The drying and wetting effects on clogging and pollutant removal through porous pavements

Les effets du séchage et du mouillage sur l'élimination de polluants et sur le colmatage de chaussées poreuses

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RÉSUMÉ

Cet article présente les principaux résultats d'une étude en laboratoire sur les effets des périodes de temps sec et pluvieux sur le rendement épuratoire et le colmatage de trois types de chaussées poreuses au cours de leur durée de vie. Les chaussées poreuses examinées sont deux chaussées en matériau monolithique (Porous Asphalt, PA et Permapave, PP) et une chaussée modulaire (Hydrapave, HP). Elles sont sollicitées de manière aléatoire avec quatre débits 'typiques' différents (de faible à fort) pendant des périodes de 13 jours, représentant chacune les précipitations annuelles à Brisbane, Australie (les expériences sont donc accélérées par rapport à la réalité). Chaque période pluviale est suivie d'une période sèche de trois heures. Des échantillons sont relevés à l'entrée et à la sortie pour mesurer les concentrations de MES, d'azote total et de phosphore total. Pour évaluer le taux de colmatage, un événement pluvial avec une période de retour de 5 ans est simulé pendant les semaines 6, 8, 12 et 16 de l'expérience. Sous une pluie typique, aucune des chaussées ne montre d'accumulation d'eau à la surface, même après l'équivalent de 15 ans de sollicitation. Par contre, pendant une forte pluie, l'eau commence à s'accumuler à la surface des chaussées PA et HP après 12 ans ; par contre, la chaussée PP ne montre aucun signe de colmatage. Les périodes sèches et pluviales ne semblent pas influencer le rendement épuratoire de la MES, qui est toujours proche de 100%. La rétention du phosphore est de 20%, avec un relargage évident pendant les débits faibles. La concentration en azote est toujours plus élevée qu'à l'entrée, sauf pendant les débits forts. Le débit de l'évènement pluvial avec une période de retour de 5 ans produit un rendement épuratoire similaire à celui du débit 'typique fort' pour les trois polluants.

ABSTRACT

This paper presents the key findings of a laboratory investigation into the effects of dry and wet weather periods on the clogging behaviour and pollutant removal efficiency of three porous pavement types over their lifespan. These pavements were monolithic Porous Asphalt (PA), Permapave (PP), and modular Hydrapave (HP). The pavements were randomly dosed with four different flow rates over a period of 13 days, which is equivalent to the average annual rainfall of Brisbane, Australia (1200 mm). A drying event of 3 hours duration was simulated between every flow. Inflow and outflow samples were collected and analysed for Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrogen (TN). To evaluate the rate of clogging, a 1 in 5 year Brisbane storm event was simulated in the 6^{th}, 8^{th}, 12^{th} and 16^{th} week. Under normal rainfall conditions, none of the pavements showed signs of clogging even after 15 years. However, under storm conditions, both PA and HP started to pond after 12 years of equivalent dosing, while Permapave showed no signs of clogging after 18 years. The drying showed no effects on TSS removal, with all systems achieving near 100% removal. The average TP removal was 20% for all flows except for low flow, which had a significant amount of leaching over time. Leaching was also observed in TN during all flows except high flows. The TSS, TP and TN results observed during storm events were similar to that of high flow.

KEYWORDS

Clogging, drying and wetting, pollutant removal, porous pavements, variable flow rates

1 IINTRODUCTION

Stormwater runoff has long been undervalued and unappreciated, but is now increasingly being recognised as a valuable commodity that should not be discharged without treatment and/or use. The increasing rate of population growth and urbanization, which contributes to increased imperviousness, higher runoff volume and decreased water quality, has further exacerbated this issue. Water sensitive urban design (WSUD) is a stormwater management approach that emphasizes sustainable practices and minimises the effects of urbanization on receiving waters. Most of the available stormwater management measures are difficult to implement on a wide scale due to existing infrastructure and space constraints. Porous pavement however, is one measure that is easily retrofitted within developed urban areas.

Porous pavements are a permeable pavement surface with an underlying stone reservoir that temporarily stores surface runoff before infiltrating into the subsoil (Ferguson, 2005). This porous surface replaces traditional pavement, allowing runoff to infiltrate directly into the soil to receive water quality treatment. They come in several forms and are either monolithic or modular. Monolithic structures consist of bound granular material without the finer aggregate grain sizes and are incorporated with void spaces to allow for infiltration; while modular structures are constructed from individual pavers, with gaps between each paver. They are usually laid on sand or fine gravel underlain by a layer of geotextile, with a layer of coarse aggregate below.

Porous pavements can be used to reduce peak stormwater runoff, increase groundwater recharge, as well as improve stormwater quality. Gburek and Urban (1980) found that as much as 70% to 80% of annual rainfall on a porous pavement goes towards groundwater recharge. The efficiency of porous pavement in attenuating peak discharges has also been confirmed in several studies (Pratt *et al.*, 1999; Bean *et al.*, 2007). In fact, the ability of porous pavements to reduce peak flood discharges and reduce runoff volume by infiltration to the underlying soil are the major reasons for their adoption in many countries (Scholz and Grabowiecki, 2007).

While porous pavements have the potential to be a highly effective treatment practice, history has unfortunately shown many failures due to poor design, construction and maintenance practices. Traditionally, porous pavement sites have had a high failure rate of approximately 75% (Galli, 1992) due to clogging. This process decreases the porosity, permeability and hence the infiltration rate of a system. Clogging can occur during or immediately after construction, or through long-term use. The performance of porous pavement, which varies depending on the local climatic, soil and plant conditions have also had a poor reputation of having insufficient infiltration capacity. Several studies have shown that with proper maintenance, porous pavement can retain its permeability (Goforth *et al.*, 1983; Gburek and Urban, 1980). Although a lot is known about the pollutant removal performance of porous pavement (Booth and Leavitt, 1999), particularly when the system is ‘new’, very few studies have been published, which address clogging and its impacts on hydraulic behaviour, and how these phenomena respond to the effects of ageing. The key mechanisms that govern clogging in different systems are also poorly understood.

As such, an experiment designed to test the effectiveness of various types of porous pavements in reducing stormwater volume and improving outflow stormwater quality was conducted. Three types of porous pavement material will be compared to deliver new insights into the nature of porous pavement clogging and consequently the treatment performance of these systems under Australian conditions. This will be achieved by investigating the rate of clogging and the treatment efficiency of key stormwater pollutants. Recommendations regarding the porous pavement design will also be developed. This paper reports on the second phase of a laboratory investigation into processes that occur within typical porous pavement systems (the case when pavements are used for attenuation of flow with no ex-filtration allowed).

2 METHODS

Three porous pavement systems that represent the range currently available in practice were chosen for this study (Figure 1). They are the traditional monolithic porous asphalt (PA), popular modular Hydrapave (HP) (known as Formpave in the UK), and Permapave (PP), a new type of monolithic pavement developed in Australia. PA consists of a standard bituminous asphalt surface, in which all the fines have been removed, a filter layer of crushed aggregate and a reservoir layer (Diniz, 1980). HP is an 80 mm thick concrete paver with a unique chamber and bevel system, which is laid on a 50 mm course of 5 mm stone (Boral Clay and Concrete, 2005). The laying course is further separated from the upper and lower sub-base by a layer of geotextile. PP is made from crushed gravel of 50 mm thickness and is placed over a layer of 5-20 mm screen crushed rock (Dymon Industries, 2007).

The laboratory study was conducted in a compressed time scale, the wetting and drying period of which has been exaggerated in order to study the clogging processes. A similar laboratory study was conducted in 2008 but only the wetting events were simulated (Yong *et al.*, 2008). The pavements were investigated for their rate of clogging as well as their treatment efficiency of key stormwater pollutants.

Laboratory Rig

The pavements were installed side by side in a 2.7 m x 0.45 m x 1.95 m rig, which was divided into three separate vertical compartments (Figure 1). HP and PP were installed according to the specifications supplied by their manufacturers, while PA was installed following the standard guidelines ((Boral Clay and Concrete, 2005; Dymon Industries, 2007).

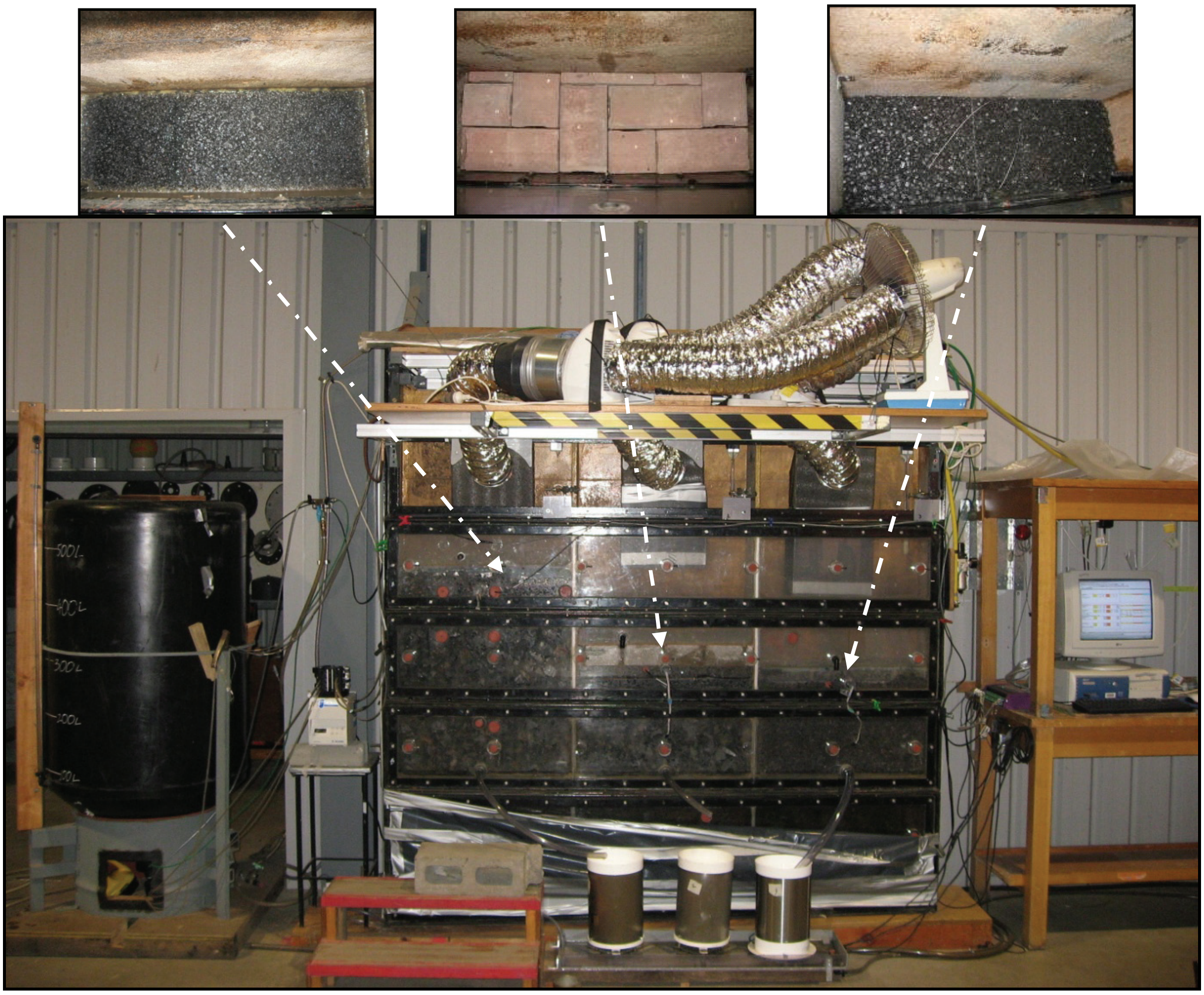

Figure 1.The experimental rig for the comparison of PA, HP and PP.

The gravel, used as the sub-base for each system, was thoroughly washed prior to the filling of the rig to ensure that they were free of fines. Each sub-base layer was compacted with a hand tamper before the pavement was placed firmly over the sub-base. As the basis of operation for HP is the infiltration of water through the small channels formed at the end of the pavers, careful measurements were taken to maintain the ratio of channel to paver area (typical of normal installation) and the exact number of pavers and channels in the rig.

The stormwater distribution system consists of a 550 L tank, a peristaltic pump, connection tubes and a specially designed pneumatic water delivery mechanism that uniformly distributes stormwater over each surface. This distribution system was continually refined until a uniform inflow of water was achieved over each of the porous pavement systems.

To simulate the drying conditions for the pavements, a range of radiant lamps and fan heaters were tested at various settings. Heat sensors were installed on the surface as well as below each pavement to determine the best heat source that achieved the most moisture loss (minimum 80%) from the pavements in 3 hours (this was assumed sufficient to represent dry conditions). The final heating system consists of a desk fan, three individual fan heaters, metal heat ducts and their corresponding rectangular insulator heat delivery boxes to convey heat at a specific setting towards the surface of each system (Figure 1). The desk fan, which was connected to the individual heaters via heat ducts, ensured a steady flow of cool air being drawn into the system to prevent the heaters from overheating, while the insulator boxes were designed such that when placed above the pavements, they were at equal distances of 30 cm from the surface of each pavement.

Experimental Procedure

Prior to the commencement of this experiment, a series of hydraulic conductivity tests were performed to determine the porosity of each individual pavement system when “new”, using clean tap water. Standard Darcy’s tests (water was fed from bottom-up) were carried out.

The inflow rates used in the experiment were reflective of sub-tropical Brisbane climate. Using the Model for Urban Stormwater Improvement Conceptualization (MUSIC) (CRCCH, 2005), the frequency curve of a typical 10 year “effective” rainfall event for Brisbane, Australia was generated. From the frequency curve, 4 flow rates, each corresponding to a different percentile group of rainfall intensity, as shown in Table 1, were chosen. Flow A was the lowest flow, followed by Flow B, C and D in increasing order. Each flow rate represented the average rainfall intensity of the 0-39, 40-59, 60-79 and 80-100 percentile groups. By multiplying the fraction represented by each of these percentile groups with their corresponding average intensities, an overall volume was obtained. A subsequent division of this overall volume with the average annual Brisbane rainfall of 1200 mm determined the duration needed to simulate 1 year’s worth of rain. A total of 10 days (continuous wet weather) was calculated to deliver 1200 mm of rain at 4 different flow rates at their corresponding percentile fractions.

Table 1. Selection of Flow Rates from 10 year Brisbane Rainfall Time Series (1988 to 1997)

Flow	**Frequency (percentile range)**	**Duration**	**Flow rate per ha.**	**Velocity**	**Pavement Area**		**Flow rate**	
		hours	**m^3/sec**	**m/sec**	**mm/hr**	**m^2**	**m^3/sec**	**ml/sec**
A	0-39	96	0.0006	5.8E-08	0.2	0.1564	9.0E-09	0.009
B	40-59	48	0.0029	2.9E-07	1.0	0.1564	4.5E-08	0.045
C	60-79	48	0.0071	7.1E-07	2.6	0.1564	1.1E-07	0.111
D	80-100	48	0.0609	6.1E-06	21.9	0.1564	9.5E-07	0.953

To determine the drying conditions, multiple batches of each pavement were tested for moisture loss. They were first soaked in water before being placed under atmospheric conditions. An average of 4 days was determined to be required for a minimum moisture loss of 80%. The same amount of moisture loss was achieved by using the fan heaters for 3 hours. Using this information and historical Brisbane rainfall data from 1988-1997 (10 years), an annual average of 21 dry events (dry for >=4 days) was determined. Each dry event was simulated with 3 hours of drying using the fan heaters, thus giving a total of 2.7 days. Hence, 1200 mm of rain and 21 dry events (equivalent to 1 year of average Brisbane rainfall) were able to be simulated in 13 days. This was achieved by randomly simulating the four different flows and incorporating a drying event of 3 hours duration between each flow.

The pavements were subsequently dosed at these flow rates, with a semi-synthetic stormwater mixture (Table 2). This method has been widely used in the past and is fully described in Hatt *et al.*, (2007b). Whilst a semi-synthetic stormwater was used, there was still reasonable variation in influent concentration, due to variations in sediment mixing within the tank. Such variation was unavoidable and is commonly observed in most experiments of this nature (Hatt *et al.*, 2007b).

Table 2. Typical Urban Stormwater Pollutant Concentrations (Duncan, 1999).

Pollutant	Target Concentration (mg/L)
Total Suspended Solids (TSS)	150
Total Nitrogen (TN)	2.6
Total Phosphorus (TP)	0.35
Copper (Cu)	0.05
Lead (Pb)	0.14
Zinc (Zn)	0.25
Cadmium (Cd)	0.0045

The pneumatic water delivery system ensured the random and equal distribution of water as well as sediments over the three surfaces, while the heating system ensured a consistent average temperature of 35˚C to simulate 18 years of actual Brisbane rain and drought conditions.

Sampling Procedure and Clogging Monitoring

An intensive sampling regime was conducted in which samples were collected from the inflow and outflow, and analysed for Total Suspended Solids (TSS), Total Phosphorus (TP), and Total Nitrogen (TN), in accordance with standard methods for the examination of water and wastewater (APHA-AQQA-WPCF, 2005). Particle size distributions (PSD) were also measured in samples that had sufficient sediment using a Beckham Coulter LS100Q Laser Diffraction Particle Size Analyser. Flow rates were monitored continuously using tipping buckets along with manual measurements.

During each sampling session, samples were taken at both the inflow and outflow. For each flow rate, a composite of three samples was taken over the entire duration of the flow event (e.g. for a 5 day sampling event, a sample would be taken on days 1, 3 and 5, and then composited into a single sample). Removal was calculated as the difference between inflow and outflow concentration, divided by the inflow concentration, all expressed in percentages.

The flow rates and temperature in, and just underneath, each pavement were also monitored continuously as previously described by Siriwardene *et al.*, (2007). The collection of every sample was accompanied by pH measurement to enable early predictions to be made about the behaviour of metals in the system. This approach was particularly beneficial as the turnaround time for the laboratory analyses of metals was approximately 3 months.

To study the rate of clogging during typical floods, a 1 in 5 year Brisbane storm (of 5 min. duration – typical design flood for small catchments where porous pavements are likely to be deployed), was simulated in each of the 6th, 8th and 12th and 16th weeks of the experiment. The intensity of these storms was 191 mm/hr. To date, 18 years of operation under Brisbane climate have been simulated.

3 RESULTS AND DISCUSSION

3.1 Clogging

Under normal rainfall conditions (4 selected rainfall intensities), none of the pavements showed signs of clogging even after 15 years of operation in Brisbane. However, during the third storm simulation, both PA and HP started to pond 5 mm and 50 mm respectively, after 12 years of operation (Table 3).

Table 3. Depth of Ponding Layer Observed over Time

Simulated Duration	**Ponding depth indicating clogging (mm)**		
	PA (above pavement)	**HP (above geotextile)**	**PP (above pavement)**
1 year – average rainfall	0	0	0
5 years – average rainfall	0	0	0
6 years – Storm 1	***0***	***0***	***0***
7 years – average rainfall	0	0	0
8 years – Storm 2	***0***	***0***	***0***
10 years – average rainfall	0	0	0
12 years – Storm 3	***5***	***50***	***0***
15th years – average rainfall	0	0	0
16 years – Storm 4	***35***	***60***	***0***
18 years – average rainfall	35	20	0

Nb: 1 year of operation under Brisbane conditions corresponds to 2 weeks of inflow.

This clogging observation worsened during the fourth storm simulation, with PA overflowing at a ponding depth of 35 mm above its surface. Permapave however, has still not showed signs of clogging after 17 years, even for a 1 in 5 year event. The clogging phenomena observed in the previous experiment (Yong *et al.,* 2008), which only simulated the wetting cycle, occurred much earlier in the operational years of the system, with PA clogging at 8 years and HP at 6 years. As such, the later occurrence of clogging as observed in this current experiment could be attributed to either the effects of drying (Hatt *et al*., 2007a) or the various flow rates, evidenced from the results for all three pavements of both experiments.

In most porous pavement designs, the pavement itself acts as pre-treatment to the stone reservoir below. Although studies have shown that porous pavements remain permeable over time (Brattebo *et al.*, 2002; Dierkes *et al.,* 2002), frequent maintenance is still necessary to prevent clogging. In all three pavements, the surface themselves act as a physical containment (via fixation, stabilization, solidification and encapsulation) to the contaminants and the aggregate, the efficiency of which varies with the overall composition and structure of each pavement material. Although the gravel layer directly below the pavement helps as a second pre-treatment measure, frequent vacuum sweeping is still critical to keep the surface clean and the systems working effectively.

3.2 Water Quality

Table 4 and Figure 2 demonstrate results on treatment performance of the three systems.

Table 4. Average TSS, TP and TN Inflow Concentrations and their Removal Percentages over Time

		TSS				TP				TN			
Simulated Duration	**Flow**	**Ave. Inflow (mg/L)**	**Removal%**			**Ave. Inflow (mg/L)**	**Removal%**			**Ave. Inflow (mg/L)**	**Removal%**		
			PA	**HP**	**PP**		**PA**	**HP**	**PP**		**PA**	**HP**	**PP**
1 year	**A**	65	100	98	100	0.37	51	55	63	2.0	-55	-53	-14
5 years	**A**	48	98	95	95	0.39	32	42	53	2.1	8	-10	-16
7 years	**A**	38	84	92	96	0.51	16	29	71	3.6	-59	-82	49
10 years	**A**	51	94	89	86	0.42	-3	32	37	2.3	-32	-96	-56
15 years	**A**	27	74	88	89	0.27	-6	-11	-18	1.3	-200	-200	-53
1 year	**B**	93	98	99	53	0.50	57	60	46	2.8	-26	0	38
5 years	**B**	103	99	100	97	0.51	32	57	58	2.9	-4	3	0
7 years	**B**	63	99	99	99	0.54	26	43	43	3.0	-25	-83	-83
10 years	**B**	96	98	99	99	0.41	14	35	41	2.7	17	-3	0
15 years	**B**	38	96	98	98	0.41	24	40	45	2.4	0	-28	-25
1 year	**C**	157	99	99	92	0.53	58	65	67	2.8	-7	4	-24
5 years	**C**	123	99	99	99	0.53	45	56	59	3.1	27	20	28
7 years	**C**	173	99	99	99	0.53	35	49	46	3.6	11	0	33
10 years	**C**	89	98	98	100	0.56	33	36	45	3.0	16	27	-7
15 years	**C**	333	99	99	100	0.52	41	39	45	2.8	11	-4	-10
1 year	**D**	100	87	91	74	0.49	51	57	38	2.7	19	30	33
5 years	**D**	150	94	95	97	0.55	41	40	47	2.8	14	4	14
7 years	**D**	137	93	94	96	0.51	40	42	46	2.7	15	15	25
10 years	**D**	140	92	94	98	0.56	34	31	38	2.9	21	21	21
15 years	**D**	203	91	97	97	0.52	35	37	42	3.0	13	16	13
6 years	**Storm 1**	**157**	**73**	**81**	**81**	**0.55**	**34**	**33**	**33**	**2.7**	**21**	**15**	**23**
8 years	**Storm 2**	**157**	**89**	**92**	**94**	**0.52**	**23**	**27**	**23**	**2.8**	**14**	**21**	**14**
12 years	**Storm 3**	**150**	**71**	**80**	**81**	**0.53**	**25**	**27**	**31**	**2.9**	**10**	**10**	**14**
16 years	**Storm 4**	**163**	**76**	**86**	**76**	**0.50**	**24**	**27**	**24**	**2.8**	**11**	**14**	**18**

TSS

The inflow concentration fluctuated between 30 mg/L and 350 mg/L (Figure 2), and was observed to increase gradually with flow (Table 4). Among the 4 different simulated flows, the lowest and highest flows were found to perform worse in pollutant removal, particularly so for PA. Although the removal efficiency appears to drop for low flows, the outflow concentrations were actually lower than during high flow (as expected). A comparison across the three pavements consistently showed PA lagging behind HP and PP, which were both on par in terms of pollutant removal. Despite the fluctuating inflow concentration, all three pavements were found to remove up to 80% of TSS after 15 years (Table 4).

The results from this experiment have further refined the findings from the previous experiment (Yong *et al.,* 2008) that middle flows perform better in TSS removal, rather than the lowest or the highest flows.

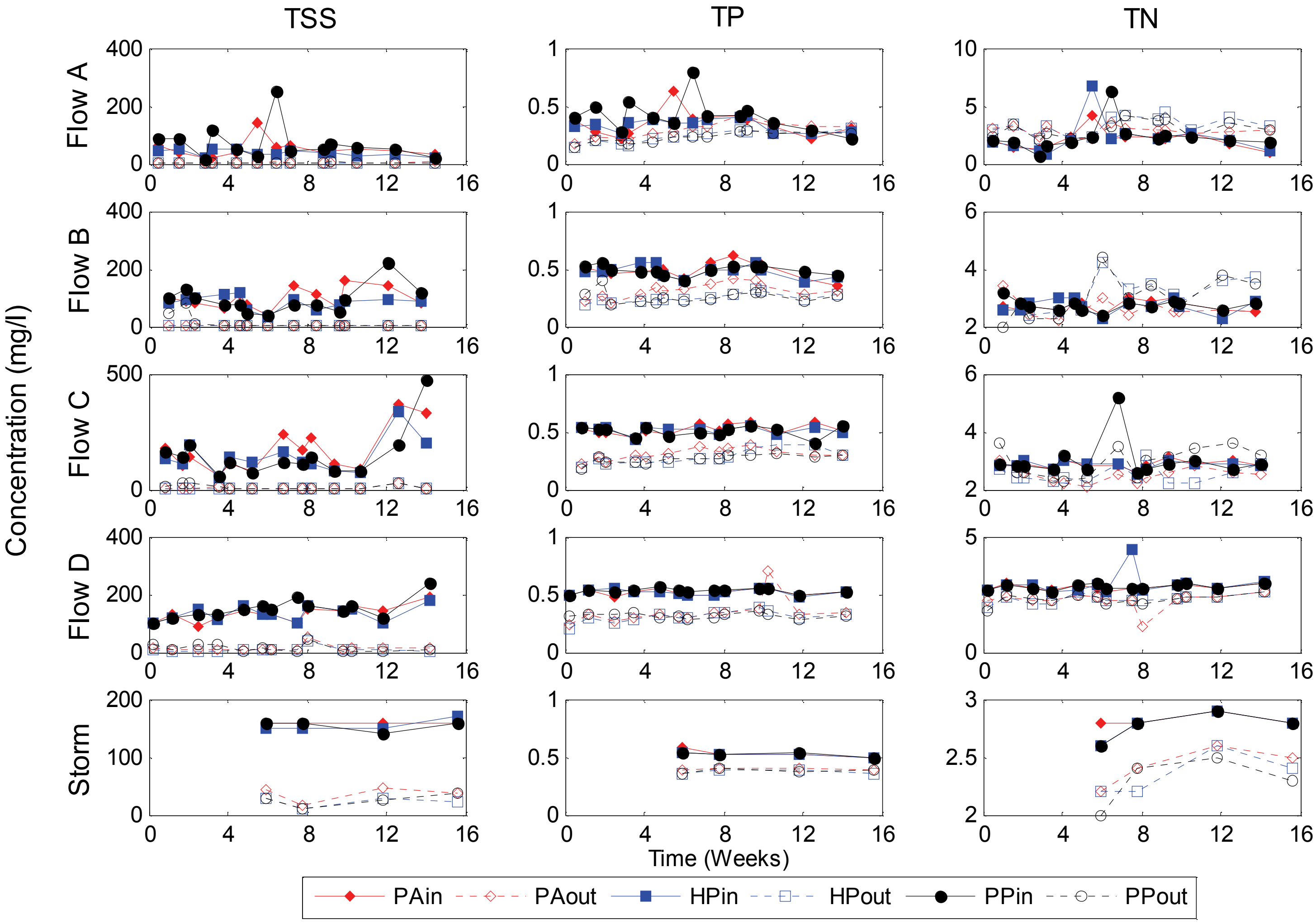

Figure 2. Inflow and Outflow Concentrations of TSS, TP and TN, measured on a Daily and Composite Basis for PA, HP and PP across flows A, B, C, D and the storm events.

TP

The average TP inflow concentration ranged from 0.25 mg/L to 0.55 mg/L (Figure 2) and was observed to increase gradually with flow. Removal rates had an initial average of 55% before dropping to 35%, with PA performing worse than HP and PP, which were both on par in removal efficiency. An interesting observation was made on the impact of flow rate on TP removal. Leaching was observed during low flow for all the pavements, particularly after years of operation, i.e. the second storm simulation in the 8th year (Table 4). This should be due to very low inflow concentrations as well as TP leaching from accumulated sediment within the system. However, a comparison of the average outflow concentration for each flow showed an interesting trend across all three pavements. Despite the variable inflow concentration, a gradual increase in the average outflow concentration was observed from low flow to high flow (Table 5). This suggests that higher flows may dislodge more particles that have accumulated over time. Future analysis of dissolved and particulate forms of phosphorus is needed to fully explain this behaviour.

TN

The average TN inflow, which ranged from 1.5 mg/L to 3 mg/L, increased gradually with flow (Figure 2). A significant amount of leaching was observed with all flows except Flow D, the removal rates of which started at 30% before dropping to an average of 15%. The same removal rates were observed during the storm simulations. Under all flow conditions, PA was consistently performing worse than the other two pavements. Unlike the previous experiment (Yong *et al.,* 2008) where only one flow rate was used (between Flow C and D) and drying was not simulated, the average outflow concentration was observed to gradually decrease from low to high flow for all pavements (Table 5). This suggests that low flows, and hence longer detention time facilitates the absorption of nitrogen accumulated within the system during dry weather spells, thus increasing the outflow concentration of TN during the subsequent wet event. As Hatt *et al.,* (2007a) showed, organic matter in soil based filters (and hence accumulated stormwater sediment in our systems) will break down between events and gradually accumulate. The nitrogen species will then start leaching during consequent wet events, with concentrations in the outflow increasing with an increase in detention time.

Table 5. Average Inflow and Outflow Concentrations for TP and TN Calculated over 18 years Across All Three Pavements for Flow Rates A, B, C D and the Storm Events.

		TP in (mg/L)	TP out (mgL)	TN in (mg/L)	TN out (mg/L)
PA	**A**	0.34	**0.30**	2.04	**2.83**
	B	0.47	**0.31**	2.68	**2.63**
	C	0.51	**0.30**	2.84	**2.49**
	D	0.52	**0.34**	2.84	**2.24**
	STORM	0.53	**0.39**	2.83	**2.43**
HP	**A**	0.32	**0.24**	2.14	**3.37**
	B	0.47	**0.25**	2.67	**3.13**
	C	0.51	**0.28**	2.84	**2.59**
	D	0.52	**0.31**	2.94	**2.32**
	STORM	0.52	**0.37**	2.78	**2.35**
PP	**A**	0.40	**0.23**	2.32	**3.10**
	B	0.47	**0.26**	2.71	**3.11**
	C	0.51	**0.26**	3.00	**2.98**
	D	0.53	**0.31**	2.86	**2.32**
	STORM	0.53	**0.38**	2.78	**2.30**

4 CONCLUSION

The results from this experiment have provided information on the effects of drought and rainfall events including storms, on the clogging behaviour and pollutant removal performance of three porous pavement types over a simulated period of 17 years. The early clogging observations and hence failure of PA and HP systems from the first phase of this laboratory investigation, which only simulated wetting, suggests that drying has a direct influence on the longer lifespan of these systems. Interesting observations and associations have also been made about the behaviour of nutrients, particularly nitrogen during high (short contact time) and low (long contact time) flows. Outflow TP concentration was found to increase gradually from low to high flows, while outflow TN concentration was found to decrease gradually from low to high flows.

These observations help inform designers and asset managers on the average life expectancy of porous pavement systems under drying and various wetting conditions in Australia, as well as the treatment performance of systems that are already in place. The knowledge gained will allow better predictions to be made of the performance of these systems over time. The decision to choose a particular system should not only be based on the climate data and environmental conditions of a potential site but also on the life expectancy and pollutant removal performance of the system, without compromising one or the other. These systems have yet to be tested and monitored in the field on a real-time basis. Future modelling work based on data collected from this study could provide a better understanding of the clogging process, thus allowing more accurate predictions to be made on the performance of systems under normal drying conditions, as well as varying inflow rates, which would be experienced in reality.

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