12. Steady-state horizontal groundwater flow

Groundwater flow is a very important issue of environmental engineering. There are several numerical models, which are well developed and widely used.

Nevertheless, sometimes an easy-to-use approximate method is required. Under natural conditions, groundwater movement is quite often an almost steady-state flow. For that reason, we included steady-state horizontal groundwater flow (1D) into this code. It is not recommended to apply this tool to problems where natural conditions are modified artificially yielding transient groundwater flow. The method applies to confined and unconfined aquifers. Groundwater recharge is considered as a steady-state inflow. The bottom of the aquifer is assumed to be horizontal and the boundaries should be complete. A river e.g. is assumed to be at least as deep as the aquifer. One of the boundaries of the flow region may be described by a flux boundary condition. The equation to describe this kind of flow is given by (Busch, Luckner, Tiemer 1993)

$$\varphi(x) = \varphi_0 + x\frac{\varphi_R - \varphi_0}{R} + \frac{q_N}{2K_s}\left(Rx - x^2\right) \qquad (35)$$

x	horizontal distance from the left hand boundary, m
R	distance between left-hand and right-hand boundary, m
q_N	groundwater recharge, **m/day** (For convenience, data input requires **mm/year**)
K_s	Saturated hydraulic conductivity of the aquifer, **m/day**
φ	Girinskij potential, indices 0 and R for left-hand and right-hand boundary, resp.

The Girinskij potential is given by

$$\varphi = \frac{H^2}{2} \qquad \text{unconfined aquifer}$$

$$\varphi = HM - \frac{M^2}{2} \qquad \text{confined aquifer} \qquad (36)$$

H	hydraulic head, m (H=0 at the bottom of the aquifer)
M	thickness of the confined aquifer

The specific groundwater flow Q, to be expressed as m^3 of water per day and per meter flow width (or length of the boundary) can be calculated by

$$Q(x) = -\left[\frac{K_s}{R}\left(\varphi_R - \varphi_0\right) + q_N\left(\frac{R}{2} - x\right)\right] \qquad (37)$$

Please note that positive Q means flow toward the right-hand boundary R. Negative Q means that water will flow towards the boundary at x=0.

Without groundwater recharge ($q_N = 0$), Q is not dependent on x. In an unconfined aquifer, groundwater recharge may lead to a water divide. Its position is given by

$$x_{ws} = \frac{K_s}{2 R q_N} \left(H_R^2 - H_0^2 \right) + \frac{R}{2} \qquad (38)$$

Values of $x_{ws} < 0$ or $x_{ws} > R$ indicate that there is no water divide between given boundaries.

13 Groundwater flow to/from a single well

Circular shaped steady-state groundwater is addressed here to provide a tool for designing a single well. Steady-state flow conditions require a range of the well that is defined by

$$R_{\max} = \sqrt{\frac{V}{q_N \pi}} \qquad (39)$$

V water withdrawal from the well, m^3/day

Eq. (39) holds for a pumped well. In the distance R_{max} the elevation of the groundwater table is unaffected by the well. The elevation of the groundwater table at the location of the well (x=0) in unconfined aquifer ($H_0 = (2\varphi_0)^{1/2}$ is given by

$$\varphi_0 = \varphi_R - \frac{\ln(R_{\max}/r_0)}{2\pi K_s} \left\{ \pi q_N \left[r_0^2 - \left(\frac{R_{\max}^2 - r_0^2}{2 \ln(R_{\max}/r_0)} \right) \right] + V \right\} \qquad (40)$$

φ_R denotes φ at the distance $R = R_{max}$ and r_0 is the radius of the well pipe, (m)

14 First approximation to reactive solute transport in soil

To obtain a first approximation to one-dimensional vertical solute transport through unsaturated soil, diffusion and dispersion may be neglected and water flow may be assumed to be steady-state. Since only piston flow would govern solute transport in this case, the problem is greatly simplified. Reactions of the solute such as decay and adsorption are considered by a first-order reaction equation and by the retardation coefficient *R*, respectively. By combination of the processes mentioned, we obtain (Jury et al., 1991, Bohne, 2005)

$$t_{bc} = \frac{RL\theta}{q} \qquad (41)$$

$$c_{\mathrm{rel}} = \exp\left(-LR\frac{\theta}{q}\frac{\ln(2)}{t_{1/2}}\right)$$

c_{rel}	relative concentration c/c_0 (c_0 is concentration at depth 0) at depth L and time t after solute application
t_{bc}	breakthrough time (days) of a solute born on soil surface
R	coefficient of retardation
L	soil depth or length of soil column, cm
q	steady-state flux through soil, cm/day
$t_{1/2}$	half-life period of the solute, days

For the volumetric water content θ, an appropriate assumption must be chosen. Quite often this will be the water content at field capacity. Assuming unit gradient conditions, *q* equals the hydraulic conductivity at that θ.

15 Breakthrough curve with step input

For non steady-state solute propagation in steady-state water flow, the convection - dispersion equation (CDE) can be solved analytically. These solutions are widely used to estimate the parameters *D* and *R* from breakthrough curve experiments. The solution proposed by Lapidus and Amundson (1952) accounts for step input of the solute.

In this computer code, following Jury et al.(1991) the effective dispersion/diffusion coefficient is estimated from the input dispersivity λ, pore water velocity *v*, water content and the diffusion coefficient in bulk water D_0 according to

$$D_{eff} = v\lambda + D_0\frac{\theta_{mobile}^{3.333}}{\theta_s^{\ 2}} \qquad (42)$$

Relative concentration as a function of time is then given by

$$c_{rel}(t)=\frac{1}{2}erfc\left(\frac{RL-vt}{2\sqrt{D_{eff}\,Rt}}\right)+\frac{1}{2}\exp\left(\frac{vL}{D_{eff}}\right)erfc\left(\frac{RL+vt}{2\sqrt{D_{eff}\,Rt}}\right) \qquad (43)$$

R coefficient of retardation
L length of soil column, cm
v pore water velocity (cm/day), $v = q/\theta$
t time, days

To estimate the parameters R and D_{eff}, the code CXTFIT (Toride et al., 1995) can be used.

16 Breakthrough curve with pulse input

This menu point resembles the previous one except that pulse input is considered. Jury & Sposito (Jury et al. 1991) came up with the equation

$$c(t)=\frac{LRm}{v\theta_{mobile}\sqrt{4\pi D_{eff}\,t^3}}\exp\left(-\frac{(LR-vt)^2}{4D_{eff}\,t}\right) \qquad (44)$$

m mass of solute applied, grams/cm^2 soil surface
c effluent concentration grams/cm^3

17. 2D transient solute propagation in steady-state 1D-groundwater flow

To estimate solute propagation in groundwater, one-dimensional horizontal and steady-state groundwater flow is considered. At the location *x*=0; *y*=0 an injection well is assumed where at time *t*=0 a solute is inserted in such a way that the aquifer from top to bottom is totally and instantaneously contaminated. Let's put the *x*-axis parallel to the direction of groundwater flow. Now the solute will propagate in a non - steady-state way and in both of the directions x, y by piston flow, diffusion and dispersion. Moreover, there may be chemical or bio-chemical reactions in the aquifer changing concentrations of the solute. Csanady (Kinzelbach, 1986) addressed this problem and came up with the solution

$$c(t,x,y)=\frac{m}{4\pi\theta_{drain}Mvt\sqrt{\lambda_L\lambda_T}}\exp\left[\frac{-(x-vt/R)^2}{4\lambda_L vt/R}-\frac{y^2}{4\lambda_T vt/R}\right]\exp(-\beta t) \qquad (45)$$

c concentration, kg/m^3
m mass of solute added, kg
θ_{drain} drainable pore space
M thickness of the water-filled region of the aquifer, m

v pore water velocity, m/day
t time, days
λ_L dispersivity in flow direction, m
λ_T dispersivity perpendicular to flow direction, assumed to be $0.1\ \lambda_L$.
x, y space coordinates, m
R coefficient of retardation
β decay coefficient, (1/days)

18. Steady-state drainage

To set up a field drainage system, the design parameters drain spacing and drain depth must be chosen. There are several methods available to calculate suitable drain spacings D (Bodenwasserregulierung, 1985, van der Ploeg et al., 1999, Skaggs, 1999, Smedema et al. 2004). These methods account for different flow conditions. We would like to denote the elevation of drains above an impervious layer by D_0. Different flow conditions may then be considered as shown in the table:

Aquifer	**Position of drain pipe**	**Hydraulic conductivity**	**Geometry**	**case no.**
Homogeneous	Drain on bottom		$D_0=0$	1.0
Homogeneous	Drain on bottom		$D_0<0.25\,D$	1.1
Homogeneous	Drain on bottom		$D_0>0.25D$	1.2
Two-layered	Drain at boundary	$K_{top}/K_{bottom}>0.1$	$D_0<0.25\,D$	2.1
Two-layered	Drain at boundary	$K_{top}/K_{bottom}<0.1$	$D_0<0.25\,D$	2.2
Two-layered	Drain at boundary		$D_0>0.25D$	2.3
Two-layered	Drain in top layer	$K_{top}/K_{bottom}>0.1$		3.1
Two-layered	Drain in top layer	$K_{top}/K_{bottom}<0.1$		3.2
Two-layered	Drain in bottom layer			4
Homogeneous		Confining layer above water-filled aquifer		5

Homogeneous aquifer, drain on bottom (case 1.0)

$$D=\frac{h_s}{\frac{1}{2}\sqrt{\frac{q_E}{K_s}-\frac{q_E\ln(\gamma)}{\pi K_s}}} \quad (50)$$

D drain spacing, m
h_s height of water table over drain at midpoint between drains
q_E groundwater recharge, m/d
K_s saturated soil hydraulic conductivity, m/d
γ =0.1 for drain pipes, 0.2 for open ditches

Homogeneous aquifer, D_0<0.25D (case 1.1)

$$b=1;\, D_1=h_s/2+D_0;\, C=2/\pi\ln(b\,D_0/u_e) \quad (51)$$

$$D = 2 D_1 \left(\sqrt{C^2 + \frac{h_s}{D_1}\left(\frac{2 K_s}{q_E} - 1\right)} - C \right) \tag{52}$$

Homogeneous aquifer, D_0>0.25D (case 1.2): Iterative solution

$$D = \frac{\pi K_s h_s}{q_E \ln(D/u_e)} \tag{53}$$

u_e effective wetted perimeter, $u_e = \gamma\, u_a$; with $u_a = \pi\,(d_a + 2r_{filter})$ for pipe drainage
d_a pipe diameter
In case of open ditches holds u_a = 3 (bed width)

Two-layered aquifer, drain base at boundary between layers (Iterative solutions, cases 2)

D_0<0.25 D and K_{top}/K_{bott} >0.1 (case 2.1)

$$D = 2 \sqrt{\frac{h_s}{q_E}\left(K_{top} h_s + 2 K_{bott} d_1\right)} \tag{54}$$

$$d_1 = \frac{D_0}{1 + \frac{4 D_0}{D}} (C + 0.32) \tag{55}$$

K_{top}, K_{bott} Hydraulic conductivity of top and bottom layer, respectively, m/d
For C see Eq. 51

D_0 < 0.25 D_0 and K_{top}/K_{bott}<0.1 (case 2.2)

$$D = 2 \sqrt{2 d_1 h_s \frac{K_{bott}}{K_{top}} \left(\frac{K_{top}}{q_E} - 1\right)} \tag{56}$$

Case 2.3 is calculated by Eq. 53, taking $K_s = K_{bott}$

Two-layered aquifer, drain in top layer (cases 3)
K_{top}/K_{bott} > 0.1 (Case 3.1)

$$D = 2 d_3 \left[\sqrt{C^2 + \frac{h_s}{d_3}\left(\frac{2 K_{top}}{q_E} - 1\right)} - C \right] \tag{57}$$

with

$$d_3 = \frac{h_s}{2} + D_0 + d_2 \frac{K_{bott}}{K_{top}} \tag{58}$$

d_2 thickness of bottom layer
In Eq. (57), C is calculated following Eq. (53) using empirical values of b varying between 1 and 5.

K_{top}/K_{bott} < 0.1 (Case 3.2)

$$D = 2 d_4 \left(\sqrt{C^2 + \frac{h_s}{d_4}\left(\frac{2 K_{top}}{q_E} + \frac{q_E}{K_{top}} - 3\right)} - C \right) \tag{59}$$

with

$$d_4 = D_0 + d_2 \frac{K_{bott}}{K_{top}} \tag{60}$$

Again C is calculated following Eq. (53) using empirical values of b varying between 1 and 5.

Two-layered aquifer, drain base in bottom layer (case 4)

$$D = 2 d_6 \left(\sqrt{C^2 + \frac{2 K_{bott}}{K_{top} d_6} \left(h_s \left(\frac{K_{top}}{q_E} - 2 \right) + d_5 \right)} - C \right) \tag{61}$$

d_5 distance drain base to upper boundary between layers
$d_6 = D_0 + d_5$
C See Eq. (51) with b=1

Homogeneous confining layer above water-filled aquifer (Case 5)

$D_0 < 0.33$ D (Case 5.1)

$$D = \frac{4 D_0}{\pi} \ln \frac{4}{\tanh \left(\frac{\pi (d_7 - 1) K_s h_s}{Q_L} \right)} \tag{62}$$

with

$$d_7 = \frac{d_8 + D_0 q_E / K_s}{h_s} \tag{63}$$

d_8 distance drain base to ground surface

$$Q_L = \frac{\pi K_s d_7 h_s}{8 D_0} \ln \left[\frac{8 D_0}{\pi \sqrt{2 \gamma d_a (h_s + \gamma d_a)}} \right] \tag{64}$$

$D_0 > 0.33$ D (Case 5.2, iterative solution)

$$D = \frac{\pi D_0}{\ln(2) + (d_7 - 1) \ln \frac{2D}{\pi d_9}} \tag{65}$$

$$d_9 = \sqrt{2 \gamma d_a (d_8 + \gamma d_a)} \tag{66}$$

For d_a see Eq. (53)

19. Non steady-state drainage

To calculate drain discharge and time-dependent groundwater level, this program utilizes a method proposed by Storchenegger (Storchenegger and Bohne, 2005, Widmoser 2010). The soil water storage W above drain base is given by

$$W = c_f h_s \theta_s + \int_0^{d_{dr} - c_f h_s} \theta(d_{dr} - c_f h_s) dh \tag{67}$$

where h_s is the elevation of the groundwater table at midpoint above drain base and d_{dr} denotes the depth of drainbase below ground surface. The coefficient $c_f = \pi/4$ accounts for a parabolic shape of the phreatic surface. As soil water retention function θ(h) the van Genuchten function is used (van Genuchten, 1980, see Eq. 1) The method accounts for water stored in the unsaturated zone assuming that hydrostatic equilibrium is maintained all the time. (See chapter „Internal drainage“).

The fundamental storage equation dW/dt = recharge – discharge, where t denotes time, yields

$$\frac{dW}{dt} = q_i - q_E = \frac{dW}{dh_s} \frac{dh_s}{dt}$$

where q_i is the infiltration rate (assumed to be time-independent) and $q_E(h_s)$ is the drain discharge as a function of h_s calculated by the Hooghoudt equation. Using Eq. (67), the derivative of W with respect to h_s is given by

$$\frac{dW}{dh_s} = c_f \theta_s + \theta(d_{dr} - c_f h_s)(-c_f) \tag{68}$$

This yields finally

$$\frac{dh_s}{dt} = \frac{q_i - q_E(h_s)}{c_f [\theta_s - \theta(d_{dr} - c_f h_s)]} \tag{69}$$

In this code, Eq. (69) is solved numerically. The Hooghoudt equation reads

$$q_E(h_s) = \frac{8 K_s d_e h_s}{D^2} + \frac{4 K_s h_s^2}{D^2} \tag{70}$$

K_s lateral saturated soil hydraulic conductivity
d_e equivalent depth of the impermeable layer blow drain
D drain spacing
r radius of drain pipe

The equivalent depth d_e is given by

$$d = \frac{D}{8(R_h + R_r)};\ R_h = \frac{(D - 1.4 D_0)^2}{8 D_0 D};\ R_r = \frac{1}{\pi} \ln\left(0.7 \frac{D_0}{r}\right) \tag{71}$$

Eq. (70) yields the drain discharge of each time step.

For a wide range of soils and q_i=0, the method described above was successfully compared with results of the simulation model Hydrus 2d (Storchenegger et al. 2005).
In the code described here, the infiltration rate is considered to be time-independent. Rise of the water table over ground surface or drop down under drain depth is not considered.

References

Barry, D.A., Parlange,J.-Y., Haverkamp, R., Ross, P.J.
Infiltration under ponded conditions: 4. An explicit predictive infiltration formula.- Soil Sci. 160 (1995),1, 8-17

Bodenwasserregulierung: Fachbereichstandard TGL 42 8122/07, Berlin 1985

Bohne, K.
An introduction into applied soil hydrology.- Catena Publisher Reiskirchen, 2005 (231 pages)

Busch, K.-F., Luckner, L., Tiemer, K.
Geohydraulik.- Borntraeger Stuttgart, 3. Aufl. 1993

Crank, J.
The mathematics of diffusion.-Oxford Science Publications, 1975, 414 pages

Durner, W.
Hydraulic conductivity estimation for soils with heterogeneous pore structure.-Water Res. Res. 30(1994) 211-223

Elrick, D.E., Reynolds, W.D.
Infiltration from constant-head well permeameters and infiltrometers.- In. Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice.-SSSA Special Publication No. 30,1992, 1-24

Fuentes, C., Haverkamp, R., Parlange, J.-Y.
Parameter constraints on closed-form soil-water relationships.-J. Hydrology 134 (1992), 117-142

Gardner, W.R. Solution of the flow equation for the drying of soils and other porous media.- Soil Sci. Soc. Proceedings 23(1959) 183-187

Gardner, W.R.
Approximate solution of a non-steady state drainage problem.- Soil Sci. Soc. of America Proceedings 26(1962) 2, 129-132

Glugla, G., P. Jankiewicz, C. Rachimow, K.Lojek, K. Richter, G.Fürtig, P. Krahe
BAGLUVA - Wasserhaushaltsverfahren zur Berechnung vieljähriger Mittelwerte der tatsächlichen Verdunstung und des Gesamtabflusses.- Bundesanstalt für Gewässerkunde, Bfg-Bericht 1342, Koblenz 2003

Hwang, S.I., Powers, S.E. (2003)
Using particle-size distribution models to estimate soil hydraulic properties. Soil Sci. Soc. Am. J. 67, 1103–1112

Jury,W.A. ,Gardner, W.R., Gardner, W.H.
Soil Physics, JohnWiley New York 1991

Kinzelbach, W.
Groundwater modelling.- Developments in Water Science 25, Elsevier Amsterdam 1986 (223 pages)

Kroes, J.G.; van Dam, J.C.; Huygen, J.; Vervoort, R.W., 1999. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment: User's Guide of SWAP version 2. Technical Document Nr. 53 DLO Winand Staring Centre, Wageningen.

Kutilek, M., Nielsen, D.R.
Soil hydrology.- Catena Publisher Reiskirchen 1994 (370 pages)

Lapidus, L., Amundson, N.R.
The effect of longitudinal diffusion in ion exchange and chromatographic columns.- Journal Phys. Chem. 56 (1952) 984-988

Lomen, D.O.,Warrick, A.W.
Linearized moisture flow with loss at the soil surface.- SoilScience Soc. of America Journal 42 (1978) 396-399

Luckner, L., van Genuchten,M.Th., Nielsen, D.R.
A consistent set of parametric models for the two-phase flow of immiscible fluids in the subsurface
Water Resources Research 25(1989) 10, 2187-2193

K. Miegel, K. Bohne, and G. Wessolek
Prediction of long-term groundwater recharge by using hydropedotransfer functions
Int. Agrophys., 2013, 27, doi: 10.2478/v10247-012-0013-y

Nemes, A., Schaap, M.G., Wösten, J.H.M. (2001)
Description of the unsaturated soil hydraulic database UNSODA version 2.0. J. Hydrology (Amsterdam) 251, 151–162

Nielsen, D.R., Wendroth, O.
Spatial and temporal statistics – Sampling field soils and their vegetation.- Catena Publilsher Reiskirchen 2003, 398 pages

Nimmo, J.R., Herkelrath, W.N., Laguna Luna, A.M.
Physically based estimation of soil water retention from textural data.- Vadose Zone Journal 6: 766-773 (2007)

Pachepsky, Y., Rawls, W.J. (ed.)
Development of pedotransfer functions in soil hydrology.- Developments in Soil Science Vol. 30, Elsevier Publishing San Diego, CA 2004

Peters, A., Durner, W.
A simple model for describing hydraulic conductivity in unsaturated porous media accounting for film and capillary flow.- Water Res. Res. 44(2008) doi:10.1029/2008/WR007136

Philip, J.R.
The infiltration joining problem Water Resour.Res. 23 (1987) 12, 2239 – 2245

Priesack, E., Durner, W.
Closed form expression for the multi-modal unsaturated conductivity function.- Vadose Zone Journal 5(2006), 121-124

Renger, M., Bohne, K., Facklam, M., Harrach, T., Riek, W., Schäfer, W., Wessolek, G., Zacharias, S.
Ergebnisse und Vorschläge der DBG-Arbeitsgruppe "Kennwerte des Bodengefüges" zur Schätzung bodenphysikalischer Kennwerte.- In: Bodenökologie und Bodengenese, Heft 40, Selbstverlag TU Berlin, 2009

Schaap, M.G., Leij, F.J., van Genuchten, M.Th.
ROSETTA: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions
Journal of Hydrology 251:163-176 (2001)

Schaap, M.G.,van Genuchten, M.Th.
A modified Mualem-vanGenuchten formulation for improved description of the hydraulic conductivity near saturation.- Vadose Zone Journal 5(2006) 27-34

Skaggs, R.W.
Drainage simulation models. Seite 469-500
In: Agriculrural Drainage, Ed.: R.W.Skaggs, J.v. Schilfgaarde.- Soil Science Soc. of America, Agronomy series, Nr. 38, Madison 1999, 1328 Seiten

Sisson, J.B.,Ferguson, A.H.,v.Genuchten, M.TH.
Simple method for predicting drainage from field plots.-Soil Science Society of Am. Journal 44(1980) 1147-1152

Smedema, L.K., Vllotman, W.F., Rycroft, D.W.
Modern land drainage.- AA Balkema Publishers, Leiden 2004

Smettem, K.R.J.,Parlange, J.Y., Ross, P.J.,Haverkamp, R.Three-dimensional analysis of infiltration from the disc infiltrometer 1.A capillary-based theory.-Water Res. Research 30 (1994) 11, 2925-2929

Storchenegger, I., Bohne, B.
A new solution to non-steady drain discharge.- 21st European Regional ICID Conference 2005, Frankfurt/Oder, Slubice/Poland

Taffa Tulu
Hydrologic data analysis and water harvesting structures.- Shaker Publishing Aachen/Germany, 2009

Toride, N., Leij, F.J., van Genuchten, M.Th.
The CXTFIT code for estimating transport parameters from laboratory or field tracer experiments.- Research Report 137 (1995) U.S. Salinity Laboratory, USDA, Riverside, CA

Van der Ploeg, R.R., Kirkham, R.H. Kirkham, D.
Steady flow to drains and wells.- S. 213-263
In: Agriculrural Drainage, Ed.: R.W.Skaggs, J.v. Schilfgaarde.- Soil Science Soc. of America, Agronomy series, Nr. 38, Madison 1999, 1328 Seiten

Van Genuchten, M. Th. (1980)
A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898

Warrick, A.W., Amoozegar-Fard, A., Loman, D.O.
Linearized moisture flow from line sources with water extraction.- Transactions of the ASAE 1979, 549-553

White, I., Sully, M.J., Perroux, K.M.
Measurement of surface-soil hydraulic properties: Disk permeameters, tension infiltrometers and other techniques.- In. Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice.-SSSA Special Publication No. 30,1992, 69-104

Wessolek, G., Bohne, K., Trinks, S.
Hydro-pedotransfer functions to predict annual capillary rise and actual evapotranspiration.- Journal of Hydrology, (2010) submitted

Widmoser, P.
Be- und Entwässerung. In: Taschenbuch der Wasserwirtschaft, Hrsg. K. Lecher, H.-P. Lühr, W.C.E.Zanke
Parey Buchverlag Berlin 2010

Zacharias, S., Wessolek, G.
Excluding organic matter contentfrom pedotransfer predictors of soil water retention.-Soil Sci. Soc. of Am. Journal71: 43-50 (2008)