



Stormwater harvesting for irrigation purposes: An investigation of chemical quality of water recycled in pervious pavement system



Ernest O. Nnadi ^{a,*}, Alan P. Newman ^b, Stephen J. Coupe ^a, Fredrick U. Mbanaso ^a

^a SUDS Applied Research Group, Coventry University, Priory Street, Coventry CV1 5FB, United Kingdom

^b Faculty of Health & Life Sciences, Coventry University, Priory Street, Coventry CV1 5FB, United Kingdom

ARTICLE INFO

Article history:

Received 10 December 2013

Received in revised form

6 May 2014

Accepted 27 August 2014

Available online 23 September 2014

Keywords:

Stormwater

Pervious pavements

Water reuse

Water quality

Irrigation

ABSTRACT

Most available water resources in the world are used for agricultural irrigation. Whilst this level of water use is expected to increase due to rising world population and land use, available water resources are expected to become limited due to climate change and uneven rainfall distribution. Recycled stormwater has the potential to be used as an alternative source of irrigation water and part of sustainable water management strategy. This paper reports on a study to investigate whether a sustainable urban drainage system (SUDS) technique, known as the pervious pavements system (PPS) has the capability to recycle water that meets irrigation water quality standard. Furthermore, the experiment provided information on the impact of hydrocarbon (which was applied to simulate oil dripping from parked vehicles onto PPS), leaching of nutrients from different layers of the PPS and effects of nutrients (applied to enhance bioremediation) on the stormwater recycling efficiency of the PPS. A weekly dose of 6.23×10^{-3} L of lubricating oil and single dose of 17.06 g of polymer coated controlled-release fertilizer granules were applied to the series of 710 mm \times 360 mm model pervious pavement structure except the controls. Rainfall intensity of 7.4 mm/h was applied to the test models at the rate of 3 events per week. Analysis of the recycled water showed that PPS has the capability to recycle stormwater to a quality that meets the chemical standards for use in agricultural irrigation irrespective of the type of sub-base used. There is a potential benefit of nutrient availability in recycled water for plants, but care should be taken not to dispose of this water in natural water courses as it might result in eutrophication problems.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

According to UNESCO (2007), about 70% of world water supply is used for agricultural irrigation and this statistic is expected to increase by 14% in the next 30 years with the ever rising world population and an increase in irrigated land by 20%. Also, agricultural land use is expected to rise by 10% in 2030 resulting in increased demand for water for irrigation (OECD, 2008). It is estimated that about half of the world population (47%) will experience severe water scarcity in 2030 if new water management policies are not introduced (OECD, 2008). This threat of global water shortage is exacerbated by global warming which is expected to make summer droughts more frequent and cause water scarcity even in developed countries.

The study reported in this paper provides data on the chemical quality and suitability of harvested stormwater using a SUDS

technique (known as pervious pavements) for agricultural irrigation. This water management strategy meets the objectives of sustainable urban drainage by achieving source control and water reuse. It is different from other studies on the reuse of water derived from “alternative” sources to high quality water, but sustainable sources for irrigation such as sewage (Amahmid and Bouhoum, 2000; Yadav et al., 2002; Debasish et al., 2003; Butt et al., 2005; Wallach et al., 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 et al., 2005), Pakistan, Mexico, Vietnam, Greece, Saudi-Arabia, Jordan and Israel for irrigation (Al-Shammiri et al., 2005).

As early as 1999, Pratt (1999) proposed that the pervious pavement system could be used as a reservoir for stormwater treatment and storage for reuse. Three years later, in the University of Florida, USA, Chen et al. (2002) conducted 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

* Corresponding author.

E-mail addresses: dr.nnadi@gmail.com, e.nnadi@yahoo.co.uk, e.nnadi@coventry.ac.uk (E.O. Nnadi).

production of bedding and foliage crops. At the end of their study, they produced high quality and market yields of the crops irrespective of the sources of the irrigation water 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 (Nnadi, 2009). 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 et al., 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 is utilizing small lot reuse, source reuse, stormwater capture, stormwater storage and distribution technologies on the Island of Hawaii for irrigation distribution system and deep infiltration trenches to capture stormwater for irrigation reuse on Oahu (Madison and Emond, 2007; DAH, 2008). In 2006, the local government in Sydney, Australia installed permeable pavements with sub-terrace water storage tanks – 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 reuse 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. However, 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) (Ensink and Hoek, 2007). However, there is need for water meant for irrigation to meet irrigation water quality standards in order not to pose a threat to soil structure, crops and consumers of edible crops (Hamilton et al., 2007).

The focus of this study was specifically on irrigation and the experiment was intended to provide information on the effects of hydrocarbons (which was an attempt to replicate oil dripping from parked vehicles onto PPS), leaching of nutrients from different layers of the PPS and in particular the effects of nutrients applied to enhance bioremediation on the suitability for irrigation of the stored water.

The experimental operation of the model system used 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 (Pratt, 1999) 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 also have important energy/physical effort advantages because of a reduced lift requirement when the water is recovered for reuse at the surface.

2. Materials and methods

It was proposed that irrigation of plants using water derived from the stone and plastic box based systems might show different 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 (Bond, 1999; Coupe 2004) 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. Although the oil retention capability of pervious pavements, under heavy loadings, has been shown to be limited (Newman et al., 2002), under loadings simulating day to day oil drippings in car parks, the structure is shown to support the establishment, growth and development of biofilms of oil degrading microbes (Newman et al., 2002; 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).

2.1. 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. 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 water courses (Puehmeier et al., 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 reported by Nnadi et al. (2014). The depth of the stone sub-bases was 150 mm which is equal to the depth of the Permavoid units. A 50 mm bedding of 10 mm pea gravel was used to support the layer of Formpave Aquaflow® paving. The stone aggregates used for the stone base and bedding layer were sieved to 50 mm and 10 mm respectively. The aggregates were washed with clean water in order to remove dusts and silts before they were used in the experiment. The geotextile (Inbitex Composite®) was sandwiched between the sub base and the bedding layer in all the models.

Table 1 shows the experimental set up and treatments applied on of the test rigs.

Table 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 fertilizer | Permavoid plastic | 3 |
| 2 | +Oil and +NPK fertilizer | Stone | 3 |
| Control 1 | +Oil and +NPK fertilizer | Permavoid plastic | Control 1 |
| Control 2 | +Oil and +NPK fertilizer | Stone | Control 1 |
| Total number of test rigs | | | 8 |

2.2. Rainfall simulation

Rainfall was simulated using a watering can fitted with a shower rose suspended above the test models at an intensity of 7.4 mm/h over 1 h 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.

2.3. Oil application

A weekly dose of 6.23 mL of Castrol GTX[®], lubricating oil (supplied by Castrol (UK) Ltd., Swindon, UK) which was successfully used by Bond (1999) was applied to the series of 710 mm × 360 mm 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. (2006) 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 0.3721 m² (which amounted to 6.62 g of oil per week) in other to replicate worst case scenario.

The weekly oil application was carried out a day before rainfall application. The oil application was conducted randomly into infiltration slots of the pervious pavement models by the means of a 10 mL syringe 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.

2.4. Nutrient addition

Osmocote[®] Plus controlled-release fertilizer granules (Grace-Sierra Horticultural Products Co., Milpitas, USA) were used for this experiment. A summary of elemental composition of the fertilizer used in this study is shown in Table 2. Table 3 shows the mass of nutrient per application of Osmocote Plus[®] controlled-release fertilizer. The nutrient release mechanism this fertilizer is reported by Adams et al. (2013). 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. The mass of Nitrogen, Phosphorus and Potassium (NPK) supplied per application of fertilizer is shown in Table 3. The systems were maintained in the dark as much as possible throughout the

Table 2
Elemental composition of Osmocote Plus controlled-release fertilizer.

| Element | Percentage composition (by weight) |
|------------|---|
| Nitrogen | 10.0% |
| Phosphorus | 4.8% (i.e. 11% of Osmocote Plus present as phosphorus pentoxide (P ₂ O ₅) soluble in neutral ammonium citrate and/or water, whilst 8.80% (3.8% P) soluble in water only) |
| Potassium | 14.9% (potassium oxide (K ₂ O), soluble in water, (chloride free) constitutes 18% of Osmocote Plus) |
| Magnesium | 0.9% (magnesium oxide (MgO) constitutes 1.50% of Osmocote Plus, 0.70% soluble in water i.e. 0.45% total Mg) |
| Boron | 0.01% |
| Copper | 0.03% (0.02% soluble in water) |
| Iron | 0.20% (of which chelated by EDTA, soluble in water: 0.04%) |
| Manganese | 0.04% |
| Molybdenum | 0.01% |
| Zinc | 0.01% (0.005% soluble in water) |

Table 3

Mass of NPK per application of Osmocote-Plus fertilizer.

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

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).

2.5. Analysis of water from test models

Samples of water from test models were collected weekly.

Calcium (Ca), Magnesium (Mg), Potassium (K), Phosphorus (P), Sodium (Na), Sulphur (S), Copper (Cu), Vanadium (V), Molybdenum (Mo), Aluminium (Al), Zinc (Zn), Iron (Fe), Cadmium (Cd), Arsenic (As), Boron (Bo), Lead (Pb), Nickel (Ni), and Manganese (Mn) were determined by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) Optima 5300DV[®] (PerkinElmer, USA).

The nitrate (NO₃) and nitrite (NO₂) in the stored irrigation water was determined using Flow Injection Analysis (FIA) using Aquatec 5400 connected to Tecator 5027 auto sampler (Tecator, Sweden).

Electrical Conductivity of water (EC_w) determined by PTI-8 digital Conductivity meter (Scientific Industries Intl. Inc. UK). The pH of water from the test models was determined by Corning M220 pH meter (Ciba Corning Diagnostics Ltd, Suffolk, England). Similarly, 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 (Horiba Co. Ltd, Japan).

3. Results and discussion

3.1. Elemental analysis

3.1.1. Calcium (Ca)

The highest level of calcium (43.69 mg/L) was observed at 5th week in the water from the Permavoid base as shown in Fig. 1(a). 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 29.77–30.38 mg/L. The average concentrations of calcium in water in the test rigs in descending order throughout the experiment were as follows: 25 mg/L > 24.94 mg/L > 16.52 mg/L > 13.97 mg/L for Stone, Permavoid, Control stone and Permavoid bases respectively as shown in Fig. 1(a). Calcium concentration of <40 mg/L is regarded as very low and concentrations between 41 and 80 mg/L are regarded as low in irrigation water analysis (Spectrum, 2013).

3.1.2. Magnesium (Mg)

Fig. 1(b) 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.

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 1.6 mg/L which was observed at the 6th week of the experiment (Fig. 1(b)). A concentration of Magnesium < 8.0 mg/L in water for irrigation is regarded as very low (Spectrum, 2013). 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

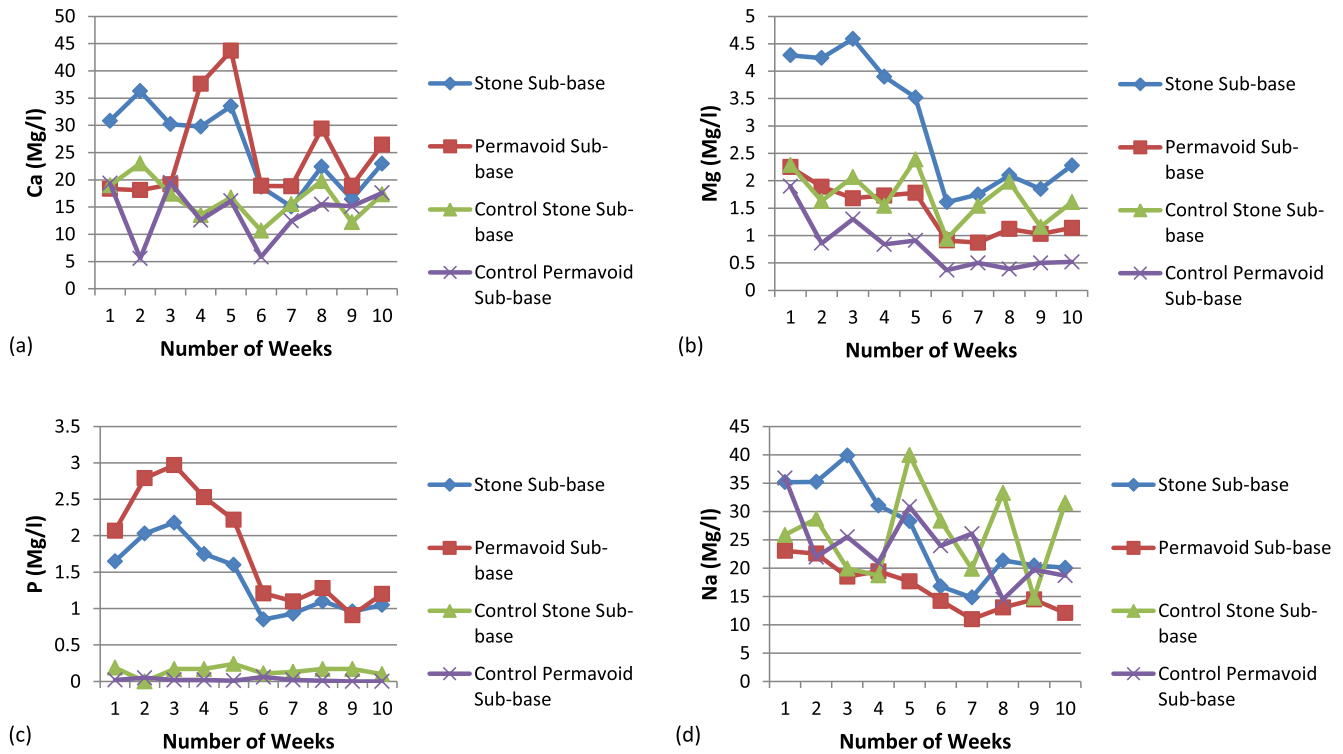


Fig. 1. (a) Ca in water from test models, (b) Mg in water from test models, (c) P in water from test models, (d) Na in waters from test models.

as very low. Supplementary addition of magnesium may be required in order to augment the magnesium shortage depending on the type of plant and availability of magnesium in soil.

3.1.3. Calculation of magnesium hazards (MH)

In irrigation water magnesium toxicity is not just a function of its absolute concentration. It also depends on the amount of calcium present. A commonly used 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 for calculation of MH is shown below and cations are in milliequivalent per litre (meq/L).

$$\text{Magnesium Hazards (MH)} = \frac{[\text{Mg}^{2+}]}{([\text{Ca}^{2+}] + [\text{Mg}^{2+}]) \cdot 100} \quad (1)$$

(Al-Shammiri et al., 2005)

Table 4 shows the average concentrations of the cations in meq/L.

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). 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. Clearly the magnesium and calcium concentrations would depend on the amount of dolomite used in the cement for the blocks and the nature of the sub base stone. In this case the stone used was granite but if crushed dolomite was used one might expect different results.

3.1.4. Phosphorus (P)

Fig. 1(c) shows that the level of phosphorus was unsurprisingly high in water from those models to which nutrients were added, ranging between 1.6 mg/L and 2.97 mg/L between the 1st week to the 5th week of the study and remained below 1.5 mg/L from the 6th week to the 10th week of the experiment. The highest level of phosphorus (2.97 mg/L) was recorded in the water from Permavoid sub base models at the 3rd week of the experiment. The difference between the Permavoid and stone based waters reduced over time, possibly reflecting the filling of adsorption sites in the stone sub base. However, the concentration of phosphorus in the water from the controls remained below 0.3 mg/L throughout the experiment. 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 in irrigation water (Spectrum, 2013). This indicates that phosphorus in the waters was within acceptable limits for irrigation water despite application of P-rich fertilizer to the treatment rigs.

3.1.5. Copper (Cu)

It was observed that the highest level of copper in water for all the systems was 0.01 mg/L. The level of copper in the water from the stone based system between weeks 1–5 was 0.01 mg/L and was non-detectable between weeks 6–10. However, copper was not detected in the water from the Permavoid based system during the same period. 0.01 mg/L of copper was also detected at the 1st, 3rd,

Table 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 |
| MH | 16.04% | 9.44% | 14.75% | 9.17% |

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 0.01 mg/L in weeks 1–2 and became non-detectable throughout the remaining eight (8) weeks of the experiment. 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). It is also lower than the levels set as standards for reuse of wastewater for irrigation by FAO (0.2 mg/L) (FAO, 2008) and that of drinking water (2 mg/L) (WHO, 2008). Furthermore, 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). Hence, the level of copper in the waters from the test rigs was very low and non-toxic despite the fact that it was present in the nutrients applied to some of the test rigs.

3.1.6. 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 et al., 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 waters. The parameter for measuring this relationship is known as Sodium Absorption Ratio (SAR). 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 as shown in Fig. 1(d). It was observed that the concentration of sodium in water from the Permavoid system was 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. 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). Concentration of Na^+ < 46 in irrigation water is recommended for some plants (Bauder et al., 2008). 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, Fipps, 2003).

3.1.7. Sodium Absorption Ratio (SAR)

Sodium Absorption Ratio (SAR) is the ratio of sodium to calcium and magnesium ion concentrations calculated in milliequivalent/litre. The Sodium Absorption Ratio was calculated from the following equation:

$$\text{SAR} = \frac{\text{Na}^+ (\text{meq/L})}{(\text{Square root } (\text{Ca}^{2+} + \text{Mg}^{2+})/2) (\text{meq/L})} \quad (2)$$

deHayr and Gordon (2006)

SAR of the water from the test rigs for 10 weeks duration of the experiment is shown in Fig. 2(a). When SAR value is <9, it is an indication of soil permeability problems (Harivandi, 1982). However, effective prediction 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 Electrical Conductivity (EC_w) will result in soil infiltration and permeability problems (Harivandi, 1982; deHayr and Gordon, 2006, FAO, 2008). An assessment of potential soil

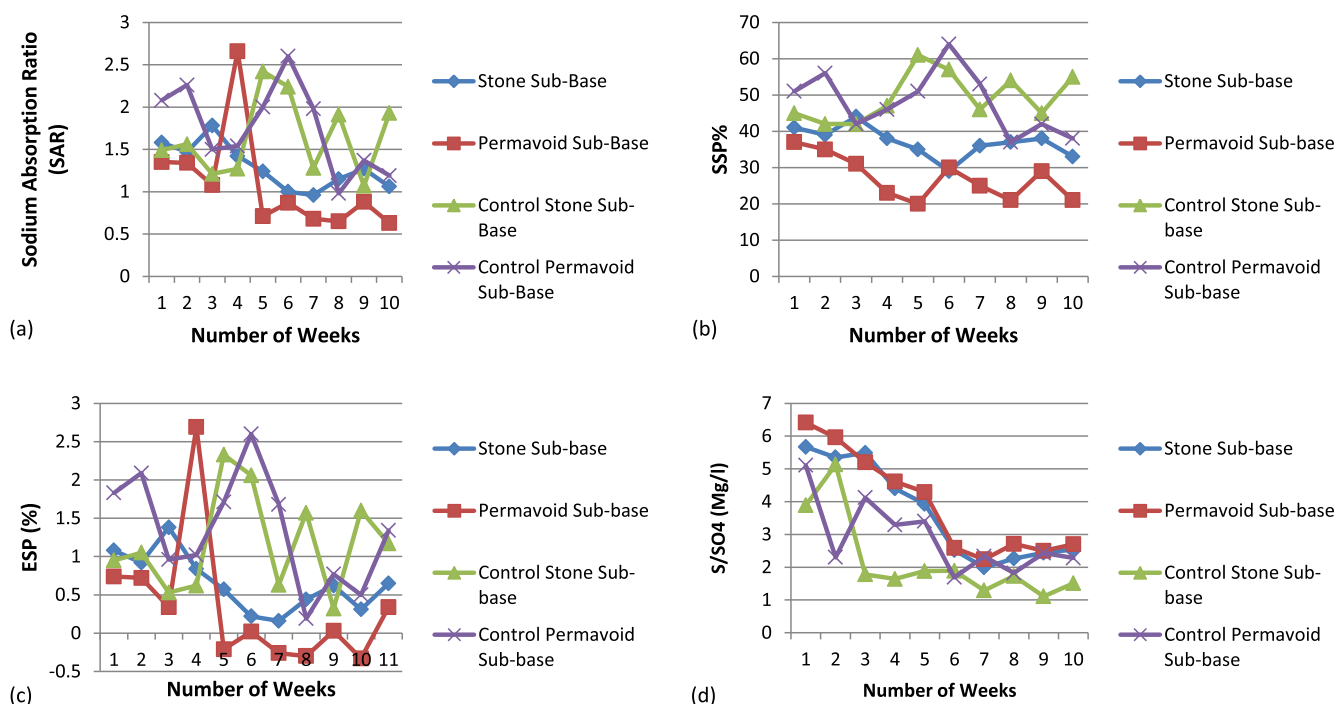


Fig. 2. (a) SAR of waters from PPS test models, (b) SSP of waters from PPS test models, (c) ESP of waters from PPS test models, (d) SO_4 in water from PPS test models.

structure, infiltration and permeability problems arising from use of waters from PPS test rigs for irrigation based on SAR and EC_w is reported in Nnadi et al. (2014).

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. However, the potential reduction in salt application during winter (gritting) by the use of the pervious pavement system was reported by Potier (2008).

3.1.8. 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 milliequivalent/liter. It measures the percentage of solubility of sodium ions relative to other positive ions present in the water.

$$SSP = \frac{Na^+ (meq/L)}{(Ca^{2+} + Mg^{2+} + K^+ + Na^+) (meq/L)} \quad (3)$$

(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 Fig. 2(b).

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 (Fipps, 2003). According to Al-Shammiri et al. (2005), this threshold of 60% was raised to 80%; with the condition that the total dissolved solids (TDS) in the water should be <10 meq/L. Hence, it is clear from the average SSP results shown above that the waters from 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.

3.1.9. 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 mathematical relationship between ESP and SAR is shown in Equation (4).

$$ESP = 100(-a + b(SAR)) / (1 + (-a + b(SAR))) \quad (4)$$

where $a = 0.0126$ and $b = 0.01475$ (Hillel, 2000)

This relationship is also shown in Equation (5) used for the calculation of ESP.

$$ESP = \frac{100 \cdot (-0.0126 + 0.01475 \cdot SAR)}{1 + (-0.0126 + 0.01475 \cdot SAR)} \quad (5)$$

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 Fig. 2(c).

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): non-sodic (<6%), sodic (6–10%), moderately sodic (10–15%), strongly sodic (15–25) and very strongly sodic (25%). The ESP values for the duration of the experiment 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.

3.1.10. 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 as reported in methods section. 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 recognized as a major contributor to salinity problems in irrigation water, but rarely toxic and may hinder the uptake of essential nutrients if excessively present in irrigation water (Bauder et al., 2008). Fig. 2(d) shows the concentrations of sulphate in the waters from the PPS test models. Waters from Permavoid and stone bases which were dosed with oil and nutrients contained more 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 et al., 2008). Hence, any concentration of sulphur <24 ppm in irrigation water as very low. Consequently, the concentration of sulphate in the irrigation water from all the test rigs is very low and sulphate addition maybe necessary in order to meet plant's sulphate requirements. However, this is dependent on the level of sulphur (SO_2 and H_2S) in the atmosphere as sulphur may be supplied through rain in rich sulphur environments (e.g. industrial and coal producing areas).

3.1.11. Iron (Fe)

Fig. 3(a) shows the concentration of iron in the waters from the test rigs. The control models contained 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 (Rowe and Abel-Magid, 1995).

Hence, any concentration of iron <0.2 mg/L is very low for irrigation. 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.

3.1.12. Cadmium (Cd)

Cadmium was not detectable in waters from all the test models. The recommended limits for cadmium in irrigation water are 0.01 mg/L and 0.05 mg/L for long and short term respectively and the FAO standard is 0.01 mg/L (Rowe and Abel-Magid, 1995). Also, the concentration of non-toxicity hazard of cadmium in water is <0.01 mg/L. Non detection of cadmium in the waters 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 (Fipps, 2003).

3.1.13. 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

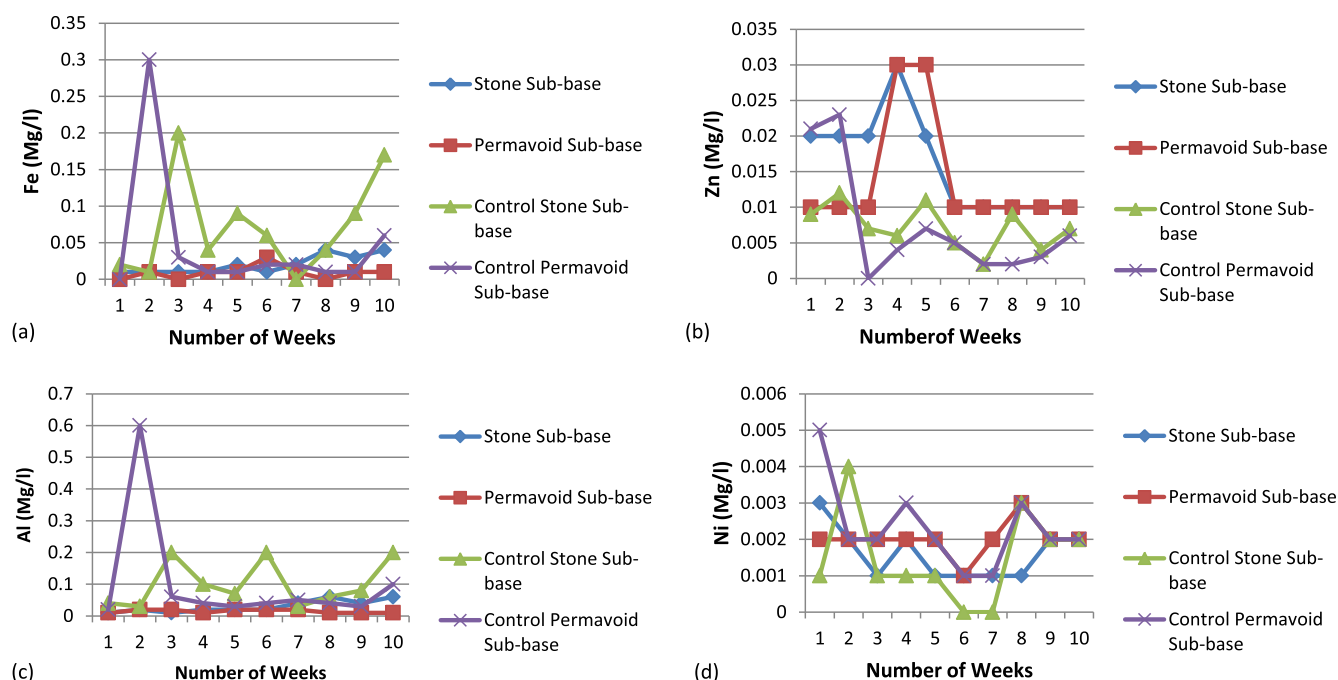


Fig. 3. (a) Fe in waters from PPS test models, (b) Zn in waters from PPS test models, (c) Al in waters from PPS test models, (d) Ni in waters from PPS test models.

These concentrations of arsenic in waters from PPS test rigs 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 concentration of <0.1 mg/L of arsenic is the level of non-toxicity hazard to crops (Spectrum, 2013). Also, Fipps (2003) 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).

3.1.14. Boron (B)

Boron was non-detectable 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 2. 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 (Sotiropoulos et al., 2003; Bauder et al., 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 1.0 mg/L to sensitive crops (Bauder et al., 2008). Rowe and Abel-Magid (1995) 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. Peterson (1999) recommended the threshold level of 0.5 mg/L as the maximum Concentration of Boron in irrigation water in Canada.

3.1.15. Vanadium (V)

Vanadium is a toxic element to plants, animals and man 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 0.1 mg/kg

and 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 0.01 mg/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., 2005) and reclaimed water for irrigation (Fipps, 2003). Spectrum (2013) stated that it is only when the concentration of vanadium is <0.1 ppm, in irrigation water that there would pose a toxicity hazard to plants. Hence, there was no risk of vanadium toxicity hazard from the waters stored in the PPS test models.

3.1.16. Lead (Pb)

Adams et al. (2013) reported that the EDTA content of Osmocote fertilizer enhances Pb accumulation. 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 1.5 mg/L (Al-Shammiri et al., 2005). The Canadian Council of Ministers of the Environment recommended the maximum concentration of 0.01 mg/L of lead in irrigation water (Peterson, 1999). However, Rowe and Abel-Magid (1995) 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 (2013), 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.

3.1.17. Zinc (Zn)

The concentrations of zinc observed in waters from the test models are shown in Fig. 3(b). The toxicity of zinc to plants varies at

different concentrations and is dependent on the pH (toxicity reduces at $\text{pH} > 6$) and soil texture (Fipps, 2003). 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 Abel-Magid (1995), 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 FAO standard concentration of 2.0 mg/L. 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 if waters PPS from test models are used for irrigation as the levels of zinc observed was lower than the recommended maximum concentrations.

3.1.18. Aluminium (Al)

The trend of aluminium concentration throughout the duration of the study is as shown below in Fig. 3(c). High concentration of aluminium may lead to non-productivity especially in acid soils ($\text{pH} < 5.5$), but aluminium toxicity is eliminated if the pH is raised above neutrality level (i.e. $\text{pH} > 7.0$) because of the precipitation of aluminium ions (Peterson, 1999; Fipps, 2003). Rowe and Abel-Magid (1995) 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. Aluminium toxicity hazard to plants from irrigation water does not exist if the concentration of aluminium is > 1 mg/L (Fipps, 2003). Since the highest concentration of aluminium from the test models was 0.6 mg/L, hence the concentration of aluminium in waters from the PPS test models was below the maximum standard concentrations and within the non-toxicity level.

3.1.19. Nickel (Ni)

The concentration of nickel in water from the test models is presented in Fig. 3(d) 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 and 1.0 mg/L especially with low soil pH (increasing acidity), but toxicity decreases from neutral ($\text{pH} 7.0$) as the pH increases (Peterson, 1999).

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 2.5 mg/L of Nickel in wastewater intended for use in irrigation (Peterson, 1999). The level of non-toxicity of nickel in irrigation water as < 2.0 mg/L. Rowe and Abel-Magid (1995) 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) that the waters from the test models did not pose a risk of toxicity from nickel when used for irrigation.

3.1.20. Molybdenum (Mo)

Molybdenum is used as an additive to oil and grease used in cars in the form the compound molybdenum disulphide (Epshteyn and Risdon, 2010). The concentration of molybdenum during the 10 weeks of the study is shown in Fig. 4(a). The standard concentration of molybdenum in irrigation water is 0.01 mg/L (Peterson, 1999; Al-Shammiri et al., 2005) and 0.5 mg/L for short term application (Fipps, 2003). The concentration of Molybdenum in irrigation water is classified as low if within the range of 0.006–0.01. Hence the concentration of molybdenum in water from the test models was low and would not pose a toxicity threat when used for irrigation.

3.1.21. 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 ≤ 5.5 (Whipker, 1999). Toxicity levels are dependent on type of plant, but ranges from 0.2 to 10 mg/L for long

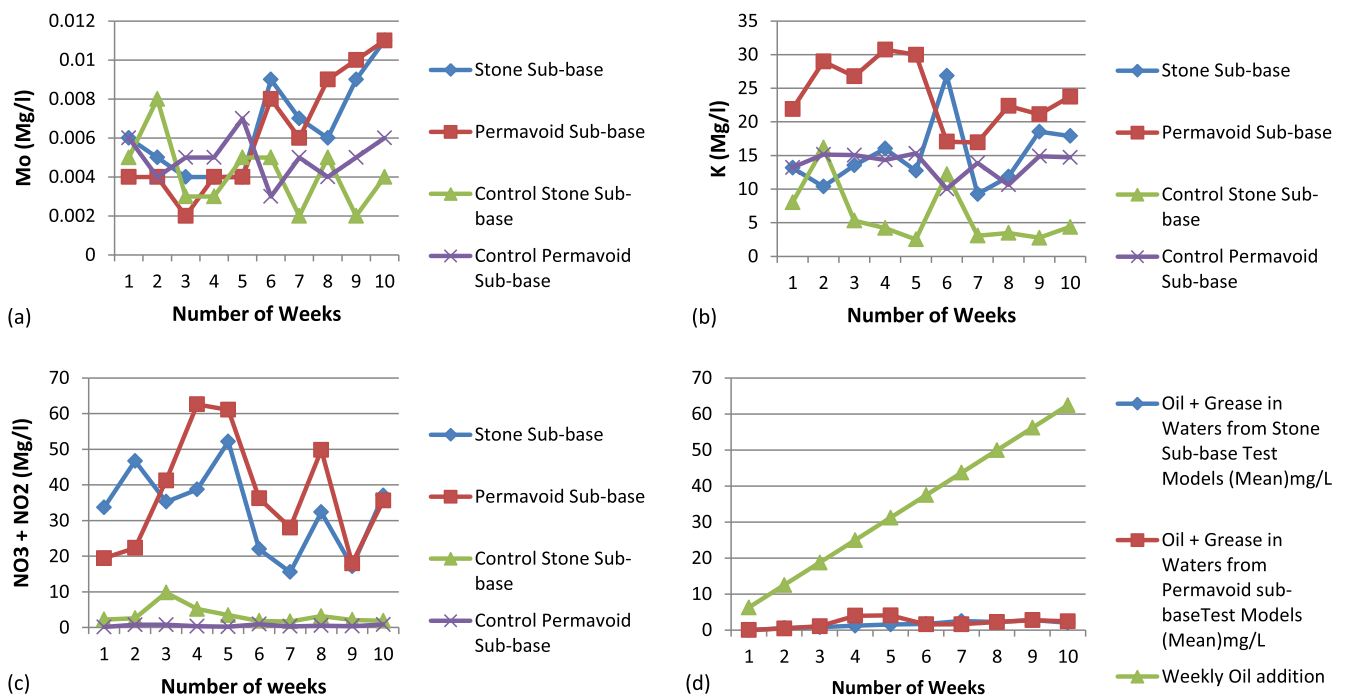


Fig. 4. (a) Mo in waters from PPS test models, (b) K in waters from PPS test models, (c) NO3 and NO2 in waters from PPS test models, (d) oil addition to and recovery from stone and permavoid test models.

Table 5

Classification of irrigation water based on electrical conductivity.

| Classes of irrigation water | EC _w (μS/cm) | EC _w of waters from PPS (μS/cm) |
|-----------------------------|-------------------------|--|
| Bauder et al. (2008) | | |
| Excellent | ≤250 | 242.50–341 |
| Good | 250–750 | |
| Permissible | 760–2000 | |
| Doubtful | 2010–3000 | |
| Unstable | ≥3000 | |

and short term irrigation respectively (Fipps, 2003). The concentration of manganese in water from all the models was <0.01 mg/L throughout the 10 weeks of the experiment. Consequently, there was no risk of manganese toxicity from water from the test models.

3.1.22. Potassium (K)

K was one of the major nutrients supplied by the added nutrient. Fig. 4(b) shows the levels of potassium in the waters from PPS test models. It is evident from 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 Permavoid sub base cannot be considered as a credible source of potassium. It is suggested 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. Concentration of potassium between 6.1 and 10.0 mg/L is regarded as high, while concentrations > 10 mg/L are classified as very high (Spectrum, 2013). Vallentin (2006), recommended the concentration limit of <80 mg/L for potassium in irrigation water. The levels of potassium observed in this study 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. Table 6 shows a comparison of some elemental constituents of irrigation waters from PPS with different international standards.

3.1.23. Nitrate and nitrite (NO₃ + NO₂) in water

Nitrogen usually occurs in the form of nitrate (NO₃⁻) in water although; it may also exist as nitrite (NO₂⁻), ammonium (NH₄⁺), nitrous oxide (N₂O) and organic nitrogen. 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). Concentrations of nitrate and nitrite in the water from the test rigs are presented below in Fig. 4(c). It is obvious that there is difference between the concentration of NO₃ + NO₂ 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 NO₃ + NO₂ in water from the stone and the Permavoid base system. clearly, the test rigs that were dosed with NPK to enhance biodegradation produced waters with higher concentrations of NO₃ + NO₂ than the test rigs that were not.

The average concentration of nitrate in wastewater ranges from 0 to 30 mg N–NO₃/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 Newman et al. (2011) observed that earlier work by Bond (1999) on the PPS 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.

Table 6

Comparison of some quality constituents of waters from PPS with different international standards.

| Elements | PPS Waters (oil & nutrient added) (mg/L) | PPS Waters (no oil & nutrient added) (mg/L) | FAO ^a (mg/L) | Standard Conc. ^b (mg/L) | USEPA ^c (mg/L) | Canada ^d (mg/L) | Nigeria ^d (mg/L) | South Africa ^e (mg/L) | Jordan ^f (mg/L) | Turkey ^f (mg/L) |
|----------|--|---|----------------------------|---------------------------------------|------------------------------|-------------------------------|--------------------------------|-------------------------------------|-------------------------------|-------------------------------|
| Li | 0.01 | 0.008 | — | 2.5 | — | — | — | 2.5 | 2.5 | 2.5 |
| Na | 26.30 | 26.01 | — | — | — | — | — | 70 | — | — |
| V | 0.01 | 0.013 | — | 0.1 | 0.1 | — | — | 0.1 | 0.1 | 0.1 |
| Al | 0.03 | 0.10 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Mo | 0.007 | 0.004 | — | 0.01 | 0.01 | — | — | 0.01 | 0.01 | 0.01 |
| Bo | 0 | 0 | — | 0.75 | 0.75 | — | — | 0.5 | 1.0 | 0.5 |
| Ca | 25.62 | 15.86 | — | — | — | — | — | — | — | — |
| P | 1.41 | — | — | — | — | — | — | — | — | — |
| Cd | 0 | 0 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| As | 0.04 | 0.002 | 0.1 | 0.1 | 0.10 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Mg | 3.01 | 1.72 | 0.2 | — | 0.2 | — | — | — | — | — |
| Cu | 0.005 | 0.007 | 0.2 | 0.2 | 0.2 | 0.2–1.0 | 0.2–1.0 | 0.2 | 0.2 | 0.2 |
| Fe | 0.02 | 0.072 | — | 5.0 | 5.0 | — | — | 5.0 | 5.0 | 5.0 |
| K | 15.02 | 6.21 | — | — | — | — | — | — | — | — |
| Pb | 0.003 | 0.001 | — | 1.5 | 5.0 | — | — | 0.2 | 5.0 | 0.2 |
| Ni | 0.002 | 0.002 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Zn | 0.02 | 0.007 | 2.0 | <0.05 | 2.0 | 1.0–5.0 | 0.0–5.0 | 1.0 | 5.0 | 1.0 |

^a FAO (2008).^b Al-Shammiri et al. (2005).^c USEPA (2012).^d Enderlein et al. (2001).^e South African Water Quality Guidelines (1996).^f Kramer and Post (nd).

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.

3.1.24. pH and electrical conductivity (EC_w) of waters stored in the pervious pavement system

The pH and EC_w of waters from the system are reported by Nnadi et al. (2014). The FAO (2008) recommended the pH range of 6.5–8.0. According to Bauder et al. (2008) and Harivandi (1982), 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 et al. (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 be achieved by addition of gypsum, which would also add sulphur to the system. The classification of EC_w of irrigation water is presented in Table 5.

The range of the average EC_w of water from the test rigs is 242.50–341 $\mu\text{S}/\text{cm}$ throughout the duration of the experiment which is within the region of 'excellent' and 'good' for irrigation.

3.1.25. Total Petroleum Hydrocarbon (TPH)

Total Petroleum Hydrocarbon (TPH) in the waters from the test models is presented in Fig. 4(b). The result 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 15.13 g and 20.03 g were recovered in water from the stone and Permavoid sub base systems respectively. This result supports the high rate of efficiency of removal of pollutants by PPS as reported by earlier researchers (Bond, 1999; Coupe, 2004; Newman et al., 2002).

4. Conclusions

The study reported in this paper has shown that pervious pavement system has the capability to recycle stormwater to a quality meets the standards for use for agricultural irrigation irrespective of sub-base type and this added advantage should be explored as an alternative and sustainable source of irrigation water for landscape areas particularly during dry season. Furthermore, this added benefit from SUDS has the potential to encourage its adoption even in hot countries where there is prolonged water scarcity in dry seasons. Also, this study further demonstrates that the pervious pavement system has a high hydrocarbon, metals and other pollutants removal efficiency even other worst case pollutant loading scenario. When water is being recycled in PPS for irrigation, there is a potential benefit of nutrient availability in recycled water for plants, but care should be taken not to dispose of this water in natural water courses as it might result in eutrophication problems.

References

- Adams, C., Frantz, J., Bugbee, B., 2013. Macro- and micro-nutrient release characteristics of three polymer-coated fertilizers: theory and measurements. *J. Plant Nutr.* 176 (1), 78–88.
- ADEWHA, 2007. Indicator: Hs-44 Urban Stormwater and Wastewater Reuse. Australian Department of the Environment, Water, Heritage and the Arts. <http://www.environment.gov.au/soe/2006/publications/drs/indicator/337/index.html> (19.09.13.).
- Al-Jamal, M.S., Sammis, T.W., Mexa, J.G., Picchioni, G.A., Zachritz, W.H., 2002. A growth-irrigation scheduling model for wastewater use in forest production. *Agric. Water Manag.* 56, 57–79.
- Al-Shammiri, M., Al-Saffer, A., Bohamad, S., Ahmed, M., 2005. Waste water quality and reuse in irrigation in Kuwait using microfiltration technology in treatment. *Desalination* 185, 213–225.
- Amahmid, O., Bouhoum, K., 2000. Health effect of urban wastewater reuse in a peri-urban area in Morocco. *Environ. Manag. Health* 11 (3), 263–269.
- Amorim, F.A.C., Welz, B., Costa, A.C.S., Lepri, F.G., Vale, M.G.R., Ferreira, S.L.C., 2007. Determination of vanadium in petroleum and petroleum products using atomic spectrometric techniques. *Talanta* 72 (2), 349–359.
- Bauder, T.A., Waskom, R.M., Davis, J.G., 2008. Irrigation Water Quality Criteria. Colorado State University: Extension-Agriculture 0.506 [online]. Available from: <http://www.ext.colostate.edu/PUBS/crops/00506.html> (19.09.08.).
- Bond, P.C., 1999. Mineral Oil Biodegradation within Permeable Pavements: Long-Term Observations (Unpublished: PhD submitted to School of Built Environment). Coventry University, UK.
- Butt, M.S., Sharif, K., Bajwa, B.E., 2005. Hazardous effects of sewage water on the environment: focus on heavy metals and chemical composition of soil and vegetables. *Manag. Environ. Qual.* 16 (4), 338–346.
- Chen Jr., J.B., Yeager, T.H., Stamps, R.H., Felter, L.A., 2002. Potential of Collected Storm Water and Irrigation Runoff for Foliage and Bedding Plant Production. University of Florida, Florida.
- Coupe, S.J., Humphrey, G.S., Alan, P.N., Tim, P., 2003. Biodegradation and microbial diversity within permeable pavements. *Eur. J. Protistol.* 39, 495–498.
- Coupe, S.J., 2004. Oil Biodegradation and Microbial Ecology within Permeable Pavements (Unpublished PhD thesis). School of Science and the Environment, Coventry University, UK.
- DAH, 2008. Agricultural Irrigation Systems. Department of Agriculture, Hawaii, USA. http://hawaii.gov/hdoa/arm/arm_irrigation.
- Debasish, S., Das, P.K., Thippeswamy, T., Babu, C.M., Ramaswamy, G.N., Rajanna, L., 2003. Studies on the effects of sewage water irrigation on growth, yield and quality of Mulberry (*Morus indica* L.). *Indian J. Seric.* 42 (2), 174–177.
- deHayr, R., Gordon, I., 2006. Irrigation Water Quality Salinity and Soil Structure Stability. No. QNRM04191. Natural Resources and Water, Natural Resource Sciences, Queensland.
- Enderlein, U.S., Enderlein, R.S., Williams, W.P., 2001. Water quality: guidelines, standards and health. In: Fewtrell, L., Bartram, J. (Eds.), *Assessment of Risk and Risk Management for Water-Related Infectious Disease*. IWA Publishing, ISBN 924154533X (WHO), 1900222280. http://www.who.int/water_sanitation_health/resourcesquality/wpcchap2.pdf (accessed 05.05.14.).
- Ensink, J.H.J., Hoek, W., 2007. New international guidelines for wastewater use in agriculture. *Editorial Trop. Med. Int. Health* 12 (5), 575–577.
- Epshteyn, Y., Risdon, T.J., 2010. Molybdenum Disulphide in Lubricant Applications – a Review. 12 Lubricating Grease Conference 28–30 January, Gao, India. <http://www.nlgi-india.org/images/PDF/Yakov%20Ephsteyn.pdf> (19.09.13.).
- FAO, 2008. Wastewater Quality Guidelines for Agricultural Use. Food and Agricultural Organisation Corporate Document Repository: Natural Resources Management and Environmental Department. <http://www.fao.org/docrep/T0551E/t0551e04.htm> (19.09.13.).
- Fiorentino, C.E., Paoloni, J.D., Sequeira, M.E., Arosteguy, P., 2007. The presence of vanadium groundwater of southeastern extreme the pampean region Argentina relationship with other chemical elements. *J. Contam. Hydrol.* 93, 122–129.
- Fipps, G., 2003. Irrigation Water Quality Standards and Salinity Management Strategies. A&M Texas University Agri Life Extension B-1667, 4-03. <http://soiltesting.tamu.edu/publications/B-1667.pdf> (19.09.13.).
- Hamilton, A.J., Stagnitti, F., Xiong, X., Kreidi, S.L., Benke, K.K., Maher, P., 2007. Wastewater irrigation: the state of play. *Vadose Zone J.* 6 (4), 823–840.
- Harivandi, M.A., 1982. The Use of Effluent Water for Turfgrass Irrigation'. Cooperative Extension: California Rurgrass Culture 32. Nos. 3 & 4. https://agops.ucr.edu/turf/publications/ctc/ctc32_34.pdf (accessed 12.09.14.).
- Hillel, D., 2000. Salinity Management for Sustainable Irrigation. World Bank, Washington, USA.
- Kramer, A., Post, J., nd. Guidelines and Standards for Wastewater Reuse. Adelphi Research Berlin project sponsored by EU. http://cgi.tu-harburg.de/~awwwweb/wbt/emwater/documents/lesson_d1.pdf (accessed 05.05.14.).
- Lazarova, V., Asano, T., 2005. Challenges of sustainable irrigation with recycled water. In: Lazarova, V., Bahri, A. (Eds.), *Water Reuse for Irrigation: Agriculture, Landscapes and Turf Grass*. CRC Press, London.
- Madison, M., Emond, H., 2007. Approaches to harnessing stormwater reuse for multipurpose benefits. In: Wilson, J. (Ed.), *Water Resources Management (WRM)*, vol. 578, 20–22 August, 2007 Held at Honolulu, Hawaii, USA.
- Mastoi, G.M., Khuhawar, M.Y., Bozdar, R.B., 2006. Spectrophotometric determination of vanadium in crude oil. *Quant. Spectrosc. Radiat. Transf.* 102, 236–240.
- Methods for the Examination of Waters and Associated Materials, 1988. Sulphate in Waters, Effluents and Solids, second ed. HMSO ISBN no. 0117522406.
- Midcoast Water, 2008. What Is Stormwater Harvesting? Our Water Our Future Fact Sheet. Midcoast Water, Australia. Available from: http://www.midcoastwater.com.au/client_images/551804.pdf.
- Nable, R.O., Banuelos, G.S., Paull, J.G., 1997. Boron toxicity. *Plant Soil* 193 (2), 181–198.
- NERC, 2003. Water quality fact sheet: nitrate. British Geological Survey: Produced for WaterAid, London [online]. http://www-esd.worldbank.org/esd/ard/groundwater/pdfreports/Water_quality_Nitrate_factsheet.pdf (19.09.13.).
- Nnadi, E.O., 2009. An Evaluation of Modified Pervious Pavements for Water Harvesting for Irrigation Purposes (Unpublished Ph.D. thesis submitted to Faculty of Engineering and Computing). Coventry University, UK.

- Nnadi, E.O., Newman, A.P., Coupe, S.J., 2014. Geotextile incorporated permeable pavement system as potential source of irrigation water: effects of re-used water on the soil, plant growth and development. *Clean-Soil Air Water* 42 (2), 125–132. <http://dx.doi.org/10.1002/clen.201300165>.
- Newman, A.P., Pratt, C.J., Coupe, S.J., Cresswell, N., 2002. Oil bio-degradation in permeable pavements by microbial communities. *Water Sci. Technol.* 45 (7), 51–56.
- Newman, A.P., Coupe, S.J., Spicer, G.E., Lynch, D., Robinson, K., 2006. Maintenance of Oil- Degrading Permeable Pavements: Microbes, Nutrients and Long- Term Water Quality Provision. In: 8th international Conference on Concrete Block Paving, 6–8th November, 2006 San Francisco, California, USA.
- Newman, A.P., Nnadi, E.O., Duckers, L., Cobley, A., 2011. Self fertilising geotextiles for use in pervious pavements: a review of progress and further developments. *Water Sci. Technol.* 64 (6), 1333–1339.
- NSCA, 2006. Annual Report July 2005–June 2006. North Sydney Council of Australia. http://www.northsydney.nsw.gov.au/resources/documents/AnnualReport_2005_2006.pdf (19.12.13.).
- OECD, 2008. Achieving Sustainable Management of Water in Agriculture. Organisation for Economic Co-operation and Development. http://www.oecd.org/document/2/0,3343,en_2649_34563_42104450_1_1_1_37425,00.html (19.09.13.).
- Peterson, H.G., 1999. Fact Sheet: Field Irrigation and water quality. Agriculture and Agri-Food Canada-Prairie Farm Rehabilitation Administration: Agriculture and Agri-Food Canada. http://www.safewater.org/PDFS/resourceswaterqualityinfo/Resource_Water_Qual_Facts.pdf (19.09.13.).
- Potier, B., 2008. UNH research says, “hold the salt”. *Campus J. Univ. N. H.* <http://unh.edu/news/campusjournal/2008/Feb/20salt.cfm> (19.09.13.).
- Pratt, C.J., 1999. Use of permeable reservoir pavement constructions for stormwater treatment and storage for re-use. *Water Sci. Technol.* 39 (5), 145–151.
- Puehmeier, T., De Dreu, D., Morgan, A.W., Shuttleworth, A., Newman, A.P., 2005. Enhancement of oil retention and biodegradation in stormwater infiltration systems. In: 10th International Conference on Urban Drainage. 21st August–26th August Copenhagen, Denmark.
- Puehmeier, T., Newman, A.P., 2008. Oil Retaining and Treating Geotextile for Pavement Applications. In: 11th International Conference on Urban Drainage (ICUD), 31st August–5th September, 2008 Edinburgh Scotland.
- Raschid-Sally, L., Carr, R., Buechler, S., 2005. Managing Wastewater Agriculture to Improve Livelihoods and Environmental Quality in Poor Countries. *Irrig. Drain.* 54 (S1), S11–S22.
- Rowe, D.R., Abel-Magid, I.M., 1995. *Handbook of Wastewater Reclamation and Reuse*. CRC Press Inc., New York.
- Schwecke, M., Simmons, B., Maheshwari, B., 2007. Sustainable use of stormwater for irrigation. *The Environmentalist* 27 (1), 51–61.
- Sotiropoulos, T.E., Therios, L.N., Dimassi, K.N., 2003. Boron toxicity in kiwifruit plants (*Actinidia deliciosa*), treated with nitrate, ammonium, and a mixture of both. *Plant Nutr. Soil. Sci.* 166 (4), 529–532.
- South African Water Quality Guidelines, 1996 Agricultural Water Use: Irrigation, second ed., vol. 4. Department of Water Affairs and Forestry http://www.dwaf.gov.za/iwqqs/wq_guide/Pol_saWQguideFRESH_vol4_Irrigation.pdf. (accessed 05.05.14.).
- Spectrum Analytical Incorporated, USA, 2013. Guide to Interpreting Irrigation Water Analysis [online]. http://www.spectrumanalytic.com/support/library/pdf/guide_to_interpreting_irrigation_water_analysis.pdf (19.09.13.).
- Stark, J.C., Jarrell, W.M., Letey, J., Valoras, N., 1983. Nitrogen use efficiency of trickle-irrigated tomatoes receiving continuous injection of nitrogen. *Agronomy* 75, 672–676.
- UNESCO, 2007. Water for People, Water for Life. The United Nations World Water Development Report. United Nations Educational Scientific and Cultural Organization (UNESCO). <http://unesdoc.unesco.org/images/0012/001295/129556e.pdf> (12.09.13.).
- UNSW, 2008. Exchangeable Sodium Percentage (ESP). University of New South Wales, Australia. http://www.terragis.bees.unsw.edu.au/terraGIS_soil/sp_exchangeable_sodium_percentage.html (19.09.13.).
- USEPA, 2012. United States Environmental Protection Agency Guidelines for Water Reuse 2012. EPA/600/R-12/618 | September 2012. Office of Wastewater Management, Office of Water, Washington, D.C.
- Vallentin, A., 2006. Agricultural use of reclaimed water – experiences in Jordan. *Water Pract. Technol.* 1 (2), 1–5.
- Wallach, R., Ben-Arie, O., Graber, E.R., 2005. Soil water repellency induced by long-term irrigation with treated sewage effluent (Technical reports: Waste Management). *J. Environ. Qual.* 34, 1910–1920.
- Warrence, K.J., Pearson, K.E., Bauder, J.W., 2003. The Basics of Salinity and Sodidity Effects on Soil Physical Properties. Land Resources and Environmental Sciences Department: Montana State University, Bozeman, USA. Available from: <http://waterquality.montana.edu/docs/methane/basics.pdf> (19.09.13.).
- Whipker, B., 1999. Iowa State University Horticultural Guide: Commercial Horticulture: Irrigation Water Quality for Container-Grown Crops. Iowa State University, USA. www.extension.iastate.edu/Publications/PM1699.pdf (19.09.13.).
- WHO, 2008. Guidelines for Drinking-Water Quality. World Health Organisation (WHO), Geneva. http://www.who.int/water_sanitation_health/dwq/secondaddendum20081119.pdf (19.09.13.).
- Wu, L., Guo, X., Brown, J., 2000. Studies of Recycled Water Irrigation and Performance of Landscape Plants under Urban Landscape Conditions. University of California: Agriculture and Natural Resources, California, USA. Slosson Report. <http://slosson.ucdavis.edu/documents/1999-20002062.pdf>.
- Yadav, R.K., Goyal, B., Sharma, R.K., Dubey, S.K., Minhas, P.S., 2002. Post-irrigation impact of domestic sewage effluent on composition of soils, crops ground water – a case study. *Environ. Int.* 28, 481–486.