Hydraulic loading capacity for groundwater recharge sites

Capacité de chargement hydraulique pour sites de recharge de la nappe phréatique

S.L.Houston, W.N.Houston, C.E.Zapata & M.J.Johnson – *Arizona State University, Tempe, AZ, USA*

ABSTRACT: Treated wastewater has gained acceptance as an augmentation to existing water supplies. Soil aquifer treatment systems, wherein the groundwater is recharged with pretreated wastewater effluent have been developed. The studies described herein address aspects of the hydraulics of infiltration for groundwater recharge. The quality of unsaturated flow simulations was found to be highly dependent upon the soil-water characteristic curve (SWCC) and the unsaturated conductivity relationship. The degree of accuracy with which the SWCC can be ascertained was studied, indicating use of a large database in conjunction with a knowledge-based system as the best way to select the optimal SWCC for a given soil. A new predictive SWCC model was developed. Data from recharge column studies show the effect of surface clogging and scarification on hydraulic loading. Low conductivity components of the underlying formation can impact the rate of recharge from surface basins.

RÉSUMÉ: Les eaux usées retraitées deviennent acceptables en tant que complément des ressources en eau existantes. Des systèmes de traitement des aquifères souterrains ont été développés, consistant à recharger la nappe phréatique avec des effluents d'eaux usées pré-traités. Les recherches présentées ici traitent des aspects hydrauliques de l'infiltration pour la recharge de la nappe phréatique. Il a été trouvé que la qualité des simulations du flux insaturé est hautement dépendante de la courbe caractéristique sol-eau (SWCC) et la fonction décrivant la conductivité à l'état insaturé. Le degré d'exactitude auquel la courbe SWCC peut être déterminée a été étudié, indiquant que l'utilisation conjointe d'une importante base de données et d'un système basé sur la connaissance, est le meilleur moyen de sélectionner la courbe SWCC optimale pour un sol donné. Un nouveau modèle de prédiction SWCC a été développé. Les données provenant d'études de recharge de colonne montrent l'effet du colmatage et de la scarification de surface sur le chargement hydraulique. Des composants de basse conductivité dans les formations souterraines peuvent affecter le taux de recharge depuis les bassins de surface.

1 OVERVIEW OF WATER REUSE AND GROUNDWATER RECHARGE STUDIES

Countries with Western European or North American standards of living require more than 2000 cubic meters of water per person per year (Bouwer 1997). Groundwater is vulnerable to overdraft and depletion, especially in arid to semi-arid regions where natural rates of recharge are low. In arid, water-limited regions treated wastewater has gained acceptance as water supply, and as an augmentation to the more conventional surface and groundwater supplies. Infiltration land treatment systems, wherein the groundwater is recharged with pretreated wastewater effluent have been developed. This process is referred to as soil aquifer treatment (SAT). SAT operations and extensive research studies have been conducted for over 20 years in Los Angeles County, California, where no measurable impact on groundwater quality or human health has been found (Nellor, et al. 1984).

A variety of treatment processes are operating as the wastewater flows downward through the vadose zone to the underlying aquifer. Surface infiltration basins are supplied water for several days, followed by several days of basin drying. The cyclic wetting and drying of the basin is necessary to improve infiltration rates and to control aerobic/anoxic conditions in the soil. During wetting, the water percolates through an unsaturated soil region to the groundwater table for storage in an unconfined aquifer system. The physical and chemical processes include filtration, adsorption, ion exchange, precipitation, and biological degradation. These processes can be effective in removal of nitrogen, phosphorus, biochemical oxygen demand (BOD), suspended solids, organics, and trace metals. In general, the removal of nitrogen and organics is a renewable process as biodegradation is involved. Certain mechanisms such as adsorption, however, are not generally considered to be sustainable.

The feasibility of an artificial recharge project is strongly tied to the hydraulic loading capacity. The hydraulic loading capacity is determined by the intake capacity at the soil-water interface, the conveyance capacity of the unsaturated zone, and the transmission capacity of the recharging aquifer. Any one of these may act as the hydraulic control on recharge. Field observations indicate that the hydraulics of water recharge basins are affected by many factors, including soil type, subsurface nonhomogeneity, the formation of a surface clogging layer, application times for wetting/drying cycles, water quality, and climatic conditions. The studies described herein address aspects of the hydraulics of infiltration for groundwater recharge with treated waste effluent. Specifically, the importance of the soil water characteristic curve in unsaturated flow modeling and the role of the surface clogging on the hydraulic loading capacity are analyzed and discussed. Additionally, a case study at the Mesa, Arizona, recharge facility is presented which emphasizes the importance of soil profile characteristics on loading rates. It should be noted that the overall research team for the SAT and recharge studies is highly multidisciplinary, including geotechnical, water resources, and environmental engineers and microbiologists, and reports are available that describe other aspects of the water reuse studies conducted at Arizona State University including bio-geochemical treatment processes (Arizona State University et al. 1998).

2 IMPORTANCE OF THE SOIL WATER CHARACTERISTIC CURVE IN UNSATURATED FLOW PREDICTIONS

Infiltration associated with soil aquifer treatment and groundwater recharge systems is a subset of the complex problem of unsaturated flow. Infiltration is the term applied to the process of water entry into unsaturated soils. Unsaturated flow through soils is generally difficult to model quantitatively due to the nonlinearity of the process, associated with the fact that the flow properties and the gradient for flow are a function of the changing soil water content (soil suction). In spite of the difficulties, engineers and scientists have developed numerous computer codes for estimating unsaturated flow. These codes utilize the Richards' equation as a constitutive model which invokes a form of Darcy's law, and require information on the variation of the unsaturated hydraulic conductivity of the soil with soil suction and the variation of the soil suction with soil water content.

Following a common procedure, saturated conductivity would be measured for the soils, as well as suction versus water content points on the soil moisture characteristic curves. Then a curve fit could be used to extrapolate the soil water characteristic curve using the process described by van Genuchten (1980), for example. Finally, a function that related unsaturated conductivity to soil suction or soil water content is adopted.

In the SAT/recharge studies, the quality of the unsaturated flow simulation was found to be highly dependent upon the specific soil water characteristic curve (SWCC) and the unsaturated hydraulic conductivity relationship, as would be expected. Unsaturated flow computer codes generally require input of the SWCC and the unsaturated conductivity function for soils in the profile. The van Genuchten/Mualem formulation below is commonly used for estimating unsaturated conductivity (van Genuchten 1980):

$$\Theta_e = \frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1+(\alpha h)^n}\right]^m \quad (1)$$

$$K_r = \frac{K}{K_s} = \Theta_e^{\frac{1}{2}}\left[1-(1-\Theta_e^{\frac{1}{m}})^m\right]^2 \quad (2)$$

where Θ_e = effective water content; θ_w = volumetric water content; θ_s and θ_r are saturated and residual water content, respectively; h = pressure head (suction positive); the parameters α, m and n are often obtained using curve-fitting techniques (note: typically $m=1-1/n$); and K_s = saturated hydraulic conductivity.

Clearly the SWCC, which relates the soil water content to the matric suction, is an important aspect of unsaturated flow modeling and unsaturated conductivity determination. Therefore, our ability to obtain accurate SWCCs was studied in connection with modeling recharge operations. In performance of the variability studies, it was deemed necessary to fit the suction data with a continuous function. Based on previous studies (e.g. Leong & Rahardjo 1996), several commonly adopted equations were chosen to fit the SWCC function. The equations included Fredlund and Xing (Fredlund & Xing 1994), van Genuchten (van Genuchten 1980), van Genuchten and Mualem (van Genuchten 1980), van Genuchten and Burdine (van Genuchten 1980), Gardner (Gardner 1958), and Brooks and Corey (Brooks & Corey 1964). The Fredlund and Xing SWCC equation reads as follows:

$$\theta_w = C(u_a - u_w) \times \frac{\theta_s}{\left[\ln\left[\exp(1) + \left(\frac{u_a - u_w}{a}\right)^b\right]\right]^c} \quad (3)$$

where:

$$C(u_a - u_w) = \left[1 - \frac{\ln\left(1 + \frac{u_a - u_w}{h_r}\right)}{\ln\left(1 + \frac{10^6}{h_r}\right)}\right] \quad (4)$$

a, b, c, h_r = fitting parameters; and $u_a - u_w$ = soil matric suction (pore air pressure minus pore water pressure).

3 STUDIES ON UNCERTAINTY ASSOCIATED WITH SWCC DETERMINATION

Despite the well-recognized importance of soil suction, it is not routinely measured in geotechnical laboratories or in the field. An investigation of practice throughout the United States showed that less than 20% of commercial geotechnical laboratories performed suction measurements on a regular basis (Zapata et al. 2000). The degree of accuracy with which the SWCC can be ascertained was studied using various procedures. To quantify the variability associated with the determination of the SWCC, it is necessary to also quantify the uncertainty associated with direct suction measurements.

Variability should be expected when direct measurement of matric suction is used to define the SWCC because it is very difficult to measure suction with precision. Several factors may contribute to this variability, including: (1) The equation used to fit the experimental data, (2) The operators' ability and experience, (3) The number of data points used to define the SWCC, (4) The range in suction covered by the actual measurements, (5) The method used to acquire matric suction data.

An iteration process that minimized the sum of the squared residuals (SS_E) was performed to fit the experimental data. Once the best-estimate SWCC was found for each soil, its 95% confidence band (95% c.b.) was determined. The confidence band is associated with the fitting process and represents the uncertainty in the fitting parameters of the equations used to represent the data. Mishra et al. (1989) provides details of the procedure for finding the confidence band for the response function at any abscissa.

The best-estimate SWCCs and their confidence bands were determined on three test soils: a sand, a silt, and a clay. The equation proposed by Fredlund and Xing was found to best fit the data for the sand, while the van Genuchten equation was found to be the best fit to the experimental data for the silt and the clay, although the Fredlund and Xing equation was a fairly close second.

In practice, an engineer is unlikely to examine many different equations to fit experimental suction data to a SWCC. Therefore, it may be useful to know what error can be expected from choosing a single equation that may not give the *best* fit to the data for a given soil. For this purpose, the equations previously discussed were fitted to the data obtained for the three soils. To quantify the variability around the best estimate value, the predicted volumetric water contents obtained by each equation were compared with the ordinates from the best-fit equation, at each level of suction. The variability was computed as follows:

$$\%\ \text{Variability} = \frac{\left|\hat{\theta}_i - \bar{\theta}_i\right|}{\theta_s} \times 100\% \quad (5)$$

where:

$\hat{\theta}_i$ = predicted volumetric water content at *i* suction level, for the equation being tested; and $\bar{\theta}_i$ = best estimate volumetric water content at *i* suction level, from the best fit equation.

To evaluate the magnitude of the variability, the 95% confidence band for the best-estimate SWCC was plotted for comparative purposes. Results showed that the variability from the use of different equations generally falls below the 95% confidence band, indicating that the equation selected introduces less variability than other factors.

The variability in the SWCC due to different operators was also analyzed by fitting a SWCC to each set of data collected from 14 different laboratories. Each of these SWCCs was then compared to the best-fit equation for each soil (i.e. Fredlund and Xing for the sand, van Genuchten for the silt and the clay). The results for the silt are depicted in Figure 1, after excluding outliers and laboratories reporting less than 3 data points. Notice that the variability exceeds that for the 95% confidence band for many of the laboratories.

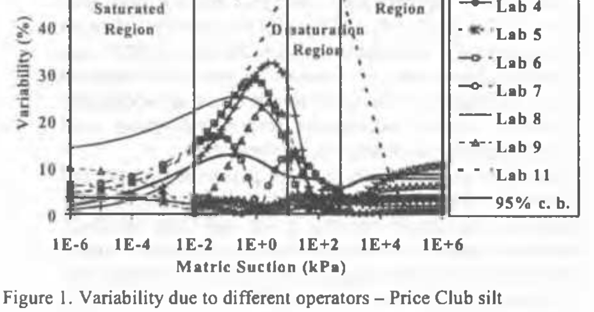

Figure 1. Variability due to different operators – Price Club silt

Variability in the SWCC when predicted from soil index properties was also studied. Several reported models used to predict the SWCC from the grain-size distribution and soil index properties were reviewed, and the variability associated with the different models was found to be small compared to direct suction measurement errors.

The high variability encountered in the experimentally obtained suction measurements and the numerous sources of error in the measured values lead to the conclusion that even some of the most experienced researchers have difficulties in getting a unique SWCC for a soil. It is likely that this problem can be addressed by using a large database in conjunction with a knowledge-based system for achieving the best fit and selecting the optimal SWCC for a given soil.

A new predictive model was developed at Arizona State University. This new model is based on statistical correlations of very simple and easy to measure soil index properties with the fitting parameters of the SWCC function proposed by Fredlund and Xing, equation 3. A database characterizing approximately 190 soils was assembled from research papers and a knowledge-based program developed by Soilvision Systems Ltd (Escario & Juca 1989; Fredlund et al. 1995; Houston et al. 1999; Livneh et al. 1970; Marinho & Stuermer 1998: Rahardjo et al. 1995; SoilVision 1997, among others). The soils were divided into two categories: soils having a Plasticity Index (PI) greater than zero and soils having a PI equal to zero. Data for approximately 70 soils with PI greater than zero and 120 soils with PI equal to zero were collected. The resulting SWCC relationships are provided in Figure 2.

The SWCC (for example, from Fig. 2) is used as input to unsaturated flow computer codes. Often the unsaturated conductivity function required by these codes is determined from the SWCC function using equations such as equation 2.

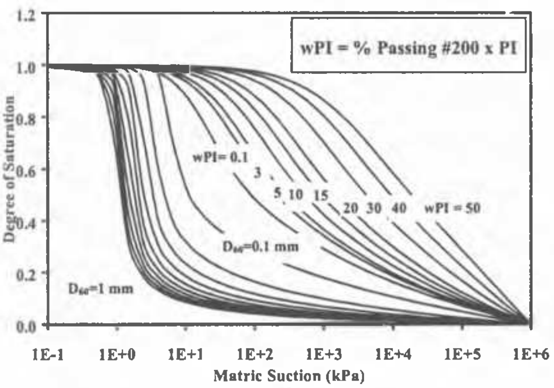

Figure 2. Predicted SWCC based on D_{60} and wPI.

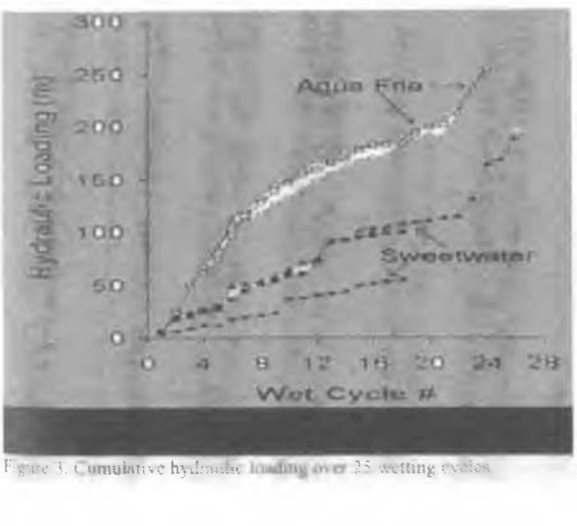

Figure 3. Cumulative hydraulic loading over 25 wetting cycles.

4 LIMITING FACTORS FOR HYDRAULIC LOADING CAPACITY

Infiltration rates from surface basins are most rapid during the early stages of the wetting cycle when negative pore water pressures are relatively high. Infiltration rates gradually decline toward a rate corresponding to the saturated hydraulic conductivity and unit gradient. However, over time the surface of the basin will clog as a result of sedimentation of fines and organic matter and growth of algae, often resulting in a substantial decrease in overall hydraulic loading capacity of the basin. Figure 3 shows the effect of surface clogging for recharge column studies conducted on two granular soils. The increased rate of infiltration shown at approximately 20 cycles of wetting with waste effluent resulted from scarification of the surface of the columns. In addition to the impedance that can occur as a result of surface clogging, subsurface soil layering may also impede the amount of recharge that can be sustained at a site, particularly when lenses of clay are present.

5 UNSATURATED FLOW MODELING FOR GROUNDWATER RECHARGE PROJECTS

In modeling recharge operations it is necessary to identify the materials, properties, and boundary conditions for the site. For SAT problems, it is particularly important to recognize components of the profile that impact the rate of recharge from the surface basins. As a sample of unsaturated/saturated flow modeling for SAT, a recharge site in Mesa, Arizona, will be discussed.

The City of Mesa, Arizona operates the Northwest Water Reclamation Plant (NWWRP) and recharge facility. The NWWRP recharge facility, operational since 1990, consists of four recharge basins with area totaling approximately 27 acres. The design capacity of the NWWRP site was 8 million gallons per day (MGD) based on recharge rates measured at other sites along the ephemeral Salt River. The volume of water recharged has averaged less than one-half of the design capacity (i.e. about 3.5 MGD). Previous studies have concluded that the site is underlain by a geologically heterogeneous alluvial formation with a higher fraction of fine-grained material than has been generally observed at other areas immediately adjacent to the Salt River channel.

Research has been conducted for the purpose of studying the hydraulics of groundwater flow beneath the spreading basins. Possible remedial activities to increase the hydraulic loading capacity will be studied and recommendations will be made regarding possible methods of hydraulic improvement.

The conceptual model is the first and most important step in obtaining meaningful results from numerical modeling of groundwater flow, especially so for formations exhibiting significant material heterogeneity. The conceptual model for the NWWRP recharge facility has been constructed based on information collected from varied sources. These sources include 'hard data', such as observational field data, material properties derived from laboratory and field testing, and soil borings as well as 'soft data', such as geological interpretation and computer-aided interpolation. The graphical software package GMS v2.1 (Owen et al. 1996) developed by researchers at the Engineering Computer Graphics Laboratory at Brigham Young University was used to organize, perform operations on, and visualize the collected data.

The flow modeling will be performed using FEMWATER (Lin et al. 1997) a three-dimensional finite element model for variably saturated single-phase flow through porous media. The high degree of nonlinearity involved in the solution of the unsaturated flow equation requires fine spatial and temporal discretizations. This is coupled with the general requirement of domain sizes 10 to 20 times the radius of the recharge source for accurate modeling of the aquifer response. Thus, the memory requirement for three-dimensional modeling soon exceeds the capabilities of most systems. In order to save computer resources, the technique of telescopic mesh refinement is employed. The results of a larger scale two-dimensional simulation of the impact of the NWWRP recharge facility (Schoneinz & Drewes 2000) are applied as boundary conditions.

Construction of a sound conceptual model is vital for obtaining meaningful results from a modeling effort. This is especially true when modeling flow in a geologically heterogeneous formation. For the modeling of the NWWRP recharge basins, the potential for hydraulic capacity limitation from the subsurface layering is great. In addition, surface clogging represents possible impedance to flow, and this can also be modeled in the computer code.

6 SUMMARY

The variability in the prediction of the SWCC from the use of different equations generally falls below the 95% confidence band, indicating that the equation selected introduces less variability than other factors. The variability in the SWCC due to different operators exceeds that for the 95% confidence band for many of the laboratories.

Data from lab column studies on granular soils showed a substantial decrease in hydraulic loading capacity over a period of 20 wet/dry cycles due to surface clogging. Hydraulic loading rates were observed to increase sharply upon surface scarification.

Low conductivity components of the underlying formation can impact the rate of recharge from the surface basins. Construction of a sound conceptual model is vital for obtaining meaningful numerical modeling results when modeling recharge in a geologically heterogeneous formation. Computer visualization and manipulation of three-dimensional data is necessary for construction of a sound conceptual model for flow modeling in a complex geologic formation.

7 ACKNOWLEDGEMENTS

This work was supported in part by the cities of Phoenix, Mesa, Tempe, Glendale, and Youngstown, Arizona, Tucson Water, the American Water Works Association Research Foundation (AWWARF), the Water Environmental Research Foundation (WERF), the National Water Resources Institute (NWRI), the US Environmental Protection Agency (EPA), and the Arizona Department of Water Resources (ADWR).

REFERENCES

Arizona State University, University of Arizona & University of Colorado. 1998. *Soil Treatability Pilot Studies to Design and Model Soil Aquifer Treatment Systems.* Denver, CO: AWWA Research Foundation and American Water Works Association.

Bouwer, H. 1997. Role of groundwater recharge and water reuse in integrated water management. *The Arabian Journal for Science and Engineering* 22(1C): 123-131.

Brooks R.H. & Corey, A.T. 1964. Hydraulic properties of porous media. *Hydrology Papers* 3. Fort Collins: Colorado State University.

Escario, V. and Juca, J. 1989. Strength and deformation of partly saturated soils. *Proc. of the Twelfth Intern. Conf. on Soil Mechanics and Foundation Engineering, Rio de Janeiro* 3: 43-46.

Fredlund, D.G. & Xing, A. 1994. Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal* 31(4): 521-532.

Fredlund, D.G., Vanapalli, S.K., Xing, A. & Pufalel, D.E. 1995. Predicting the shear strength function for unsaturated soils using the soil-water characteristic curve. In Alonso & Delage (eds), *Unsaturated Soils.*

Gardner, W.R. 1958. Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. *Soil Science* 85: 228-232.

Houston, W.N., Houston, S.L., Zapata, C.E., Manepally, C. & Lawrence, C. 1999. Influence of compressibility on use and interpretation of soil water characteristic curves. In *Proc. of the XI Panam. Conf on Soil Mechanics and Geotechnical Engineering, Foz do Iguassu*: 947-954.

Leong, E.C. & Rahardjo, H. 1996. A review on soil-water characteristic curve equations. *Geotechnical Research Report NTU/GT/96-5.* Singapore: Nanyang Technological University.

Lin, H.J., Richards, D.R., Talbot, C.A., Yeh, G.T., Cheng, J.R., Cheng, H.P. & Jones, N.L. 1997. FEMWATER: a three-dimensional finite element computer model for simulating density-dependent flow and transport in variably saturated media. *Technical Report CHL-97-12.* U.S. Army Engineers Waterways Experiment Station.

Livneh, M., Kinsky, J. & Zaslavsky, D. 1970. Correlation of suction curves with the plasticity index of soils. *Journal of Materials, JMLSA* 5(1): 209-220.

Marinho, F.A.M. & Stuermer, M.M.M. 1998. Aspects of the storage capacity of a compacted residual soil. In *Proc. of the Second Intern. Conf. on Unsaturated Soils. Vol. 1. Beijing, China, 27-30 Aug. 1998.*

Mishra, S., Parker, L.C. & Singhal, N. 1989. Estimation of soil hydraulic properties and their uncertainty from particle size distribution data. *Journal of Hydrology* 108: 1-18.

Nellor, M.H., Baird, R.B. & Smyth, J.R. 1984. *Health Effects Study, Final Report.* Whittier: Sanitation District of Los Angeles County.

Owen, S.J., Jones, N.L. & Holland, J.P. 1996. A comprehensive modeling environment for the simulation of groundwater flow and transport. *Engineering with Computers* 12: 235-242.

Rahardjo, H., Chang, H.M.F. & Lim, T.T. 1995. Shear strength and in situ matric suction of a residual soil. In Alonso & Delage (eds), *Unsaturated Soils*: 637-643.

Schonheinz, D. & Drewes, J.E. 2000. Groundwater flow modeling for the NWWRP Mesa. *Arizona State University, Department of Civil and Environmental Engineering Technical Report.*

SoilVision User's Guide. 1997. Version 1.2 [Computer software]. Saskatoon, Saskatchewan, Canada: SoilVision Systems, Ltd.

van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44(5): 892-898.

Zapata, C.E., Houston, W.N., Houston, S.L. & Walsh, K.D. 2000. Soil-water characteristic curve variability. In C.D. Shackelford, S.L. Houston & N.Y. Chang (eds), *Advances in Unsaturated Geotechnics, ASCE-GEO Institute Geotechnical Special Publication* 99. Also *Proceedings of Sessions of Geo-Denver 2000, Denver, CO, 5-8 August 2000.*