VERIFICATION DOCUMENT FOR HWIR99 SURFACE IMPOUNDMENT MODULE

Work Assignment Manger and Technical Directions: Dr. Zubair A. Saleem
U.S. Environmental Protection Agency
Office of Solid Waste
Washington, DC 20460

Prepared by: HydroGeoLogic, Inc.
1155 Herndon Parkway, Suite 900
Herndon, VA 20170
Under Contract No. 68-W7-0035

U.S. Environmental Protection Agency
Office of Solid Waste
Washington, DC 20460

July 1999

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Acknowledgments

A number individuals have been involved with the verification of the surface impoundment module. Dr. Zubair A. Saleem of the U.S. EPA, Office of Solid Waste, provided overall technical coordination and review throughout this work. Verification and report preparation was conducted by Dr. Varut Guvanasen and Mr. Theodore P. Lillys of HydroGeoLogic, Inc..

1.0 BACKGROUND

The HWIR99 surface impoundment module (referred to herein as the SI module) has been developed and documented (RTI, 1999). The module comprises the following interconnected compartments:

- Liquid compartment; and
- Sediment compartment.

The two compartments are described in detail in the HWIR99 surface impoundment module background document (RTI, 1999). One of the major assumptions is that mass transfer through the two compartments, at any given time, is steady state.

Immediately below the sediment compartment is the vadose zone into which leachate from the sediment compartment is discharged. The vadose zone comprises two zones: the clogged native material zone (by invading suspended solids in the leachate) immediately below the compacted sediment, and the native zone unaffected by the invading suspended solids. The latter is immediately below the former. The leaching rate (or infiltration rate) through the vadose zone is governed by the hydraulic properties and pressure distribution in the compacted sediment in the sediment compartment, in the clogged native material, and in the unaffected native material.

RTI was responsible for the development of most of the module. HydroGeoLogic was responsible for the development of the sub-module that determines the hydraulic properties of the compacted sediment and the clogged native material (Tech. Memo., HydroGeoLogic, 1999).

2.0 VERIFICATION PLAN

The verification was carried out in stages, described below:

Stage 1 Verification of mass fluxes in the liquid and sediment compartments, assuming that the water fluxes in the sediment compartment were correct.

Stage 2 Verification of hydraulic properties in the compacted sediment.

Stage 3 Verification of the infiltration rates and water pressure profiles in the vadose zone, based on the assumption that the hydraulic conductivities in the compacted sediment were correct. The surface impoundment segment of EPACMTP (U.S.EPA, 1997) was used to compare with the SI module.

The verification approach and results described herein are based on an assumption that initial verification of the SI module has been conducted. The emphasis of the current verification is on the consistency of the outputs of the SI module.

3.0 SOFTWARE VERIFIED AND DATA USED

The SI Module is written in Microsoft Visual C++, Version 6.0. A version of the SI Module source code and documentation was received by HydroGeoLogic on April 20, 1999. Several deficiencies identified in the SI Module during the execution of the verification plan were brought to the attention of RTI (see Section 4). A revised version of the SI Module was transmitted to HydroGeoLogic on May 18, 1999.

The verification plan was executed using the site simulation files (SSF) and global result files (GRF) generated by the HWIR99 Software User Interface (SUI) for a non-degrading Benzene release from a surface impoundment (SI) at site identifier "1632106". These files are presented in Appendix C. The concentration in waste level (CW) was set to "3". A complete description of input and output file formats used in HWIR99 is given in Section 4.0 of "The Vadose and Saturated Zone Module Extracted from EPACMTP for HWIR99" (U.S. EPA, 1998).

4.0 VERIFICATION DESCRIPTION

4.1 Stage 1 - Verification of Mass Fluxes through the Liquid and Sediment Compartments

Mass fluxes through the liquid and sediment compartments were verified by spreadsheet calculation assuming that sediment hydraulic conductivity and infiltration calculations were correct. Equations pertaining to the determination of mass fluxes in the liquid and sediment compartments presented in SI module documentation (RTI, 1999) were entered into a spreadsheet. Input values were taken from this site, chemical and source SSF files. Print statements were added to the SI module source code to report internal constants, intermediate, and final values. Monthly mass fluxes calculated for years 1 and 25 of a 50-year simulation by the spreadsheet and module are presented in Figures 1, 2 and 3. The results of the analysis, summarized in Table 1, show very good agreement between the spreadsheet calculations and the output of the SI module in the sr.grf file. Contents of spreadsheet calculations are presented in Appendix A.

4.2 Stage 2 - Sediment Hydraulic Conductivity Verification

Hydraulic conductivities of the consolidated sediments were verified by spreadsheet calculation assuming that the rates of sedimentation were correct. Equations presented in documentation provided to RTI (Tech. Memo., HydroGeoLogic, 1999) to calculate consolidated sediment hydraulic conductivity were entered into a spreadsheet. Input values were taken from site and source SSF files. Print statements were added to the SI module source code to report internal constants, intermediate, and final values, particularly, the sediment thickness. Initially, monthly sediment conductivities for years 1 and 25 of a 50-year simulation generated by the SI module did not agree with spreadsheet results.

Upon further examination of the SI module source code, the following inconsistencies were discovered:

1) Coding of the equation to determine the final stress in the consolidatable sediment, $ó_{vf}$, was not consistent with the documentation. A sign was incorrect.

2) Coding of the equation to determine the coefficient C1 for the filter cake hydraulic conductivity was not consistent with the documentation. A sign was incorrect.

3) The value of the Constant A (line 1166 in Tank.cpp) should be replaced by 570 as a result of the changes 1) and 2).

4) The value of the Compression Index (C_c) (line 1164 in Tank.cpp) should be 1.02, not 0.55 (see HydroGeoLogic, 1999).

After correcting the above inconsistencies, monthly consolidated sediment hydraulic conductivity values were recalculated by SI module and compared to the spreadsheet results. The monthly values of consolidated sediment hydraulic conductivity for years 1 and 25 from the revised SI module and spreadsheet are presented in Table 2 and are in excellent agreement. Contents of spreadsheet calculations are presented in Appendix B.

4.3 Stage 3 - Infiltration Rate Verification

The EPACMTP (U.S. EPA, 1997) has a code segment that may be used to calculate infiltration rate from surface impoundment. The formulation implemented in the SI module to calculate infiltration rates was similar to the formulation used in the EPACMTP. Therefore, the EPACMTP code segment was used to verify the SI module infiltration rate calculations for Month 6 of Years 1 and 25 of a 50-year simulation. Input values were taken from the site and source SSF files. Print statements were added to the SI module source code to report parameter values to be used as inputs by the EPACMTP, pressure heads, and infiltration rates prior to any heuristic capping calculations. Additional code was added the SI module to calculated the infiltration rate between layers to verify that continuity was preserved.

Care was taken to ensure that the representations of the flow system are the same for both EPACMTP and the SI module. To this end, restrictions implemented for Monte Carlo analyses limiting the unsaturated zone to a single layer were removed from the EPACMTP. This permitted the simulation of clogged native material directly beneath the sediment layer in addition to the unclogged native material. A comparison of the flow system representations by EPACMTP and by the SI module is summarized in Table 3. The discretization of the unsaturated zone used by the SI module was duplicated in the EPACMTP so that pressure head profiles could be compared. Likewise, to obtain comparative calculations of equal precision, it was necessary to insert input values directly into the EPACMTP source code (the format of the EPACMTP input file limits the precision of input variables). The verification was carried out after the changes in Stage 2 had been incorporated.

Initial infiltration rates calculated by SI Module and the EPACMTP at year 1, month 6, and year 25, month 6 are presented in Table 4. Pressure head profiles for year 1, month 6 and year 25, month 6 are presented in Tables 5 and 6, respectively. As shown in Table 4, it is clear that the infiltration rates computed by the module are significantly different from those computed by the EPACMTP. The pressure profiles show that the SI module does not enforce the atomospheric boundary condition at the water table.

Upon closer inspection of the source code, it was discovered that the SI module was deficient in the following areas:

1) The boundary condition at the water table, Ø = 0 (atmospheric pressure at water table), was not enforced (this is evident Table 6);

2) The convergence criteria on Ø at the water table stated in the document (RTI, 1999) were inconsistent with those in the code;

3) The convergence criterion was not enforced on the pressure head at the water table but on the pressure head at the top of the sub-layer adjacent to the water table;

4) The entire depth of sediment was assumed to be resistive to flow. The computed value for the hydraulic conductivity of consolidated sediments should be applied only to that portion of the sediment layer.

Although the SI module converged to a solution, the *violation of the atmospheric condition at the water table resulted in a non-physical solution.*

HydroGeoLogic suggested the following corrective actions to RTI in order to remedy the deficiencies identified in the SI module:

1) Enforce the boundary condition at the water table, Ø = 0;

2) Calculate the pressure heads in the upward direction from the water table to the sediment compartment;

3) Use the consolidated sediment thickness for pressure calculations and assume the unconsolidated portion is subject to hydrostatic pressures.

A revised SI module was transmitted to HydroGeoLogic on May 18, 1999. New simulations were performed using the revised SI module for Month 6 of Years 1 and 25. Infiltration rates for the SI module and the EPACMTP are presented in Table 7, and pressure profiles are presented in Tables 8 and 9. Infiltration rates computed by the revised SI module are in very good agreement with those computed by the EPACMTP as are the pressure profiles.

5.0 SUMMARY OF VERIFICATION RESULTS

The HWIR99 SI module developed and documented by RTI has been successfully verified. The major components of the SI module verified were the two interconnected liquid and sediment compartments. In addition, the computation of the consolidated sediment hydraulic conductivity was also verified. The liquid compartment was in excellent agreement with spreadsheet calculations. The sediment compartment determination of infiltration rates was lacking an appropriately enforce boundary condition resulting in potentially non-physical solutions. Minor inconsistencies were identified in the computation of consolidated sediment hydraulic conductivities. Verification of a revised SI module showed very good agreement with infiltration rates computed by the EPACMTP. A summary of each verification stage is provided below.

<u>Stage 1</u> The mass flux calculations through the liquid and sediment compartments have been verified. Agreement between the module-generated fluxes and the hand-calculated fluxes is excellent.

<u>Stage 2</u> Hand-calculated values of consolidated sediment hydraulic conductivities differed from those generated by the SI module. Upon closer inspection, several inconsistencies were identified in the SI module source code. Once these inconsistencies were corrected, agreement between the module-generated and hand-calculated conductivities is excellent.

<u>Stage 3</u> Initial results generated by the SI module were found to be inconsistent with those generated by the EPACMTP. Pressure head profiles generated by the SI module were found to be significantly different from those generated by the EPACMTP with identical hydraulic properties. Three corrections were suggested: 1) enforce boundary condition, Ø=0, at the water table; 2) calculate pressures in the upward direction; and 3) only use the consolidated sediment thickness in gradient calculations. Infiltration rates and pressure head profiles generated by SI module and the EPACMTP are in excellent agreement after corrections were implemented.

In addition, the revisions to the SI module have resulted in a more computationally efficient module:

- Run time of SI module as delivered: 68 seconds
- Run time of revised SI module: 1.5 seconds

6.0 REFERENCES

HydroGeoLogic. Technical Memorandum “Effective Hydraulic Conductivity of Consolidatable Filter Cake, 1999.

RTI. Source Models for Tanks and Surface Impoundments. Prepared by Research Triangle Institute of Office of Solid Waste, U.S.EPA, 1999.

U.S.EPA. EPA’s Composite Model for Leachate Migration with Transformation Products, EPACMTP. Background Document, Office of Solid Waste, U.S. EPA, 1997.

APPENDIX A

LIQUID COMPARTMENT MASS FLUX SPREADSHEET EQUATIONS

SI Module Spreadsheet Equations

SI Module Parameter	Parameter Description	Value/Equation	Equation Number*
bio_yield	Biomass yeild [g/g]	0.657331744	I
CBOD	BOD (influent) [g/cm^3]	0.01815112669	I
C_in	Chemical Concentration (influent)[mg/L]	0.1	I
EconLife	Economic Life of SI [y]	50	I
d_imp	Impeller diameter [[cm]	61	I
n_imp	Number of impellers /aerators	11	I
w_imp	Impeller speed [rad/s]	126	I
g_c	Gravitational constant [cm/s^2]	980	I
d_setpt	Fraction of SI occupied by sediments	0.375	I
d_wmu	Depth of WMU [m]	1.92	I
A_wmu	Area of WMU [m^2]	=SrcArea	I
A_tot	Total area of WMU [m^2]	=A_wmu	I
F_aer	Fraction surface area-turbulent	0.2660303929	I
A_aer	Aerated surface area of WMU [m^2]	=A_tot*F_aer	23
A_q	Quiescent surface area of WMU [m^2]	=A_wmu-A_aer	23
focW	Fraction organic carbon in waste solids	0.5450995462	I
J	Oxygen transfer factor [lbO_2/h-hp]	3	I
kba1	Biologically active solids/total solids	0.8996387615	I
MWt_H2O	Molecular weight of water [g/mol]	18	I
rho_H2O	Density of water [g/cc]	0.998	I
MWt_air	Molecular weight of air [g/mol]	28.8	I
D_O2w	Diffusivity of O_2 in water [cm^2/s]	0.000024	I
O2eff	Oxygen transfer correction factor	0.8057382283	I
De	Diffusivity of ether in water [cm^2/s]	0.0000085	I
Powr	Total power to impellers/aerators [hp]	825	I
rho_part	Density of solids [g/cc]	3.407534859	I

SI Module Parameter	Parameter Description	Value/Equation	Equation Number*
TSS_in	Total suspended solids (influent) [g/cc]	0.007492781126	I
TSS_2	Total suspended solids (sediments) [g/cc]	=rho_part/3	?
kbs	Decay rate in sediment compartment [1/s]	0	I
k_hyd	Catalyzed hydrolysis rate [1/day]	0	I
kbm	Complex 1st order decay rate [m^3/Mg-s]	0	I
d_tot	Total depth of WMU [m]	=d_wmu	I
V_tot	Total volume of WMU [m^3]	=A_wmu*d_wmu	U
Q_in	Volumetric flow rate into WMU [m^3/s]	0.0009872472168	I
thetaL1	Volumetric fraction of liquid in liquid compartment	=1-TSS_1/rho_part	8
thetaL2	Volumetric fraction of liquid in sediment compartment	=1-TSS_2/rho_part	8
FtoD	Fetch to depth ratio	=SQRT(4 * A_wmu/PI())/d_liq1	28
pVdiff	Diffusion velocity in sediment [m/s]	=k_lq * thetaL2 ^ 0.89 / (1 + thetaL2 ^ 0.89)	37
Sc_gas	Gas phase Schmidt number	=mu_air/(rho_air * Da)	27
Re	Gas phase Reynolds number	= d_imp ^ 2 * w_imp * rho_air / mu_air	27
p_imp	Power number	=0.85 * (550 * Powr / n_imp) * g_c2 / (62.428 * rho_H2O * w_imp ^ (3) * (d_imp/30.48)^(5))	27
Fr	Foud Number	=w_imp^(2) * (d_imp / 30.48) / g_c2	27
U_star	Friction velocity [m/s]	=0.01*windspeed*SQRT(6.1 + 0.63*windspeed)	30
Sc_liq	Liquid phase Schmidt number	=mu_H2O/(rho_H2O * Dw)	30
a	Equation constant	=IF(U_star > 0.3,34.1,144)	30
b	Equation constant	=IF(U_star > 0.3,1,2.2)	30
g_c2	Gravitational constant [lb_m-ft/s^2-lb_f]	=0.03283 * g_c	27
k_gq	Quiescent mass transfer coefficient for gas phase [m/s]	=0.00482 * windspeed ^ (0.78) * Sc_gas ^ (-2/3) * F ^ (-0.11)	33

SI Module Parameter	Parameter Description	Value/Equation	Equation Number*
k_lq1	Liquid phase mass transfer coffecient 1[m/s]	=0.00000278*(Dw/De)^(2/3)	29
k_lq2	Liquid phase mass transfer coffecient 2 [m/s]	=0.000001+ (a * 0.0001) * U_star ^ (b) * Sc_liq^(-0.5)	30
k_lq3	Liquid phase mass transfer coffecient 3 [m/s]	=(0.000000002605 * FtoD + 0.0000001227) * windspeed^2 * (Dw/De)^(2/3)	31
k_lq4	Liquid phase mass transfer coffecient 4 [m/s]	= 0.0000002611 * windspeed * windspeed * (Dw/De)^(2/3)	32
k_lq	Final liquid phase quiescent surface mass transfer coefficient [m/s]	=IF(windspeed<3.25,k_lq1,IF(FtoD<14,k_lq2,IF(FtoD<=51.2,k_lq3, k_lq4)))	29-32
k_gt	Gas phase turbulent surface mass transfer coefficient [m/s]	= 0.000000135 * Re ^ (1.42) * p_imp ^ (0.4) * SQRT(Sc_gas) * Fr ^ (-0.21) * Da * MWt_air / d_imp	27
k_lt	Liquid phase turbulent surface mass transfer coefficient [m/s]	= (0.00822 * J * Powr * 1.024 ^ (Temp - 20) * O2eff * MWt_H2O) / (10.76 * A_aer *rho_H2O) * SQRT(Dw/D_O2w)	26
KOL_q	Overall mass transfer coefficient for quiescent surface area [m/s]	= 1/(1/k_lq + 1/(HCL * k_gq))	25
KOL_t	Overall mass transfer coefficient for turbulent surface area [m/s]	= 1/(1/k_lt + 1/(HCL * k_gt))	24
Kol	Overall mass transfer coefficient for WMU [m/s]	=IF(KOL_t=0,KOL_q, (KOL_t * A_aer + KOL_q * A_q)/A_tot)	23
delta_d	Net sediment accumulation for a time step [m]	=v_b * tstep * (365*86400) * (1 - kba1 * (1 - EXP(-k_dec * tstep * 365*86400)))	61
d_sed2	Depth of sediment [m]	0.255108137709719	I
Qleach	Specific flow rate through sediments [m/s]	0.00040192032988864	I
T_ambient	Ambient temperature [ºC]	5.03	I
windspeed	Wind speed [m/s]	3.75	I
P_rain	Monthly average rainfall [m/d]	0.00065	I
P_evap	Monthly average evaporation [m/d]	0.00099	I
k_dec	Anaerobic decay constant [1/s]	3.40279963132999E-07	I

SI Module Parameter	Parameter Description	Value/Equation	Equation Number*
rho_air	Density of air [g/cc]	0.001232600798475	I
mu_air	Viscosity of air [g/cm-sec]	0.000174387704	I
mu_H2O	Viscosity of water [g/cm-sec]	0.014317387778321	I
Da	Diffusivity in air [cm^2/s]	0.29460690754589	I
Dw	Diffusivity in water [cm^2/s]	0.00122749889885273	I
HLC	Henry's Law constant [m^3-atm/mole]	0.25420666036466	I
Kds	Soil/water partitioning coefficient	4.4919196199255	I
Sol	Constituent solubility in water (g/m^3)	26876.438629346	I
T_waste	Influent waste temperature [ºC]	17.56	I
Temp	Liquid temperature in WMU [ºC]	=(T_waste + (25*(1 + F_aer)*A_wmu)/(4180000*Q_in)*T_ambient)/ ((1 + (25*(1 + F_aer)*A_wmu)/(4180000*Q_in)))	63
d_liq1	Depth of water in WMU [m]	=d_tot-d_sed2	U
Vol1	Volume of water in WMU [m^3]	=V_tot - Vol2	U
Vol2	Volume of sediments in WMU [m^3]	=A_q * d_sed2	U
Q_out	Volumetric flow rate (effluent) [m^3/s]	=IF(Q_in-Qleach+A_tot*(P_rain-P_evap)/86400<=0.01*Q_in,0.01*Q_in, Q_in-Qleach+A_tot*(P_rain-P_evap)/86400)	48
etss2	Maximum solids removal efficiency	0.9999	55
TSS_out	Total suspended solids (effluent) [g/cc]	=IF(Q_in/Q_out*(TSS_in + bio_yield*CBOD)*(1-etss2) > TSS_2,TSS_2, Q_in/Q_out*(TSS_in + bio_yield*CBOD)*(1-etss2))	58
TSS_1	Total suspended solids in liquid compartment [g/cc]	=EXP((LN(TSS_in) + LN(TSS_out))/2)	11
v_b	Sediment burial rate [m/s]	=(Q_in *(TSS_in + bio_yield*CBOD) - Q_out*TSS_out)/(A_tot*TSS_2)	59
v_r	Resuspension velocity [m/s]	=Q_in/A_q*TSS_1/TSS_2	49
v_s	Sedimentation velocity [m/s]	=IF(TSS_1=0,0,(v_r+v_b)*TSS_2/TSS_1-Qleach/A_tot)	60
thetaLout	Volumetric fraction of liquid influent	=1-TSS_out/rho_part	8

SI Module Parameter	Parameter Description	Value/Equation	Equation Number*
Fd1	Relative concentration of soluble constituent in liquid compartment	=1/(thetaL1+Kds*TSS_1)	9
Fd2	Relative concentration of soluble constituent in sediment compartment	=IF(d_sed2=0,1,1/(thetaL2+Kds*TSS_2))	9
Fdout	Relative concentration of soluble constituent in effluent	=1/(thetaLout+Kds*TSS_out)	9
Fp1	Relative concentration of sorbed constituent in liquid compartment	=Kds*TSS_1/(thetaL1+Kds*TSS_1)	10
Fp2	Relative concentration of sorbed constituent in sediment compartment	=IF(d_sed2=0,0,Kds*TSS_2/(thetaL2+Kds*TSS_2))	10
Fpout	Relative concentration of sorbed constituent in effluent	=Kds*TSS_out/(thetaLout+Kds*TSS_out)	10
K1	Simplification constant 1	=Q_out * (_Fd1/Fdout) + Qleach + _Fd1* (Kol * A_tot + k_hyd * Vol1 *thetaL1 + pVdiff * A_tot) + Vol1*(kbm*kba1*TSS_1) + v_s * A_tot * _Fp1	15
K2	Simplification constant 2	=Q_out * (_Fd1/Fdout) + _Fd1 *(Kol * A_tot + k_hyd * Vol1 * thetaL1) + Vol1 * (kbm * kba1 * TSS_1)	16
K3	Simplification constant 3	=A_tot * (v_r * _Fp2 + pVdiff * _Fd2)	17
K4	Simplification constant 4	=(Qleach + Vol2 * thetaL2 * k_hyd) * _Fd2 + kbs * Vol2 + v_b * A_tot * _Fp2	18
Ctot_2	Total concentration in sediment compartment [g/m^3]	=(_K1 - _K2) * (Q_in * C_in) / (_K2 * _K3 + _K1 * _K4)	22
Ctot_1	Total concentration in liquid compartment [g/m^3	=(Q_in * C_in + _K3 * Ctot_2) / _K1	21
E_wmu	Emission rate in [g/m^2-sec]	=Ctot_1 * _Fd1 * Kol	GRF
SWConc	Runoff concentration [g/m^3]	=Ctot_1	GRF
L_wmu	Leachate flux [g/m^2/d]	=Ctot_2 * _Fd2*Qleach/A_tot * 86400	GRF

*Note : A number refers to an equation number from SI Module documentation;
An “I” refers to an input;
A “?” refers to unreferenced equation or input;
A “U” refers to an undocumented internal parameter
A”GRF” refers to parameters output to SR.GRF

APPENDIX B

SEDIMENT COMPARTMENT HYDRAULIC CONDUCTIVITY SPREADSHEET EQUATIONS

Sediment Compartment Spreadsheet Equations

SI Module Parameter	Parameter Description	Parameter Value / Equation
b	Constant	0.337
Cc	Compression Index	1.02
g	Gravitational Acceleration [m/s^2]	9.8
A	Constant	570
e_0	Initial Void Ratio	2
H	Depth of SI unit [m]	1.92
z	Vertical downward distance from top of consolidatable sediment [m]	=0.5*Dfc
Rhow	Density of water [kg/m^3]	998
Rhos	Sediment grain density [kg/m^3]	3407.534859
theta	Porosity	0.667
Dfc	Thickness of consolidated sediments (filter cake) [m]	0.01298698
Ds	Thickness of unconsolidated sediments [m]	=Dfc
a_v	Coefficient of Compressibility	=0.435*Cc/(0.5*sigma)
sigma	Vertical effective stress [Newtons/m^2]	= (H - Ds - Dfc) * Rhow * g + (1 - theta) * Ds * Rhos * g + theta * Ds * Rhow * g + (1 - theta) * z * Rhos * g + theta * z * Rhow * g - (H - Dfc) * Rhow * g + z/ Dfc * (H - Dfc) * Rhow * g
C2	Intermediate coefficient	=-a_v*((1 - theta)* Rhos* g + theta* Rhow* g + ((H - Dfc)* Rhow* g) / Dfc)/A
C1	Intermediate coefficient	= (e0 - a_v*((H - Ds - Dfc) * Rhow * g + (1 - theta) * Ds * Rhos* g + theta * Ds * Rhow * g - (H - Dfc) * Rhow * g))/A
hydc_sed	Hydraulic conductivity of filter cake [m/s]	=1/(1/(Dfc*(1- 1/b)*C_2) * ((C_1 + C_2*Dfc)^(1-1/b) - C_1^(1-1/b)))

APPENDIX C

SI MODULE SSF & GRF FILES

Source module SSF for SI at location 1632106

1,
"SISI1632106.ssf","data group",
24,
"bio_yield",0,"FLOAT",0,"g/g",
0.657331744,
"C_in",0,"FLOAT",0,"mg/L",
0.1,
"CBOD",0,"FLOAT",0,"g/cm3",
0.01815112669,
"d_imp",0,"FLOAT",0,"cm",
61,
"d_setpt",0,"FLOAT",0,"fraction",
0.375,
"d_wmu",0,"FLOAT",0,"m",
1.92,
"dmeanTSS",0,"FLOAT",0,"cm",
0.001260738859,
"EconLife",0,"INTEGER",0,"year",
50,
"F_aer",0,"FLOAT",0,"fraction",
0.2660303929,
"focW",0,"FLOAT",0,"mass fraction",
0.5450995462,
"hydc_sed",0,"FLOAT",0,"m/s",
8.482069147e-007,
"J",0,"FLOAT",0,"lb O2/h-hp",
3,
"k_dec",0,"FLOAT",0,"1/s",
6.389893979e-007,
"kba1",0,"FLOAT",0,"unitless",
0.8996387615,
"MWt_H2O",0,"FLOAT",0,"g/mol",
18,
"n_imp",0,"INTEGER",0,"unitless",
11,
"NumEcon",0,"INTEGER",0,"",
1,
"O2eff",0,"FLOAT",0,"unitless",
0.8057382283,
"Powr",0,"FLOAT",0,"hp",
825,
"Q_wmu",0,"FLOAT",0,"m3/s",
0.0009872472168,
"rho_l",0,"FLOAT",0,"g/cm3",

0.998,
"rho_part",0,"FLOAT",0,"g/cm3",
3.407534859,
"TSS_in",0,"FLOAT",0,"g/cm3",
0.007492781126,
"w_imp",0,"FLOAT",0,"rad/s",
126,

Site layout SSF for SI at location 1632106 (Abbreviated version)

1,
"slSI1632106.ssf","data group",
204,

"MetSta",0,"STRING",0,"",
"23044",
"NumAir",0,"INTEGER",0,"",
466,
"NumAqu",0,"INTEGER",0,"",
1,
"NumAquWell",0,"INTEGER",0,"",
107,
"NumBinC",0,"INTEGER",0,"unitless",
7,
"NumBinNC",0,"INTEGER",0,"unitless",
4,
"NumEcoBin",0,"INTEGER",0,"unitless",
5,
"NumEcoRing",0,"INTEGER",0,"unitless",
3,
"NumFarm",0,"INTEGER",0,"",
3,
"NumFarmRcpType",0,"INTEGER",0,"",
4,
"NumHab",0,"INTEGER",0,"unitless",
8,
"NumHabGroup",0,"INTEGER",0,"unitless",
3,
"NumHabType",0,"INTEGER",0,"unitless",
5,
"NumHumRcp",0,"INTEGER",0,"unitless",
200,
"NumHumRcpType",0,"INTEGER",0,"",
4,
"NumReceptor",0,"INTEGER",0,"unitless",
62,
"NumRecGroup",0,"INTEGER",0,"unitless",
9,
"NumRing",0,"INTEGER",0,"",
3,
"NumTrophicLevel",0,"INTEGER",0,"unitless",
5,
"NumVad",0,"INTEGER",0,"",

1,
"NumWBN",0,"INTEGER",0,"",
2,
"NumWSSub",0,"INTEGER",0,"",
10,
"NyrMax",0,"INTEGER",0,"years",
10000,
"SettingID",0,"STRING",0,"",
"SI1632106",
"SiteGeoRefX",0,"FLOAT",0,"m",
335461.906,
"SiteGeoRefY",0,"FLOAT",0,"m",
3572174,
"SiteLatitude",0,"FLOAT",0,"degrees",
32.27424,
"SiteLongitude",0,"FLOAT",0,"degrees",
-106.74707,
"SiteUTMZone",0,"INTEGER",0,"",
13,
"SoilType",0,"STRING",0,"",
"S",
"SrcArea",0,"FLOAT",0,"m^2",
16188,
"SrcDepth",0,"FLOAT",0,"m",
1.92,
"SrcId",0,"STRING",0,"",
"SI1632106",
"SrcLocX",0,"FLOAT",0,"m",
0,
"SrcLocY",0,"FLOAT",0,"m",
0,
"SrcLWSNumSubArea",1,"INTEGER",0,"",
1,1,
"SrcLWSSubAreaArea",2,"FLOAT",0,"m2",
1,
1,16188,
"SrcLWSSubAreaIndex",1,"INTEGER",0,"unitless",
1,1,
"SrcNumLWS",0,"INTEGER",0,"",
1,
"SrcPh",0,"FLOAT",0,"pH units",
11.76504326,
"SrcTemp",0,"FLOAT",0,"degrees Celsius",
17.56,
"SrcType",0,"STRING",0,"",

"SI",
"TermFrac",0,"FLOAT",0,"fraction",
0.01,
"VadALPHA",0,"FLOAT",0,"1/cm",
0.1489877647,
"VadBETA",0,"FLOAT",0,"unitless",
2.776502042,
"VadID",1,"STRING",0,"",
1,"SI1632106",
"VadLWSIndex",1,"INTEGER",0,"",
1,1,
"VadPh",0,"FLOAT",0,"pH units",
8.129740952,
"VadSATK",0,"FLOAT",0,"cm/hr",
22.17184598,
"VadTemp",0,"FLOAT",0,"degrees Celsius",
17.5,
"VadThick",1,"FLOAT",0,"m",
1,30.5,
"VadWCR",0,"FLOAT",0,"L/L",
0.04554795782,
"VadWCS",0,"FLOAT",0,"L/L",
0.43,

Source module GRF for SI at location 1632106

1,
"sr.grf","data group",
18,
"AnnInfil",2,"FLOAT",0,"m/d",
1,
50,0.005216529401,0.005216529401,0.005216529401,0.005216529401,0.005216529401,
0.005216529401,0.005216529401,0.005216529401,0.005211177811,0.004922095431,
0.004554847067,0.004225716788,0.003966387086,0.003707248377,0.003488017882,
0.003299127252,0.003120537246,0.002958009764,0.002811644175,0.002684303332,
0.002559741892,0.002450889924,0.002352247302,0.002252973104,0.002176336872,
0.002094443472,0.002028512858,0.001959330002,0.001896389008,0.001837053609,
0.001785551094,0.001734575531,0.00168533454,0.001641334886,0.001598998233,
0.001558263241,0.001516542813,0.001480139122,0.001442168574,0.001407086374,
0.001371610996,0.001339937298,0.001312228853,0.001279329059,0.001253536533,
0.001226975597,0.00120341855,0.001179495338,0.001155495397,0.002539721805,
"LeachFlux",2,"FLOAT",0,"g/m2/d",
1,
50,4.678957706e-009,4.65727388e-009,4.645742468e-009,4.709112931e-009,
4.678825885e-009,4.740799759e-009,4.720702579e-009,4.714562239e-009,
4.782284923e-009,4.392317565e-009,4.034997694e-009,3.838494016e-009,
3.534459183e-009,3.272731651e-009,3.107854614e-009,2.962514987e-009,
2.839786951e-009,2.71270379e-009,2.543989258e-009,2.38460175e-009,
2.296769226e-009,2.1891337e-009,2.09553367e-009,2.035413831e-009,
1.953052867e-009,1.903946018e-009,1.835769978e-009,1.770876628e-009,
1.740955682e-009,1.638275061e-009,1.581906992e-009,1.575021605e-009,
1.501620532e-009,1.448158671e-009,1.424454614e-009,1.398927709e-009,
1.379387183e-009,1.357209926e-009,1.304536148e-009,1.24979099e-009,
1.230242848e-009,1.196321329e-009,1.168854437e-009,1.154985917e-009,
1.124520396e-009,1.115317793e-009,1.089069549e-009,1.066220085e-009,
1.060525976e-009,2.239983014e-009,
"LeachFluxNY",1,"INTEGER",0,"",
1,50,
"LeachFluxYR",2,"INTEGER",0,"year",
1,
50,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,
29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,
"NyrMet",0,"INTEGER",0,"year",
50,
"SrcCE",0,"LOGICAL",0,"",
"F",
"SrcH2O",0,"LOGICAL",0,"",
"T",
"SrcLeachMet",0,"LOGICAL",0,"",

"F",
"SrcLeachSrc",0,"LOGICAL",0,"",
"T",
"SrcOvl",0,"LOGICAL",0,"",
"F",
"SrcSoil",0,"LOGICAL",0,"",
"F",
"SrcVE",0,"LOGICAL",0,"",
"T",
"SWConcTot",1,"FLOAT",0,"mg/L",
50,9.010289848e-007,8.969322559e-007,8.949024421e-007,9.071241218e-007,
9.012813756e-007,9.129567887e-007,9.090642882e-007,9.081709903e-007,
9.222385451e-007,8.956796486e-007,8.8954477e-007,9.112021112e-007,
8.936006339e-007,8.84893783e-007,8.931936985e-007,8.995520207e-007,
9.11018741e-007,9.181513043e-007,9.058013029e-007,8.897297637e-007,
8.986337543e-007,8.94141983e-007,8.921399958e-007,9.043250555e-007,
8.982720029e-007,9.099923138e-007,9.060800614e-007,9.050699655e-007,
9.190890001e-007,8.929670572e-007,8.867457791e-007,9.088642251e-007,
8.917727157e-007,8.828290064e-007,8.9143367e-007,8.983658838e-007,
9.10146968e-007,9.174209966e-007,9.051502364e-007,8.889878594e-007,
8.976804398e-007,8.93487608e-007,8.913147869e-007,9.038110351e-007,
8.978837093e-007,9.095252006e-007,9.056492969e-007,9.045025026e-007,
9.186023425e-007,8.9352918e-007,
"SWConcTotNY",0,"INTEGER",0,"",
50,
"SWConcTotYR",1,"INTEGER",0,"year",
50,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,
29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,
"VE",1,"FLOAT",0,"g/m2/d",
50,0.0005269170076,0.0005269170436,0.0005269170757,0.000526917005,0.0005269170389,
0.0005269169434,0.000526916769,0.0005269169993,0.0005269169181,0.0005269173222,
0.0005269175036,0.0005269177732,0.0005269179477,0.0005269180213,0.0005269179281,
0.0005269177636,0.0005269178673,0.0005269179463,0.0005269180653,0.0005269184393,
0.0005269185379,0.0005269183038,0.0005269186162,0.0005269185232,0.0005269186082,
0.0005269184914,0.0005269180792,0.0005269185336,0.0005269181396,0.0005269187375,
0.0005269183103,0.0005269185608,0.0005269183603,0.0005269183195,0.0005269182319,
0.0005269179173,0.0005269179038,0.0005269180517,0.0005269181451,0.0005269184947,
0.0005269185705,0.0005269183534,0.0005269186638,0.0005269186784,0.0005269186989,
0.0005269185059,0.0005269181044,0.0005269185536,0.0005269181632,0.0005269185232,
"VENY",0,"INTEGER",0,"",
50,
"VEYR",1,"INTEGER",0,"year",
50,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,
29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,

FIGURES

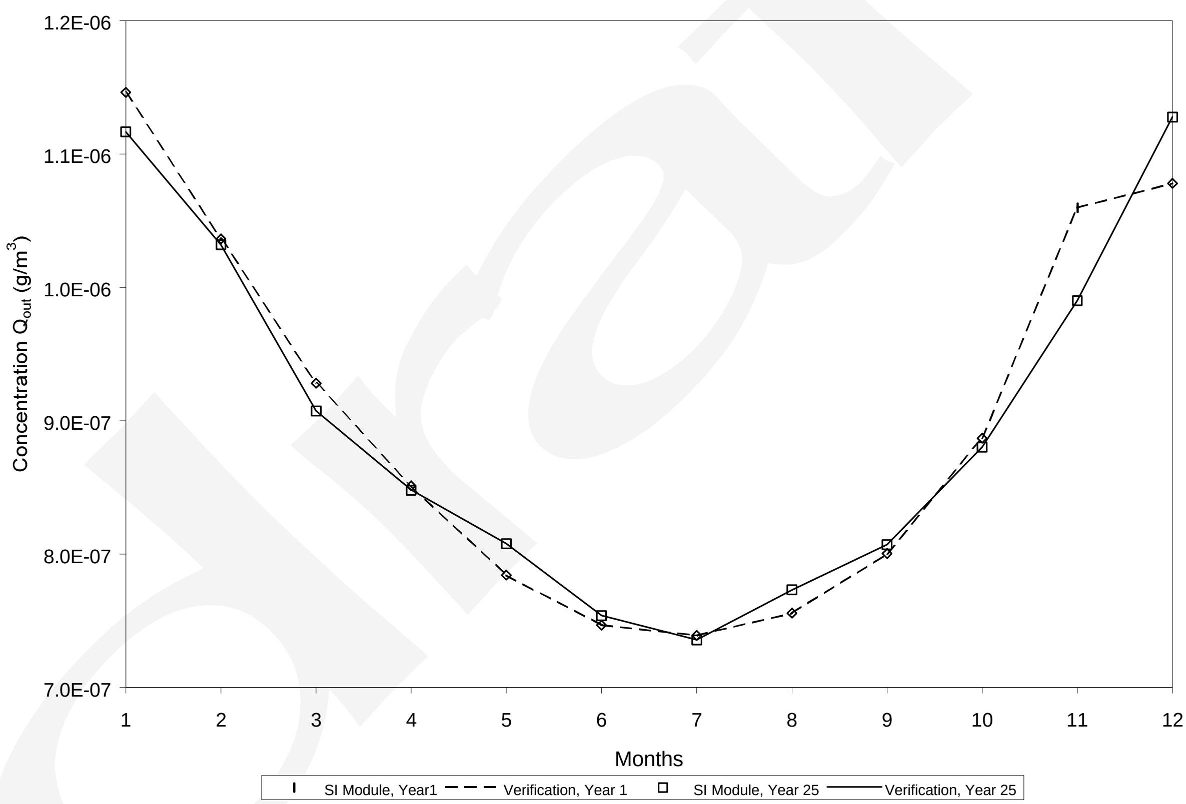

Figure 1 **Monthly Concentrations of Q_{out} from SI Module and Verification Spreadsheet, Month 6, years 1 and 25**

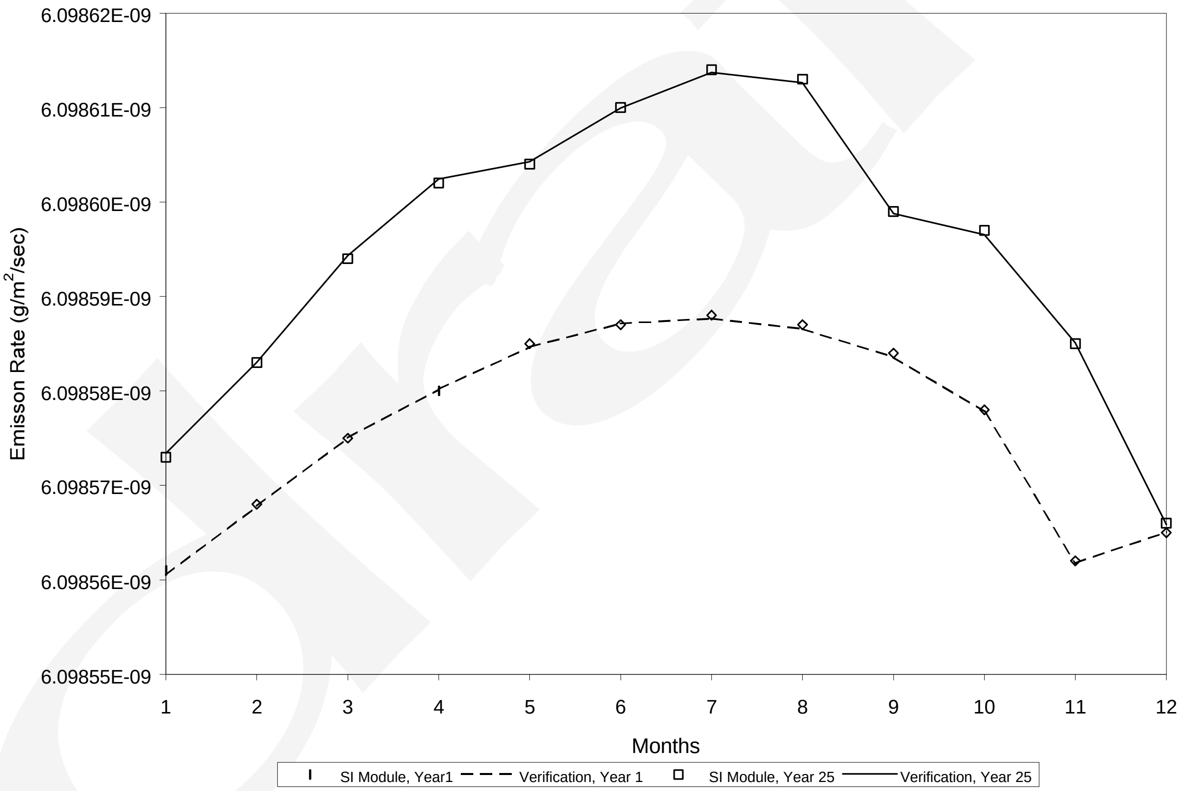

Figure 2 Monthly Air Emissions from SI Module and Verification Spreadsheet, Month 6, Years 1 and 25

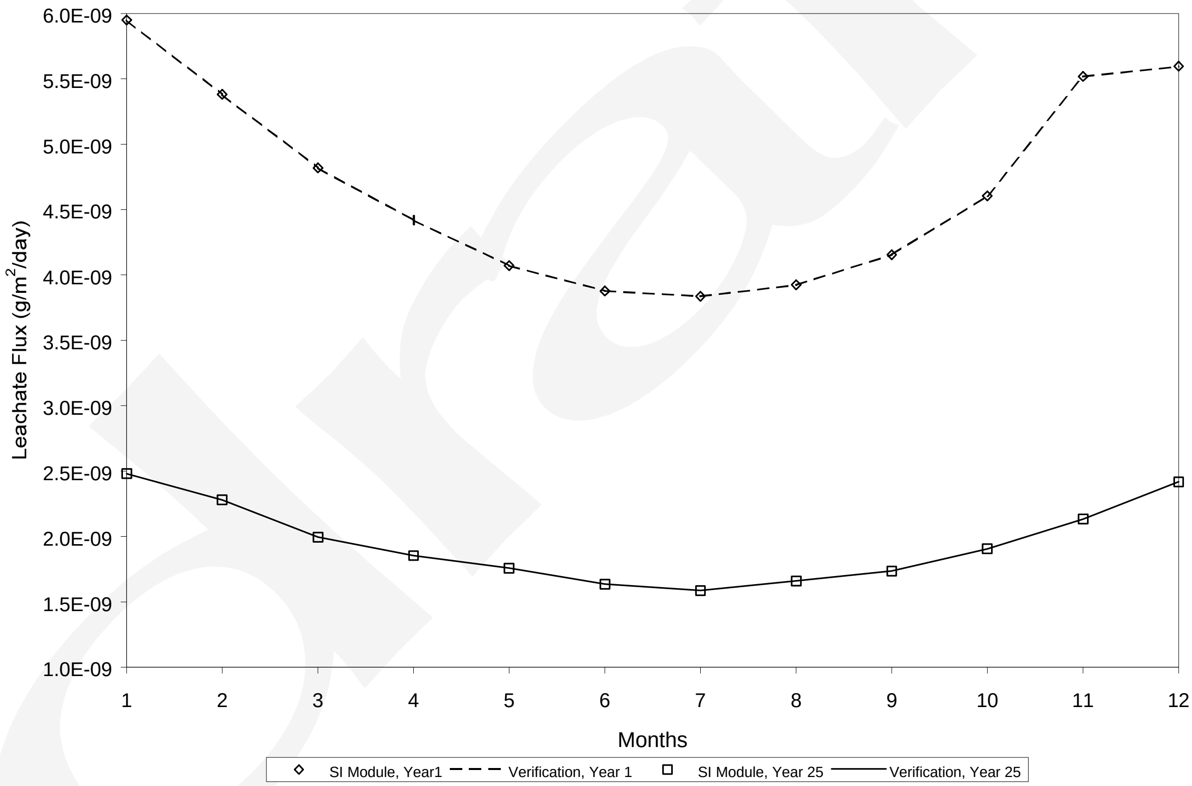

Figure 3 Monthly Leachate Flux from SI Module and Verification Spreadsheet, Month 6, Years 1 and 25

TABLES

TABLE 1 COMPARISON BETWEEN FLUXES READ-IN FROM THE SOURCE GRF FILE, GENERATED BY THE SI MODULE, AND MANUALLY CALCULATED

Year	Data Source	Volatile Emissions [g/m^2/day]	Surface Runoff Concentration [mg/L]	Leachate Flux [g/m2/day]
1	SR.GRF	5.269e-04	9.010e-07	4.679e-09
	HWIR SI	5.269e-04	9.010e-07	4.679e-09
	Verification	5.269e-04	9.011e-07	4.679e-09
25	SR.GRF	5.269e-04	8.983e-07	1.953e-09
	HWIR SI	5.269e-04	8.983e-07	1.953e-09
	Verification	5.269e-04	8.983e-07	1.953e-09

TABLE 2 FINAL COMPARISON BETWEEN THE SI MODULE AND MANUALLY CALCULATED HYDRAULIC CONDUCTIVITIES OF CONSOLIDATED SEDIMENTS

	Month	Thickness of Filter Cake [m]	Conductivity of Filter Cake [m/s]	
			Verification	SI Module
Year 1	1	1.078E-02	1.329E-09	1.329E-09
	2	1.115E-02	1.332E-09	1.332E-09
	3	1.152E-02	1.335E-09	1.335E-09
	4	1.188E-02	1.337E-09	1.337E-09
	5	1.225E-02	1.340E-09	1.340E-09
	6	1.262E-02	1.343E-09	1.343E-09
	7	1.299E-02	2.123E-09	1.345E-09
	8	1.335E-02	1.348E-09	1.348E-09
	9	1.372E-02	1.350E-09	1.350E-09
	10	1.409E-02	1.353E-09	1.353E-09
	11	1.446E-02	1.356E-09	1.356E-09
	12	1.483E-02	1.358E-09	1.358E-09
Year 25	1	1.239E-01	2.096E-09	2.096E-09
	2	1.242E-01	2.098E-09	2.098E-09
	3	1.246E-01	2.100E-09	2.100E-09
	4	1.250E-01	2.103E-09	2.103E-09
	5	1.254E-01	2.105E-09	2.105E-09
	6	1.257E-01	2.107E-09	2.107E-09
	7	1.261E-01	2.110E-09	2.110E-09
	8	1.265E-01	2.112E-09	2.112E-09
	9	1.268E-01	2.114E-09	2.114E-09
	10	1.272E-01	2.117E-09	2.117E-09
	11	1.276E-01	2.119E-09	2.119E-09
	12	1.282E-01	2.123E-09	2.123E-09

TABLE 3 FLOW SYSTEM REPRESENTATIONS BY THE HWIR99 SI MODULE AND EPACMTP

Layer	**HWIR99 SI MODULE**	**EPACMTP**
1	Compacted sediment layer (1 sublayer) Saturated	Liner (1 sublayer) Saturated
2	Clogged native material (5 sublayers) Variably saturated	Layer 1 of the Vadose zone (5 sublayer) Variably saturated
3	Vadose zone (5 sublayers) Variably saturated	Layer 2 of the Vadose zone (5 sublayers) Variably saturated

TABLE 4 INITIAL INFILTRATION RATES GENERATED BY EPACMTP AND THE SI MODULE

Simulation	EPACMTP Infiltration rate (m/y)	HWIR99 SI MODULE Infiltration rate (m/y)
Year 1, Month 6	6.9215	3.4836
Year 25, Month 6	1.0828	0.5458

TABLE 5 INITIAL PRESSURE HEAD DISTRIBUTIONS GENERATED BY THE EPACMTP AND SI MODULE FOR YEAR 1, MONTH 6

Depth [m]	Pressure Head [m]		Compartment
	HWIR SI Module	**EPACMTP**	
0.00	0.000	0.000	Liquid
1.92	-1.001E-01	-8.673E-02	Sediment
2.17	-1.017E-01	-8.687E-02	
2.29	-1.135E-01	-8.783E-02	
2.36	-1.728E-01	-9.161E-02	Clogged Native Materials
2.39	-8.365E-01	-1.008E-01	
2.42	-1.564E+04	-1.345E-01	
16.46	-2.518E+08	-1.345E-01	
23.48	-3.777E+08	-1.345E-01	
26.99	-4.407E+08	-1.345E-01	Unclogged Native Materials
28.75	-4.722E+08	-1.327E-01	
30.50	-5.037E+08	0.000	

TABLE 6 INITIAL PRESSURE HEAD DISTRIBUTIONS GENERATED BY EPACMTP AND THE SI MODULE FOR YEAR 25, MONTH 6

Depth [m]	Pressure Head [m]		Compartment
	HWIR SI Module	EPACMTP	
0.00	0.000	0.000	Liquid
1.92	-0.141	-0.124	Sediment
2.17	-0.151	-0.125	Clogged Native Materials
2.29	-0.217	-0.126	
2.36	-1.046	-0.132	
2.39	-1.036E+4	-0.144	
2.42	-8.885E+5	-0.184	
16.46	-4.034E+7	-0.184	Unclogged Native Materials
23.48	-6.007E+7	-0.184	
26.99	-6.993E+7	-0.184	
28.75	-7.486E+7	-0.180	
30.50	-7.797E+7	0.000	

TABLE 7 REVISED INFILTRATION RATES GENERATED BY EPACMTP AND THE SI MODULE

Simulation	EPACMTP Infiltration rate (m/y)	HWIR99 SI MODULE Infiltration rate (m/y)
Year 1, Month 6	6.9215	6.9053
Year 25, Month 6	1.0828	1.0840

TABLE 8 REVISED PRESSURE HEAD DISTRIBUTIONS GENERATED BY THE EPACMTP AND SI MODULE FOR YEAR 1, MONTH 6

Depth [m]	Pressure Head [m]		Compartment
	HWIR SI Module	EPACMTP	
0.00	0.000	0.000	Liquid
1.92	-8.675E-02	-8.673E-02	Sediment
2.17	-8.673E-02	-8.687E-02	Clogged Native Materials
2.295	-8.715E-02	-8.783E-02	
2.3575	-8.982E-02	-9.161E-02	
2.3888	-1.009E-01	-1.008E-01	
2.42	-1.351E-01	-1.345E-01	
16.46	-1.351E-01	-1.345E-01	Unclogged Native Materials
23.48	-1.354E-01	-1.345E-01	
26.99	-1.346E-01	-1.345E-01	
28.745	-1.329E-01	-1.327E-01	
30.50	0.000	0.000	

TABLE 9 REVISED PRESSURE HEAD DISTRIBUTIONS GENERATED BY EPACMTP AND THE SI MODULE FOR YEAR 25, MONTH 6

Depth [m]	Pressure Head [m]		Compartment
	HWIR SI Module	EPACMTP	
0.00	0.000	0.000	Liquid
1.92	-1.243E-01	-1.243E-01	Sediment
2.17	-1.244E-01	-1.246E-01	Clogged Native Materials
2.295	-1.259E-01	-1.262E-01	
2.3575	-1.297E-01	-1.316E-01	
2.3888	-1.441E-01	-1.435E-01	
2.42	-1.843E-01	-1.836E-01	
16.46	-1.836E-01	-1.836E-01	Unclogged Native Materials
23.48	-1.836E-01	-1.836E-01	
26.99	-1.835E-01	-1.835E-01	
28.745	-1.804E-01	-1.804E-01	
30.50	0.000	0.000	