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Evaluation of Pervious and Macro-Pervious Pavements as Harvesting Systems for Localized Landscape and Horticultural Irrigation.

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ABSTRACT

Pervious pavements have been used as water harvesting systems and studies have shown the value of water derived from pervious pavements as irrigation water for landscaping. An alternative system is a modification known as a *macro-pervious pavement system.* These devices infiltrate water through discrete points into a porous subbase offering all the benefits of the pervious pavement along with an ability to use the specially designed infiltration systems as a means of protecting the sub surface environment from major oil spillages. This paper reports ongoing research aimed at assessing the suitability of water derived from both pervious and macro-pervious pavement installations for irrigation use. Results are reported from ongoing field studies of a 6 year old macro-pervious pavement and, for comparative purposes, a 10 year old pervious pavement system which illustrates the great potential of pavement derived water from both types of system and some of the problems which require care in the management of the irrigation system.

INTRODUCTION

Forming a subset of the set of pervious pavement systems (PPSs), a more recent approach are alternative systems which have been described as macro-pervious pavement systems (MPPSs) which direct stormwater underground through a system of widely distributed, but distinct infiltration points (Newman *et al.*, 2013) which allows the use of traditional impervious surfacing. The design of a MPPS should provide a treatment process that removes stormwater pollutants and should detain the bulk of these pollutants in a position where they can be easily removed. In 2011, extensive study was started (Newman *et al.,* 2013) on a MPPS installed as a prison car park in Scotland. That investigation concentrated on the qualities of the effluent from the point of view of it being a discharge to a local watercourse. This paper is an extension to that study which, 3 years later, considers both the ongoing quality of water as an effluent for release to a water body and further extends the study into a consideration of the value of the water derived from such a site for landscape irrigation. Sampling will continue, to be followed by extensive further pot trials. Data is also presented from samples collected from a traditional pervious car parking surface. The traditional PPS has shown a poor pollution retention performance when challenged by major hydrocarbon releases (Newman *et al.,* 2004).The MPPS investigated in this study is equipped with devices to retain, at the surface, the bulk of any major spill, thus protecting the pollution attenuation mechanisms in the underground parts of the system. Readers are directed to the original paper for further details (Newman *et al.,* 2013).

Irrigation Using Harvested Rainwater

With the application of innovative and sustainable construction methods and technologies, stormwater can be transformed to become a resource. Our group has carried out studies involving irrigation with PPS effluent (Nnadi *et al.,* 2015; Nnadi *et al*., 2014) using water from laboratory models. If stormwater is to be used to support plants, there is a need for such water to meet irrigation water quality standards so as not to pose a threat to either soil structure or the plants themselves or the workforce (Hamilton *et al.,*2007). Particularly, if the amount of water applied to the soil is not sufficient to allow downward percolation of the applied water below the root zone, it is inevitable that minerals from the irrigation water will accumulate at that level. In such circumstances, it is important to take into account, amongst other things the total concentration of soluble salts and the sodium adsorption ratio (SAR), which is a parameter dependent upon the relative molar concentrations of sodium to other cations (Ashraf and Harris, 2004). The assessment of impact of irrigation water on soil will therefore usually be based on electrical conductivity (EC) (as a surrogate for the concentration of total salts and SAR) (deHayr, and Gorden, 2006) as well as the concentrations of toxic substances. The main aim of the current study was to examine the quality of waters from well established MPPS and the PPS installations from the point of view of the suitability of the waters for irrigation and/or release to the local watercourse. Sampling from both sites is ongoing and we currently await the onset of winter, particularly at the MPPS site in Scotland where it is expected that the addition of salt for de-icing purposes will complicate the management of the irrigation water. It is intended that this will be discussed in detail at the conference.

MATERIALS AND METHODS

Main Study Site – Scotland

The main study site and sampling regime is described in detail elsewhere (Newman *et al.,* 2013). The following is a brief description to aid understanding of the data. The car park was constructed in 2008 and consisted of a 3 sub-catchments (two of around 1350 m^2 and one of 300 m^2.)The majority of the surface of the car park consists of impervious asphalt with surface water collected by linear shallow gravity separator units discharging into a secondary pollution attenuation system below the pavement. It then flows into the crushed limestone subbase which drains towards separate flow control chambers in each of the sub-catchments to allow flow control through an orifice plate at each outlet. These provide convenient sampling points. Twelve months after the car park was completed a sampling regime was instigated in which grab samples were collected from each of the three flow control chambers. Samples were initially collected from April 2011 to September 2012 and then, following consideration of the data, sampling was recommenced in 2014. After the first round of additional sampling it was found that the smaller of the 3 sub-catchments was producing effluent which was extremely high in sodium. Further investigation led to the discovery that the sub-catchment was impacted by salt which was stored there for the purpose of melting ice in winter. This sub–catchment was then removed from the sampling programme as unsuitable for irrigation use.

Supplementary Sampling Site - England.

For comparative purposes and with a view to providing an alternative source of irrigation water for our planned pot trials, 3 additional sampling operations were carried out at a long established PPS car park. This factory car park was constructed within an experimental test bed in Bury, Lancashire and has been in use for 10 years. The details of the test bed upon which this car park was built have recently been published (Newman *et al.,* 2014). The parking area consisted of two bays each of 2400mm width and 4800mm length. The bays are underlain by an impermeable membrane and the construction consists of Formpave Aquaflow® blocks overlaying a laying course of 6-10mm limestone laid onto a Terram 1000 geotextile covering a Permavoid® polypropylene subbase replacement system. The system is drained via a 100mm uPVC pipe attached to the membrane and exiting through the retaining wall which forms the front face of the test bed. The two bays are isolated from the other bays in the test bed. Grab samples were collected during significant rain events that had been preceded by a dry period of at least 7 days. At the time of writing samples had been collected between June and December.

Physical and Chemical Analysis

Details of the analysis and quality control (QC) procedures are given elsewhere (Newman *et al*.,2014).Characterisation of samples included: suspended solids (TSS), heavy metals (lead, zinc, chromium, nickel, cadmium and copper), organic pollutants (total petroleum hydrocarbons (TPH), benzene, toluene, ethyl benzene, xylenes (collectively BTEX) and methyl tertiary butyl ether (MTBE) and nutrients (total oxidised nitrogen, ammonium and total phosphorus). In June 2014, additional parameters were added. These were considered essential to the evaluation of the water as an irrigation source and included sodium, potassium, calcium ,magnesium and boron (determined by ICP–OES) and electrical conductivity. Each quality parameter is described in the results section by the un-weighted mean and maximum concentrations for each catchment over all sampling events for which data is available (except for pH which is described with the range and median).

RESULTS AND DISCUSSION

For reasons of brevity, those parameters for which the evidence provided in Tables 1-7 below indicate that the effluent from both the MPPS and the PPS sampling sites is satisfactory , both as a source for irrigation and for release to the nearby watercourses will not be discussed in detail. These include the heavy metals reported in Table1, where all results are below both the limits required for release to the watercourse and are also well below the concentrations required for use as irrigation water. For suspended solids (Table 2), there is a distinct lack of nationally mandated effluent standards. A limit of 30mg/l is proposed as an effluent standard but it can be seen that to date most measurements have been below 20mg/l.

TABLE 1 Heavy Metals

Element /Units	Catchment/ No. of Sampling Events	Mean	Max	Derived Effluent Standard[1]	Irrigation Water Limit		
					Long Term	Short Term	
Lead /μgl^{-1}	**MPPS- Prison Car Park**			144	5000	10000	Rowe and Abdel-Magid (1995)
	FC1, n=12	<2	2.1				
	FC2, n=12	<2	<2				
	FC3, n=9	<2	<2				
	PPS-Factory Car Park						
	SEL1-n=3	2.9	8.7				
Zinc /μgl^{-1}	**MPPS- Prison Car Park**			1000	5000	-	National Academy of Sciences -in Harivandi (1982)
	FC1, n=12	46	280				
	FC2, n=12	24	34				
	FC3, n=9	20	<6				
	PPS-Factory Car Park						
	SEL1-n=3	23	34				
Copper/μgl^{-1}	**MPPS- Prison Car Park**			144	200	5000	Rowe and Abdel-Magid (1995)
	FC1, n=12	14	43				
	FC2, n=12	9	56				
	FC3, n=9	12	22				
	PPS-Factory Car Park						
	SEL1-n=3	24	71				
Chromium/μgl^{-1}	**MPPS- Prison Car Park**			68	100	-	Nnadi et al., (2014)
	FC1, n=12	0.8	2.1				
	FC2, n=12	1.8	2.5				
	FC3, n=9	<0.3	5.7				
	PPS-Factory Car Park						
	SEL1-n=3	5.3	7				
Cadmium/μgl^{-1}	**MPPS- Prison Car Park**			1.8	10	50	Rowe and Abdel-Magid (1995)
	FC1, n=12	<0.2	<0.2				
	FC2, n=12	<0.2	<0.2				
	FC3, n=9	<0.2	<0.2				
	PPS-Factory Car Park						
	SEL1-n=3	<0.2	<0.2				
Nickel/μgl^{-1}	**MPPS- Prison Car Park**			400	500	50	Harivandi, (1982).
	FC1, n=12	1.4	14				
	FC2, n=112	3.4	12				
	FC3, n=9	9.7	2				
	PPS-Factory Car Park						
	SEL1 n=3	4.4	5.4				

[1] See Newman *et al.,* (2013) for the method by which these standards were derived.

Table 2 illustrates that the TSS concentrations comply with both effluent release and irrigation water standards. Table 2 also contains data for TPH and it is clear that typical effluent limits are not even approached. The irrigation limits are dependent of the solubility of the various carbon chain fractions (except for C_9-C_{14} where a limit of

1.8mg/l applies). Since no measurements of TPH exceeded this value and in the absence of free product on the effluents it can be concluded that, from, the point of view of total hydrocarbons, it would have no detrimental effect if used for irrigation. It must be remembered though that no major hydrocarbon spillage is recorded for either site and had this occurred the PPS at the English site may be expected to perform rather worse than this

TABLE 2 Total Petroleum Hydrocarbons and Suspended Solids

Pollutant /Units	Catchment/ No. of Sampling Events	Mean	Max	Effluent Standard	Suggested Irrigation Water Limit	Source of Suggested Irrigation Water Limit
Total Petroleum Hydrocarbons /mgl^{-1}	**MPPS- Prison Car Park**			5[I,] 15 [II]	1.8 for C_9-C_{14} (C_7-C_9 and C_{15}-C_{27} criteria exceed solubility)	New Zealand Govt. (2011)
	FC1, n=12	0.07	0.19			
	FC2, n=12	0.15	0.35			
	FC3, n=9	<0.01	0.15			
	PPS-Factory Car Park					
	SEL1-n=3	<0.01	<0.01			
TSS mg/l	**MPPS- Prison Car Park**			30[III]	50	FAO (2008)
	FC1, n=12	3.4	13			
	FC2, n=12	4.8	12			
	FC3, n=9	4.3	18			
	PPS-Factory Car Park					
	SEL1-n=3	14	42			

[I] Limit for Class 1 petrol interceptor (British Standards Institution, 2002)

[II] Texas Commission on Environmental Quality (2012)

[III] Usual standard for the UK aggregate industry. Minerals Industry Research Organisation (ND)

The BTEX concentrations (not tabulated) were all below the 1µg/l limits of detection for these compounds. Typical of the conservative end of the range of effluent standards for these compounds is 50µg/l for benzene applied by the Texas Commission on Environmental Quality (2012). Thus, the effluent limits are not even being approached. The irrigation water limits for BTEX proposed by the New Zealand Govt. (2012) range from 800µg/l for benzene to as high as 39mg/l for toluene. MTBE was also invariably below its detection limit (10µg/l). Neither effluent or irrigation water standards for MTBE could be found in the literature but since the State of Florida mandate a drinking water limit of 50µg/l in drinking water, this value could be seen as a conservative limit for effluent release and a very conservative irrigation water limit. Clearly, neither the waters from the MPPS or the PPS studied here would be affected for irrigation purposes by the BTEX compounds or MTBE.

Boron (not tabulated) was always below the 40µg/l limit of detection, and thus well below the 500µg/l soil pore water limit for the most sensitive plants (Bauder *et a*l., 2014). Examining the major cation concentrations in (Table 3) individually, before considering them in combination, we can see that calcium, magnesium and potassium are low compared to any irrigation water limits and most authors would expect that at least magnesium and potassium would need to be supplemented for optimum plant growth (Nnadi *et al .,*2014). It is with sodium that we see the first real difference between the two sites. The source of sodium in run-off from car parking areas is often salt applied for de-icing purposes.

TABLE 3 Major Cations

Element/Units	Catchment/ No. of Sampling Events	Mean	Max	Irrigation Water Limits	Source of Suggested Irrigation Water Limit
Sodium/mgl^{-1}	**MPPS- Prison Car Park**			70	South African Govt. (1996).
	FC1, n=12	37.5	80		
	FC2, n=12	27.2	46		
	FC3, n=1	-	1000		
	PPS-Factory Car Park				
	SEL1-n=3	7.6	10		
Calcium /mgl^{-1}	**MPPS- Prison Car Park**			80[I]	Spectrum, (2013)
	FC1, n=12	7.8	15		
	FC2, n=12	8.8	20		
	FC3, n=1	-	42		
	PPS-Factory Car Park				
	SEL1-n=3	51	63		
Magnesium/ mgl^{-1}	**MPPS- Prison Car Park**			8[I]	Spectrum, (2013)
	FC1, n=12	0.44	1.2		
	FC2, n=12	0.64	1.8		
	FC3, n=1	-	0.33		
	PPS-Factory Car Park				
	SEL1-n=3	5.96	7.9		
Potassium/mgl^{-1}	**MPPS- Prison Car Park**			80	Vallentin (2006),
	FC1, n=12	0.8	1.1		
	FC2, n=12	0.96	1.8		
	FC3, n=1	-	8.4		
	PPS-Factory Car Park				
	SEL1-n=3	2.93	3.1		

[I] These values are the concentrations at the top of the “low” range indicated by this source and are not really limits in the sense of this being harmful to plants or soil.

The PPS car park is some 320 km south of the MPPS in Scotland. It is subject to very little application of salt. The that the two larger MPPS sub-catchments studied are probably being indirectly affected by the stored salt. Although the mean concentrations are below the suggested 70mg/l irrigation water limit the maximum concentration recorded at catchment FC1 slightly exceeds this. However, it is not the sodium in isolation that is the greatest concern when considering irrigation. Table 6 shows the calculated sodium absorption ratio for the two sites. The sodium absorption ratio (SAR) is a parameter which measures the potential for irrigation water to cause harm to soil structure by swelling of clay minerals and is dependent on the molar ratios of sodium to calcium and magnesium (see Bauder *et al.,* 2014).
Both sites (apart from FC3 at the Scottish site) fall into the category which indicates little or no hazard even with the elevated sodium levels observed. The effect of SAR on soil structure is also dependent on electrical conductivity (EC) because the swelling effect on clay minerals with a low EC is greater than high EC waters with

the same sodium content (Bauder *et al.,* 2014). These authors indicate that with a SAR <3 problems do not become likely unless the EC is less than 0.2 dS/m. For a SAR between 3 and 6 this rises to 0.4 dS/m and between 6 and 12 SAR the minimum EC at which problems become likely is 0.5dS/m. Clearly even with the salt contamination evident at the site in Scotland water from neither site would be likely to give rise to problems of infiltration as a result of the SAR (except the water from FC3 which was directly affected by salt storage).

TABLE 4 Sodium Absorption Ratio

	Sodium Absorption Ratio		**Low**	**Medium**	**High**	**Very High**
			Little or no Hazard	Appreciable but manageable hazard	Unsatisfactory for most crops	Unsatisfactory for most crops
	Mean	**Max**				
MPPS- Prison Car Park			0-10	10-18	18-26	>26
FC1n=4	3	7				
FC2n=4	3	8				
FC 3n=1		30				
PPS-Factory Car Park						
SEL1n=2	0.21	0.26				

Electrical conductivity (Table 5) is also used as an important measure of irrigation water suitability independent of SAR. It can be seen that from an irrigation point of view both sites (except FC3) fall into the “No Limitations” category as proposed by Bauder *et al.,* (2014). The pH of irrigation water is also an important factor and Table 6 indicates that for the water to be of general use with no need to moderate the pH only the PPS site is, based on the data available, suitable. The high pH of the MPPS effluent as indicated in Table 6 is considered to be due to the limestone used as the subbase/storage volume in that installation. If the all or some of the subbase were to be replaced either with a non-calcareous stone such as granite or with a plastic sub- base replacement as was used in the PPS installation, it would be possible to moderate the pH at source. Rather than adjusting the pH post harvesting, it would be possible both to increase the void volume under the MPPS by replacing

TABLE 5 Electrical Conductivity

Catchment /No. of Sampling Events	**Electrical Conductivity** dS/m 20°C		**Irrigation Water : Limitations for Use** (according To Bauder *et al.* (2014))			
	Mean	**Max**	**None**	**Some**	**Moderate**	**Severe**
MPPS-Prison Car Park			<0.75	0.76-1.5	1.51-3	>3
FC1n=4	0.17	0.32				
FC2n=4	0.14	0.19				
FC 3n=1		4.7				
PPS-Factory Car Park						
SEL1 n=3	0.29	0.33				

the limestone subbase with plastic subbase replacement units (using the additional void space created to store the water within the car park) and, at the same time, reduce the pH. If post harvesting modification of pH is selected, it could be part of a process where fertiliser is added along with irrigation water (fertigation). Table 7 indicates that whilst the release of nutrients is generally not a problem from a “discharge to watercourse” point of view, both nitrogen and phosphorus availability are well below that which would be considered optimum for plant growth. The maximum value of TON (29mg/l) in FC1 represents a single excursion and it is believed that the pulse of nitrogen was as a result of disposal of some inappropriate wastewater into the system, a possibility that any surface water system is subject to. Adding the nitrogen as ammonium nitrate could be a useful way of providing

TABLE 6 pH

	Catchment/No. of Sampling Events	**Observed Data**			**Irrigation Water Limits**		**Source of Irrigation Water Limit(s)**
	MPPS-Prison Car Park	**Median**	**Max**	**Min**	**Min**	**Max**	
pH	FC1, n=12	9.2	10.2	8.2	5	9	State of Alaska (2003)
	FC2, n=12	9.4	11.1	7.9			
	FC3, n=9	10.6	11.2	6.7			
	PPS-Factory Car Park						
	SEL1 n=3	7.75	7.8	7.7			

TABLE 7 Nitrogen and Phosphorus

Nutrient /Units	**Catchment/ No. of Sampling Events**	**Mean**	**Max**	**Derived Effluent Standard**	**Maximum Conc. to avoid plant damage.**	**Typical[1] application rate for bent grass turf kg/100m^2/yr**
Total Oxidised Nitrogen/mgl^{-1}	**MPPS- Prison Car Park**					
	FC1, n=12	3.5	29	Not Available	Not Applicable	0.8-1.25 Total Nitrogen
	FC2, n=12	0.5	0.92			
	FC3, n=9	0.4	0.71			
	PPS-Factory Car Park					
	SEL1-n=2	1.4	2.8			
Ammonia N /mgl^{-1}	**MPPS- Prison Car Park**					
	FC1, n=12	<0.2	<0.2	0.42	<7mg/l for sensitive plants	
	FC2, n=12	<0.2	<0.2			
	FC3, n=9	<0.2	<0.2			
	PPS-Factory Car Park					
	SEL1 n=0					
Total P /mg/l	**MPPS- Prison Car Park**				No limit but many jurisdictions control application rates	
	FC1, n=12	<0.3	<0.3	2.4		0.27-0.41
	FC2, n=12	<0.3	<0.3			
	FC3, n=9	<0.3	13			
	PPS-Factory Car Park					
	SEL1 n=2	<0.3	0.42			

[1] converted to metric units from data presented by Seedland Inc. (2012)

nitrogen whilst moderating pH. Addition of P as acidulated mono potassium phosphate or phosphoric acid would also assist in lowering the pH.

CONCLUSION

Carefull management of catchments will be required if stormwaters harvested from either PPS or MPPS installations are to be used routinely for irrigation in areas where salt is used in winter. In many temperate areas, this is bound to cause issues and at some times of the year, it may be necessary to divert water away from the storage system used to capture the treated stormwater during the period where snow and ice are melting. In areas where road salt is not applied, this would not be an issue. It seems that provided care is taken either with the construction of the system or post harvesting to ensure that the pH is controlled, to a suitable level for the chosen plants, then stormwater from either device would provide an excellent irrigation resource. There were no issues associated with the toxic components of the stormwater at either site from either an irrigation or effluent release point of view. This is despite the oldest of the systems having been in use for 10 years. The problem with utilising a traditional PPS, rather than a MPPS, for this purpose is that a major oil release, such as the loss of a full sump of oil would immediately contaminate a large volume of the subsurface leading to long term losses of oil as sheen that could be detrimental to plants. With the MPPS studied here however, a great majority of oil would be collected in the channel collectors such that it could be easily recovered without harming the subsurface environment.

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