# COMPUTER-AIDED DESIGN OF PERMEABLE CONCRETE BLOCK PAVEMENT FOR REDUCING STRESSORS AND CONTAMINANTS IN AN URBAN ENVIRONMENT

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## ABSTRACT

Permeable pavement is a key component in reproducing pre-development hydrologic regimes, because it can reduce surface runoff, improve water quality and recharge groundwater. In designing a permeable pavement installation, it is fundamentally important to provide and maintain 1. a surface infiltration and 2. a storage capacity that allow an adequate volume of stormwater to be captured and treated by the facility. This paper details the underlying method and function of a free-ware computer program that uses the U.S. Environmental Protection Agency (USEPA) stormwater management model (SWMM) for the design of permeable pavement installations.

## 1. INTRODUCTION

Urbanization increases flows and contaminant loads to receiving waters from automobile traffic, pavement surfaces, atmospheric deposition and biological organisms. Frequently ignored, thermal enrichment is also a critical stressor of aquatic habitats and ecology downstream of urban areas. Because of the detrimental impacts of these contaminants, and increasing concern for the natural environment, current practices in stormwater management have moved away from traditional best management practices (BMPs) such as detention ponds. BMPs for quantity control are being replaced by infiltration techniques that combine both stormwater quantity and quality control, by lowering stormwater runoff volumes, recharging groundwater and mitigating the transportation of stressors and contaminants.

Impairment of receiving waters is reduced by infiltration. For instance, thermal enrichment of stormwater is one of most important effects of urbanization in cold-water fishery areas - it destroys fish and aquatic ecosystems, and affects other indicators like oxygen concentration or pollutant concentration, because of the temperature dependence of many related processes (James and Verspagen, 1996). Many species of fish are extremely sensitive to temperature changes during their life cycle, and the impact of increased temperatures on rivers and streams is magnified during storm events – it reduces dissolved oxygen saturation levels, increases respiration rates, and disrupts the food chain. The relationship between thermal enrichment and percent imperviousness is well known (James and Xie, 1999). Moreover, previous workers established that urban surfaces in watersheds have the greatest influence on the stream temperature of headwater streams (Xie and James, 1994).

Another important pollutant that is removed or reduced by permeable pavement is related to turbidity, viz. the concentration of settleable or suspended solids (James and Thompson, 1996; James and Shaheen, 1997).

One type of infiltration practice is permeable pavement. Permeable pavement is a structural stormwater BMP that has been proven capable of reducing surface runoff, improving stormwater quality and recharging groundwater (Thompson and James, 1995). Infiltration capacity of the permeable pavement depends on factors such as surface infiltration cell characteristics, applied street dust and dirt, pavement use, maintenance, and sub-surface water storage (Kresin et al., 1996). Provision of sufficient surface infiltration capacity to allow an adequate volume of stormwater runoff to be captured and treated by the facility is key (Kipkie and James, 1999). It is not difficult to design and construct a system with appropriate infiltration capacities, but maintaining infiltration capacity over several years is a challenge. Infiltration basins, infiltration trenches, and porous pavements all change in their response to rainfall as time progresses, due to clogging and maintenance practices. Several different types of permeable pavement are available, and an example that provides drainage cells external to the shape of the paver stone, such that structural forces are not transmitted through the drainage cell, is shown in Figure 1. A typical application is shown in Figure 2. Further details are provided by Rollings and Rollings (1993).

Computer code called *PCSWMM for Permeable Pavers* (PCSWMMPP) was developed for use with the USEPA SWMM, to allow planners and designers to simulate the response of permeable pavements in long term modeling applications. Performance of a permeable pavement installation is controlled by the infiltration capacity of the permeable pavement, storage capacity of the reservoir in the base, and the infiltration capacity of the underlying, or native soil. Parameters such as the infiltration capacity of the permeable pavement were determined in our special field and laboratory studies. Since permeable pavers are used for long term applications, the code was written for continuous simulations, and accounts for degradation (over time) and the regeneration (by mechanical means) of this capacity. Certain hydrological design conditions must be met. Firstly, because of the relatively small areas involved, short computational time steps (e.g. 1 minute) are required, as are short duration design events (e.g. 1 hr). Secondly, the reservoir in the pavement sub-base must be properly sized, based on its drainage outlet capacity and the porosity of the constituent crushed rock.

**Figures 1 and 2. UNI Eco-Stone permeable pavers and a typical application.**

## 2. PCSWMM FOR PERMEABLE PAVEMENT

PCSWMM for Permeable Pavements (PCSWMMPP) was developed specifically for the hydrologic design of permeable pavements.

It allows the user to develop a model of a permeable pavement installation, run the model with a selected design storm, and analyze the results of the model to determine whether the design was successful. A successful design is assumed to be one in which the entire volume of the design storm is captured by the permeable pavement installation (i.e. no surface runoff occurs). PCSWMMPP focuses on the hydrologic and hydraulic aspects of permeable pavement design - no structural requirements are addressed or analyzed.

Probably the two main concerns that PCSWMMPP addresses are: (1) what is the maximum depth of water that will occur in a design with design storm X?, and (2) how long will it take to drain the water from the base layer given the design parameters specified (i.e. length of time for the regeneration of storage capacity)?

PCSWMMPP's model analysis engine is the Runoff module of SWMM4.3. While the SWMM engine was not explicitly developed for modeling permeable pavements, we believe it is generic and powerful enough to be adapted to this use. Only a small portion of the capabilities of SWMM is utilized in PCSWMMPP, specifically, the surface routing, infiltration, and groundwater routines. For our purposes the Runoff module represents the permeable pavement installation as an idealized catchment with certain surface infiltration properties, and subsurface properties. The Runoff module accepts an arbitrary rainfall hyetograph and makes a step by step accounting (conservation of mass) of water movement through the permeable pavement installation: surface detention, overland flow, infiltration, subsurface storage, and subsurface drainage.

User input is via an Input Wizard, which is an interface that steps the user through the required parameters of the model (James and James, 1995). Output includes an indication of design success, a summary report and graphs. The summary echoes the user-defined input and tabulates numerical results. Graphs include the input function (design storm), surface runoff (if any), depth of water in the base material, and drainage flow from the base material, for the duration of the model run.

As illustrated in Figure 3, the permeable pavement model comprises four distinct components:
- paver and bedding layer,
- unsaturated zone of the base material,
- saturated zone of the base material, and
- subgrade.

These components are assumed to be homogenous, at least as far as the modeled hydrological processes are concerned. Movement of water through the porous pavement installation is controlled by five processes as shown in Figure 4. Each of these processes is accounted for in the model, and details of each are given below.

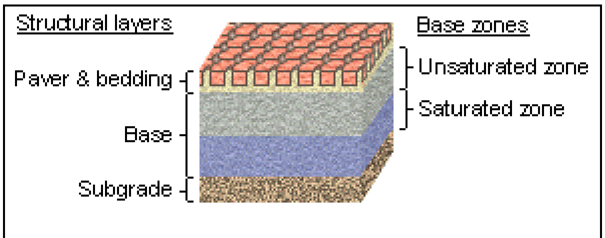

Fig 1. Permeable Paver Model Components

**Figure 3. Permeable paver model components.**

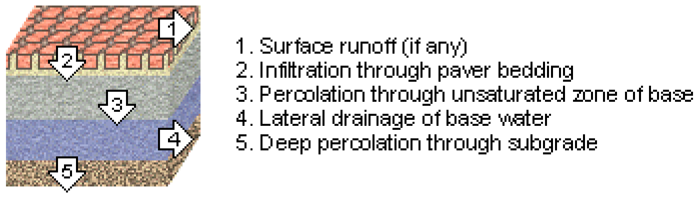

Fig 2. Processes modeled

**Figure 4. Processes modeled.**

The model's input function (driving force) takes the form of a user-specified rainfall hyetograph (a design storm). Output functions of the model include a time history of the surface runoff flow rate, water depth in base, and lateral drainage flow rate, for the duration of the model simulation period. From these output functions, some objective functions are calculated, including the maximum depth of water in the base, the total volumes of water escaping in surface runoff (if any), lateral base drainage, and deep percolation, and the remaining water in the base.

Design success is determined from the output functions of the model. For a design to be deemed successful, the permeable pavement installation must capture a high proportion or all the stormwater falling on the surface of the installation. In other words, there must be little or no surface surface runoff for the duration of the simulation.

As indicated earlier, the PCSWMMPP interface limits the SWMM program to simple permeable pavement designs. A number of the parameters required by the model are not available for input by the user – they have been assigned default values based on assumptions of paver properties.

In the following sections, both the modeling theory and the adaptation of SWMM for permeable pavement modeling are examined. For more detailed explanations of methods and techniques, refer to the SWMM documentation (Huber and Dickinson, 1988, and James, Huber and James, 1998).

2.1 Surface Runoff

There are three possible fates of rainfall falling on the surface of a permeable pavement installation:

- infiltration to the base material,
- evaporation , or
- runoff (overland flow).

Conversion of rainfall excess (rainfall less infiltration and/or evaporation) into runoff is discussed in this section. Runoff (if any) is generated from the surface of the porous pavement installation by a non-linear reservoir approximation, coupling the Manning's equation in US units with the continuity equation:

$$Q = W \cdot \frac{1.49}{n}(d - d_p)^{5/3} S^{1/2} \tag{1}$$

where,
$Q$ = runoff
$W$ = width of catchment
$n$ = Manning's roughness coefficient
$d$ = depth of surface water
$d_p$ = depth of depression storage
$S$ = slope of catchment

and,

$$\frac{dV}{dt} = A \cdot i^* - Q \tag{2}$$

where, $A$ = area

$i^*$ = rain excess = rain intensity – evaporation rate - infiltration rate

This is a spatially "lumped" configuration and assumes no special shape. If the catchment width, W, (an input parameter in the SWMM Runoff module) is taken to represent the width of overland flow, the non-linear reservoir will behave as a rectangular drainage area. Of the variables presented in the equations above, only area, slope and width are user-definable through the PCSWMMPP interface. The remaining two parameters: *roughness* and *depth of depression storage*, are defined in the program by the properties of the permeable pavement surface. Each is discussed below.

2.1.1 Maximum length of overland flow L

Normally, the catchment width ($W$) parameter is used for calibration (i.e. adjusted to calibrate SWMM to observed runoff hydrographs). However, at least in the case of rectangular catchments, the maximum length of overland flow ($L$), when used in combination with the area of the catchment ($A$), provides a good estimate of the catchment width parameter since $W = A/L$. This parameter ($L$) represents the length of the longest overland flow pathway to the inlet (surface drainage) location. As this model limits the user to single catchment installations (normally SWMM allows the catchment area to be divided into any number of subcatchments – each one being modeled as discussed above), the *maximum length of overland flow* parameter may be modified to account for extra storage in the system. If a drainage network exists, more storage will be present in the design than can be modeled here. This storage attenuates and somewhat delays the runoff hydrograph peaks and allows for greater infiltration. Lost storage can be accounted for by increasing the maximum length of overland flow (and thus reducing the “width” of the catchment). The amount of this adjustment is left to the discretion of the user.

2.1.2 Installation area A

Normally the surface area of the installation is assumed to be the extent of the catchment area - but “run-on” from adjacent surfaces is also allowed. This surface area also defines the area of base available for subsurface storage.

2.1.3 Slope S

The catchment slope should reflect the average along the pathway of overland flow to inlet (surface drainage) locations. For a simple geometry the calculation is simply the elevation difference divided by the length of flow. For more complex geometries, several overland flow pathways may be delineated, their slopes determined, and a weighted slope computed using a path-length-weighted average. Alternatively it may be sufficient to simulate what is considered to be the hydrologically dominant slope for the conditions being simulated.

2.1.4 Manning’s roughness n

Surface roughness is preset by the program to a typical UNI Eco-Stone permeable pavement value of 0.03. This value should be modified by experience, as observations become available.

2.1.5 Depression storage $d_p$

Depression storage is a volume that must be filled prior to the occurrence of surface runoff. It represents a loss or "initial abstraction" caused by surface ponding, surface wetting, interception and evaporation. Water stored as depression storage is subject to infiltration (and evaporation), so that it is continuously and rapidly replenished. The default depression storage set by PCSWMMPP is 0.06 in (1.5 mm) (another value that will change with experience).

## 2.2 Infiltration through pavers and bedding

Infiltration through the paver and bedding layer is modeled using the Green-Ampt equation (Bedient and Huber, 1988), which has physically-based parameters that, in principle, can be predicted *a priori*. The formulation is a two-stage model. The first step computes the volume of water, $F_s$ which will infiltrate before the surface becomes saturated. From this point onward, infiltration capacity, $f_p$, is computed directly by:

$$\text{For } F < F_s : f = i \text{ and } F_s = \frac{S_u \, IMD}{i / K_s - 1} \text{ for } i > K_s; \tag{3}$$

No calculation of $F_s$ is done for $i \le K_s$.

$$\text{For } F \ge F_s : f = f_p \text{ and } f_p = K_s \left( 1 + \frac{S_u \, IMD}{F} \right) \tag{4}$$

where
- $f$ = infiltration rate, ft/sec [m/s],
- $f_p$ = infiltration capacity, ft/sec [m/s],
- $i$ = rainfall intensity, ft/sec [m/s],
- $F$ = cumulative infiltration volume for this event, ft [m],
- $F_s$ = cumulative infiltration vol. required to cause surface saturation, ft [m],
- $S_u$ = average capillary suction at the wetting front, ft water [m],
- $IMD$ = initial moisture deficit for this event, ft/ft [m/m], and
- $K_s$ = saturated hydraulic conductivity of soil, ft/sec [m/s].

Infiltration is thus related to the volume of water infiltrated as well as to the moisture conditions in the paver and bedding layer. For time steps where the water level in the installation has risen to the surface, the amount of infiltration is set to zero. The Green-Ampt infiltration equation has three parameters to be specified $S_u$ , $K_s$ and *IMD*.

### 2.2.1 Saturated hydraulic conductivity $K_s$

The saturated hydraulic conductivity $K_s$ is also referred to as the permeability of the material. This parameter is entered in units of either in/hr or mm/hr and defines the rate at which water moves through the paver/bedding layer when saturated.

### 2.2.2 Moisture Deficit IMD

Moisture deficit *IMD* is defined as the fraction difference between soil porosity and actual moisture content. Coarse bedding materials tend to have lower porosities than fine bedding materials, but drain to lower moisture contents between storms because the water is not held to the same extent in the pores. Consequently, *IMD* for dry antecedent conditions tends to be higher for coarse bedding materials. This parameter is the most sensitive of the three parameters.

### 2.2.3 Capillary suction $S_u$

Mean capillary suction $S_u$ is perhaps the most difficult parameter to measure. It can be derived from soil moisture-conductivity data but such data are rare for most soils, but it is very difficult to give satisfactory estimates of infiltration parameters that will apply to all soils encountered – the user should be prepared to adjust preliminary estimates in the light of available data such as infiltrometer tests, measurements of runoff volume, or local experience.

## 2.3 Percolation through the unsaturated zone of the base

Percolation represents the vertical flow of water from the unsaturated zone of the base layer to the saturated zone of the base layer, and is the only inflow for the saturated zone. This process is modeled with the groundwater subroutine (GROUND). GROUND simulates two zones - an upper (unsaturated) zone and a lower (saturated) zone (James and Ulan, 1997, review the algorithm).

For the purposes of this application, both zones are contained in the homogeneous base layer of the permeable pavement installation.

Flow from the unsaturated to the saturated zone is controlled by a percolation equation for which parameters may either be estimated or calibrated, depending on the availability of the base data. Water available for base percolation is calculated at each time step as the volume of water infiltrating to the base from the surface of the installation (i.e. infiltrating through the paver and bedding layer). GROUND can include losses from the upper zone (evapotranspiration, ET) and losses and outflow from the lower zone (deep percolation), saturated zone evapotranspiration, and base lateral drainage. For single event (short duration) simulations, ET is assumed to be negligible and thus zeroed out. Deep percolation to the subgrade and lateral base drainage are discussed in the following sections. Again, readers should refer to the SWMM documentation for a more rigorous discussion of the groundwater routines.

The percolation equation used was formulated from Darcy's Law for unsaturated flow, in which the hydraulic conductivity *K* is a function of the moisture content *TH*. The final form is:

$$PERC = HKTH \cdot \left[ 1 + PCO \cdot \frac{(TH - FC)}{DWT1/2} \right] \tag{5}$$

and

$$HKTH = HKSAT \cdot EXP[(TH - FC) \cdot HCO] \tag{6}$$

where *PERC* = percolation rate (positive downward), nonzero when *TH* > *FC*.
*HKTH* = hydraulic conductivity as a function of moisture content,
*HKSAT* = saturated hydraulic conductivity,
*PCO* = *PSI*/*TH* in the region between *TH* and *FC*,
*TH* = moisture content,
*PSI* = soil water tension (negative pressure head) in the unsaturated zone,
*FC* = field capacity,
*DWT1* = average depth of the upper zone, and
*HCO* = calibration parameter.

*HKSAT*, *PCO, TH, FC* and *HCO* are required by the percolation component of the model.

Equations (5) and (6) were developed for the vertical movement of water through natural soils. Here it is used to model movement through the large pores of a uniform base material (e.g. crushed stone). Little information is available on the suitability of this equation for this type of percolation. A further concern is the lack of data on suitable parameter values. However, percolation through the base material is unlikely to be a controlling factor in permeable pavement design. In other words, the initial infiltration of water through the paver/bedding layer is comparatively slow – once the water reaches the unsaturated zone of the base, it should move quickly to the saturated zone.

2.4 Lateral drainage of the saturated zone of the base

Base layer discharge represents lateral flow from the saturated zone of the base to the receiving water (e.g. drainage tile outlet):

$$GWFLW = A1 \cdot (D1 - BC)^{B1} \tag{7}$$

where *GWFLW* = beginning-of-time-step base layer flow rate (per installation area),
*A1* = lateral drainage coefficient,
*B1* = lateral drainage exponent,
*D1* = depth of saturated zone, and
*BC* = elevation of bottom of drainage system.

User-specified parameters in this equation are *A1, B1*, and *BC*. The elevation of the bottom of the drainage system *BC* indicates the base layer water elevation below which there is no lateral drainage - if the depth of the saturated zone *D1* is less than *BC, GWFLW* is set equal to zero. In drainage tile systems this normally corresponds to the invert elevation of the drainage tile. The functional form of the equation was selected in order to approximate various horizontal flow conditions. Since base layer drainage flow can be a significant volume, an average flow for each time step is found by iteration. The effect of receiving water elevation on drainage flow is assumed to be negligible for this system and no reverse flow is permitted (i.e. filling of the base layer from reverse flow in the drainage system).

2.5 Deep percolation through the subgrade

Deep percolation represents a lumped sink term for unquantified losses from the saturated zone of the base. Two primary losses are assumed to be percolation through the confining layer and lateral outflow to somewhere other than the receiving water. The arbitrarily chosen equation for deep percolation is:

$$DEPPRC = DP \cdot \frac{D1}{DTOT} \tag{8}$$

where *DEPPRC* = beginning-of-time-step deep percolation rate,
*DP* = percolation coefficient derived from water table recession curves,
*D1* = depth of saturated zone, and
*DTOT* = depth of base layer

The ratio of *D1* to *DTOT* allows *DEPPRC* to be a function of the static pressure head above the confining layer (subgrade). Although *DEPPRC* will be small in most cases, it is included in the iterative process so that an average over the time step can be used. By using the average, large continuity errors will be avoided should *DEPPRC* be set at a larger value.

The percolation coefficient *DP* is the only user-definable variable in this equation. Setting *DP* to a typical saturated hydraulic conductivity *k* for the subgrade soil type is a starting point. However, assigning a saturated hydraulic conductivity to *DP* is probably an overly conservative approach because 1. following the logic of the equation above, this percolation rate would only be achieved when the entire base material is saturated, and 2. it assumes that the subgrade is fully saturated at the start of the simulation. Normally the infiltration rate is higher for unsaturated soils. Also, the user should note that *k* values have a wide range – sometimes 1000 fold even in the same soil classification. The final selection of *DP* is left to the user.

## 3. MODEL INTERFACE

The interface allows the user to develop a permeable pavement design and evaluate its performance with one or more design storms. The interface is divided into three main sections: Input Wizard, Summary Report, and Graph(s).

3.1 Input Wizard

The Input Wizard guides the user through the process of developing a permeable pavement design in five successive steps. Each step focuses on the parameters required for one of the five processes identified. Help for each step is provided through on-screen illustrations and hyper-links. Users can revisit the Input Wizard at any time to modify any parameters and rerun the analysis. The design project can be saved and subsequently reopened at any time.

### 3.2 Summary Report

The report highlights a number of objective functions, including the maximum depth of water reached in the base material, the total volumes of water escaping in surface runoff (if any), lateral base drainage, and deep percolation, and the remaining water in the base. A continuity balance is also provided for determining the scope of the computational errors (if any). The report's analysis results are extracted from the SWMM output file generated by the SWMM engine. The original output file, which contains extensive information and additional timeseries, can be accessed from the Summary menu.

### 3.3 Graphs

Output functions of the model are all in the time domain and can be most easily analyzed in the form of graphs. This section provides the user with graphs of the outflow time series of water from the base drainage system, the surface runoff (if any) from the installation, and the depth of water in the base material. A fourth graph displays the input function (design storm) that drives the simulation.

## 4. DETERMINING THE SUCCESS OF THE DESIGN AND MODEL VALIDATION

After the run, PCSWMMPP automatically loads the results (from the output file generated by SWMM), checks for a successful run and prepares the Summary Report and the Graphs.

Success of the run is dictated by whether the depth of water in the base material remained less than a user selectable proportion, say 85%, of the base depth throughout the run (Borgwardt, 1997). If the saturation of the base material exceeds 85%, the base thickness should be increased accordingly. The Analysis Results screen of the Input Wizard (which appears after a model run) indicates whether the design was successful, a judgement based solely on the maximum depth of water reported by SWMM in the base layer.

After the model has been run, selected parameters can be adjusted if needed (by returning to the appropriate Input Wizard step) and the model re-run.

## 5. CONCLUSIONS

Rather than making a simplistic solution seem technically advanced, PCSWMMPP renders the powerful and complex SWMM model easy to use. The program allows quick implementation of a BMP in SWMM. Exceptionally user-friendly, it is freely available from any of the authors. Readers should note however that to the authors' knowledge, the SWMM code for groundwater and infiltration has not been comprehensively tested against a specific permeable pavement field program – in other words, the new permeable paver code has technically not been verified. Until the code is field proven, questions remain on the applicability of the percolation routine of the Runoff module to open graded base materials such as crushed rock.

## 6. ACKNOWLEDGEMENTS AND LIMITATIONS

This work is based on the findings of a sequence of Professor James' graduate students. In reverse chronology, they are: Mat Wilson, Chris Gerrits, Craig Kipkie, Chris Kresin, Brian Verspagen, Reem Shahin, Mike Thompson, Julie Ulan and Jenny Xie. Special mention goes to Nick Emery, who performed a literature search for parameter estimates.

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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.