequently, the decision was made to proceed with a highly modified design for the full-scale test rig for infiltration studies.

Figure 7.2 Small scale test measurement of rainfall intensity

7.2.4 *Large Scale Design of Test Rig*

Based on the result of the initial small scale laboratory test (shown in Figure 7.2), a large scale modified version of the model was designed and constructed in the hydraulic laboratory in Coventry University.

This laboratory has an underground water reservoir, which is constantly supplied by mains water. Two Weir Unimac$_{\mathrm{MKII}}$ pumps (Weir pumps Ltd, Glasgow, UK) enable the reservoir to supply water to a huge tank on the roof of the building through connected pipes. This tank on the roof maintains a constant head of water through a water re-circulation system which allows overflow water return to the underground reservoir. The tank on the roof supplied water to the over head tank of 120cm x100cm x 60cm of the infiltration test rig system through a water pipe of inner diameter 1.7mm fitted with a tap. This over-head tank was suspended at the height of 170cm from the base tank by steel bars welded to the base tank to provide adequate support. Holes of between 1-3mm diameter were made at the base of the overhead tank (20 holes per m^2) with a hand drill in other to simulate the diameter of raindrops. A hole of 4.2cm diameter was also made by hand drill at the side (right hand side) of the over-head tank (from the base); and an overflow outlet pipe of 25mm bore and 50cm in length was plugged into the hole and connected to the base tank to enable recirculation of water. The base tank was an already existing (in the laboratory) semi-underground tank of 230cm × 180.5cm × 160cm which was connected to the underground reservoir tank. The author made use of this base tank as a compartment for the pervious Pavement models (120cm x100cm x 60cm models used for experiment) undergoing test and ensured that the test rig was constructed in such a way that the system was directly overhead the base tank.

Also, a hole of 4.2cm was made at the side (left-hand side) of the over-head tank (from the base) and a plastic acute angle connector of 1.4mm diameter and length 2cm was fitted to the hole, facing upwards. Then, a clear calibrated (from base to top) glass tube of diameter 3mm was plugged into the connector from the base to the top of the tank. A rubber float of 1mm diameter was placed inside the glass tube in other to indicate the level of water in the tank at any time without having to climb up to look into the over-head tank.

A spider web like network of propylene sheets designed with spaces in-between the sheets of dimension 90cm x 46cm x 60cm originally manufactured for Permavoid UK Ltd for cooling towers was used a raindrop spreader. Two rain spreader boxes were joined together and suspended 30cm below the overhead tank. A cross-section of the raindrop spreader is shown in figure 7.3 and 7.4 below

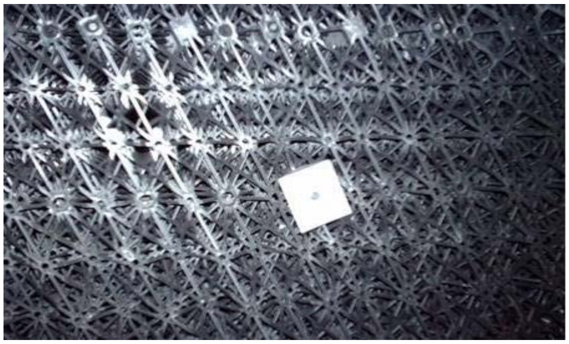

Figure 7.3 Cross-section of the Raindrop Maker

Figure 7.4 Raindrop Maker in Action

A steel rainwater collection (iron) tray of dimension 120cm × 100cm × 25cm was constructed with a water outlet hole of 10mm diameter made from the base of the tray with an electric drill. The tray was painted with Hammerite anti-rust primer® (ICI, UK) in other to avoid rust and placed on 2.5cm diameter and 2.6cm length castor rollers 34cm below the ‘spider web’ box. The function of this tray was to enable the measurement of simulated rainfall intensity.

Figure 7.5 shows the schematic diagram of the large test rig, while Figure 7.6 shows the picture of the test rig installed in Coventry University.

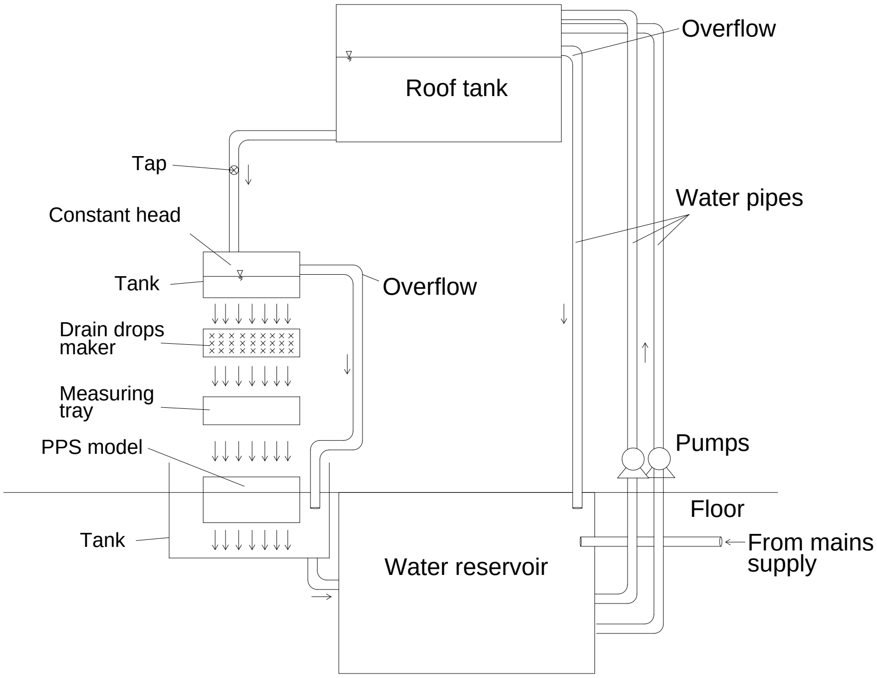

Figure 7.5 Schematic Diagram of Test Rig

Figure 7.6 Photograph of Test Rig Mounted in Laboratory at Coventry University

7.2.5 *Operation of the Large Scale Test Rig*

Water was supplied to the over-head tank of the test rig from the tank on the roof through the pipe by adjusting the tap (Figure 7.5). The system was allowed to stabilize and until a desired constant head of water was achieved in the over-head tank. The head of water measured by observing the level of water in the glass tube fitted to the over-head tank. Simulated rain at this head of water was collected in the tray until water starts to come out of the outlet at the base of this tray (Figure 7.7). Time was allowed for this to stabilize and simulated rainfall intensity was measured at each head of water in the overhead tank by determining the rate of flow and quantity of water from the outlet in the tray by measuring the outflow of water from tray per time with a pre-weighed bucket and stop watch. After determining the simulated rainfall intensity, the tray was then pushed away on the castors, hence allowing simulated rainfall on the pervious pavement model being tested (Figure 7.8). The test rig was calibrated and validated based on reproducible tests.

Figure 7.7 Water Rushing Out of Outlet Made in Metal Tray Mounted on Test Rig During Measurement of Intensity of Simulated Rainfall

Figure 7.8 Modified PPS Set-up in the Test Rig

7.2.6 *Determination of the Drop Size and Relationship with Intensity of the Rainfall Simulator in the Test Rig*

At a SUDSnet Meeting held in Coventry on the 7th of September, 2006; when the initial design of the water infiltration experiment was proposed (Nnadi *et al.* 2006), a suggestion from the floor was that the rainfall droplet size produced by this system should be determined at least to confirm that the droplets produced were of a size consistent with that of a heavy rainstorm.

The first attempt at this was conducted according to the pellet flour method developed by Hudson (1963) and used by Kukal and Sur (2004), Herngren *et al.* (2005). Following this method, an attempt was made to measure the mean drop size distribution (D50) by spreading a thin layer of non-compacted flour (supplied by ASDA Coventry, UK) on a tray and quickly passing the flour through the simulated rain shower at known rainfall intensity. According to the methodology, the flour would be dried and pellets formed sieved according to the ranges of their sizes, counted and weighed. This process would be repeated at different simulated rainfall intensities to determine the relationship between mean drop size distribution and intensity.

It was not possible to determine the raindrop size through the pellet flour method as presented in page 288. Therefore, the author decided to try other methods. However, methods in literature such as high speed photographic method, Staining technique, oil-capturing method (Lal and Elliot 1994); raindrop spectrometer; disdrometer and force transducer (Jayawardena and Rezaur 2000); and optical spectro pluviometer (Campos *et al.* 2006) could not be used because of the following reasons:

- High speed camera capable of taking raindrop photographs as described by the author was unavailable in Coventry University and funds were unavailable for the author to purchase such camera
- Staining and oil-capturing techniques were capable of polluting the water supply system which was the source of water supply to the test rig as shown in Figure 7.5
- Raindrop spectrometer, force transducer and disdrometer as well as optical spectro pluviometer were unavailable in Coventry University and funds was not available for the author to purchase them

Therefore, the author decided to try a simplified photographic method using FinePix A500 digital camera (Fujifilm Japan) set at 5mN (factory default) image quality setting. A 30cm graduated ruler was fixed to the raindrop maker (hanging downwards). The objective was to take a photograph of raindrops as close as possible to a graduated scale in order to be able to obtain raindrop diameter measurement with the help of the ruler. Photographs were taken while the test rig was operating at different rainfall intensities. Photographs that showed no raindrop or raindrops far from the ruler (indicated by them throwing a shadow on the ruler only much larger than the raindrop image) were discarded while the ones that showed raindrops close to the ruler such that the diameter of raindrop(s) could be read-off the graduated ruler were used to determine the range of raindrop size of the test rig. These photographs are shown in Figure 7.9.

The author is aware that the photographic method described above would not give exact measurement of the diameter of raindrop of simulated rainfall generated by the test rig, but offered an opportunity for the author to have sufficiently accurate measurement of the range of raindrop simulated by the test rig in order to satisfy the comments made by the Sudsnet meeting (2006), remembering that size distribution is an important characteristic of rainfall (Campos *et al.* 2006).

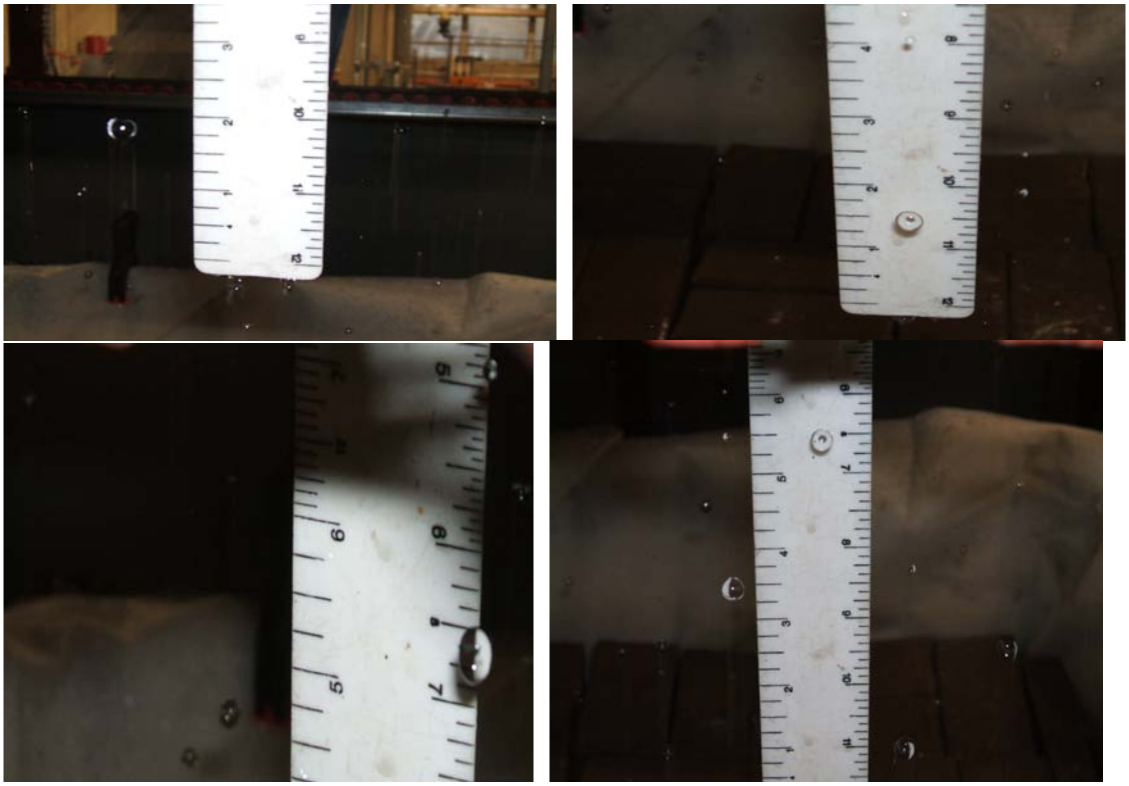

Figure 7.9 Examples of Photographs Used in Raindrop Size Measurements

7.2.7 *Test of Infiltration and Water Retention Capability of the Pervious Pavement System using the Test Rig*

The test rig described above was used to test infiltration capability of the layers of a typical Hanson-Formpave model with Inbitex Composite geotextile and for comparison, an attempt was made to test an alternative geotextile (Remavoid Biomat Geotextile, Permavoid Ltd, Amsterdam, The Netherlands) (see Puehmeier and Newman 2008).

7.2.7.1 *1st Test: Sub-Base Layer and Geotextile*

The sub base was laid to a thickness of 350mm with aggregates of 20-25mm (supplied by Cliffe Hill Quarry Leicestershire, UK). An inbitex composite® geotextile (supplied by Hanson-Formpave Ltd UK) cut to the size of 150cm ×130cm was laid on the sub-base layer covering all the inner sides of the box and firmly attached to the edges of the box with G-clamps in order to ensure that water only infiltrate through the geotextile to the sub base layer as shown Figure7.0a and 7.0b. Two halved Hanson Formpave paving blocks were placed one on top of another on the geotextile at the four corners of the box in order to ensure that the geotextile rests firmly on the sub-base. A measuring tape and pencil were used to mark out 10cm at the centre of the inbitex composite® geotextile installed in the model. Then, a sharp stainless steel scalpel was used to make a 10cm slit on the ‘marked out’ line at the centre of the geotextile for the 1st test. This slit was extended to 20cm for the 2nd test.

The test procedure was as described in earlier in page 276. The maximum rainfall intensity at which infiltration through the system was achieved without the head of water exceeding the depth of the blocks was recorded.

Figure 7.10 1st Test: Sub-Base Layer and Geotextile

The test was carried out 5 times at the same intensity and slit size and the mean value was recorded. Figure 7.10 shows the test of the sub base and the geotextile layer.

7.2.7.2 *2nd Test: Sub Base, Geotextile and Bedding Layers*

For this test, Clean 5mm aggregate stone (sourced from Cliffe Hill Quarry) was installed on the inbitex composite geotextile in the model described above as bedding layer according to Hanson-Formpave standard at a thickness of 50mm. Figure 7.11 shows the set up of the model with bedding layer incorporated.

Figure 7.11 2nd Test: Sub-Base, Geotextile and Bedding Layers

Tests were conducted at geotextile slit length of 20cm as it was observed that the slit length of 10cm on the inbitex composite was too small to achieve target infiltration capacity when bedding layer was added. The test was carried out 5 times at the same intensity and slit size and the mean value was recorded.

7.2.7.3 *3rd Test: Sub-Base, Geotextile, Bedding Layers and Pavement Blocks*

After conducting the 2nd test, Formpave aquaflow® paving blocks were laid on the bedding layer as shown in Figure 7.12 below. The complete permeable pavement system was then tested in the rig using the protocol described earlier in the 1st test.

Figure 7.12 3rd Test: Complete Pervious Pavement System

7.3 Results and Discussion

7.3.1 *Preliminary Infiltration Experiment: Modified PPS with Inbitex Composite*

It was observed from the preliminary infiltration studies that a high rate of infiltration through the slit of Inbitex composite geotextile was possible, but dependent on the size of slit. However, this study was unable to establish the relationship between the size of this slits and the rate of infiltration at different rainfall intensities. It also failed to indicate the rate of infiltration through the modified PPS. It could not point towards the hydraulic mechanism within the PPS especially at the point of infiltration through these slits under high rainfall intensity.

The preliminary results showed a lot of variability and poor reproducibility as shown in Figure 7.13

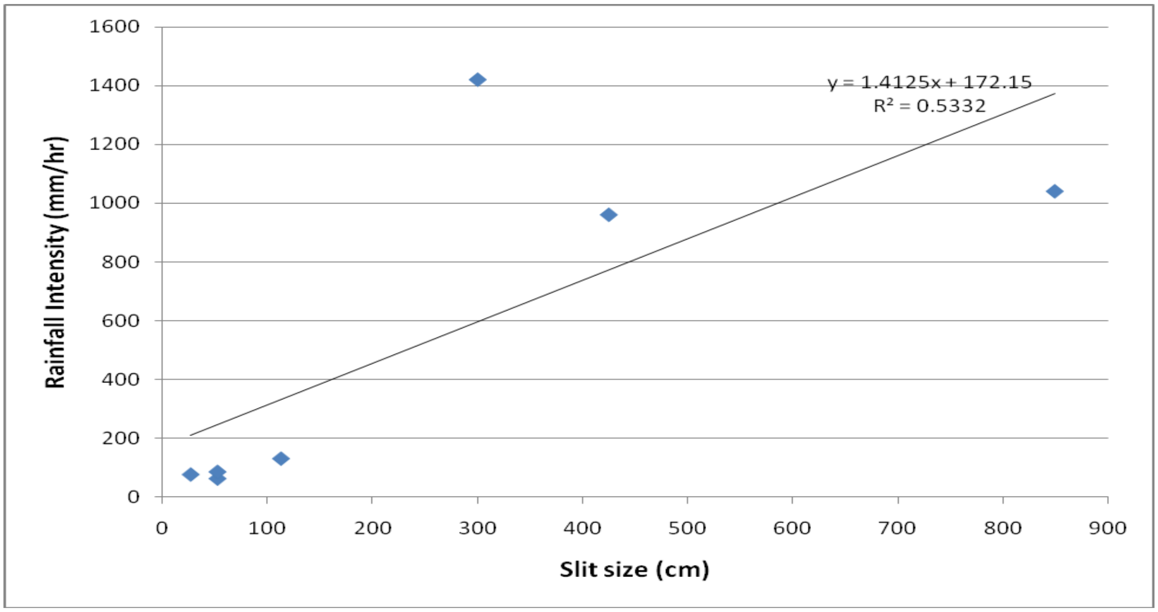

Figure 7.13 Preliminary Infiltration Experiment: Relationship Between Rainfall Intensity and Slit Size

The variability shown in these studies was at least partially attributed to the simulation of rainfall from hose pipes connected to public water supply system. These experiments were conducted in the afternoon when water supply from the public mains was under high usage at the factory site where these experiments were conducted; and hence could not supply water constantly and sufficiently in order to operate effectively as a rainfall simulation device for infiltration studies. Another factor was the fact that large mounts of water were passed through the system once only. This meant that it was not possible to allow extended equilibration periods without wasting a large amount of water (and causing a small flooding problem in the exterior yard where the experiment was carried out). This meant that the establishment of the point of "failure" was probably highly imprecise.

This highlighted the need for a rainfall simulator with the capability of simulating high volume rainfall without depending on public water supply system. It was also considered to design a system that would prevent waste of water since many replicates would be required for statistically valid results. Hence, it was decided to construct a test rig for high infiltration studies.

7.3.2 *Full Scale Test Rig - Validation Tests*

Calibration tests were used to establish the relationship between the head of water in the upper storage tank and the simulated rainfall intensity (as shown in Figure 7.14) as well as the long term stability of water flow and hence validate the suitability of the system as a test rig for monitoring infiltration of simulated high volume rainfall by pervious pavement and other urban drainage systems. The relationship between the head of water in the upper storage and simulated rainfall intensity was found to be highly correlated (Figure 7.14).

Further validation tests showed that the test rig was capable of supplying water constantly and sufficiently for infiltration test of pervious pavement models which was one of the reasons for its design. Also, this test rig is water conservative through its recirculation process which means that water was never wasted during its calibration and validation tests and the system could conveniently be used indoors without a flooding issue and allowing long periods for the establishment of equilibrium.

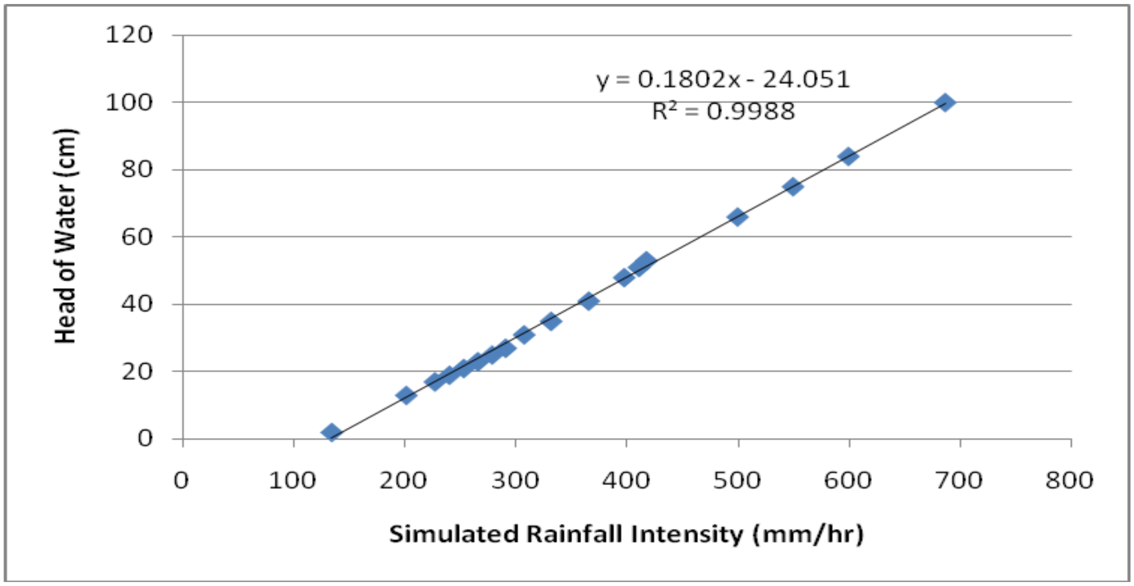

Figure 7.14 Full Scale Test Rig: Relationship between Head of Water and Intensity

The result of infiltration test of the pervious pavement system using the test rig for high infiltration tests is reported in page 293.

7.3.3 *Determination of Rainfall Drop Size of Rainfall Simulated by the Test Rig*

This test was conducted but failed to yield the expected results. As the flour was passed through the shower of raindrops simulated by the test rig even at the lowest possible rainfall intensity, the flour was observed to be flooded instead of producing expected pellets even after 3 days drying period at 110°C in an electric oven.

The failure of this method was initially attributed to over exposure of the flour to raindrops. Ogunye and Boussabaine (2002), while using the pellet flour method had observed that exposure of the flour for more than 1second was capable of causing coalescence of the pellets which would make the test unsuccessful. Consequently, several attempts were made to expose the flour to raindrops in less than 1 second. However, the resultant flour after each exposure and drying was a combination of pellets which could not be measured.

Consequently, it was proposed that the simulated rainfall intensity was high (even at the lowest intensity). Hence, the pellet flour method was considered an unsuccessful method for determination of the drop size of simulated raindrops of the test rig.

Therefore, as mentioned previously, the author established a simplified photographic method to measure the raindrop diameter (which was described in page 278).The result of the measurements of the diameter of raindrops simulated by the test rig from 20 photographs (shown in Figure 7.9) is presented in table 7.1 below. Measurements of 20 individual photographs are shown in Appendix 2.

Table 7.1 Diameter of Raindrops Test Rig Measured from 20 Photographs

Photograph	Diameter of Raindrop Measured (mm)							
1	8.97	6.21	2.76	1.38	1.03	-	-	-
2	5.52	3.79	3.45	2.41	2.07	-	-	-
3	8.28	4.83	4.14	3.45	2.75	2.41	1.72	-
4	8.28	5.52	5.17	3.79	3.10	2.07	1.72	-
5	6.21	5.86	4.83	4.48	2.75	2.41	1.38	0.69
6	5.86	5.52	5.17	4.48	2.76	1.03	0.69	-
7	6.90	5.86	5.52	4.83	3.45	2.07	-	-
8	5.52	5.17	4.14	2.07	2.76	2.07	1.03	-
9	7.59	5.17	4.83	2.76	2.41	2.07	1.72	-
10	5.17	4.83	2.07	-	-	-	-	-
11	5.17	4.83	-	-	-	-	-	-
12	6.21	5.52	4.83	4.14	3.45	2.07	1.38	-
13	5.52	4.48	4.14	3.79	3.10	2.76	2.41	-
14	5.52	4.14	3.45	2.07	-	-	-	-
15	7.59	6.21	5.17	4.14	2.41	2.07	1.38	-
16	8.97	5.17	3.79	-	-	-	-	-
17	4.83	4.14	3.79	3.45	2.07	-	-	-
18	5.17	4.83	-	-	-	-	-	-
19	7.59	5.86	4.83	4.48	3.10	-	-	-
20	5.52	4.83	3.79	3.45	2.07	-	-	-

Rain drop size distribution (DSD) is a basic characteristic of every rainfall (Uijlenhoet and Stricker 1999a, Uijlenhoet and Sempere-Torres, 2006). According to Uijlenhoet and Sempere-Torres (2006), DSD is defined traditionally as “*…the expected (mean) number of raindrops per unit of raindrop diameter interval and per unit volume of air. According* *to this definition, the notion of a raindrop size distribution is a mixture of two different concepts, namely that of spatial distribution of raindrops in a volume of air (which governs the raindrop concentration) and that of the probability distribution of their sizes".*

Hence, if the raindrop size distribution is denoted by N(D). Then, the expected (mean) number of raindrops with diameters between D and D +dD^2 per unit volume of air can be represented as N(D)dD (Uijlenhoet and Stricker 1999a,b).

Dimensionally, N(D) = L^{-4}, where L= length; the unit for diameter (D) = mm and Volume of air = m^3 ; therefore, the unit of N(D) = mm^{-1} m^{-3} (Uijlenhoet and Stricker, 1999a). A detailed review of different relationships and derivations of raindrop distribution was reported Uijlenhoet and co-workers e.g. (Uijlenhoet and Stricker 1999a; Uijlenhoet and Stricker 1999b, Uijlenhoet *et al.* 2005, Uijlenhoet and Sempere-Torres (2006),

The DSD is also dependent on rainfall intensity as well as other rainfall characteristics such as fall velocity and; the fall velocity (V) is a function of the Kinetic Energy (KE = $mV^2/2$) of the rainfall (Blanquies, Scharff, and Hallock 2003) as the drops impacts on the pavement blocks. A detailed review of the relationship between the kinetic energy of rain and rainfall intensity was conducted elsewhere (Salles, Poesen and Sempere-Torres 2002, Fox 2004).

Table 7.2 clearly shows the variety of raindrop size, diameter and volume produced by the test rig. This result is reasonably consistent with reported natural raindrop diameter

(The Columbia Encyclopedia, 2008). According to The Columbia Encyclopedia (2008), natural raindrop diameter ranges from 0.02inches (0.5mm) to 0.33inches (8mm). The famous Wilson Bentley (1885-1931) also known as the "*Snowflake and Raindrop man*" categorized raindrop diameter into five sizes namely: Very Small (<0.033inches/<0.85mm); Small (0.033 - 0.055inches/0.85 - 1.4mm); Medium (0.067 - 0.125inches/1.7 - 3.2mm); Large (0.143 - 0.200inches/3.6 - 5.1mm) and Very large (>0.200inches/>5.1mm) (Heidorn 2001).

Table 7.2 Categories of Rain Drop Size Obtained from Test Rig Arranged According to Wilson Bentley's Classification (Heidorn 2001)

Drop Size Category	Diameter Range	% of Total Drops (109) in Photograph	Volume of Drops (mm^3)
Very Small	< 0.033inches; < 0.85mm	1.84	< 0.322
Small	0.033 - 0.055inches; 0.85 - 1.4mm	6.42	0.322 – 2.51
Medium	0.067 - 0.125inches; 1.7 - 3.2mm	33.95	2.57 – 17.16
Large	0.143 - 0.200inches; 3.6 - 5.1mm	26.61	24.44 - 69.48
Very Large	> 0.200inches; > 5.1mm	31.19	> 69.48

Table 7.2 shows the distribution of the size of the raindrops obtained from rainfall simulated by the test rig. The author proposed that the relative high % of very large, large and medium sized drops could be explained by the high rainfall intensity (up to 600mm/h) obtainable from the test rig. Fox (2004) observed that for high rainfall intensities to occur; only certain drop-size-distribution (DSD) of rain drops is required

converse to wider variety in lighter rainfall. According to The Columbia Encyclopedia (2008), very large raindrops of up to 8mm could be obtained from thunderstorms and intense rainfalls.

The volume of the raindrops can be determined by the formula for calculating the volume of a sphere since raindrops are considered spherical in shape (Blyth, Benestad and Krehbiel 1997, Elert 2001, Uijlenhoet and Sempere-Torres 2006; Saylor and Sivasubramanian 2007).

Therefore,

Volume of sphere = Volume of raindrop = $4/3\pi r^3$ *Equation 7.1*

Where,

$\pi = 22/7$; r = radius; $2r = D$; D = diameter

Diameter of raindrops obtained = (0.69 – 8.97) mm

Mean diameter of raindrop = (0.69 + 8.97) mm/2 = 4.83mm

Therefore volume of smallest raindrop of diameter (0.69mm) = $4/3 \times 22/7 \times (0.345\text{mm})^3$

$= 0.17\text{mm}^3 = \mathbf{0.00017cm^3}$

Similarly, volume of largest raindrop of diameter (8.97mm) = $4/3 \times 22/7 \times (4.485\text{mm})^3$

$= 378.05\text{mm}^3 = 0.37805\text{cm}^3$

$\mathbf{\sim 0.38\ cm^3}$

It follows that the volume of mean raindrop diameter (4.83mm) = 472.18mm^3

$= 0.4722\text{cm}^3$

$\mathbf{\sim 0.47\ cm^3}$

Mass = density × Volume *Equation 7.2*

Therefore,

Mass of mean raindrop = density of water × Volume of raindrop

But density of water = $1 g/cm^3$; mean volume of raindrop = $0.47 cm^3$

Therefore, mass of raindrop = $1 g/cm^3 \times 0.47 cm^3$ = **0.47g**

7.3.4 *Infiltration Test of the Modified Pervious Pavement System*

Table 7.3 shows the result of infiltration and water retention tests of the components of a typical Hanson-Formpave pervious pavement system incorporated with the Inbitex Composite® geotextile. As stated in the methodology, the 10cm slit test was discontinued because it was observed that satisfactory infiltration at the target intensity was not achievable when bedding layer and the blocks were added.

Figure 7.3 shows increase in water rainfall holding capacity as a result of addition of each component of the pervious pavement system. However, the result actually shows differences in infiltration rate that would be a consequence of the head of water over the slit at the "failure" condition since the system was maintained at equilibrium during the tests (see pages 282-283) and the equilibrium head used was different for different parts of the experiment.

Table 7.3 Infiltration and Water Retention Capacity of Components of the Pervious Pavement System

Components of PPS	Slit size (cm)	Area of Model (m^2)	Rainfall Intensity (mm/hr)
Sub-Base +Geotextile	10	1.2	107
Sub-Base +Geotextile	20	1.2	200
Sub-Base +Geotextile + Bedding Layer	20	1.2	230
Sub-Base +Geotextile + Bedding Layer + Blocks	20	1.2	600
Alternative geotextile (Puehmeier 2008)	20	1.2	600

Furthermore, the difference observed after the addition of bedding layer and gravel could be as a result of the opening of the 20cm slit as the mass of gravel and subsequently pavement blocks exerted pressure on the slit widening it as the slit deformed to conform to the underlying stone sub base, hence allowing more water to infiltrate through the system.

The important issue of the result of these experiments is that they show that a typical Hanson-Formpave pervious pavement system of area of 1.2m^2 installed with Inbitex Composite® modified by making slits of 20cm is capable of infiltrating 600mm/h rainfall intensity without the occurrence of flooding in an unrestricted attenuation condition. A report of test of permeable pavements conducted by HR Wallingford (2007) concluded that an initial 5mm rainfall depth is required for wetting of the components of the pervious pavement system and that for short rainfall events; the rate of flow of water onto the pavement is higher than the peak discharge from the pavement. Furthermore, that equilibrium condition is achieved for extended rainfall events and that the existence of variability in response of the pavement to a given rainfall event depends on antecedent rainfall if the event is significant (HR Wallingford, 2007). While the attainment of equilibrium supports the measurement of infiltration at the state of equilibrium of the simulated rainfall event, the 5mm wetting capacity significantly shows according to HR Wallingford (2007), that rainfall events not exceeding 5mm depth on the pervious pavement system will not generate runoff. Thus in any rain event using a standard geotextile the first 5mm of rain would not be available to a stormwater collection system. If time had permitted, the author would have carried out a comparative study of this phenomenon between standard geotextiles and Inbitex composite as the author recognises that such comparisons would be very valuable.

The result of these tests provides modeling information for choosing slit type and length to achieve maximum infiltration relative to the rainfall intensity of the site without compromising pollution control. This will optimize the use of this modified PPS as source control, stormwater harvesting and storage device.

An example of how this result can be applied is as follows:
What is the length of slits on geotextile required for a 30m^2 paving?
1.2m^2 PPS performed well with 20cm slit (Table 7.3)
Therefore, 30m^2 PPS will require 500cm slit (i.e. 16.67cm slit per m^2) for optimal performance based on result from this thesis.

However, this length of slit maybe achieved without practically making slits on the geotextile by laying the rolls of geotextile "edge to edge" as shown in Figure 7.15 below.

Hence, for 30m^2 area:

Assuming that the geotextile is produced 5m/roll

Then 4 rolls will be required to cover 30m^2, which will offer an opportunity for 4 slit lengths at the joints of each roll.

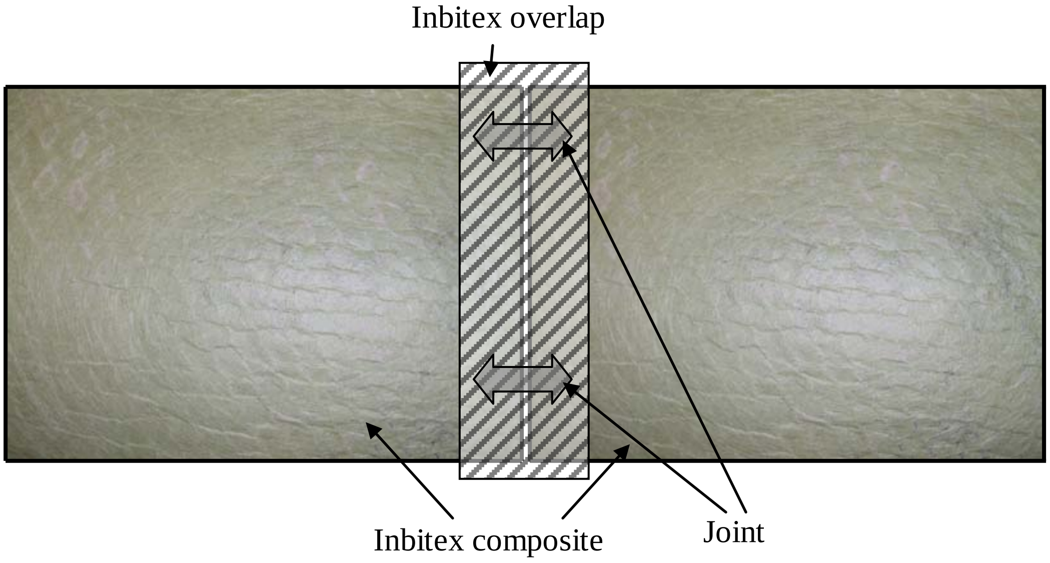

Figure 7.15 Proposed Installation Method of Geotextile to Form Slit Lengths

- The results of infiltration experiments presented in this chapter shows that it is possible to achieve sufficient infiltration through a modified pervious pavement system for water harvesting and storage using the system.

- Conclusively, this result (stated above) in addition to results already presented in Chapters 3-6 indicates that the potential of recycling water using the pervious pavement system is huge and the prospect of reusing water stored in the system for agricultural irrigation (without compromising health and safety as well as plant growth and development) is substantial and encouraging.
- The author is aware of the limitations of this study and has made suggestions for further studies in Chapter 8.

In the next chapter, the conclusions of this study, suggestions for further studies as well as a brief remark on the conclusions of this study.

Chapter 8: Conclusions and Suggestions for Further Studies

8.1 Conclusions

The conclusions of the findings of this research work are presented in this chapter and includes conclusions drawn from the extensive literature review carried out in this study as well as each set of experiments earlier presented in Chapters 3, 4, 5, 6, and 7 in order to clearly present the findings of each experiment.

At the beginning of this thesis, issues of global water scarcity, the continued depletion of world water resources in the face of climate change were raised. The global challenges to meet agricultural water requirement which has continued to increase with the increasing world population were also highlighted especially in the third world and developing countries. This study also recognized the impact of seasonal and erratic nature of rainfall supply on availability of water especially for agricultural uses which accounts for about 80% of world water usage. Through extensive literature review which was presented in almost all the chapters of this thesis, the author highlighted studies which have been conducted both in Coventry University (over a decade) and elsewhere on sustainable urban drainage system (SUDS) as a credible replacement for the conventional drainage system as well as the role of a particular SUDS device-the pervious pavement system in control of stormwater pollution, flood control (source control), provision of renewable energy (recent development) and the potential to provide alternative source of water supply for low grade uses and agricultural irrigation which is the main subject of this study. This information provided important basis for the design and conduction of the experiments presented in this study.

The conclusions of this study are presented in sections representing studies presented in Chapters 3-7.

Chapter 3: Water Quality of Waters Derived from a Range of Pervious Pavement Systems

The experiments and results presented in Chapter 3 provided an understanding of wider range of pervious pavement systems and also provided important information on the capability of these systems to deal with pollution. At the design phase of the experiments presented in Chapter 3, the author was faced with the problem of choice of source of water for the laboratory based experiment which would sufficiently replicate field conditions without introducing significant bias to the results of the experiments. Distilled water would have been ideal for this study, but the author considered it impracticable to use distilled in this study as large quantity of water was required. Tap water was readily available to use for this study, but there was need to show that this source of water would not significantly introduce bias to the outcome of this study. With the fore-going in mind, the author conducted preliminary experiments (reported in Chapter 3) on extraction of metals using de-ionized water, tap water and rain. The result showed that there was no significant difference between extraction of metals using either de-ionized water, tap water or rain water. Consequently, tap water was used in laboratory studies to effectively replicate field conditions where rainfall was the extracting liquid. The author is aware of the limitations of the use of tap water in this study as chlorinated water (tap water) may inhibit microbial activities (Ohio State University 2009, WHO 2009), which is essential for biodegradation. However, it was expected that the effect of the use of chlorinated water in the worst case, would be better than using other sources of water (such as rainwater) which may introduce significant levels of nutrients and dust to the experiment.

In order to further demonstrate capability of pervious pavement systems to retain pollutants, an experiment was designed (reported in chapter 3) whereby weekly loading of 12mgL/0.5m^2 of oil and 10.5g/0.5m^2 of sediments pollution at 13mm/hr rainfall intensity (twice monthly) using tap water were simulated on pervious pavement systems in laboratory based study for 9 months. Analysis of the effluents collected from the pervious pavement systems showed that the concentration of metals were below the WHO guidelines for drinking water, standards and recommended metal limits for irrigation and use of reclaimed wastewater used for irrigation (Tables 3.1 to 3.7). This result was consistent with earlier research works by Bond (1999), Coupe (2005) and Puehmeier, (2008). Furthermore, the results demonstrated the potential of recycling stormwater within the pervious pavement system and informed the design of experiments to investigate the chemical and electrochemical qualities of the water when harvested and stored in the pervious pavement system for irrigation purposes. Pot trial experiments using direct application of the stored water as irrigation water on plants confirmed that the water produced was highly suitable for agricultural irrigation (see Chapter 5). The author acknowledges that except in exceptional circumstances, it is unlikely that water stored in the pervious pavement system would be sufficient for irrigation for a full growing season, the aim is to harvest and store water during the wet seasons for re-use during the dry seasons.

Chapter 4: The Chemical Quality of Water Stored In Pervious Pavement System- Effects of Sub-base Type and Enhancement of Oil Biodegradation Using Inorganic Nutrients

In experiments to investigate the quality of stored water in the pervious pavement models (reported in Chapter 4), Elemental analysis, sodium absorption ratio (SAR), potassium absorption ratio (PAR), pH, electrical conductivity (EC), total suspended solids (TSS) indicated that the recycled water pose no threat to soil structure and plants if applied as irrigation fluid. The application of nutrients to the test rigs in order to enhance the biodegradation process resulted in the presence of some nutrients (NPK) in the stored water contrary to the result of earlier work by Bond (1999). However, it may be necessary to apply nutrients such as sulphur and nitrogen in order to meet plants needs depending on the type of plant and soil. Depletion of nutrients from the waters supplied by the system is expected to be continuous except additional nutrients are administered to the surface of the paving blocks. The rate of this depletion is also expected to be dependent on factors such as the rainfall intensity, the volume of water used for irrigation per day , volume of water stored in the test rig at each time as well as the rate of leaching of nutrients from the sub-base (if it is stone based), bedding layer and paving blocks. Consequently, monitoring of the nutrients with consideration to the need of plants is recommended by the author as it will facilitate the supplemental addition of depleted nutrients which are required by the crops. While this proposal could be considered practicable in the case of horticultural crops, the author is aware that it may be difficult to apply in the case of landscaping. However football fields and lawns are typical examples of where the application of this proposal may be beneficial in landscaping applications. Furthermore, the problem of eutrophication may arise if there is excessive release of effluents from the test rigs directly into surface waters. However the above problem and that of contamination of ground water are not expected to occur if the water is used for irrigation or released into the soil as the soil‘s natural attenuation mechanism as well as plant uptake are expected to deal with the excess nutrients before it gets to the ground water. The author is of the view that if these nutrients are controlled correctly, the effect of their application is expected to be no worse than fertilizer addition to crops.

The result of analysis of oil in water stored in the PPS (presented in chapter 4), further supports earlier studies by Bond (1999), Coupe (2004), Newman *et al.* (2004a,b) as well as the reported work in Chapter 3 that the pervious pavement system retains hydrocarbons effectively and that the normal level of hydrocarbon found in stormwater is not expected to pose a problem when stormwater is recycled in the system for irrigation. This was achieved despite the fact that the pervious pavement system was incorporated with Inbitex Composite geotextile with slits-the first study to attempt to look at oil retention in such a modified pervious pavement system.

Chapter 5: Effects of Stored Water in the Pervious Pavement Used for Irrigation on Plant Growth and Development

Results of pot trial experiments (presented in Chapter 5) indicated that the irrigation waters from the pervious pavement system was used to achieve 100% germination rate of seeds of tomatoes and ryegrass (as far as could be ascertained). Furthermore, the irrigation fluid supported growth and development of the plants to fruiting; and 2nd harvest in the cases of tomato and ryegrass respectively. The above results were achieved irrespective of the type of sub-base (stone or plastic). Metal analysis showed that the edible parts of the plants contained metals within internationally acceptable levels for human and live stock consumption.

Chapter 6: Microbiological Water Quality

The microbiological water quality experiments and the investigation of the water treatment by the test rig (presented in Chapter 6) showed that the baseline concentration of bacteria in model pervious pavement system was about 10^6colonies/mL. *Escherichia coli* introduced into the system were not retained within the system. About 85% of the introduced *E.coli* (potential pathogenic organism) was removed from the pervious pavement system on the first day of rainfall and re-growth was not observed in this study. It was observed in studies conducted in Australia that less than 30% of *E.coli* was washed off by ‘first flush’ of stormwater (i.e. by 30% of runoff event) (McCarthy, 2008). The study concluded that the ‘end flush’ was occurring instead of first flush phenomenon. The author did not observe the end flush phenomenon in this study and hence, concluded that the removal of *E.coli* was not as a result of the first flush phenomenon. Furthermore, based on the result of observed in this study, the author concluded that the pervious pavement system would not offer conducive environment for the persistence of potential pathogenic bacteria as the they are used to persisting in intestines of living organisms where the temperature is higher than that of the test rigs. However, in tropical countries of the world and during summer season in temperate countries, rise in soil temperature and sustained introduction of the organism from adjoining areas may pose a health hazard in water recycling application as the number of colonies may increase. Furthermore, the observed persistence of *E.coli* in environmental samples (left outdoor) further supports that consistent addition of the organism in water recycling and storage applications without adequate control measures may pose a risk during reuse. The author also concluded that in the case of reuse of stored water for irrigation, the method of irrigation is of great importance as drip and sub-irrigation methods are expected to minimize the risk of contamination from potential pathogenic bacteria (*E.coli* was used as an indicator in this study) as the irrigation will be applied to the root zone of the crops where the organism is not expected to persist. Conversely, sprinkler irrigation is not recommended as this method is expected to disperse the organism and hence, increase the chances of contamination especially through leaves and fruits as well as to the farmers who may be infected through the dispersed droplets.

In the same experiment reported in the Chapter 6, it was observed that the population of protists increased with the addition of the *E.coli*. The author concluded that this increase was due to available food sources which were the introduced *E.coli* and existing indigenous micro-organisms (e.g. bacteria) in the pervious pavement system that became active as a result of the presence of nutrients in solution as well as the addition of water (simulated rainfall) and the broth solution introduced during the addition of *E.coli*. The removal of *E. coli*, and the increase in the number of protists as well as their variability was observed in all test rigs irrespective of presence of geotextile or not. Hence, the author concluded that the presence of the geotextile layer had no affect on these biological mechanisms. However, the author expects that further studies will provide more information on this issue (see section 8.2 in this Chapter). Also, the active response of potential pathogenic bacteria to the presence of nutrients as observed in this thesis raises questions about the addition of nutrients to the pervious pavement system in order to stimulate oil biodegradation in field conditions if the PPS is also to be used for water recycling and storage applications. There is no doubt that these nutrients would be an added advantage if the stored water are to be reused for agricultural irrigation purposes as observed in the water quality and plant irrigation experiments reported in chapters 4 and 5 of this thesis. The author concluded that this advantage should be balanced with microbial water quality especially if the stored water is not intended to be reused for irrigation especially where the risk of continuous contamination from adjoining areas is relatively high. Furthermore, the duration of storage of the recycled water in the PPS before reuse is another issue which should be considered. The author is of the view that longer storage before reuse should be considered in high risk areas as it is expected to expose the potential pathogenic bacteria to unfavourable conditions (e.g. temperature) over a longer period which is expected to discourage their persistence. Furthermore, in a case where the PPS is also to be used as a source of renewable energy as in the case of ground source heat systems (GSHS) (Coupe and Nnadi 2007), the author is of the view that temperature fluctuations in the storage tank (Coupe *et al.* 2008b) may favour the persistence of potential pathogenic bacteria in the stored water in the system (this view was supported by Grabowiecki, Scholz and Coupe 2008) if there is significant and continuous contamination episode from adjoining areas (which may likely come from sewage system); while this is a subject for further studies, the author concluded that such joint usage should be discouraged until there is sufficient research information on the microbial safety of such stored water.

In the *Acanthamoba polyphaga* introduction experiments reported in Chapter 6, it was observed that the organism was non-detectable after the 1st week of the experiment. Based on this result, the author concluded that the complete removal of the organism from the pervious pavement system indicated the capability of the system to offer biological treatment in the case of occurrence of contamination episode with potential pathogenic protists and that the system does not offer a suitable habitat to the protist.

The author's proposal that the absence of the organism (*A. polyphaga*) in the effluent after 1 week maybe attributed to predatory activities of other eukaryotes (that took advantage of the newly introduced *A .polyphaga)* as observed by Nisbet (1984) could not be verified by this research work as this reported feeding pattern was not directly observed in the course of this study. Hence, this issue is inconclusive and should be subject of further studies (see section 8.2 in this chapter)

In the analysis of the components of the test rigs used in the experiment (reported in Chapter 6), a very low number of active *Acanthamoeba polyphaga* was detected on all the components of the rig materials from top to bottom, but more active cells were relatively found higher up in the pervious pavement system. Consequently, the author concluded that *A.polyphaga* was capable of moving through the rig components either by passive or active means enabled by its micro size and its ubiquitous characteristics. However, this movement was not directly observed in this study and is recommended for further studies (section 8.2).

Higher number of active cells of *A.polyphaga* was observed in pervious pavement system models that received either oil or nutrient addition or both oil and nutrient additions

(Chapter 6) relative to models that received no additions as no active cell was found in these models. Therefore, the author concluded that the presence of oil and nutrient in the pervious pavement system models supported the persistence of *A.polyphaga* as oil is a source of carbon when broken down and NPK supplied essential nutrients for the oil degrading microbes which in turn are a food source for the protists. Again, as stated earlier in the case of potential bacteria, the application of nutrients in field conditions to stimulate biodegradation of pollutants should be treated with caution and consideration should be made of reuse application of the stored water in view of the fact that it activates the potential pathogenic organisms.

A.polyphaga was not detected on the outdoor and indoor aggregates. This demonstrated that the risk of *A.polyphaga* contamination from test rig materials is very remote and any opportunistic contamination of the pervious pavement system by the organism in high levels may only emanate from adjoining areas. In such cases, if the stored water is to be reused for agricultural irrigation, the author concluded that drip irrigation should be preferred to surface irrigation as it is expected to minimise the risk of infection of workers and crops.

Chapter 7: An Evaluation of the Use of Stored Water Derived from Pervious Pavement s Systems for Irrigation Purposes

Another factor addressed in the investigation into the suitability of the pervious pavement systems for water harvesting was the capability to capture the water available in rainfall (especially during wet seasons). The Design of a test rig for high infiltration studies (reported in Chapter 7) made it possible for high infiltration studies to be conducted on the pervious pavement system. The calibration of the test rig which produced over 600mm/hr rainfall intensity was successful and established an almost linear relationship between the simulated rainfall intensity and head of water in the storage tank. Thus, allowing a relatively easy method of setting up water flow for a given demand and providing a quick estimate of flow. An initial attempt to determine the raindrop size produced by the test rig using flour pellet method was unsuccessful. It was concluded that this method will not work due to the high rainfall intensity generated by the test rig. Consequently, a cost-effective method using digital photographic method was developed and used successfully to determine the drop size of simulated rainfall by the test rig. Results obtained by this method indicated that the raindrop diameter varied from 0.69 - 8.97mm and consistent with the high rainfall intensity generated by the test rig. Categorization of rain drop size showed 1.84%, 6.42%, 33.95%, 26.61% and 31.19% for very small, small, medium, large and very large drops respectively. It was concluded that the large proportion of medium, large and very large raindrops was as a result of the relatively high rainfall intensity generated by the test rig.

Infiltration tests on the pervious pavement system incorporated with the novel inbitex composite geotextile modified with slits (reported in Chapter 7) showed that when the system was maintained at equilibrium, a difference in infiltration capability was observed after the addition of the bedding layer and blocks to the subbase layer with the geotextile (modified with 20cm slit) incorporated between the sub-base and bedding layers over a pervious pavement area of 1.2m^2. Part of the difference in infiltration capability was attributed to the mass of the gravel (bedding layer) and paving blocks exerting pressure on the slit made on the geotextile thus allowing more water to pass through the system. This hydrologic mechanism is not yet clear and should be subjected to further studies (section 8.5) as the process may be capable of compromising pollution retention properties. If the slits are to be produced at the joints of the geotextile as proposed in Chapter 7 (page 297), then this needs to be optimized.

Further tests (reported in Chapter 7) provided what may be regarded as prescriptive information to drainage Engineers on the choice of geotextile and slit length per square metre of geotextile whose objective is to maximize infiltration through the pervious pavement system for water storage and recycling purposes relative to the rainfall intensity obtainable in the area without compromising pollution control function of the pervious pavement system. Also prescribed a method of laying of the geotextile which might make it unnecessary to practically make slits on the geotextile as the joining of the geotextile edge to edge (depending of the area of the geotextile per roll as well as the pavement area) could provide the desired slit mechanism. Summarily, the results demonstrated that the pervious pavement system so modified could support water recycling by controlling pollution, infiltrating sufficient water for storage and minimizing the loss of stored water through evaporation.

- Summarily, the pervious pavement system offers a great opportunity for stormwater recycling and storage which could be utilized for many purposes such as irrigation and asthetic uses. It is obvious that issues concerning water quality are enormous; this research work has made attempt to investigate some of these issues and point-out what the author regarded as the way forward in others. The outcome of this research supports that recycling and storage of stormwater in the pervious pavement system is possible and viable.

- Furthermore, this study also reported that the water recycled and stored in the pervious pavement system could be used for irrigation of crops to produce food fit for human and animal consumption without endangering human and animal life as well as not posing a threat to the soil structure.
- Also, this study reported that although the threat of potential pathogenic bacteria (e.g. *E.coli*) and protist (*A. polyphaga*) to the stored water is real, the removal of *A.polphaga* and *E.coli* demonstrated that the organisms does not have prolonged residence time within the pervious pavement system and that the pervious pavement system is effective in the removal of potential pathogenic pollutants such as *A.polyphaga* and *E.coli* should they find their way into the system.

8.2 Suggestions for Further Studies

In the introduction of this study, the author accepted that the objectives of this study were ambitious for a three year PhD programme. However, this study has provided conclusive information on many issues regarding water quality and reuse of stored water in the pervious pavement system as presented earlier in section 8.1 of this chapter and what the author considered as the way forward in other issues. This study also raised many issues which require further scientific investigation, since it is obvious that issues pertaining to water quality are enormous. With the fore-going in mind, the following issues raised by this study are suggested for further studies which in many ways serve to highlight what the author considers as short comings in the research reported in this thesis.

1. This study recognized that salinity of irrigation water could pose a major problem to soil structure (Chapter 4). The waters stored in the pervious pavement system studied did not pose soil structure problems, but there is need to study this aspect further. For example, the potential impact of salt application on pervious pavement systems (gritting) during winter seasons on the stored water quality in view of the effect such water could have (if salinity is high) on soil structure if it is used for irrigation.
2. In chapter 3, the $CaCO_3$ chemistry of test rig 4a and 4b was noted as a potential reason for the difference in the concentration and availability of metals observed in the effluents from porous concrete models 4a and 4b which were contrary to the author's expectations. In view of works done by Stead-Dexter and Ward (2004) and Codling and Dao (2007) on the effects of pH and $CaCO_3$ on the

mobility of Pb and other metals in solution, the author considers that a long- term study should be conducted on the $CaCO_3$ chemistry of the pervious pavement system especially porous concrete and the potential effects it could have on the mobility of metals in solution within the system. This further study would be designed to determine whether such chemical relationship (if any) has the potential to compromise the capability of the PPS to remove metals and other pollutants in stormwater in both the short and long terms.

3. Continuous pollution of the pervious pavement systems studied in chapter 3 to their ‘breakthrough periods’ described as ‘catastrophic failure oil addition’. This was not conducted as at the time of writing this report due to the need to comply with the University’s deadlines. However, the project is still on-going. It was proposed that at two months to the end of the study, a simulation of sump failure would be carried out on the test models. This would be conducted by applying 5 litres of oil in one dose to the centre of each of the models 24 hours before the next rainfall event. It was proposed that the oil would be applied from a plastic bucket with a calibration mark generated by filling 5kg distilled water. After pouring the oil onto the surface of the model from the bucket, the bucket would be allowed to drain onto the surface in an inverted position for about 10 minutes. The rainfall and sediment addition would be carried out as normal as it was proposed that the retention of the residual oil by the bucket would be the same for each of the models and would be ignored. This experiment is expected to provide information on the how much oil pollution that these pervious pavement systems can withstand before the breakthrough of free product and hence, determine the life span of these systems.

4. The experiments presented in chapters 3, 4, and 6 were conducted with clean oil (where oil addition was carried out). Although Coupe *et al.* 2006b observed that results of laboratory based studies conducted with clean could be applied to field conditions, the author is aware of variability which may occur when clean oil is used in laboratory based studies to replicate field conditions as also observed by Dange (2008). These issues as well as the reason for the decision by the author to apply clean oil in these experiments are presented in page 93 of this thesis. Consequently, the author suggests that these experiments should be repeated with used oil in order to compare the results presented in this thesis in chapters 3, 4 and 6 to a situation where used oil is applied instead of clean oil. At the same time, it might be useful to add road dust along the lines of the experiment reported in Chapter 3.

5. In the experiments reported in chapter 5, the major nutrients supplied through the added nutrient (NPK) could usefully be a subject of further studies in order to ascertain the slow release process of these nutrients in situations where the applied on PPS designed for water storage. This is to ascertain the rate of nutrient addition and the extent to which nutrients are used for formation of biofilms.

Furthermore, the microbiological activities should be investigated by monitoring CO_2 and temperature.

6. Relatively higher concentration of K and PAR was observed in Permavoid based test rigs in results of experiments presented in Chapter 4. The author could not attribute this to any particular reason since the plastic sub base could not be said to be a credible source of K. However, the author suggested that this could either be as a result of an error or as a result of the pronounced voids in the plastic sub base which makes it easier for K to leach into the stored water than in the case of the stone sub base where the voids between the stones are less (than in the plastics) (page 138). Further investigation of the mobility of K in the stone and permovoid based systems are suggested in order to provide information on the reason for this observed increase in K.

7. In plant growth experiments reported in chapter 5, relatively higher level of Zn (>60mg/kg) was observed in soil samples treated with DI water and planted with Tomato relative to the level of Zn observed in the soil treated with DI water and plated with ryegrass (<35mg/kg). The author suggested that this could be as a result leaching, sampling error, effect of peat content of the compost used as soil, as well as the mobility of Zn. A further study is expected to provide more information on the rate of removal of Zn and other metals by landscaping crops compared to horticultural crops. Gray and Mclaren (2005) also recommended further studies to provide more information on the use of ryegrass for

phytoremediation. The author also suggests a repeat of the pot trial experiments reported in Chapter 5 with different types of composts and soil in order to compare the results presented in Chapter 5 with a situation where soil or other growing media is used instead of seed compost. This information is expected to be useful in Africa and Latin America where the growing media is predominantly soil.

8. In the investigation of the microbial water quality reported in Chapter 6, the author could not study viruses and helminthes due to time and resource constraints. However, the author is aware the risk these potential pathogenic organisms could pose in water recycling and application within the pervious pavement system as presented in pages 215 - 227. The author suggests that viruses and helminthes should also be studied in order to complete the holistic study of the microbial safety of the recycled water within the pervious pavement system.

9. In Chapter 6, the author suggested that the removal of *A.polyphaga* from the test rigs within 1 week could be attributed to the feeding pattern of the indigenous eukaryotes, which may have taken advantage of the newly added *A.polyphaga* (page 257). However, this theory was not investigated in this study. Therefore, the author is of the view that further studies would provide more information on this theory and as well as provide an opportunity for a complete investigation of the protozoan community which was not conducted in this study.

10. In the results of infiltration experiments presented in Chapter 7, the author recognized that the hydrologic mechanism at the point of infiltration of water through the slits made on the geotextile as well as the pressure exerted on the these slits by the bedding layer and pavement blocks may have an effect on the infiltration of water through the pervious pavement system modified for water harvesting (see page 294-295). Hydrologic investigation is suggested in order to provide more information on these mechanisms and possibly to inform changes in the construction techniques used when using Inbitex composite® to help in the reduction of evaporative losses.

11. In chapter 7, the author reported the results of tests conducted by HR Wallingford (2007) on the typical Hanson-Formpave pavement system (see page 295). This test results reported that the Hanson-Formapave pavement system incorporated with standard geotextile has a 5mm wetting capacity, such that rainfall events on the system not exceeding 5mm will not generate run-off. Due to time constraints, comparisons of this phenomenon with systems incorporated with Inbitex composite was not carried out by this study. However, the author recognizes that such comparison would be very valuable and therefore, suggests that that this comparison should be conducted.

8.3 Evidence of Originality and Innovations of Thesis

The author is of the view that this study made the following major contributions to knowledge:

- Confirmation of the pollution control capability of the porous pavement system as earlier determined by previous studies

- Design of Experimental rig to reproducibly create very high and realistic rainfall events over model pavement structures. There is no evidence from literature, that a high flow test rig like this has been designed or used before in the world.

- In this study the performance of a new geotextile, Inbitex Composite® in the pervious pavement system was determined for the first time. Furthermore, this study also tested for the first time, the performance of a pervious pavement system modified by the incorporation of Inbitex Composite® geotextile with slits and made prescriptions as to how this new geotextile could be best installed in a modified pervious pavement system in order to achieve high infiltration without compromising pollution control.

- This study is the first to test the practical use of the pervious pavement system for water harvesting and storage for reuse in irrigation. In order to achieve this, the author took what could be considered as a holistic approach to water quality issues and determined the chemical, electrochemical and microbiological quality of water stored in the system as well as investigated the public health concern of the potential existence of pathogenic organisms in waters stored in unconventional water storage system as the pervious pavement system. It is also the first study to determine that the pervious pavement system have the capability to recycle water that will meet international standards for irrigation and that the system does not offer a conducive environment for potential pathogenic organisms if contamination incident occurs from adjoining areas.

- Furthermore, this study also became the first to practically relate SUDS to agricultural benefit by demonstrating practically, how a SUDS device (pervious pavement system) could be used in addition to its urban drainage control role, as a source of supply of high quality irrigation water to cultivate crops fit for human and animal consumption despite high application of pollutants.

- This study contrary to the observation of Bond (1999), determined that the use of slow-release fertilizer could lead to eutrophication problems in cases where the water is channeled to natural water courses. Furthermore, active response of potential pathogenic bacteria to the presence of slow-release fertilizer was observed in this study. This raises a huge question on the need to add fertilizer to the pervious pavement system. While Coupe (2004) had demonstrated that oil degrading microbes would respond positively to food sources in the system and hence, there was no significant need for simulation by nutrient addition, the author concluded in the study presented here that fertilizer addition should only be conducted if the waters are to be used for irrigation where the nutrients would be beneficial to the plants and that even in this case, the microbiological water quality should be constantly monitored and the addition suspended if the risk of contamination from adjoining areas is high.

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APPENDICES

Appendix 1

Calibration of Test Rig for High Infiltration Studies

Head(cm)	Flow1(ml)	Flow2(ml)	Mean Flow(ml)	Flow1(l/h)	Flow 2(l/h)	Mean Flow(l/h)	Intensity1(mm/hr)
2	2678.5	2752	2715.25	160.71	165.12	162.915	133.925
13	4022.5	4184	4103.25	241.35	251.04	246.195	201.125
17	4540.5	4592.5	4566.5	272.43	275.55	273.99	227.025
19	4801.5	4901	4851.25	288.09	294.06	291.075	240.075
21	5059	5202	5130.5	303.54	312.12	307.83	252.95
23	5315	5398.5	5356.75	318.9	323.91	321.405	265.75
25	5573	5628	5600.5	334.38	337.68	336.03	278.65
27	5813.5	5892.5	5853	348.81	353.55	351.18	290.675
31	6148	6231.5	6189.75	368.88	373.89	371.385	307.4
35	6635.5	6780	6707.75	398.13	406.8	402.465	331.775
41	7313.5	7409	7361.25	438.81	444.54	441.675	365.675
48	7954.5	8001.5	7978	477.27	480.09	478.68	397.725
51	8221	8256.5	8238.75	493.26	495.39	494.325	411.05
53	8353	8409	8381	501.18	504.54	502.86	417.65
66							500
75							550
84							600
100							687.22

Appendix 2

Raindrop Measurement using Photographic Method

Raindrop size measurement using photographic method: **Photo 1**
(1inch on photo = 1.45inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
13	8.97
9	6.21
4	2.76
2	1.38
1.5	1.03

Raindrop size measurement using photographic method: **Photo 2**
(1inch on photo = 1.35inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
8	5.52
5.5	3.79
5	3.45
3.5	2.41
3	2.07

Raindrop size measurement using photographic method: **Photo 3**
(1inch on photo = 1.4inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
12	8.28
7	4.83
6	4.14
5	3.45
4	2.75
3.5	2.41
2.5	1.72

Raindrop size measurement using photographic method: **Photo 4**
(1inch on photo = 1.72inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
12	8.28
8	5.52
7.5	5.17
5.5	3.79
4.5	3.10
3	2.07
2.5	1.72

Raindrop size measurement using photographic method: **Photo 5**
(1inch on photo = 1.45inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
9	6.21
8.5	5.86
7	4.83
6.5	4.48
4	2.75
3.5	2.41
2	1.38
1	0.69

Raindrop size measurement using photographic method: **Photo 6**
(1inch on photo = 1.6inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
6.5	4.48
7.5	5.17
8	5.52
8.5	5.86
7.5	5.17
1	0.69
1.5	1.03
4	2.76

Raindrop size measurement using photographic method: **Photo 7**
(1inch on photo = 1.65inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
7	4.83
8	5.52
5	3.45
3	2.07
8.5	5.86
10	6.90

Raindrop size measurement using photographic method: **Photo 8**
(1inch on photo = 1.5inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
8	5.52
4	2.76
6	4.14
3	2.07
7.5	5.17
1.5	1.03
2.5	1.72

Raindrop size measurement using photographic method: **Photo 9**
(1inch on photo = 1.8inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
7.5	5.17
4	2.76
7	4.83
11	7.59
3	2.07
2.5	1.72
3.5	2.41

Raindrop size measurement using photographic method: **Photo 10**
(1inch on photo = 1.5inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
7	4.83
7.5	5.17
3	2.07

Raindrop size measurement using photographic method: **Photo 11**
(1inch on photo = 1.83inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
7	4.83
7.5	5.17

Raindrop size measurement using photographic method: **Photo 12**
(1inch on photo = 1.65inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
6	4.14
7	4.83
3	2.07
8	5.52
6	4.14
2	1.38
9	6.21
5	3.45

Raindrop size measurement using photographic method: **Photo 13**
(1inch on photo = 1.35inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
6.5	4.48
6	4.14
4.5	3.10
5.5	3.79
4	2.76
8	5.52
3	2.07
3.5	2.41

Raindrop size measurement using photographic method: **Photo 14**
(1inch on photo = 1.45inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
8	5.52
6	4.14
3	2.07
5	3.45

Raindrop size measurement using photographic method: **Photo 15**
(1inch on photo = 1.65inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
9	6.21
3	2.07
6	4.14
7.5	5.17
11	7.59
2	1.38
3.5	2.41

Raindrop size measurement using photographic method: **Photo 16**
(1inch on photo = 1.65inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
13	8.97
7.5	5.17
5.5	3.79

Raindrop size measurement using photographic method: **Photo 17**
(1inch on photo = 1.5inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
3	2.07
5	3.45
6	4.14
7	4.83
5.5	3.79

Raindrop size measurement using photographic method: **Photo 18**
(1inch on photo = 1.45inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
7	4.83
7.5	5.17

Raindrop size measurement using photographic method: **Photo 19**
(1inch on photo = 1.5inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
8.5	5.86
4.5	3.10
11	7.59
7	4.83
6.5	4.48

Raindrop size measurement using photographic method: **Photo 20**
(1inch on photo = 1.65inches as measured)

Diameter of raindrops on photograph (mm)	Actual diameter of Raindrops (mm)
7	4.83
8	5.52
5	3.45
3	2.07
5.5	3.79

Appendix 3

Methodology for Digestion and Analysis of Sediment for Metals (Chapter 3)

Digestion of Sediment

Approximately 0.6g (3d.p) of the sample was accurately weighed using a weighing balance. The weighed samples were put into a fluorocarbon digestion vessel from the Milestone Microwave digestion System (Model MLS 1200 Mega), Leutkirch Germany.
In other to achieve repeatability, 4 more aliquots of the sample were used. One acid blank and 2 spiked blanks were used for the digestion run using 1000mgl^{-}1 analytical standard solutions of the metals (supplied by Fischer Ltd UK).

3ml of concentrated Nitric Acid and 3ml of hydrogen peroxide (both analytical grade) were added to each of the 7 digestion vessels (contents described above). Other 13 vessels in the rotor were filled with distilled water in other to complete the operational capacity of the rotor which is 20 vessels. The vessels were the sealed with torque Wrench (supplied by manufactures) according to the manufacturer’s instructions. Care was taken to ensure that water was not trapped under the plastic calibrated spring as instructed by manufacturer. The digestion was then carried according to the manufacturer’s instructions using the programme shown below

Microwave Protocol used in Digestion of Sediments

Time (minutes)	Energy (W)
2	250
1	0
5	400
4	580
3	0 (Cool)

At the end of the digestion, and after 5 minutes cooling period, the contents of the 7 vessels (except those filled with distilled water) were decanted into 50ml volumetric flasks and made up to the mark with distilled water and allowed to settle before ICP analysis.

Concentrations of Spiked Solutions

Element	Spike Solution 1	Spike Solution 2
Zinc (Zn)	0.4	0.8
Copper (Cu)	1.2	2.4
Lead (Pb)	4.0	8.0
Nickel (Ni)	4.0	8.0

Analysis

1000mgl^{-1} Standard solutions used in preparation of the spikes were used in preparation spikes were used to prepare the standards for ICP analysis. The approximate concentration of the standard solutions (mgL^{-1}) used for calibration of the ICP are shown in table below. A preliminary suite of the samples was run on ICP in other to ascertain the concentration of each metal in the samples. The standard concentrations were then computed based on this information. The sample concentrations from ICP analysis were in mgl^{-1} which was then converted to mgkg^{-1} using the equation shown below:

$$\text{Concentration in Solid (mgkg}^{-1}\text{)} = \frac{\text{Conc. In undiluted digest Solution (mgL}^{-1}\text{)} \times 50}{\text{Mass of Sample (g)}}$$

It was checked to ensure that the blank values were not greater than 1% of the calibration range and that the two spike solutions were correct within 5% of the expected value.

Approximate Concentrations for Calibration Standards for ICP (mgl^{-1})

Element	Standard Solution Concentrations				
Zn	0.0	0.5	1.0	1.5	2.0
Cu	0.0	1.5	3.0	4.5	6.0
Pb	0.0	5	10	15	20
Ni	0.0	5	10	15	20
Cd	0.0	0.5	1.0	1.5	20

Determination of the Solubility of Metals in Sediment in Water

A series of dissolution experiments were conducted to determine the solubility of heavy metals in the sediment in three different types of water. The waters used were: tap water, rainwater and de-ionized water. Rainwater was chosen as it is slightly acidic and metals are known to be more soluble under acidic conditions (Forstner and Wittmann, 1985). Tap water was considered as it was used in rainfall simulation in the experiment and was collected from the public water system in Coventry University. However, rainwater was collected by placing a clean, dry and open 10 litres capacity bucket at the roof of James Starley Building in Coventry University during a rainfall event. De-ionized water used in this experiment was supplied by ReAgent Chemical services Cheshire, UK.

The method used for dissolution was based on MAFF (1986). 15g of homogenized and sieved (described above) street dust was suspended in 50ml of water (tap water, rainwater and de-ionized water in each case) in a 100ml round bottomed flask. The flask was covered with a rubber cork and shaken for 1hour using automated shaker. The supernatant liquid was filtered out using 47mm whatman filter paper.

Analysis of Zn, Cd, Cu, Pb and Ni was conducted using ICP as earlier described above in chapter 4

Total Suspended Solids (TSS)

The method used for determination of TSS is based on the method presented in the Yorkshire Water Methods of Analysis Manual 1988 with the following modifications.

- Drying times were extended from 1 hour to 4 hours
- Cooling times were extended from 5 minutes to 1 hour
- The filter diameter used was 47mm not 70mm
- No provision was made for the removal of the contribution of the free oil since it was considered as an important part of the non-dissolved phase of the sample.

Materials

- Filters papers – Whatman grade GF/C, 47mm
- Hartley type funnel/ clamp devices (47mm)
- Vacuum system –supplied in analytical Laboratory, Coventry University

Method

- A pencil was used to label the edge of a batch of 18 filter papers with identification marks representing the 9 test rigs at the region of the filter paper that would be covered with a clamp (2 filter papers for one test rig)
- Each filter paper was mounted on a clamp and washed with 100ml of de-mineralized water
- Each filter was then removed and dried on a Petri dish at 105 degrees Celsius in electric oven for at least 4 hours
- The papers were cooled in a dessicator for at least 4 hours
- Each Filter paper was then weighed to 1mg using a certified analytical balance. The balance was checked before use using 100mg, 1g and 50g certified masses to ensure that the balance recorded a mass within 0.1mg of the mass of the certified masses.
- A set of 18 Petri dishes were labeled with the mark on the filter papers using a mounted needle and dried for 4 hrs at 105 degrees Celsius in electric oven
- The Petri dishes were then cooled in a dessicator for 4 hours and weighed. The weights were recorded
- The filter papers were then transferred to funnels with forceps, clamped down
- Sample of effluent from each test model of more than 800ml was thoroughly hand shaken
- 250ml of the sample was measured out from the step above using a volumetric flask and poured gradually through the filter papers, shaken at intervals. The effluent that passed through the filter paper was collected in a 500ml beaker

- When the flask was empty, 10ml of reverse osmosed water was used to wash 3 times to wash the flask, passing each wash through the appropriate filter paper
- The filter papers were then transferred to each similarly labeled Petri dish using forceps and dried at 105 degrees Celcius for 4 hours
- The filter papers and Petri dishes were cooled in a dessicator for 4 hours and weighed together.
- TSS was calculated using the equation shown below

Msolids =Mfinal – (Mfilter + Mdish)

TSS (mg/l) = (Msolids / Vsample) × 1000

Where:

Mfilter = Mass of clean filter (g)
Mdish = Mass of Petri dish (g)
Mfinal = Mass of filter + Petri dish + filtered Solids (g)
Vsample = Volume of sample filtered (litre)

Appendix 4

Extractable Cd, Cu, Ni, Zn, Pb with DI water, Tap water and Rain

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
DI	5	3.352222	0.670444	0.663993679
Tap Water	5	3.458889	0.691778	0.661430296
Rain	5	3.314444	0.662889	0.642974444
Cd	3	0.01	0.003333	1.88079E-37
Cu	3	5.331556	1.777185	0.001078337
Ni	3	0.466667	0.155556	5.13086E-05
Zn	3	0.411556	0.137185	0.000442288
Pb	3	3.905778	1.301926	0.009269646

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Types of Water	0.002245	2	0.001122	0.461888132	0.6459	4.458970108
Metals	7.854155	4	1.963539	808.1008661	1.85E-10	3.837853355
Error	0.019439	8	0.00243			
Total	7.875838	14				

Appendix 5

Oil in Test rig Models 1a, 1b, 2a, 2b, 3, 4a, 4b, 5 and Pavement

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	9	0.009	0.001	2.5E-07
Row 2	9	0.009	0.001	0
Row 3	9	0.009	0.001	0
Row 4	9	0.007	0.000778	1.94E-07
Row 5	9	0.008	0.000889	1.11E-07
Row 6	9	0.011	0.001222	4.44E-07
Row 7	9	0.005	0.000556	2.78E-07
Row 8	9	0.008	0.000889	1.11E-07
Row 9	9	0.008	0.000889	1.11E-07
Column 1	9	0.011	0.001222	1.94E-07
Column 2	9	0.005	0.000556	2.78E-07
Column 3	9	0.009	0.001	2.5E-07
Column 4	9	0.007	0.000778	1.94E-07
Column 5	9	0.009	0.001	0
Column 6	9	0.008	0.000889	1.11E-07
Column 7	9	0.007	0.000778	1.94E-07
Column 8	9	0.01	0.001111	1.11E-07
Column 9	9	0.008	0.000889	1.11E-07

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	2.4E-06	8	2.99E-07	2.091644	0.049463	2.086757694
Columns	2.84E-06	8	3.55E-07	2.479784	0.020765	2.086757694
Error	9.16E-06	64	1.43E-07			
Total	1.44E-05	80				

Appendix 6

TPH Analysis

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.5134	34.32
Variance	0.800638	356.928
Observations	10	10
Pearson Correlation	0.921506	
Hypothesized Mean Difference	0	
df	9	
t Stat	-5.74078	
P(T<=t) one-tail	0.00014	
t Critical one-tail	1.833113	
P(T<=t) two-tail	0.00028	
t Critical two-tail	2.262157	

Appendix 7: Sodium Absorption Ratio (SAR)

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	4	6.5	1.625	0.100967
Row 2	4	6.63	1.6575	0.169492
Row 3	4	5.57	1.3925	0.097558
Row 4	4	6.89	1.7225	0.402825
Row 5	4	6.37	1.5925	0.584625
Row 6	4	6.71	1.6775	0.759492
Row 7	4	4.9	1.225	0.313433
Row 8	4	4.69	1.1725	0.284825
Row 9	4	4.59	1.1475	0.047358
Row 10	4	4.81	1.2025	0.292492
Row 11	4	5.766	1.4415	0.09431
Column 1	11	14.223	1.293	0.064181
Column 2	11	11.935	1.085	0.340505
Column 3	11	18.018	1.638	0.193056
Column 4	11	19.25	1.75	0.23644

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	2.01191	10	0.201191	0.953525	0.501481	2.16458
Columns	3.112219	3	1.037406	4.916688	0.006768	2.922277
Error	6.32991	30	0.210997			
Total	11.45404	43				

Appendix 8: Descriptive Statistics for Sodium Absorption Ratio (SAR)

Column1		*Column2*		*Column3*		*Column4*	
Mean	1.293	Mean	1.085	Mean	1.638	Mean	1.75
Standard Error	0.076385	Standard Error	0.17594	Standard Error	0.132478	Standard Error	0.14661
Median	1.27	Median	0.88	Median	1.56	Median	1.75
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.25334	Standard Deviation	0.583528	Standard Deviation	0.439381	Standard Deviation	0.486251
Sample Variance	0.064181	Sample Variance	0.340505	Sample Variance	0.193056	Sample Variance	0.23644
Kurtosis	-0.28051	Kurtosis	5.782273	Kurtosis	-0.76782	Kurtosis	-0.60913
Skewness	0.51807	Skewness	2.23165	Skewness	0.54798	Skewness	0.104818
Range	0.82	Range	2.03	Range	1.35	Range	1.62
Minimum	0.96	Minimum	0.63	Minimum	1.07	Minimum	0.98
Maximum	1.78	Maximum	2.66	Maximum	2.42	Maximum	2.6
Sum	14.223	Sum	11.935	Sum	18.018	Sum	19.25
Count	11	Count	11	Count	11	Count	11

Appendix 9: Descriptive Statistics for Potassium Absorption Ratio (PAR)

Column1		*Column2*		*Column3*		*Column4*	
Mean	0.463	Mean	0.715	Mean	0.23	Mean	0.598
Standard Error	0.06566	Standard Error	0.06136	Standard Error	0.053769	Standard Error	0.044091
Median	0.365	Median	0.74	Median	0.16	Median	0.59
Mode	0.36	Mode	#N/A	Mode	0.12	Mode	0.63
Standard Deviation	0.207635	Standard Deviation	0.194036	Standard Deviation	0.170033	Standard Deviation	0.139427
Sample Variance	0.043112	Sample Variance	0.03765	Sample Variance	0.028911	Sample Variance	0.01944
Kurtosis	2.743688	Kurtosis	1.762444	Kurtosis	0.625558	Kurtosis	3.553133
Skewness	1.689218	Skewness	-0.71471	Skewness	1.408544	Skewness	1.411392
Range	0.69	Range	0.71	Range	0.48	Range	0.51
Minimum	0.26	Minimum	0.3	Minimum	0.08	Minimum	0.42
Maximum	0.95	Maximum	1.01	Maximum	0.56	Maximum	0.93
Sum	4.63	Sum	7.15	Sum	2.3	Sum	5.98
Count	10	Count	10	Count	10	Count	10

Appendix 10: Na in Stone and Control Stone Sub Base

t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	26.303	26.098
Variance	76.50656	60.47251
Observations	10	10
Pooled Variance	68.48953	
Hypothesized Mean Difference	0	
df	18	
t Stat	0.055389	
P(T<=t) one-tail	0.478219	
t Critical one-tail	1.734064	
P(T<=t) two-tail	0.956438	
t Critical two-tail	2.100922	

Appendix 11: Bulk Density

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	44.4	8.88	7.90615
Row 2	5	30.96	6.192	14.08822
Row 3	5	7.56	1.512	0.22432
Row 4	5	5.89	1.178	0.38722
Column 1	4	8.14	2.035	3.124167
Column 2	4	15.09	3.7725	13.23936
Column 3	4	15.61	3.9025	13.22009
Column 4	4	26.75	6.6875	29.32249
Column 5	4	23.22	5.805	23.31937

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	209.9847	3	69.99489	22.89174	2.97E-05	3.490295
Columns	53.73187	4	13.43297	4.393236	0.020379	3.259167
Error	36.69177	12	3.057648			
Total	300.4083	19				

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	4.72	0.944	0.01503
Row 2	5	4.02	0.804	0.00213
Row 3	5	82.3	16.46	54.733
Row 4	5	87.3	17.46	38.493
Row 5	5	65.1	13.02	248.972
Row 6	5	232.7	46.54	779.128
Row 7	5	16.1	3.22	0.687
Row 8	5	18.1	3.62	0.517
Row 9	5	4.8	0.96	1.253
Row 10	5	39	7.8	5.155
Row 11	5	254	50.8	7.2
Row 12	5	189	37.8	1200.2
Column 1	12	92.19	7.6825	206.5891
Column 2	12	133.62	11.135	285.5758
Column 3	12	204.32	17.02667	476.6525
Column 4	12	282.62	23.55167	646.4895
Column 5	12	284.39	23.69917	685.7914

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	18466.17	11	1678.742	10.7896	2.96E-09	2.014046
Columns	2499.505	4	624.8763	4.016199	0.007314	2.583667
Error	6845.915	44	155.589			
Total	27811.59	59				

Appendix 12: Metals in Stem of Tomato Plant

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	1.4	0.28	0.062
Row 2	5	19.5	3.9	0.57
Row 3	5	95.2	19.04	9.883
Row 4	5	23.3	4.66	81.443
Row 5	5	16.8	3.36	0.743
Row 6	5	75	15	15.735
Column 1	6	40.9	6.816667	60.07767
Column 2	6	65.8	10.96667	82.94667
Column 3	6	41.5	6.916667	63.00567
Column 4	6	30.7	5.116667	34.42167
Column 5	6	52.3	8.716667	102.0297

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1397.295	5	279.4589	17.73712	9.6E-07	2.71089
Columns	118.632	4	29.658	1.882378	0.152972	2.866081
Error	315.112	20	15.7556			
Total	1831.039	29				

Appendix 13: Metals in Fruit

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	4	0.13	0.0325	0.004225
Row 2	4	26.37	6.5925	0.396225
Row 3	4	235.3	58.825	1889.043
Row 4	4	12.93	3.2325	1.918225
Row 5	4	0.4	0.1	0.04
Row 6	4	63.7	15.925	10.41583
Column 1	6	61.1	10.18333	189.3857
Column 2	6	61.4	10.23333	216.2827
Column 3	6	154.1	25.68333	2377.842
Column 4	6	62.23	10.37167	201.1544

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	10288.06	5	2057.611	6.658554	0.001871	2.901295
Columns	1070.185	3	356.7284	1.154395	0.35962	3.287382
Error	4635.266	15	309.0177			
Total	15993.51	23				

Appendix 14: Bulk Density of Leaves (L), Stem (S) and Fruit (FR) of Tomatoes

Treatment	wet wt(L)	dry wt(L)	wet wt (S)	dry wt (S)	wet wt (FR)	dry wt (FR)		Total Dry wt (L+S+FR)	
Bk4A1	21.57	4.06	22.67	4.14	22.14	1.91		10.11	
Bk4A1	18.38	3.65	20.82	3.87	40.05	2.85		10.37	
Bk4A1	25.83	5.06	28.57	5.2	1.27	0.35		10.61	
Bk4A1	22.57	4.2	19.36	3.55	37.69	2.58		10.33	
Mean A1	**22.0875**	**4.2425**	**22.855**	**4.19**	**25.2875**	**1.9225**		10.355	
Bk4A2	23.77	4.19	17.36	3.1	58.14	3.35		10.64	
Bk4A2	26.17	4.75	25.15	4.86				9.61	
BK4A2	23.58	4.27	22.84	4.24	24.88	2.11		10.62	
Bk4A2	12.96	3.09	21.42	3.6	35.08	2.79		9.48	
Mean A2	**21.62**	**4.075**	**21.6925**	**3.95**	**29.525**	**2.0625**		10.0875	
Bk4A3	22	4.28	21.18	3.94	38.86	2.98		11.2	
Bk4A3	19.12	3.88	20.11	3.93	32.6	2.44		10.25	
Bk4A3	25.44	4.58	25.53	4.69	24.08	1.98		11.25	
Bk4A3	25.9	5.15	24.18	4.85				10	
Mean A3	**23.115**	**4.4725**	**22.75**	**4.3525**	**23.885**	**1.85**		10.675	
Bk3B1	16.55	3.66	15.54	3.49	42.93	3.17		10.32	
Bk3B1	17.25	3.62	21.14	3.85	49.14	3.22		10.69	
Bk3B1	20.5	4.35	22.97	3.97	22.73	1.75		10.07	
Bk3B1	17.44	3.59	16.63	3.11	49.63	3.35		10.05	
Mean B1	**17.935**	**3.805**	**19.07**	**3.605**	**41.1075**	**2.8725**		10.2825	
Bk3B2	28.35	5.06	26.82	5.29	0.45	0.14		10.49	
Bk3B2	23.29	5.36	23.85	5.42				10.78	
Bk3B2	20.42	4.68	21.11	4.67	15.72	1.41		10.76	
Bk3B2	18.18	4.65	21.49	4.46	63.51	4.63		13.74	
Mean B2	**22.56**	**4.9375**	**23.3175**	**4.96**	**19.92**	**1.545**		11.4425	
Bk3B3	16.96	3.28	15.41	3.08	47.49	3.34		9.7	
Bk3B3	14.88	3.59	22.45	4.46				8.05	
Bk3B3	21.57	4.96	20.94	4.56	55.87	3.57		13.09	
Bk3B3	15.67	4.06	16.61	3.98	55.16	3.78		11.82	
Mean B3	**17.27**	**3.9725**	**18.8525**	**4.02**	**39.63**	**2.6725**		10.665	
Bk4CA	14.66	3	16.99	3.38				6.38	
Bk4CA	16.96	3.64	18.69	3.91				7.55	
Bk4CA	13.26	2.83	16.99	3.39				6.22	
Bk4CA	13.84	2.59	16.34	3.35				5.94	
Mean CA	**14.68**	**3.015**	**17.2525**	**3.5075**	**0**	**0**		6.5225	
Bk3CB	10.55	2.98	14.06	3.46	18.2	1.44		7.88	
Bk3CB	15.35	4.09	16.88	4.47	2.88	0.37		8.93	
Bk3CB	16.47	4.38	21.31	5.57				9.95	
Bk3CB	12.15	3.28	13.37	3.65				6.93	
Mean CB	**13.63**	**3.6825**	**16.405**	**4.2875**	**5.27**	**0.4525**		8.4225	
DI1	5.94	1.57	4.25	1.6				3.17	
DI2	7.43	2.13	9.73	2.91				5.04	
DI3	7.01	1.95	6.52	2.08				4.03	
DI4	9	2.63	10.58	3.15				5.78	
Mean DI	**75.05**					**7.345**	**2.07**	**7.77**	**2.435**

Appendix 15: Flowering (FL) and Fruiting (FR) Record for Tomatoes

Treatment	**FL date**	**FL days PP**	**FR date**
Bk4A1	87.5	19-Sep	54
Bk4A1	76	16-Sep	51
Bk4A1	101	19-Sep	54
Bk4A1	65.5	19-Sep	54
Mean A1	**82.5**		
Bk4A2	55	18-Sep	53
Bk4A2	85	19-Sep	54
BK4A2	86	19-Sep	54
Bk4A2	75	19-Sep	54
Mean A2	**75.25**		
Bk4A3	73.8	16-Sep	51
Bk4A3	75.5	13-Sep	48
Bk4A3	94	17-Sep	52
Bk4A3	91	19-Sep	54
Mean A3	**83.575**		
Bk3B1	72	20-Sep	55
Bk3B1	84.5	20-Sep	55
Bk3B1	101	20-Sep	55
Bk3B1	86	20-Sep	55
Mean B1	**85.875**		
Bk3B2	93	19-Sep	54
Bk3B2	100	17-Sep	52
Bk3B2	88	18-Sep	53
Bk3B2	73.5	16-Sep	51
Mean B2	**88.625**		
Bk3B3	74.5	17-Sep	52
Bk3B3	112	20-Sep	55
Bk3B3	72.5	19-Sep	54
Bk3B3	83.5	20-Sep	55
Mean B3	**85.625**		
Bk4CA	81	24-Sep	59
Bk4CA	77	15-Oct	80
Bk4CA	73	15-Oct	80
Bk4CA	81.5	20-Sep	55
Mean CA	**78.125**		
Bk3CB	69	14-Sep	49
Bk3CB	85	13-Sep	48
Bk3CB	92	16-Sep	51
Bk3CB	75		
Mean CB	**80.25**		
DI1	59.5	16-Oct	51
DI2	77.5	27-Sep	62
DI3	78.2	06-Oct	71
DI4	85	24-Sep	59
Mean DI	**75.05**		

Appendix 16:
Tomato Height at Harvest

Treatment	Height(cm)	FL	FR	No. of FR
Bk4A1	87.5	19-Sep	03-Oct	1
Bk4A1	76	16-Sep	28-Sep	1
Bk4A1	101	19-Sep	22-Oct	0
Bk4A1	65.5	19-Sep	03-Oct	2
Bk4A2	85	19-Sep		0
Bk4A2	86	19-Sep	07-Oct	1
Bk4A2	75	19-Sep	28-Sep	1
Bk4A3	73.8	16-Sep	20-Sep	1
Bk4A3	75.5	13-Sep	20-Sep	1
Bk4A3	94	17-Sep	17-Sep	1
Bk4A3	91	19-Sep		0
Bk3B1	101	20-Sep	10-Oct	1
Bk3B1	86	20-Sep	30-Sep	2
Bk3B1	84.5	20-Sep	27-Sep	1
Bk3B1	72	20-Sep	01-Oct	1
Bk3B2	93	19-Sep	24-Oct	2
Bk3B2	88	18-Sep	11-Oct	1
Bk3B2	100	17-Sep		0
Bk3B2	73.5	16-Sep	24-Sep	1
Bk3B3	74.5	17-Sep	26-Sep	1
Bk3B3	112	20-Sep		0
Bk3B3	83.5	20-Sep	28-Sep	1
Bk3B3	72.5	19-Sep	26-Sep	1
Bk4CA	81	24-Sep		0
BK4CA	77	15-Oct		0
Bk4CA	73	15-Oct		
Bk4CA	81.5	20-Sep		0
Bk3CB	92	16-Sep		0
Bk3CB	85	13-Sep	20-Oct	1
Bk3CB	69	14-Sep	03-Oct	1
BK3CB	75	19-Sep	0	0
D1	85	24-Sep		
D2	88	24-Sep		
D3	78.2	06-Oct		
D4	77.5	27-Oct		0

FL=Flowering date
FR=Fruit Date
No. of Fruit

A1-A3=stone sub base
B1-B2=Plastic sub base
CA= ctrl stone sub base
CB=ctrl for plastic sub base
DI= Di-ionised water treatment

Appendix 17
Metals in Tomato Leaf

Treatments	**Cd(mg/l)**	**Cu(mg/l)**	**Fe(mg/l)**	**Ni(mg/l)**	**Pb(mg/l)**	**Zn(mg/l)**
A1L1	0	0.035	0.476	0.023	0.013	0.089
A1L2	0	0.031	0.45	0.023	0.008	0.113
A1L3	0	0.037	0.549	0.026	0.004	0.128
Mean A1	**0**	**0.034**	**0.492**	**0.024**	**0.008**	**0.11**
A2L1	0	0.038	0.519	0.027	0.009	0.194
A2L2	0	0.038	0.526	0.028	0.007	0.14
A2L3	0	0.034	0.471	0.023	0.009	0.137
Mean A2	**0**	**0.037**	**0.505**	**0.026**	**0.008**	**0.157**
A3L1	0	0.022	0.35	0.017	0.008	0.088
A3L2	0	0.036	0.53	0.027	0.011	0.134
A3L3	0	0.038	0.739	0.033	0.012	0.104
Mean A3	**0**	**0.032**	**0.54**	**0.026**	**0.01**	**0.109**
B1L1	0	0.046	0.77	0.023	0.015	0.133
B1L2	0	0.04	0.641	0.023	0.017	0.108
B1L3	0	0.034	0.498	0.019	0.01	0.136
Mean B1	**0**	**0.04**	**0.636**	**0.022**	**0.014**	**0.126**
B2L1	0	0.037	0.712	0.021	0.013	0.144
B2L2	0	0.035	0.532	0.018	0.012	0.177
B2L3	0	0.037	0.705	0.021	0.016	0.144
Mean B2	**0**	**0.036**	**0.65**	**0.02**	**0.013**	**0.155**
B3L1	0	0.047	0.739	0.041	0.011	0.13
B3L2	0	0.045	0.896	0.035	0.01	0.14
B3L3	0	0.043	0.721	0.035	0.012	0.164
Mean B3	**0**	**0.045**	**0.785**	**0.037**	**0.011**	**0.145**
CAL1	0	0.046	0.896	0.034	0.01	0.143
CAL2	0	0.042	0.735	0.047	0.024	0.147
CAL3	0	0.043	0.758	0.051	0.017	0.131
Mean CA	**0**	**0.044**	**0.796**	**0.044**	**0.017**	**0.14**
CBL1	0	0.038	0.664	0.055	0.019	0.126
CBL2	0	0.036	0.73	0.027	0.025	0.131
CBL3	0	0.036	0.605	0.024	0.017	0.198
Mean CB	**0**	**0.037**	**0.666**	**0.035**	**0.02**	**0.152**
DIL1	0	0.039	0.605	0.028	0.016	0.163
DIL2	0	0.053	0.906	0.03	0.017	0.201
DIL3	0	0.067	0.963	0.042	0.015	0.201
Mean DI	**0**	**0.053**	**0.825**	**0.033**	**0.016**	**0.188**

Mg/Kg	**Stone Base**	**Permavoid Base**	**Ctrl Stone Base**	**Ctrl Permavoid Base**	**DI Water**
Cd	0	0	0	0	0
Cu	3.4	4	4.4	3.7	5.3
Fe	51.2	69	79.6	66.6	82.5
Ni	2.5	2.6	4.4	3.5	3.3
Pb	0.9	1.3	1.7	2	1.6
Zn	12.5	14.2	14	15.2	18.8

Appendix 18: Metals in Stem of Tomato

Treatments	**Cd** mg/l	**Cu**(mg/l)	**Fe**(mg/l)	**Ni** (mg/l)	**Pb**(mg/L)	**Zn**(mg/l)
A1S1	0	0.051	0.166	0.005	0.032	0.191
A1S2	0.009	0.05	0.15	0.004	0.029	0.201
A1S3	0	0.038	0.117	0.005	0.028	0.145
Mean A1	**0.003**	**0.046**	**0.144**	**0.005**	**0.03**	**0.179**
A2S1	0.002	0.045	0.195	0.004	0.026	0.182
A2S2	0	0.015	0.103	0.003	0.029	0.068
A2S3	0	0.028	0.235	0.004	0.031	0.116
Mean A2	**0.001**	**0.029**	**0.178**	**0.004**	**0.029**	**0.122**
A3S1	0	0.045	0.152	0.008	0.033	0.186
A3S2	0	0.042	0.2	0.006	0.031	0.18
A3S3	0.009	0.049	0.192	0.008	0.024	0.219
Mean A3	**0.003**	**0.045**	**0.181**	**0.007**	**0.029**	**0.195**
B1S1	0	0.039	0.169	0.01	0.032	0.201
B1S2	0.001	0.043	0.149	0.005	0.028	0.188
B1S3	0.001	0.023	0.087	0.004	0.03	0.102
Mean B1	**0.001**	**0.035**	**0.135**	**0.006**	**0.03**	**0.164**
B2S1	0	0.049	0.399	0.405	0.067	0.151
B2S2	0	0.051	0.281	0.71	0.098	0.163
B2S3	0.003	0.049	0.277	0.68	0.096	0.17
Mean B2	**0.001**	**0.05**	**0.319**	**0.6**	**0.087**	**0.161**
B3S1	0.001	0.012	0.066	0.006	0.029	0.045
B3S2	0	0.05	0.197	0.018	0.031	0.168
B3S3	0	0.049	0.249	0.028	0.034	0.183
Mean B3	**0**	**0.037**	**0.171**	**0.017**	**0.031**	**0.132**
CAS1	0	0.048	0.215	0.007	0.029	0.174
CAS2	0.001	0.045	0.253	0.016	0.03	0.167
CAS3	0.001	0.026	0.118	0.004	0.03	0.08
Mean CA	**0.001**	**0.04**	**0.195**	**0.009**	**0.03**	**0.14**
CBS1	0.005	0.039	0.22	0.005	0.031	0.141
CBS2	0.003	0.024	0.152	0.004	0.028	0.087
CBS3	0.001	0.017	0.08	0.003	0.032	0.049
Mean CB	**0.003**	**0.027**	**0.151**	**0.004**	**0.03**	**0.092**
DIS1	0.014	0.053	0.297	0.009	0.029	0.223
DIS2	0.006	0.047	0.184	0.006	0.031	0.194
DIS3	0.001	0.044	0.208	0.007	0.029	0.187
Mean DI	**0.007**	**0.048**	**0.23**	**0.007**	**0.03**	**0.201**

Mg/kg	**Stone Sub-base**	**Permavoid Sub-base**	**Ctrl Stone base**	**Ctrl Plastic base**	**DI Water**
Cd	0.2	0.1	0.1	0.3	0.7
Cu	4	4	4	2.7	4.8
Fe	16.8	20.8	19.5	15.1	23
Ni	0.5	20.8	0.9	0.4	0.7
Pb	2.9	4.9	3	3	3
Zn	16.5	15.2	14	9.2	20.1

Appendix 19: Metals in Tomato Fruits

	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Treatments	**Cd**	**Cu**	**Fe**	**Ni**	**Pb**	**Zn**
A1F1	0	0.06	0.357	0.032	0	0.19
A1F2	0	0.059	0.356	0.036	0	0.173
A1F3	0	0.059	0.391	0.027	0	0.172
Mean A	**0**	**0.059**	**0.368**	**0.032**	**0**	**0.178**
A2F1	0	0.063	0.357	0.09	0	0.153
A2F2	0	0.058	0.286	0.038	0	0.136
A2F3	0	0.065	0.338	0.036	0	0.17
Mean A2	**0**	**0.062**	**0.327**	**0.055**	**0**	**0.153**
A3F1	0	0.062	0.384	0.018	0	0.147
A3F2	0	0.056	0.326	0.019	0	0.136
A3F3	0	0.062	0.407	0.031	0	0.154
Mean A3	**0**	**0.06**	**0.372**	**0.02**	**0**	**0.146**
B1F1	0	0.061	0.363	0.018	0	0.142
B1F2	0	0.061	0.394	0.02	0	0.139
B1F3	0	0.064	0.377	0.023	0	0.161
Mean B1	**0**	**0.062**	**0.378**	**0.02**	**0**	**0.147**
B2F1	0	0.062	0.483	0.022	0	0.148
B2F2	0	0.058	0.34	0.02	0	0.138
B2F3	0	0.062	0.383	0.021	0	0.147
Mean B2	**0**	**0.06**	**0.402**	**0.021**	**0**	**0.144**
B3F1	0	0.065	0.351	0.031	0	0.156
B3F2	0	0.061	0.334	0.028	0	0.149
B3F3	0	0.065	0.398	0.029	0	0.159
Mean B3	**0**	**0.064**	**0.361**	**0.029**	**0**	**0.155**
CBF1	0	0.074	1.24	0.02	0.004	0.203

Mg/Kg	Stone Base	Permavoid Base	Ctrl Permavoid Base
Cd	0	0	0
Cu	6	6.2	7.4
Fe	35.6	38	124
Ni	3.6	2.3	2
Pb	0	0	0.4
Zn	15.9	14.9	20.3

Appendix 20:
Metals in Tomato Fruit from Retail Markets

	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
sample	**Cd**	**Cu**	**Fe**	**Ni**	**Pb**	**Zn**
T1	0	0.062	0.354	0.056	-0.002	0.121
T2	-0.001	0.061	0.367	0.046	-0.006	0.122
T3	-0.001	0.065	0.395	0.051	0	0.13
Blank 1	-0.002	-0.004	-0.005	0	-0.002	0
Blank 2	-0.002	-0.005	-0.006	0.001	-0.003	-0.002
Blank 3	-0.002	-0.006	-0.004	0.001	0.002	-0.003
Spike 1	0.453	0.459	0.454	0.444	0.456	0.445
Spike 2	0.6	0.552	0.548	0.591	0.542	0.519
Spike 3	0.453	0.443	0.452	0.462	0.452	0.432

Blank corrected

	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
sample	**Cd**	**Cu**	**Fe**	**Ni**	**Pb**	**Zn**
T1	0.002	0.066	0.359	0.056	0	0.121
T2	0.001	0.066	0.373	0.045	-0.003	0.124
T3	0.001	0.071	0.399	0.05	-0.002	0.133
Observed	**Cd**	**Cu**	**Fe**	**Ni**	**Pb**	**Zn**
Spike 1	0.455	0.463	0.459	0.444	0.458	0.445
Spike 2	0.602	0.557	0.554	0.59	0.545	0.521
Spike 3	0.455	0.449	0.456	0.461	0.45	0.435

Expected	**Cd**	**Cu**	**Fe**	**Ni**	**Pb**	**Zn**
	0.5	0.5	0.5	0.5	0.5	0.5
% Recovery	**Cd**	**Cu**	**Fe**	**Ni**	**Pb**	**Zn**
	91	92.6	91.8	88.8	91.6	89
	120.4	111.4	110.8	118	109	104.2
	91	89.8	91.2	92.2	90	87

Soln in 100ml

sample	**Cd**	**Cu**	**Fe**	**Ni**	**Pb**	**Zn**
T1	0.2	6.6	35.9	5.6	0	12.1
T2	0.1	6.6	37.3	4.5	-0.3	12.4
T3	0.1	7.1	39.9	5	-0.2	13.3
Mean T	0.133	6.77	37.7	5.03	0	12.6

	g	g	g	g	g	g
mass	1	1	1	1	1	1

Mg/Kg

	Cd	**Cu**	**Fe**	**Ni**	**Pb**	**Zn**
Mean T	0.133	6.77	37.7	5.03	0	12.6

Appendix 21

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	0	0	0
Row 2	5	20.8	4.16	0.543
Row 3	5	348.9	69.78	153.542
Row 4	5	16.3	3.26	0.593
Row 5	5	7.5	1.5	0.175
Row 6	5	74.7	14.94	5.588
Column 1	6	70.5	11.75	393.587
Column 2	6	91.1	15.18333	720.7777
Column 3	6	104.1	17.35	953.527
Column 4	6	91	15.16667	663.2747
Column 5	6	111.5	18.58333	1025.838

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	18306.13	5	3661.227	152.9062	3.18E-15	2.71089
Columns	162.8787	4	40.71967	1.700602	0.189373	2.866081
Error	478.8853	20	23.94427			
Total	18947.9	29				

Appendix 22

Description of Media (Chapter 6)

As reported earlier in chapter 6, the media used in these experiments were: Nutrient Agar, MacConkey Agar and Eosin Methylene Blue Agar (EMBA). However, Nutrient Broth and Page's Ameoba Saline Solution (PAS) were used to culture E.coli and Acanthamoeba polyphaga respectively before introduction into the test rigs.

Nutrient Agar is used for culturing bacteria (in some cases fungi) and counting of micro-organisms in water faeces, sewage, etc through the formation of colonies which occurs when inoculations takes place on nutrient agar http://www.bd.com/ds/technicalCenter/inserts/Nutrient_Agar.pdf

MacConkey Agar is used for isolation and enumeration of gram negative, lactose fermenting enteric micro-organisms. It is also famous for inhibiting the formation of colonies by gram – positive microbes http://www.bd.com/ds/technicalCenter/inserts/MacConkey_Agars.pdf MacCoonkey Agar is described by the National Standard Method of United Kingdom (2004) as "A selective medium onto which *Escherichia coli* (including O157), *Salmonella* species and other *Enterobacteriaceae* may be sub-cultured for further testing when isolated from food and water samples".

Eosin Methylene Blue Agar (EMBA) is also used for isolation of enteric gram negative microbes. The eosin and methylene blue dyes inhibit the growth of gram –positive micro-organisms and hence enable the enumeration of the gram-negative ones (http://www.waksmanfoundation.org/labs/lsu/water.html Accessed: October, 2008). Fermentation of the lactose content of EMBA by coliforms results in the darkening of the colonies formed and hence its use for confirmatory tests (Ngole *et al*. 2006). *Entrobacter aerogenes* colonies develop a dark centre with a light border and are called “fish eye” colonies while Escherichia coli colonies turns dark with green metallic sheen (Ngole *et al*, 2006; WFM, 2008) which is used as a confirmatory sign for the presence of the E.coli (Ngole *et al*, 2006;).However, other non -lactose fermenting micro-organisms forms pale or colourless colonies (http://www.waksmanfoundation.org/labs/lsu/water.html Accessed: October, 2008).

Appendix 23: PUBLICATIONS AND CONFERENCE PAPERS

- Nnadi, E.O; Newman, A.P; Coupe, S.J; Puehmeier, T and Duckers, L. *Irrigation Using Permeable Paving as the Source of Water on the Soil; Plant Growth and Development*. Abstract Accepted for the 1st African Regional Geosynthetic Conference holding at Cape Town, South Africa from 2nd - 5th September, 2009.

- Nnadi, E.O; Newman, A.P and Puehmeier, T. *An evaluation of the use of stored water derived from permeable paving systems for irrigation purposes* Paper Presented at the 11th International Conference on Urban Drainage (ICUD) held at Edinburgh, UK from 31st August – 5th September, 2008.CD-ROM Conference Proceedings.

- Coupe, S.J; Nnadi, E.O and Oyelola, O. *Water recycling Using permeable paving as the source: Biological water safety and the fate of introduced microbial contaminants* Paper presented at the 11th International Conference on Urban Drainage (ICUD) held at Edinburgh, UK from 31st August – 5th September, 2008. CD-ROM Conference Proceedings.

- Coupe, S.J and Nnadi, E.O. *Biological Water Quality of Recycled Water in the Permeable Paving*. A Paper Presented at the Annual Conference of the Royal Geographical Society(RGS) held at London, UK 25th - 27th August, 2008

- Nnadi, E.O. *An Evaluation of the Hanson-Formapave Aquaflow Pavement System for Water Harvesting.* A Presentation to the Board of Hanson-Formpave at Hanson–Formpave Head Office, Gloucestershire, UK on 24th April, 2008.

- Coupe, S.J and Nnadi, E.O. Paper entitled '*Water recycling and ground Source heat pump system within permeable paving – System Consideration and On-site Construction Considerations'* A Paper Presented at the SUDSNET National Conference hosted by Coventry University, UK on 14th November, 2007

- Charlesworth, S.; Nnadi, E.O. and Howard, R. A Poster entitled '*The investigation of pollutant retention by Tarmac Aquifa Pervious Pavements*' presented at the SUDSNET National Conference at Coventry University, UK on 14th November, 2007

- Nnadi, E.O; Duckers, L.; Newman, A.P; Coupe, S.J and Puehmeier, T. *An Evaluation of Suitability of Pervious Pavements for Rainfall Harvesting*. A paper Presented at the Research Symposium hosted by Coventry University, UK, on 28th March, 2007

- Nnadi, E.O; Newman, A.P; Coupe, S.J and Puehmeier, T. *Design and Validation of a Test Rig for High Rainfall Infiltration Studies*. A Paper Presented at the SUDSNET Student Conference hosted by Coventry University, UK, on 7th September, 2006

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