INFILTRATION AND PONDING

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Summary

The original model of Green and Ampt is used as a basic tool to obtain quantitative understanding of infiltration and associated soil properties. Indeed, their result is a limiting case of any description of soil-water behavior.

At the next level of approximation, most soils can be adequately described by interpolating between two limiting behaviors, one being the Green and Ampt soil, the other being that of a Gardner soil. For the latter, soil profiles do not have to be discontinuous as in the original Green and Ampt model. Also, the time condensation approximation appears as an exact result for this case.

Finally, a third level of approximation gives further corrections leading to better descriptions of soil-water profiles and ponding times that can be used to assess the errors of the time condensation approximation.

1. Introduction

Accurate description of infiltration and post-ponding runoff remains a fundamental problem in hydrology. Water added to an unsaturated soil will be absorbed until it ponds at the surface. The prediction of ponding time is especially crucial as the time condensation approximation (TCA) remains a widespread practical tool. Recall that the TCA basically assumes that at ponding there is a unique relationship between the cumulative infiltration and the flux, independent of previous history. In order to estimate the portion of precipitation that enters the soil and that which becomes overland flow, calculations require estimates of ponding time as the first step. Subsequently, infiltration after ponding is a key quantity that needs to be quantified. It is often handled by empirical results that must be used carefully as their application cannot be universal depending as they do on local conditions.

The Green and Ampt (1911) model is the earliest physically based conceptual infiltration model and to this day can be considered as having played a fundamental role in the description of infiltration. Although it possesses well known shortcomings, these can be redressed and incorporated into new models, which remain both physically based and usable in practice. Existing models have been reviewed extensively in recent times; see, for example, Haverkamp et al. (1988), Parlange and Haverkamp (1989), Clausnitzer et al. (1998), Skula et al. (2003) and Mishra et al. (2003).

Besides the Green and Ampt model, the main models that have been reviewed include those of Kostiakov (1932), Mezencev (1948), Philip (1957; 1969), Talsma and Parlange (1972), Schwarzendruber (1974), Smith and Parlange (1978), Parlange et al. (1982) and Parlange et al. (1985). Based on these and similar papers, general conclusions can be drawn. For any particular case, empirical and physically based models can be of comparable precision. Not surprisingly, the Green and Ampt model has been one of the most used and widely studied. It is amenable to practical applications, and by extension one can deduce that it has a theoretical basis that captures behavior of soil water movement.

However, there is little doubt that its practical value is limited by its rather drastic physical assumptions. Apart from its simplicity, its great importance is that all physically based models must reduce to it when the same physical assumptions are made. Consequently, it is a valid limiting case that cannot be ignored.

In the next sections, we shall look again at the Green and Ampt model in detail and extensions that improve its theoretical and practical value. One of its key simplifications is the assumption of a sharp infiltrating front, i.e., of piston flow. We shall relax this constraint using the standard model of flow in unsaturated soil due to Richards (1931). In particular, we show that by writing Richards' equation in integral form, it can be solved with approximate analytical techniques, subsequently giving rise to physically based infiltration equations.

Exact solutions of Richards' equation are not of primary interest here, except when they directly affect the discussion. This is not to minimize their importance; on the contrary, exact solutions have been crucial both to test numerical schemes and as a guide to obtain approximate solutions. A sample of exact solutions can be found elsewhere (e.g., Parlange and Braddock, 1980; Parlange et al., 1980a; Clothier et al., 1981; Rogers, 1983; Broadbridge and White, 1987, 1988; Sander et al., 1988a; Barry and Sander, 1991; Barry et al., 2002). Our focus is also limited to the archetypal case of one-dimensional flow in a semi-infinite medium, with the soil surface at $z = 0$ (z positive downwards) and uniform initial water content (which can always be taken as zero by taking the excess water as the variable). Also, we consider only capillarity and gravity, these being the two main forces affecting infiltration and redistribution of water in the soil profile. Other forces can be very important in specific cases. Amongst other processes one can mention there are (i) the effects of air movement and entrapment (Sander et al., 1988b,c; Culligan et al., 2000; Hammecker et al., 2003), (ii) soil layering and surface sealing (Parlange et al., 1984; Römkens et al., 1986; Baumhardt et al., 1990, 1991; Vandervaere et al., 1998; Corradini et al., 2000; Assouline, 2004;), (iii) flow instability (Hill and Parlange, 1972; Philip, 1972; Raats, 1973; Parlange and Hill, 1976; Baker and Hillel, 1990; Selker et al., 1992) and its relationship to water repellency (Bond, 1964; Bauters et al., 1998; Bauters et al., 2000; DiCarlo et al., 2000) and (iv) hysteresis (Liu et al., 1995; DiCarlo et al., 1999). Several fundamental studies of hysteresis which are relevant here can also be mentioned (e.g., Parlange, 1976; Hogarth et al., 1988; Viaene et al., 1994; Si and Kachanoski, 2000; Braddock et al., 2001).

2. The Green and Ampt (1911) Model

Despite being published nearly 100 years ago, this model remains, from a theoretical point of view, the most basic of physically based infiltration models. As it can be manipulated relatively easily it is, in spite of its physical limitations, still widely used in practice. The practical TCA method can be justified using the Green and Ampt model, following the fundamental paper of Mein and Larson (1973), see also Poulovassilis et al. (1991), Liu et al. (1998) and Brutsaert (2005). This feature has made it even more attractive as a practical hydrological tool.

Mathematical properties of the Green and Ampt solution, for instance its description as a branch of the Lambert W-function and its relationship as a solution of Richards' equation have been demonstrated (Barry et al., 1993, 2005; Parlange et al., 2002). However, its practical use requires the determination of physical parameters. These are curve-fitted in most cases to infiltration and soil data and therefore tend to apply primarily for the conditions of the fitting, e.g., see Aggelides and Youngs (1978), McCuen et al. (1981) and Rawls et al. (1983).

The original Green and Ampt solution has also proved to be quite flexible in field applications when other processes have additionally to be considered: solute transport, non-aqueous flow, overland flow and the possibility of erosion, presence of a water table, spatial variability, layered and crusted soils, initial water content and structure varying with depth, air entrapment (e.g., see Thooyamani and Norum, 1987; Charbeneau and Asgian, 1991; Huang and van Genuchten, 1995; Kao and Hunt, 1996; Chu, 1997; Yu et al., 1997; Vandervaere et al., 1998; Selker et al., 1999; Wang et al., 1999; Fiedler and Ramirez, 2000; Govindaraju et al., 2001; Hammecker et al., 2003; Nahar et al., 2004). Note that, although the model has been applied to redistribution it has some difficulty in integrating hysteresis effects (Ogden and Saghafian, 1997; Nielsen and Perrochet, 2000).

2.1. Derivation

Consideration of Darcy’s law for piston flow in a soil yields (e.g., Neuman, 1976):

$$q = K_\mathrm{s}\left(H_\mathrm{s} + I/\theta_\mathrm{s} - H_\mathrm{f}\right)\theta_\mathrm{s}/I\,, \qquad (1)$$

where q [L T^{-1}] is the Darcy flux, K_s [L T^{-1}] the surface (here saturated) conductivity, H_s [L] the ponded water thickness, θ_s the surface water content (here saturated and measured relative to the constant initial water content), I [L] is the cumulative infiltration and H_f [L] is the negative pressure at the wetting front. In addition to piston flow, Eq. (1) assumes that the soil-water conductivity K [L T^{-1}] is independent of the soil water pressure. As we shall see later, this last assumption is the main reason for the difficulties associated with Eq. (1). In the limit of small time, $t \to 0$, $I \to 0$ and $q \to \infty$; Eq. (1) then shows that:

$$Iq \to K_\mathrm{s}\theta_\mathrm{s}\left(H_s - H_\mathrm{f}\right). \qquad (2)$$

This quantity can be associated to the sorptivity S [L T$^{-1/2}$] (Parlange, 1975; Neuman, 1976) by

$$S^2 = 2K_\mathrm{s}\theta_\mathrm{s}\left(H_\mathrm{s} - H_\mathrm{f}\right), \qquad (3)$$

thus relating H_f to a physical parameter S, with $I \to S\sqrt{t}$ and $2q \to S/\sqrt{t}$ for short times. Physically, S quantifies the capillary forces affecting water movement in the soil; these forces of course are affected by the soil’s moisture status and surface boundary condition. Equation (3) not only shows the relation between H_f and S, but also predicts the dependence of S on H_s, whereby increasing H_s increases the rate at which water initially enters the soil, as would be expected intuitively. Indeed, this prediction, noted explicitly by Green and Ampt (1911), is extremely accurate as shown by more detailed analyses (Parlange et al., 1988, 1992; Broadbridge, 1990). In the particular case when H_s is constant, Eq. (1) is integrable since $q \equiv dI/dt$, giving

$$K_\text{s}t = I - (S^2/2K_\text{s})\ln\left(1 + 2IK_\text{s}/S^2\right). \tag{4}$$

The short time expansion of Eq. (4) is,

$$I = S\sqrt{t} + \frac{2}{3}K_\text{s}t + \ldots \tag{5}$$

The second term $2K_\text{s}t/3$ in Eq. (5) is a consequence of assuming that K is independent of soil-water pressure. Gardner (1958) postulated a very different behavior to be discussed in the following. It leads, even for a piston flow, to an infiltration law (Talsma and Parlange, 1972) where the second term in the short time expansion is $K_\text{s}t/3$ instead of $2K_\text{s}t/3$. This result is also consistent with the measurements of Talsma (1969). In spite of this fundamental difficulty, the success of the Green and Ampt model in field applications can be partially attributed to the large scatter of field observations. Agreement between the Green and Ampt model predictions and observations can also be artificially improved by using varying properties (Ahuja and Tsuji, 1976; Haverkamp et al., 1988).

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Bibliography

Aggelides, S. and Youngs, E.G., 1978. Dependence of parameters in Green and Ampt infiltration equation on initial water content in draining and wetting states. Water Resources Research, 14(5): 857-862. [Linking Green and Ampt parameters to physical measurements]

Ahuja, L.R. and Tsuji, G.Y., 1976. Use of Green-Ampt equation with variable conductivity. Soil Science Society of America Journal, 40(4): 619-622. [Extension of Green and Ampt]

Argyrokastritis, I. and Kerkides, P., 2003. A note to the variable sorptivity infiltration equation. Water Resources Management, 17(2): 133-145. [Infiltration with curve fitted sorptivity]

Assouline, S., 2004. Rainfall-induced soil surface sealing: A critical review of observations, conceptual models, and solutions. Vadose Zone Journal, 3(2): 570-591. [Processes and modeling of soil sealing]

Baker, R.S. and Hillel, D., 1990. Laboratory tests of a theory of fingering during infiltration into layered soils. Soil Science Society of America Journal, 54(1): 20-30. [Experiments illustrating the concept of flow instability]

Barry, D.A., Parlange, J.-Y., Sivapalan, M. and Sander, G. C., 1993. A class of exact solutions for Richards' equation. Journal of Hydrology, 142(1-4): 29-46. [Shows Green-Ampt solution can be generalized to soils where the sharp front assumption does not apply]

Barry, D.A., Parlange, J.-Y., Haverkamp, R. and Ross, P.J., 1995. Infiltration under ponded conditions. 4. An explicit predictive infiltration formula. Soil Science, 160(1): 8-17. [Implicit formula in earlier paper is made explicit]

Barry, D.A., Parlange, J.-Y., Li, L., Jeng, D.-S. and Crapper, M., 2005. Green-Ampt approximations. Advances in Water Resources, 28(10): 1003-1009. [Simple yet highly accurate Green-Ampt analytical approximations]

Barry, D.A., Parlange, J.-Y., Lisle, I.G., Li, L., Jeng, D.-S., F. Stagnitti, F. and Sander, G.C., 2002. Scope for further analytical solutions for constant-flux infiltration into a semi-infinite soil profile or redistribution in a finite soil profile. Water Resources Research, 38(12), 1265, DOI: 10.1029/2001WR000611. [Explores the potential for new solutions to Richards' equation]

Barry, D.A. and Sander, G.C., 1991. Exact solutions for water infiltration with an arbitrary surface flux or nonlinear solute adsorption. Water Resources Research, 27(10): 2667-2680. [Solutions for time-dependent surface condition in semi-infinite domain]

Baumhardt, R.L., Römkens, M.J.M., Parlange, J.-Y. and Whisler, F.D., 1991. Predicting soil-surface seal conductance from incipient ponding and infiltration data. Journal of Hydrology, 128(1-4): 277-291. [Relations of infiltration and ponding to surface sealing]

Baumhardt, R.L., Römkens, M.J.M., Whisler, F.D. and Parlange, J.-Y., 1990. Modeling infiltration into a sealing soil. Water Resources Research, 26(10): 2497-2505. [Physical modeling of infiltration and surface sealing]

Bauters, T.W.J., DiCarlo, D.A., Steenhuis, T.S. and Parlange, J.-Y., 1998. Preferential flow in water-repellent sands. Soil Science Society of America Journal, 62(5): 1185-1190. [Influence of water repellency on finger formation]

Bauters, T.W.J., Steenhuis, T.S., DiCarlo, D.A., Nieber, J.L., Dekker, L.W., Ritsema, C.J., Parlange, J.-Y. and Haverkamp, R., 2000. Physics of water repellent soils. Journal of Hydrology, 231-232: 233-243. [Soil water properties of water repellent soils and implication for flow instability]

Bond, R.D., 1964. The influence of the microflora on physical properties of soils II. Field studies on water repellent sands. Australian Journal of Soil Research, 2(1): 123-131. [Early field observations of flow patterns linked to fingering]

Boulier, J.F., Parlange, J.-Y., Vauclin, M., Lockington, D.A. and Haverkamp, R., 1987. Upper and lower bounds of the ponding time for near constant surface flux. Soil Science Society of America Journal, 51(6): 1424-1428. [Discussion of integral inequalities]

Braddock, R.D., Parlange, J.-Y. and Lee, H., 2001. Application of a soil water hysteresis model to simple water retention curves. Transport in Porous Media, 44(3): 407-420. [Analytical application of a model of hysteresis]

Broadbridge, P., 1990. Solution of a nonlinear absorption model of mixed saturated-unsaturated flow. Water Resources Research, 26(10): 2435-2443. [Exact results for a special soil type very useful for testing generalized approximations]

Broadbridge, P. and White, I., 1987. Time to ponding – Comparison of analytic, quasi-analytic and approximate predictions. Water Resources Research, 23(12): 2302-2310. [Comparisons that demonstrate utility of time-to-ponding approaches]

Broadbridge, P. and White, I., 1988. Constant rate rainfall infiltration – A versatile nonlinear model. 1. Analytic solution. Water Resources Research, 24(1): 145-154. [Exact results for a special soil type]

Brutsaert, W., 1968. Adaptability of an exact solution to horizontal infiltration. Water Resources Research, 4(4): 785-789. [Discussion of a fundamental exact solution of the non-linear diffusion equation]

Brutsaert, W., 1976. The concise formulation of diffusive sorption of water in a dry soil. Water Resources Research, 12(6): 1118-1124. [Mathematical description of nonlinear diffusion in a soil]

Brutsaert, W., 2005. Hydrology – An Introduction. Cambridge University Press. [Modern, quantitative hydrology]

Charbeneau, R.J. and Asgian, R.G., 1991. Simulation of the transient soil-water content profile for a homogeneous bare soil. Water Resources Research, 27(6): 1271-1279. [Successful application of Green and Ampt]

Chu, S.T., 1997. Infiltration model for soil profiles with a water table. Transactions of the ASAE, 40(4): 1041-1046. [Extension of Green and Ampt for nonuniform initial water content]

Clausnitzer, V., Hopmans, J.W. and Starr, J.L., 1998. Parameter uncertainty analysis of common infiltration models. Soil Science Society of America Journal, 62(6): 1477-1487. [A comparison of existing infiltration equations]

Clothier, B.E., Knight, J.H. and White, I., 1981. Burgers' equation: Application to field constant-flux infiltration. Soil Science, 132(4): 255-261. [Investigation of a simple yet nonlinear model for infiltration]

Corradini, C., Melone, F. and Smith, R.E., 2000. Modeling local infiltration for a two-layered soil under complex rainfall patterns. Journal of Hydrology, 237(1-2): 58-73. [Water flow in an inhomogeneous soil with arbitrary boundary conditions]

Culligan, P.J., Barry, D.A., Parlange, J.-Y., Steenhuis, T.S. and Haverkamp, R., 2000. Infiltration with controlled air escape. Water Resources Research, 36(3): 781-785. [Novel method for determining soil properties based on air pressure changes in the soil]

DiCarlo, D.A., Bauters, T.W.J., Darnault, C.J.G., Steenhuis, T.S. and Parlange, J.-Y., 1999. Lateral expansion of preferential flow paths in sands. Water Resources Research, 35(2): 427-434. [Influence of hysteresis to maintain column flow]

DiCarlo, D.A., Bauters, T.W.J., Darnault, C.J.G., Wong, E., Bierck, B.R., Steenhuis, T.S. and Parlange, J.-Y., 2000. Surfactant-induced changes in gravity fingering of water through a light oil. Journal of Contaminant Hydrology, 41(3-4): 317-334. [Influence of water repellency on flow instability]

Elrick, D.E. and Robin, M.J., 1981. Estimating sorptivity of soils. Soil Science, 132(2): 127-133. [Review of sorptivity estimates]

Fiedler, F.R. and Ramirez, J.A., 2000. A numerical method for simulating discontinuous shallow flow over an infiltrating surface. International Journal for Numerical Methods in Fluids, 32(2): 219-240. [A successful application of Green and Ampt]

Fleming, J.F., Parlange, J.-Y. and Hogarth, W.L., 1984. Scaling of flux and water content relations - Comparison of optimal and exact results. Soil Science, 137(6): 464-468. [Similarity solutions]

Gardner, W.R., 1958. Some steady state solutions of unsaturated moisture flow equation with application to evaporation from a water table. Soil Science, 85(4): 228-232. [Introduces Gardner's fundamental law on soil properties]

Govindaraju, R.S., Morbidelli, R. and Corradini, C., 2001. Areal infiltration modeling over soils with spatially correlated hydraulic conductivities. Journal of Hydrologic Engineering, 6(2): 150-158. [A successful application of Green and Ampt]

Green, W.A. and Ampt, G.A., 1911. Studies on soils physics: 1. The flow of air and water through soils. Journal of Agricultural Science, 4(1): 1-24. [Very simple yet versatile model of infiltration]

Hammecker, C., Antonino, A.C.D., Maeght, J.L. and Boivin, P., 2003. Experimental and numerical study of water flow in soil under irrigation in northern Senegal: Evidence of air entrapment. European Journal of Soil Science, 54(3): 491-503. [Extension of Green and Ampt with air compression]

Haverkamp, R., Kutilek, M., Parlange, J.-Y., Rendon, L. and Krejca, M., 1988. Infiltration under ponded conditions. 2. Infiltration equations tested for parameter time-dependence and predictive use. Soil Science, 145(5): 317-329. [Comparison of the validity of general infiltration equations]

Haverkamp, R., Parlange, J.-Y., Starr, J.L., Schmitz, G. and Fuentes, C., 1990. Infiltration under ponded conditions. 3. A predictive equation based on physical parameters. Soil Science, 149(5): 292-300. [Accurate infiltration equation]

Heaslet, M.A. and Alksne, A., 1961. Diffusion from a fixed surface with a concentration-dependent coefficient. Journal of the Society for Industrial and Applied Mathematics, 9(4): 584-596. [Fundamental expansion solution for a power law diffusivity]

Hill, D.E. and Parlange, J.-Y., 1972. Wetting front instability in layered soils. Soil Science Society of America Proceedings, 36(5): 697-702. [First laboratory experiment for column flow]

Hogarth, W.L., Hopmans, J., Parlange, J.-Y. and Haverkamp, R., 1988. Application of a simple soil-water hysteresis model. Journal of Hydrology, 98(1-2): 21-29. [Hysteresis model based on simplification of the independent domain theory]

Hogarth, W.L., Parlange, J.-Y. and Braddock, R.D., 1989. First integrals of the infiltration equation. 2. Nonlinear conductivity. Soil Science, 148(3): 165-171. [Similarity solutions]

Hogarth, W.L., Sardana, V., Watson, K.K., Sander, G.C., Parlange, J.-Y., Haverkamp, R., 1991. Testing of approximate expressions for soil water status at the surface during infiltration. Water Resources Research, 27(8): 1957-1961. [Comparison of infiltration equations]

Huang, K. and van Genuchten, M.Th., 1995. An analytical solution for predicting solute transport during ponded infiltration. Soil Science, 159(4): 217-223. [Solute transport with Green and Ampt water movement]

Kao, C.S. and Hunt, J.R., 1996. Prediction of wetting front movement during one-dimensional infiltration into soils. Water Resources Research, 32(1): 55-64. [A successful application of Green and Ampt]

Kostiakov, A.N., 1932. On the dynamics of the coefficient of water percolation in soils and on the necessity of studying it from a dynamic point of view for purposes of amelioration. Transactions of the Sixth Commission of the International Society of Soil Science, Part A (Moscow): 17-21. [Widely used yet fully empirical model]

Kunze, R.J. and Nielsen, D.R., 1982. Finite-difference solutions of the infiltration equation. Soil Science, 134(2): 81-88. [Infiltration equation based on truncated time expansion]

Liu, M.-C., Parlange, J.-Y., Sivapalan, M. and Brutsaert, W., 1998. A note on the time compression approximation. Water Resources Research, 34(12): 3683-3686. [Introduction of the modified TCA technique]

Liu, Y.P., Parlange, J.-Y., Steenhuis, T.S. and Haverkamp, R., 1995. A soil-water hysteresis model for fingered flow data. Water Resources Research, 31(9): 2263-2266. [Direct measurement of scanning curves from fingering]

Lockington, D., Parslow, J. and Parlange, J.-Y. 1988. Integral estimates of the sorptivity. Soil Science Society of America Journal, 52(4): 903-908. [Application of the double integral technique]

McCuen, R.H., Rawls, W.J. and Brakensiek, D.L., 1981. Statistical analysis of the Brooks-Corey and the Green-Ampt parameters across soil textures. Water Resources Research, 17(4): 1005-1013. [Linking model parameters to physical measurements]

Mein, R.G. and Larson, C.L., 1973. Modeling infiltration during a steady rain. Water Resources Research, 9(2): 384-394. [A fundamental study based on Green and Ampt]

Mezencev, V.J., 1948. Theory of formation of the surface runoff (in Russian). Meteorologia i gidrologia, 3: 33-40. [Early model of infiltration]

Milly, P.C.D., 1985. Stability of the Green-Ampt profile in a delta function soil. Water Resources Research, 21(3): 399-402. [Theoretical description of Green and Ampt properties]

Mishra, S.K., Tyagi, J.V. and Singh, V.P., 2003. Comparison of infiltration models. Hydrological Processes, 17(13): 2629-2652. [Thorough comparison of 14 infiltration models]

Nahar, N., Govindaraju, R.S., Corradini, C. and Morbidelli, R., 2004. Role of run-on for describing field-scale infiltration and overland flow over spatially variable soils. Journal of Hydrology, 286(1-4): 36-51. [A successful application of Green and Ampt]

Neuman, S.P., 1976. Wetting front pressure head in infiltration model of Green and Ampt. Water Resources Research, 12(3): 564-566. [Green and Ampt and sorptivity]

Nielsen, P. and Perrochet, P., 2000. Watertable dynamics under capillary fringes: Experiments and modelling. Advances in Water Resources, 23(5): 503-515. [Needs hysteresis which preludes the use of Green and Ampt]

Ogden, F.L. and Saghafian, B., 1997. Green and Ampt infiltration with redistribution. Journal of Irrigation and Drainage Engineering-ASCE, 123(5): 386-393. [Extension of the Green-Ampt model]

Parlange, J.-Y., 1971. Theory of water-movement in soils. 2. One-dimensional infiltration. Soil Science, 111(3): 170-174. [Early integral description of infiltration]

Parlange, J.-Y., 1972. Theory of water movement in soils. 8. One-dimensional infiltration with constant flux at surface. Soil Science, 114(1): 1-4. [Early integral description of infiltration for a flux boundary condition]

Parlange, J.-Y., 1975. Solving flow equation in unsaturated soils by optimization - Horizontal infiltration. Soil Science Society of America Journal, 39(3): 415-418. [Introduction of the double integral technique]

Parlange, J.-Y., 1976. Capillary hysteresis and the relationship between drying and wetting curves. Water Resources Research, 12(2): 224-228. [A simple application of the independent domain methods]

Parlange, J.-Y., Barry, D.A. and Haverkamp, R., 2002. Explicit infiltration equations and the Lambert W-function. Advances in Water Resources, 25(8-12): 1119-1124. [Examines Green-Ampt model making use of Lambert’s function]

Parlange, J.-Y., Barry, D.A., Parlange, M.B. and Haverkamp, R., 1992. Note on the sorptivity for mixed saturated-unsaturated flow. Water Resources Research, 28(9): 2529-2531. [Theory taking into account ponded conditions at the surface]

Parlange, J.-Y., Barry, D.A., Parlange, M.B., Lockington, D.A. and Haverkamp, R., 1994. Sorptivity calculation for arbitrary diffusivity. Transport in Porous Media, 15(3): 197-208. [Highly accurate sorptivity approximation]

Parlange, J.-Y., Barry, D.A., Parlange, M.B., Hogarth, W.L., Haverkamp, R., Ross, P.J., Ling, L., Steenhuis, T.S., 1997. New approximate analytical technique to solve Richards equation for arbitrary surface boundary conditions. Water Resources Research, 33(4): 903-906. [Extension of the Heaslet-Alksne method to nonlinear diffusion with gravity]

Parlange, J.-Y. and Braddock, R.D., 1980. A note on some similarity solutions of the diffusion equation. Zeitschrift Fur Angewandte Mathematik Und Physik, 31(5): 653-656. [A review of similarity results]

Parlange, J.-Y., Braddock, R.D. and Chu, B.T., 1980a. First integrals of the diffusion equation: An extension of the Fujita solutions. Soil Science Society of America Journal, 44(5): 908-911. [First integrals for a power law diffusivity]

Parlange, J.-Y., Braddock, R.D. and Lisle, I.G., 1980b. Third-order integral relation between sorptivity and soil water diffusivity using Brutsaert’s technique. Soil Science Society of America Journal, 44(5): 889-891. [Further improvements on sorptivity estimates]

Parlange, J.-Y. and Haverkamp, R., 1989. Infiltration and ponding time. In: H. Morel-Seytoux (Editor), Unsaturated flow in Hydrological Modeling. Kluwer, Dordrecht, pp. 103-134. [A review of infiltration and ponding]

Parlange, J.-Y., Haverkamp, R., Rose, C.W. and Phillips, I., 1988. Sorptivity and conductivity measurement. Soil Science, 145(5): 385-388. [Application of the falling head technique]

Parlange, J.-Y., Haverkamp, R. and Touma, J., 1985. Infiltration under ponded conditions. 1. Optimal analytical solution and comparison with experimental observations. Soil Science, 139(4): 305-311. [Application of the double integral technique for ponded conditions]

Parlange, J.-Y., Haverkamp, R., Rand, R.H., Rendon, L., Schmitz, G.H., 1987. Water movement in soils. The role of analytical solutions. Soil Science Society of America, Future Developments in Soil Science Research: 11-21. [Paper discussing the proper use of analytical results]

Parlange, J.-Y. and Hill, D.E., 1976. Theoretical analysis of wetting front instability in soils. Soil Science, 122(4): 236-239. [Physically based theory of instability]

Parlange, J.-Y., Hogarth, W., Ross, P., Parlange, M.B., Sivapalan, M., Sander, G.C. and Liu, M.-C., 2000. A note on the error analysis of time compression approximations. Water Resources Research, 36(8):

2401-2406. [A discussion of TCA]

Parlange, J.-Y., Hogarth, W.L., Barry, D.A., Parlange, M.B., Haverkamp, R., Ross, P.J., Steenhuis, T.S., DiCarlo, D.A. and Katul, G., 1999a. Analytical approximation to the solutions of Richards' equation with applications to infiltration, ponding, and time compression approximation. Advances in Water Resources, 23(2): 189-194. [Further development of Heaslet-Alksne method considering gravity and with analysis of the TCA]

Parlange, J.-Y., Hogarth, W.L. and Parlange, M.B., 1984. Optimal analysis of the effect of a surface crust. Soil Science Society of America Journal, 48(3): 494-497. [Including a surface crust in the double integral model of infiltration]

Parlange, J.-Y., Hogarth, W.L., Parlange, M.B., Haverkamp, R., Barry, D.A., Ross, P.J. and T.S. Steenhuis, T.S., 1998. Approximate analytical solution of the nonlinear diffusion equation for arbitrary boundary conditions. Transport in Porous Media, 30(1): 45-55. [Further development of Heaslet-Alksne method without gravity]

Parlange, J.-Y., Lisle, I. and Braddock, R.D., 1982. The three-parameter infiltration equation. Soil Science, 133(6): 337-341. [Interpolation between the Talsma-Parlange and Green-Ampt infiltration models]

Parlange, J.-Y. and Smith, R.E., 1976. Ponding time for variable rainfall rates. Canadian Journal of Soil Science, 56(2): 121-123. [Versatile yet simple ponding time relationship]

Parlange, J.-Y., Steenhuis, T.S., Haverkamp, R., Barry, D.A., Culligan, P.J., Hogarth, W.L., Parlange, M.B., Ross, P. and Stagnitti, F., 1999b. Soil properties and water movement. In: Oxford University Press (Editors M.B. Parlange and J.W. Hopmans), Vadose zone hydrology: Cutting across disciplines, New York, pp. 99-129. [Review of modeling and prediction of water flow in soil from micro- to macro-scales]

Parslow, J., Lockington, D. and Parlange, J.-Y. 1988. A new perturbation expansion for horizontal infiltration and sorptivity estimates. Transport in Porous Media, 3(2): 133-144. [Sorptivity estimates for complex diffusivity functions]

Perroux, K.M., Smiles, D.E., and White, I., 1981. Water movement in uniform soils during constant-flux infiltration. Soil Science, 45(2): 237-240. [Integral relation for constant flux]

Philip, J.R., 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. Soil Science, 84(3): 257-264. [An early mathematical approach to infiltration]

Philip, J.R., 1969. Theory of infiltration. Advances in Hydrosciences, 5: 215-296. [Review of mathematical modeling of infiltration]

Philip, J.R., 1972. Future problems of soil-water research. Soil Science, 113(4): 294-300. [Contains an interesting discussion of instability effects]

Poulovassilis, A., Kerkides, P., Elmaloglou, S. and Argyrokastritis, I., 1991. An investigation of the relationship between ponded and constant flux rainfall infiltration. Water Resources Research, 27(7): 1403-1409. [Extension of Green and Ampt]

Raats, P.A.C., 1973. Unstable wetting fronts in uniform and nonuniform soils. Soil Science Society of America Journal, 37(5): 681-685. [A general discussion of instability]

Rawls, W.J., Brakensiek, D.L. and Miller, N., 1983. Green-Ampt infiltration parameters from soils data. Journal of Hydraulic Engineering-ASCE 109(1): 62-70. [Using Green and Ampt for real soils]

Reichardt, K., Nielsen, D.R. and Biggar, J.W., 1972. Scaling of horizontal infiltration into homogeneous soils. Soil Science Society of America Proceedings, 36(2): 241-245. [Discussion of the generality of an exponential diffusivity]

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. Physics, 1(5): 318-333. [Governing equation for unsaturated flow]

Rogers, C., Stallybrass, M.P. and Clements, D.L., 1983. On two phase flow filtration under gravity and with boundary infiltration: Application of a Bäcklund transformation. Nonlinear Analysis, Theory, Methods and Applications, 7(7): 785-799. [Exact analytical solution for two-phase flow for specific class of soils]

Römkens, M.J.M., Baumhardt, R.L., Parlange, M.B., Whisler, F.D., Parlange, J.-Y. and Prasad, S.N. 1986.

Rain-induced surface seals - Their effect on ponding and infiltration. Annales Geophysicae Series B-Terrestrial and Planetary Physics, 4(4): 417-424. [Experimental and theoretical results on the effects of surface seals]

Ross, P.J. and Parlange, J.-Y., 1994. Comparing exact and numerical solutions of Richards equation for one-dimensional infiltration and drainage. Soil Science, 157(6): 341-344. [Application of traveling wave solutions]

Salvucci, G.D. and Entekhabi, D., 1994. Explicit expressions for Green-Ampt (delta-function diffusivity) infiltration rate and cumulative storage. Water Resources Research, 30(9): 2661-2663. [Approximations for Green-Ampt infiltration]

Sander, G.C., Parlange, J.-Y., Kühnel, V., Hogarth, W.L., Lockington, D. and O'Kane, J.P.J., 1988a. Exact nonlinear solution for constant flux infiltration. Journal of Hydrology, 97(3-4): 341-346. [Exact solution based on Bäcklund transformation]

Sander, G.C., Parlange, J.-Y. and Hogarth, W.L., 1988b. Air and water flow, part 1, horizontal flow with an arbitrary flux boundary condition. Journal of Hydrology, 99(3-4): 215-223. [Extension of the double integral technique to include air movement]

Sander, G.C., Parlange, J.-Y. and Hogarth, W.L., 1988c. Air and water flow, part 2, gravitational flow with an arbitrary flux boundary condition. Journal of Hydrology, 99(3-4): 225-234. [Double integral techniques including air movement with gravity]

Schwartzendruber, D., 1974. Infiltration of constant flux rainfall into soil as analyzed by the approach of Green and Ampt. Soil Science, 117(5): 272-281. [Early model of infiltration]

Selker, J., Parlange, J.-Y. and Steenhuis, T., 1992. Fingered flow in two dimensions. 2. Predicting finger moisture profile. Water Resources Research, 28(9): 2523-2528. [Theoretical and experimental results of the structure of finger profiles]

Selker, J.S., Duan, J.F. and Parlange, J.-Y., 1999. Green and Ampt infiltration into soils of variable pore size with depth. Water Resources Research, 35(5): 1685-1688. [Looking at infiltration in inhomogeneous soils]

Si, B.C. and Kachanoski, R.G., 2000. Unified solution for infiltration and drainage with hysteresis: Theory and field test. Soil Science Society of America Journal, 64(1): 30-36. [Showing that hysteresis is more important for drainage]

Sivapalan, M, and Milly, P.C.D., 1989. On the relationship between the time condensation approximation and the flux concentration relation. Journal of Hydrology, 105(3-4): 357-367. [Relation between TCA and the double integral prediction of infiltration]

Skukla, M.K., Lal, R. and Unkefer, P., 2003. Experimental evaluation of infiltration models for different land use and soil management systems. Soil Science, 168(3): 178-191. [Comparison of some infiltration models]

Smith, R.E. and Parlange, J.-Y., 1977. Optimal prediction of ponding. Transactions of the ASAE, 20(3): 493-496. [Optimized ponding formula]

Smith, R.E. and Parlange, J.-Y., 1978. Parameter-efficient hydrologic infiltration model. Water Resources Research, 14(3): 533-538. [Simplest application of double integral results for infiltration]

Talsma, T., 1969. Infiltration from semi-circular furrows in the field. Australian Journal of Soil Research, 7(3): 277-84. [Short time measurements of infiltration]

Talsma, T. and Parlange, J.-Y., 1972. One-dimensional vertical infiltration. Australian Journal of Soil Research, 10(2): 143-150. [Limiting infiltration formula that is opposite extreme to that of Green and Ampt]

Thooyamani, K.P. and Norum, D.I., 1987. Explicit infiltration equations based on the Green-Ampt model. Canadian Journal of Civil Engineering, 14(5): 710-713. [Extension of Green and Ampt]

Vandervaere, J.-P., Vauclin, M., Haverkamp, R., Peugeot, C., Thony, J.-L. and Gilfedder, M., 1998. Prediction of crust-induced surface runoff with disc infiltrometer data. Soil Science, 163(1): 9-21. [Extension of Green and Ampt]

Viaene, P., Vereecken, H., Diels, J. and Feyen, J., 1994. A statistical analysis of six hysteresis models for the moisture retention characteristic. Soil Science, 157(6): 345-355. [Thorough review of hysteresis models]

Wang, Q.J., Shao, M.G. and Horton, R., 1999. Modified Green and Ampt models for layered soil infiltration and muddy water infiltration. Soil Science, 164(7): 445-453. [Extension of Green and Ampt results]

Yu, B., Rose, C.W., Coughlan, K.J. and Fentie, B., 1997. Plot-scale rainfall-runoff characteristics and modeling at six sites in Australia and Southeast Asia. Transactions of the ASAE, 40(5): 1295-1303. [Experiments showing the limitations of Green and Ampt results]

Biographical Sketches

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David Lockington, is the Head of Environmental Engineering in the School of Engineering, as well as the Director of the Centre for Water Studies, at the University of Queensland, Australia. He is also the Director of the Engineering, Technology and Design Research Program in the national Cooperative Research Centre for Sustainable Tourism. His research interests center on modeling fluid flow in unsaturated porous media, variable density groundwater flow and contaminant transport. A particular interest is the use of these models in quantifying coastal catchment processes such as: subsurface estuary dynamics; submarine groundwater discharge; tidal marsh, wetlands and island hydrology; and seawater intrusion. He is a member of the editorial board of Advances in Water Resources and is a Fellow of the Institute of Mathematics and its Applications.

Frank Stagnitti, a mathematician, soil physicist and environmental scientist, is an expert in the study of agricultural and hydrological systems, particularly in the fields of solute and contaminant transport, bioremediation and ecotoxicology, groundwater flow, coastal processes and wetlands technology. Dr Stagnitti has established an international research profile in the field of environmental systems modeling. In the last five years, he has published in excess of 50 manuscripts in international, high-impact journals and invited to present keynote addresses at conferences in Europe, USA and Asia. He has attracted significant research funding within Australia, mainly through the Australian Research Council and has participated in a number of international projects, mainly funded by the EU under the 5th and 6th Framework programs. Dr. Stagnitti is a member of several scientific advisory committees and boards including the Australian Research Council, Center of Excellence in Light Metals and the Victorian Partnership in Advanced Computing. He currently holds the position of Associate Dean Research for the Faculty of Science and Technology at Deakin University and is a full Professor and Chair in Aquatic Science in the School of Life and Environmental Science. Dr Stagnitti is a Fellow of Australian Mathematics Society, a Fellow of Institute of Mathematics and its Applications (UK), a member of American Mathematics Society, a Chartered Mathematician and a Chartered Scientist registered in the UK.

Shmuel Assouline, is a senior research scientist at the Agricultural Research Organisation (Volcani Center) of Israel. His research includes flow and transport processes in porous media. He is also involved in projects dealing with new irrigation practices and technologies and soil and water conservation methods. Dr. Assouline has authored and co-authored about 60 refereed publications. He is Associate Editor of Vadose Zone Journal.

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R. Haverkamp, is “Directeur de Recherche” at CNRS (French National Research Center) and works at the research laboratory LTHE in Grenoble, France. His research is focused on flow processes in the vadose zone with a particular interest on the scaling of these flow processes. His work involves field and theoretical work including large scale watershed modeling. As is clear from his numerous co-authored publications, most of his research is carried out in close collaboration with colleagues from various international research laboratories. He has been involved in national and international projects in many parts of the world. He initiated a spin-off computer software company working on hydroinformatics.

Bill Hogarth, is Pro Vice Chancellor Teaching and Learning and Head of the Faculty of Science and Information Technology at the University of Newcastle, Australia. He was previously Dean of the Faculty of Environmental Sciences at Griffith University, Australia. His teaching and research interests are in environmental modeling with a strong emphasis on the numerical aspects. The particular focus of his research has been on soil processes concentrating on soil infiltration, soil erosion and more recently wind erosion.