THE USE OF PERMEABLE CONCRETE BLOCK PAVEMENT IN CONTROLLING ENVIRONMENTAL STRESSORS IN URBAN AREAS

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ABSTRACT

Appropriately designed interlocking concrete block pavers may reduce the amount of pollutants reaching receiving waters by allowing water to be infiltrated into the subsurface layers. Over the course of a number of graduate student dissertations, the University of Guelph investigated the hydrologic performance of permeable concrete paving stone installations of various ages. The primary objective of the studies was to determine the relationship, if any, between infiltration capacity and the age of a permeable concrete paver installation for various land uses and maintenance practices. A summary of the interim findings is presented.

1. INTRODUCTION

Appropriately designed interlocking concrete block pavers may reduce the amount of pollutants reaching receiving waters, by allowing water to infiltrate into the subsurface layers. Permeable pavement allows stormwater to quickly infiltrate the surface layer to enter a high-void aggregate base layer, which forms a detention reservoir. The captured runoff is stored in this reservoir until it either percolates into the underlying subgrade, or is routed through a perforated underdrain system to a conventional stormwater conveyance. A permeable pavement can be used as an alternative in the building of roads, parking lots and other areas where traditional pavement would normally be used.

The term *stressor*s is used in the title of this paper, as it is taken here to include 1. traffic and parking lot contaminants, 2. heat due in the first place to insolation on the pavement, and 3. flow variations arising from the imperviousness of paved areas. The increase in the intensity or loading of these parameters, over what they would have been in the natural state, is referred to as *enrichment.*

There are many different types of porous pavements, including: porous asphalt pavement (PAP), porous concrete pavement (PCP), modular interlocking concrete bricks with internal drainage cells (MICBID), and modular interlocking concrete bricks with external drainage cells (MICBEC).

PAPs and PCPs are constructed without any fine matter in the aggregate, and consist of an open graded asphalt or concrete mixture with a high percentage by weight of aggregate larger than a number four sieve (6 mm diameter). The asphalt or concrete mixture laid to a thickness of 13-25 mm results in a surface with better surface storage capabilities than conventional paving surfaces and also allows for water to be quickly drained below the road surface or discharged to the road's edge (Goforth et al., 1983, Pagotto et al., 2000).

While PAPs and PCPs provide some excellent advantages such as decreased runoff, reduced traffic noise and improved skid resistance (Fwa et al., 1999), it has been found that these types of installations are very susceptible to surface compaction and clogging, and are very difficult to clean (Rushmoor Borough Council, 1998). The void space cannot be cleaned by any combination of street sweeping or pressure washing and the only alternative is to remove and replace the upper layer approximately every 8 years. Fwa et al. (1999) state that there is no way to predict the useful life of PAP, because it is dependent on the porous layer to maintain a high drainage capacity. They also state that there is no reliable way to predict the clogging potential of porous asphalt mixtures. PAPs and PCPs are prone to rutting when subjected to traffic. They exhibit lower surface temperatures than conventional pavements, causing ice to form more easily than conventional pavements (St. John and Horner, 1997, Rushmoor Borough Council, 1998). These disadvantages may preclude their use in parking lots and other low-traffic areas. The Rushmoor Borough Council (1998) made the following statement regarding the use of PAP: "The problems with safety during the winter period outweigh the benefits of noise and spray reduction…[the state of New Hampshire is] not proposing to extend their trials of porous asphalt."

Both MICBIC and MICBEC pavers are constructed with impermeable concrete, and provide drainage through open cells. The concrete used is a high density, no-slump concrete that is formed in steel molds and compressed and vibrated in a carefully controlled process (Evans, 1989). The two types of modular interlocking concrete brick pavers are quite different. MICBIC pavers have drainage cells built within the structure of the individual blocks whereas MICBEC pavers form a void space between them when laid together, as shown in Figure 1, and an underlying reservoir structure as shown in Figure 2. MICBEC have high structural strength.

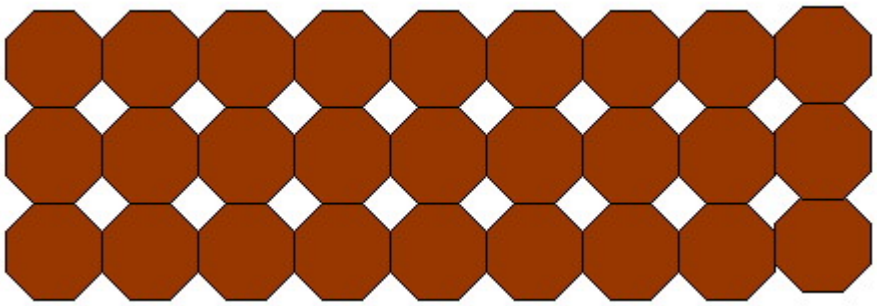

Figure 1. Schematic of Ecostone permeable concrete block paving stone pavement (Gerrits, 2001).

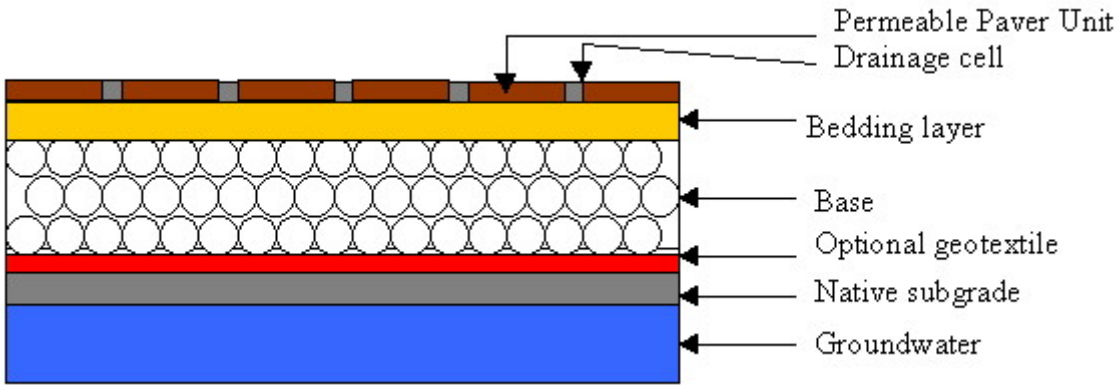

Figure 2. Sectional view of a permeable concrete block paving stone pavement (Gerrits, 2001).

Currently permeable concrete paving stone pavements are primarily used in low-traffic areas such as parking lots, sidewalks, footpaths, side streets, alleyways and laneways.

Some major airports have also started using permeable concrete block paving stone pavements along the edges of the runways to collect runoff. Permeable pavers have been used in Europe, in one or another form, for over 35 years for streets and sidewalks due to their low maintenance and aesthetic value. They have also been used in port and airfield applications in Europe for more than 15 years, the first application in airfields being at Luton International Airport in England (Concrete Paver Institute, 1991).

Over the course of several related graduate student dissertations (Li, 2003; Wilson, 2002; Gerrits, 2001; ul Haq, 2001; Kipkie, 1998; Ulan, 1996; Kresin, 1996; Thompson, 1995; Verspagen, 1995; Shahin, 1994; Xie, 1993), the University of Guelph investigated pavements of various types and ages. The MICBEC pavement studied was Uni Eco-Stone (R), which has a drainage cell area of approximately 12% of the total area (Borgwardt, 1994). Results for other permeable paving stones may vary significantly from those obtained in these tests, and require additional testing.

The primary objective of most of these studies was to determine if there was a relationship between infiltration capacities on the one hand, and factors such as the age of the installation, adjacent land uses, and pavement maintenance on the other. More widely available, papers based on the dissertations have been published in a series of annual monographs (James and Shahin, 1997; James and Thompson, 1996; James and Verspagen, 1996; Kresin et al., 1996; Thompson and James, 1995; Xie and James 1994)

2. CONSTRUCTION OF PERMEABLE CONCRETE BLOCK PAVING STONE PAVEMENTS

Permeable concrete block paving stone pavements are constructed by excavating the area to a depth determined by a number of factors (e.g. cost, height of the water table, frequency of rainfall, volume of stormwater to be detained, permeability of the underlying subgrade, downstream drainage considerations) and back-filling with clean aggregate. The purpose of this aggregate is twofold: 1. it will allow a section of nearly infinite infiltrability for temporary storage of the rainwater and overland runoff and 2. it will also act as a pollutant filter and trap. This pavement base will store the water until it can naturally percolate into the native subgrade and eventually back into the water table as groundwater recharge.

The base material generally comprises a 25-50 mm thick layer, vibrated in situ using a plate vibrator (Evans, 1989). The base material is often quite wet, and must not be susceptible to heaving due to freezing and thawing (Field, et al., 1982). It comprises mainly large sized stones, which transmit mechanical loads from the surface and store the infiltrated stormwater (Field et al., 1982).

3. ADVANTAGES OF PERMEABLE CONCRETE BLOCK PAVING STONE PAVEMENTS

The main advantage of permeable concrete block paving stone pavements is their ability to reproduce the flow reduction and water quality improvement properties of natural surfaces and vegetation. Another important advantage is their ability to reduce the amount of overland flow reaching receiving waters, thereby reducing peak flows in rivers and streams (Pratt et al. 1989, Legret et al., 1996). When comparing the performance of permeable concrete block paving stone pavements to traditional pavements, Pratt et al. (1989) found that the discharge rates from permeable pavements were significantly lower (30% of peak rainfall rate) and the time of concentration was greater (5 to 10 minutes, compared to 2 to3 minutes for traditional pavements).

Permeable pavements also exhibit good pollutant removal characteristics, closely mimicking the pollutant removal properties of natural soil (Pratt et al., 1989).

Legret et al. (1996) showed that heavy metals (Pb, Cu, Cd and Zn in particular) accumulated at the surface of drainage cells, as well as at the geotextile layer beneath the base material in permeable pavement installations. The installation also limited further migration of heavy metals into the subgrade beneath the structure (less than 15cm in the investigation by Legret et al., 1996). In addition, permeable pavements provide the surface roughness necessary to provide sufficient depression storage to manage pollutants before they wash off (Balades et al. 1995).

Cahill (1994) referring to no-fines asphalt suggested that clogging of the pore space with fine material was one of the major drawbacks of permeable pavements. Suspended sediment in the stormwater, and traffic depositing heavy loads of clay particles onto the surface, led to the porous space becoming permanently clogged. Additionally, clay particles that percolate into the base material settle at the bottom of the recharge bed, reducing the storage volume and the ability to transmit the stored water back into the groundwater system (Pratt et al., 1989, Pratt et al., 1995).

Permeable pavement installations can also be used to effectively remove water from the driving surface and reduce hydroplaning. And, finally, where underground explosive gases are a problem, open, aerated pavement evidently is safer than impervious, heavy pavement.

4. SURFACE SEALING

The single greatest factor that reduces the infiltration capacity of a *soil* is surface sealing, viz. the formation of a thin compact layer on the surface (Schwab et al., 1994). Surface sealing also significantly reduces the infiltration capacity of *permeable pavements* (Balades et al., 1995), occurring when soil aggregates are broken down by rainfall energy (Bosch and Onstad, 1988). After breakdown, the particles become dispersed and are trapped within the upper layers of the construction above the base (Pratt et al, 1995). After the upper surface becomes clogged with larger sized particles (i.e. sand), finer particles become entrapped within the larger particles, since they can no longer infiltrate into the system. The fine materials may be clay, silt, or other material associated with tire wear and the pavers themselves. The filtering capacity will gradually decrease until an impermeable matrix, or surface crust, forms (Balades et al., 1995). Surface sealing can occur on any unprotected soil surface, except the coarsest sands and gravels. As the sealing of the surface progresses with rainfall duration, the infiltration rate decreases exponentially (Bosch and Onstad, 1988). The surface crust is generally less than 2 mm thick (Balades et al., 1995) and once it is formed, the infiltration capacity will not decrease any further (Ferguson, 1994).

Surface sealing can be greatly reduced or eliminated when the soil surface is protected (Schwab et al., 1994). Mulch, crop residue and vegetation can all be used to reduce surface sealing by intercepting the incoming rain droplets, thereby reducing the potential energy and mitigating or eliminating their sealing effect (Ferguson, 1994). The presence of vegetation and the condition of the surface have greater influence on infiltration rates than soil texture and type. The presence of vegetation increases the percentage of macropores within the soil matrix and the organic matter produced by vegetation stabilizes the soil aggregates, which aids in maintaining the soil structure and porosity (Ferguson, 1994).

Consider now a surface of permeable paving stones. Maintenance is necessary to limit clogging risks and pollution (Legret et al., 1996). A number of studies have investigated possible methods of periodically removing the crust material from the pore space of permeable pavement installations e.g. Balades et al. (1995) and Pratt et al. (1995).

One possible method is washing with water at high pressure, using a man-operated portable, or vehicle-mounted pressure-washing unit. Power-washing would ideally be done in the direction of the nearest strip of grass.

The material that has been washed from the EDC, perhaps rich in organic matter and pollutants, would then be washed into the grass where it can then be taken up, or left to naturally biodegrade. Nieswand et al. (1990) reported that buffer strips, or naturally vegetated zones, could be used to protect the quality of water near waters receiving overland runoff. They also reported that the naturally vegetated areas can remove sediment and attached dissolved pollutants by providing opportunities for filtration, deposition, infiltration absorption, adsorption, decomposition and volatilization.

5. STUDIES AT THE UNIVERSITY OF GUELPH

Using a rainfall simulating infiltrometer, test plots at several installations were subjected to two simulated rainfalls of known intensity and duration (Kresin, 1996). Data collected during the second rainfall was used to calculate effective infiltration capacity. As described by Thompson (1995), four types of pavement were constructed both in the engineering parking lot and laboratory: impervious asphalt, impervious interlocking stone and two permeable paver pavements. The study investigated the flux of water and contaminants including heat. The instrumented structures allowed the effect of the different surfaces on quality of runoff to be assessed. The results showed that for MICBEC pavement there was a reduction in surface contaminants and temperatures compared to impervious asphalt pavement.

The University also conducted a laboratory investigation of pavement leachate (Shahin, 1994). Runoff volume, pollutant load, and the quantity and quality of pollutants in water percolating through these pavements under different simulated rainfall durations and intensities, were studied. Real rainwater was carefully collected from a large glass roof and used in the laboratory. Stored rainwater was carefully reconstituted chemically to restore the same pH as fresh rain. The results obtained were compared to available literature, and to the data collected from the four similar test pavements in the University parking lot. It was found that pH of the rain is a significant factor, with asphalt having the least buffering. Permeable pavers reduced both runoff and contaminants most, while asphalt produced most of both. The contaminants of interest were phenols, pH, zinc, iron and oils and grease. Many contaminants originate in the rainwater.

Gerrits (2001) collected and analyzed samples of material taken from the EDCs, bedding layer and base of the University parking lot permeable concrete block paving stone pavements. Samples were analyzed following accredited laboratory procedures. The concentrations of heavy metals within the EDCs were found to be less than the Ontario Ministry of the Environment's Guideline Concentrations for Selected Metals in Soils. All of the metals tested were below the MOE guideline level, and, with the exception of zinc, below the expected value for Ontario soils.

The thermal enrichment of surface runoff from an impervious asphalt surface and the concrete porous paving stone was also studied (Verspagen, 1995). The laboratory pavements were heated and a rainfall simulator was used to generate rainfall and cool the pavement. Thermocouples were used to monitor the temperature in the sub-grade and at the surface. Additionally, the inlet and outlet water temperatures were monitored. The primary objective of the research was to measure the thermal enrichment of surface runoff, by monitoring the change in temperature between the simulated rainfall at the inlet and the surface runoff at the outlet. This data was used to develop a relationship that can be used to calculate the temperature of the surface runoff as a result of heat transfer between the respective pavement surfaces and the surface runoff.

Gerrits (2001) conducted further research on the parking lot permeable concrete block paving stone pavement to investigate whether the infiltration capacity of pavers decreases with increased age and compaction and whether infiltration may be improved by maintaining the surface.

It should be noted that the installation was by then 8 years old and had not been carefully maintained, subjected only to street cleaning annually in spring. Moreover, the parking lot had been used as construction access for a large building project. Gerrits determined:

- the infiltration capacity throughout the so-called high, medium and low traffic applications and ponded regions of the 8 year old parking lot installation
- a relationship between the amount of external drainage cell (EDC) material removed and the subsequent improvement in infiltration capacity throughout the so-called high, medium and low traffic application areas and ponded regions
- a relationship between the amount of volatile organic carbon (VOC) and percentage of fine matter in the EDC material in high and low travel and ponded regions of the parking lot pavement
- a relationship between the chemical constituents in the EDC material and the physical characteristics of the different regions.

Wilson (2002) studied a pavement in the special apparatus depicted in Figure 3. Parking lot particulates were applied to a permeable concrete block paving stone pavement, and subject to intense rain. Figure 4 illustrates a typical condition with applied street dust and dirt, and with an array of containers for rain sampling. Wilson found that the quantities of sediment that can be applied without causing a decline in performance of the pavers is determined by the porosity of the drainage cell fill material. Results from his experiments, using a fill with 34% porosity, suggest the possibility of reduced maintenance than previously recommended. After the application of 1.4 kg/m^2 of permeable pavers, the average infiltration rate at the paver surface may decline to a rate below the inflow rates (1/25-year design storm of 5-minute duration with an intensity of 230 mm/h). More frequently observed rainfall events with lower rainfall intensities might produce different results. After the accumulation of 3.9 kg/m^2 of permeable pavers, the drainage cell material became functionally clogged. However, over a large section of permeable pavers, heterogeneity of the infiltration rates over different sections may uphold the performance of the pavers for some time.

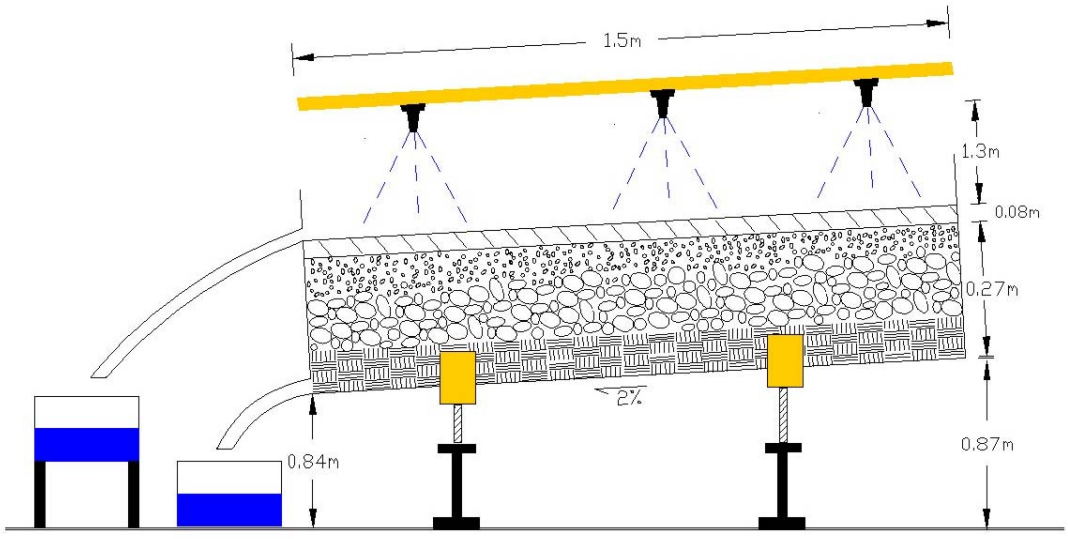

Figure 3. Experimental apparatus used for particulate rate clogging studies.

Wilson (2002) found that MICBEC permeable pavers should be maintained when the surface is affected by partial clogging. This should correspond to an accumulation of between 1.4 and 3.9 kg/m^2 street dust and dirt (D&D). For one of the test pavements studied, Figure 5 presents the peak flow rates for both surface runoff and base drainage. The anomalous blip was caused by an extended dry period during the experiment.



Figure 4. Permeable pavement surface with applied street dust and dirt (The containers are used for rain sampling).

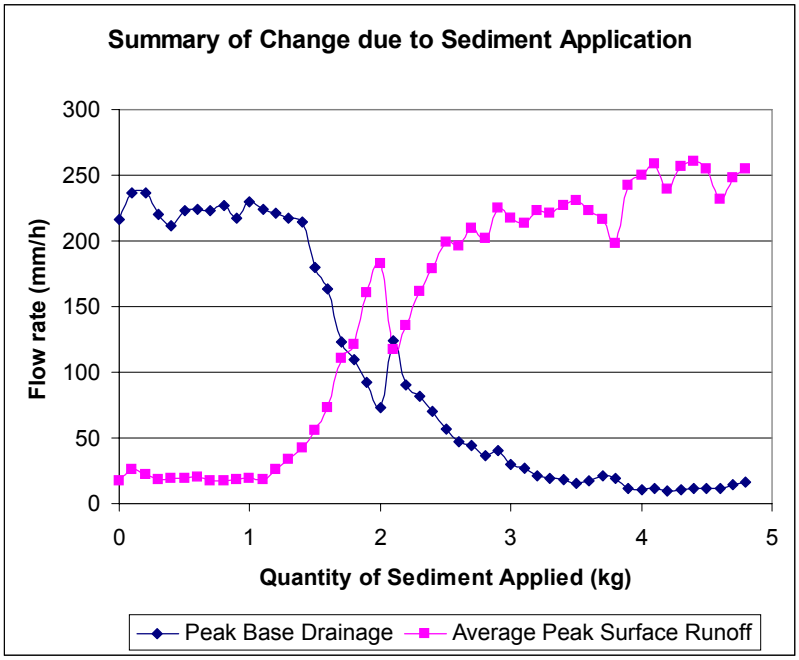

Figure 5. Peak flow rates for base drainage and surface runoff, affected by surface particulates.

Finally, a model (PCSWMM for Permeable Pavers) was developed to estimate the hydrologic performance of permeable concrete block paving stone pavements, as reported elsewhere in these proceedings (see the accompanying paper by James, James and von Langsdorff).

6. SUMMARY OF INTERIM FINDINGS

The general findings of the study were as follows:

- Infiltration capacity was found to be spatially variable and dependent on traffic, percentage of fine mater in the EDC, and the test installation base specifications. The infiltration capacity was also found to be dependent, to a lesser degree, on the percentage of VOC in the EDC.
- Infiltration rates were found to be higher in so-called low average daily traffic applications, where regeneration to the critical infiltration capacity could be accomplished by removing as little as 15mm of EDC material.
- Infiltration rates in so-called medium ADT applications were found to be less than in the low traffic applications. Regeneration to the critical infiltration capacity could not be reached by removal of 25mm of EDC material. However the results suggest that this could be possible with removal of more EDC material. Some degree of regeneration was noted at all excavation depths
- Infiltration rates in the so-called high average daily traffic applications were found to be the lowest, and only a small amount of regeneration could be obtained.
- The percentage of fine matter in the EDC material was found to be inversely proportional to the infiltration rate.
- The infiltration rate was found to be lower in areas where water ponded for more than one hour after a storm event, compared with areas where water had not ponded. The percentage of fine matter in the EDCs was found to be slightly greater within the top 5 mm below the surface and approximately equal for all other depths. The percentage of VOC was found to be significantly higher in the frequently flooded areas, for all depths.
- The percentage of VOC in the EDC was found to be similar for all so-called average daily traffic applications, and much greater in vegetated areas, underneath the large coniferous tree along the grass verge. The infiltration rate was found to be not greatly affected by the percentage of VOC, with the exception of plots where it was much greater than the average percentage of VOC. In this case, the infiltration rate was found to be an order of magnitude greater than it was in the unvegetated area.
- The concentration of heavy metals within the EDCs was found to be less than the Ontario Ministry of the Environment's Guideline Concentrations for Selected Metals in Soils. All of the metals tested were below the MOE guideline level, and, with the exception of zinc, below the expected value for Ontario soils.
- It is necessary to minimize the amount of fine matter accumulating within the EDC. This may be done by periodically cleaning the permeable concrete block paving stone pavement installation to keep the EDCs clear of fine matter. The frequency of cleaning will be dependent on the so-called average daily traffic application, as well as land use practices on and adjacent to the test installation.
- The percentage of VOC in the EDC material helped to keep fine matter from accumulating within the EDCs. Whenever possible, coniferous trees should be encouraged to grow along permeable concrete block paving stone pavement installations and on any islands or verges within the parking lot. Vegetation should not be discouraged from growing within the EDCs.
- No fine matter should be used in the base as it decreases the infiltration capacity and the ability to regenerate the infiltration capacity.

7. ACKNOWLEDGEMENTS

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William James was born in Johannesburg in 1937. He received the B.S. degree in Civil Engineering from the University of Natal (Durban) in 1958, the postgraduate Diploma of Hydraulic Engineering from the Delft Technological University, Holland in 1962, the Ph.D. degree from Aberdeen University, Scotland in 1965, and the D.Sc. degree from the University of Natal in 1986. He started his professional career as a Provincial Water Engineer, in Natal in 1958. With time out for graduate studies, he has worked as a Provincial Water Engineer in Natal, a consulting engineer in Durban and Cape Town, city engineer on hydrologic and water distribution projects, and professor. From 1965 to 1970 he was lecturer and senior lecturer in charge of Hydraulics in the Civil Engineering Department at the University of Natal in Durban. In 1971 he joined the Civil Engineering Department at McMaster University in Hamilton, Ontario, Canada where he was Professor of Civil Engineering until 1986. He was then appointed Cudworth Professor of Computational Hydrology in the Civil Engineering Department at the University of Alabama in Tuscaloosa, Alabama; Chair of Civil Engineering at Wayne State University; and, from 1988 to 1993, Director of the School of Engineering at Guelph. At these Universities he has advised over 70 graduate students. He has been visiting Professor at the Universities of Lund and Lulea in Sweden, Queen's in Canada, the University of Witwatersrand in South Africa, and visiting scholar at University of Michigan in Ann Arbor. He has presented more than 70 professional seminars in Canada, the U.S., and overseas in Australia, Europe and South Africa.

Dr. James presently heads an Urban Water Systems research group that includes doctoral and masters level graduate students, and part-time undergraduate student assistants. Most of the work relates to computational hydrology and hydraulics, involving implementation, adaptation, and improvement of large computer packages, dealing with urban hydraulics and hydrology, pipe networks, thunderstorm dynamics, water quality modelling, flood plain hydrology, and receiving waters and lakes. He has published 250 scientific papers and over 230 technical reports and books, and is organizer of a series of annual international conferences in Toronto, and is active on research committees of the American Society of Civil Engineering and of the Canadian Society of Civil Engineering. He has extensive consulting experience through Computational Hydraulics International, in Guelph, Ontario (CHI).

With his wife, Bill James has also dabbled in Industrial Archeology, leading to creation of the Hamilton Pumphouse Museum, and in pedagogy, particularly the use of computer assisted instruction. Recreational interests: Sailing (mainly long distance off-shore cruising, out of Georgian Bay), tennis, mountaineering (to be truthful, when younger - several first ascents, in Baffin Island, Drakensberg, Scotland etc.), canoeing (best in NWT and Yukon) and now in my dotage, a class-1 rugby referee.