# INTEGRATED MANAGEMENT OF IRRIGATION AND URBAN STORMWATER INFILTRATION

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*REFERENCE: Proceedings of the 2003 Georgia Water Resources Conference*, held April 23-24, 2003, at the University of Georgia. Kathryn J. Hatcher, editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

**Abstract.** New microscale techniques have become available to assist urban designers in better water management. Urban water management has focused on two different areas: stormwater, and water supply. The focus of stormwater management is shifting towards Low-Impact Development, which emphasizes better management of urban stormwater through reductions in postdevelopment runoff by increasing onsite infiltration. Water supply planning has been enhanced by the emergence of the field of end-use demand management; the focus of much of which has been on outdoor irrigation. Implementation of these two objectives requires evaluation of processes at smaller scales in order to focus on changes being contemplated at a parcel level. A modeling approach is presented which incorporates decentralized options for management of both stormwater and urban water supply. Management options that can be evaluated with this approach include restrictive irrigation policies and rainwater harvesting. A simpler model based upon SCS (Soil Conservation Service) hydrology is then calibrated to the more complex model using a commercially available nonlinear solver. A method for calculation of costs to the consumer and evaluation of total system cost is presented.

## INTRODUCTION

Urban planning and associated water management has long focused upon centralized and separate management of stormwater, water supply, and wastewater. Unfortunately, these systems have been unable to cope with the management of diffuse, nonpoint source pollution, including stormwater. A new emphasis on sustainability in urban water management has led to a reevaluation of past urban design practices (Heaney et al. 1999). Sustainable water systems, according to Butler and Parkinson (1997) and Veldkamp et al (1997) require:

1. Minimization of the generation of wastewater.
2. Reuse of water, as close as possible to its point of origination
3. A close match between the quality of water required, and the quality of water delivered for an intended use.

$CH_2M$ Hill (2001) compares the pre- and post-development downstream hydrographs of conventional development designs with those which use Low Impact Development (LID) using the HSPF model. $CH_2M$ Hill (2001) concluded was that the LID design was more cost-effective, and better mimic pre-development conditions. Coombes et al. (2002) develop a similar set of observations in South Australia; and found that rainwater harvesting could significantly reduce both water supply costs and stormwater infrastructure costs. Both of these studies used an aggregate modeling approach, distributing the estimates to each parcel by division. Evaluating decisions being made upon a parcel by parcel basis, however, requires a more refined model.

Irrigation practices are usually only incorporated into urban runoff modeling by antecedent moisture conditions. However, in continuous modeling, soil moisture conditions should be updated constantly in order to provide an accurate depiction of infiltration and subsequent runoff. Grimmond and Oke (1986a 1986b) develop an urban water balance model that includes rainfall, runoff, infiltration, evaporation, and deterministic practices such as irrigation. They conclude that including irrigation in stormwater modeling would be a useful advance as it would assist in a more close approximation of antecedent moisture conditions. Grimmond and Oke (1986b) found that irrigation was a significant component of the urban water budget. A similar model, Aquacycle, was developed by Mitchell et al. (1997) and Mitchell (1998) which incorporates the evaluation of decentralized rainwater reuse and infiltration systems using a water budget approach. Irrigation management is also important from a nonpoint source pollution control perspective. Meeks (2002) describes a study in Irvine, California, in which landscape irrigation conservation is instituted as part of the implementation of the nonpoint source control component of a TMDL (Total Maximum Daily Load) program. This approach is based upon the institution of evapotranspiration (ET) controllers on landscape irrigation timers. Evaluation of these practices at smaller scales has been enhanced by the development of a new database as part of the American Water Works Association Residential End Use Study (Mayer et al. 1999). This study focused on identifying the end uses of water by parcel in 12 cities for 2-weeks during the peak irrigation season and 2 weeks in the nonirrigation season. Stadjuhar (1997) found that outdoor irrigation was dependent upon climatic factors, but was also highly variable and difficult to characterize. This is contrasted with indoor use in which the causes of the variability was much more easily understood (Harpring 1997)

Courtney (1997) developed an hourly water budget based simulation model that mimicked the operating policy of the U. of Colorado's automatic irrigation system. The overall imperviousness of the campus is about 60% so there is ample opportunity for infiltrating some of this stormwater runoff. The results of this study indicate that, while much of the stormwater can be infiltrated, it is unclear how much of this water will ultimately be used to satisfy ET. Integration of irrigation practices into urban stormwater modeling at small scales that would enable evaluation of different options for water supply and urban stormwater control is required to evaluate small scale urban water management decisions. An approach is presented in the following section to accomplish this objective.

## METHODOLOGY

This model makes extensive use of available Geographic Information Systems (GIS) information on a portion of a subdivision of Boulder, Colorado (see Figure 1). The block being evaluated, shown in Figure 2, is based upon a detailed breakdown of the subdivision by pervious and impervious areas in Lee and Heaney (2003). This work focuses on the rainfall-runoff response from impervious areas, primarily the Directly Connected Impervious Area (DCIA) fraction. The authors found that uncertainty in estimating this fraction, (also known as effective imperviousness) contributes heavily towards uncertainties in the peak runoff estimate. The methodology developed in this paper supports analysis directed towards the other side of the envelope, i.e., the pervious areas, and non-DCIA areas that contribute to them.

### Development of an Integrated Hydrologic Model

The approach used in the hydrologic analysis was based upon simple water budget principles. This is done by setting a control volume around the soil column, as if it was a reservoir, as shown in the following equation:

$$\Delta S = P - R + I - ET \qquad \textbf{(1)}$$

where

$\Delta S$ = the change in soil moisture storage between period $i$ and $i+1$, or $S_{i+1} - S_i$

$P$ = precipitation, mm

$R$ = runoff volume, mm

$I$ = irrigation, mm

$ET$ = evapotranspiration, mm

Soil moisture is largely governed by what infiltrates through the soil and is lost by evapotranspiration due to vegetation during the growing season. In general, the units of soil moisture are either dimensionless, or expressed in terms of millimeters of water associated with a given thickness of the soil layer. Soil moisture cannot exceed the porosity of the soil properties. A multilayered approach was developed by setting up a balance for each soil moisture layer. In times of

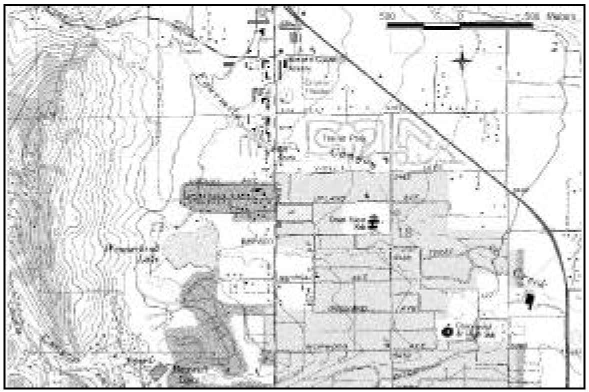

**Figure 1. Location of study area (Boulder, Colorado).**

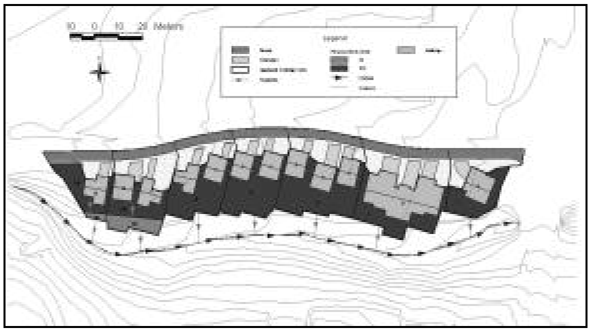

**Figure 2. Study area catchment.**

exceedance, excess soil moisture is lost to a layer below or to deep percolation. Runoff is the fraction of rainfall that does not infiltrate. The Green-Ampt method for determining infiltration was chosen because its parameters are readily available in the SCS Soil Surveys such as Moreland (1975) Parameters that govern the Green-Ampt method are the hydraulic conductivity, the soil suction head, and the difference between moisture content and porosity (Chow et al. 1988). The new ASCE standard ET procedure was used to calculate potential reference evapotranspiration (Allen 1998) Because of the relatively small size of the block, a small time step of 5 minutes was chosen for rainfall and runoff processes. Much of the activity associated with rainfall and runoff on small catchments of this size can be seen on a small time scale of this magnitude (or less). ET was based upon hourly calculations. Soil moisture was kept constant over an hourly calculation cycle as well. This is in keeping with the observations that soil moisture does not change drastically over time. The values are summed or averaged to daily values for later cost evaluation.

Runoff for each parcel is based upon the algorithms found in the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) as described in Huber et al. (1988). Pervious area effective rainfall is calculated after infiltration in the previous time step is subtracted. Runon and irrigation are added in similar to rainfall events; runoff is spread out uniformly over the surface, in the following time step. Runoff for the block is determined by routing hydrographs of each of the parcels through the drainage swale located to the south of the block. A kinematic wave approach was used to aggregate and lag the flows going from west to east.

The algorithms described here have been incorporated into a standalone Visual Basic version 6.0 program, called the Total Water Balance Model (TWBM). The model reads the database component of the ArcView version 3.2 shape files associated with the GIS, and takes user input to create new Microsoft Access database files in which components of the water budget are stored for each time step. This approach is an alternative to using arrays to key variables; and is similar to a linked list data structure. The result is a quicker and more efficient program as only the current time step and the previous time step's values are kept in storage in a single iteration. Irrigation thus becomes a design variable. By storing values in the database files they can later be retrieved and/or aggregated via Structured Query Language (SQL) statement. This allows a large degree of flexibility in terms of evaluating various water budget components.

## Development of a Simplified Continuous SCS Model

For comparative purposes, a simplified continuous runoff model based upon SCS triangular unit hydrograph theory was developed (Pilgrim and Cordery 1993), using the SCS method coupled with standard unit hydrograph convolution. According to Rawls et al. (1993), this method calculates runoff based upon two parameters, the SCS Curve Number, *CN*, and the time of concentration, $t_c$.

A spreadsheet model using Microsoft Excel and Visual Basic for Applications (VBA) was then developed which produces a continuous runoff hydrograph based upon a historical rainfall record. By changing *CN* and $t_c$. with different hydrologic conditions, it can then be adapted to different soil moisture conditions.

The SCS method has the advantage of easy adaptability to spreadsheet analysis and has been used in GIS-based hydrology (Sample et al. 2001). Another advantage of the model is the direct analogy with soil moisture storage over the watershed. Additionally, development of a calibrated SCS model, also known as a metamodel, incorporates some of the processes usually neglected in more simplified models, such as irrigation policies. The model can then be calibrated to the more complex model by changing values for *CN* and $t_c$ by setting the objective of minimizing the root mean square difference between the SCS model and the TWBM. This is a nonlinear optimization problem. For such methods, global optimality is typically not guaranteed. However, convergence to a good solution, or "near" optimal, can be made by use of a nonlinear solution algorithm from Frontline (2002). This method is based upon evolutionary, or genetic algorithms, and is packaged as an enhancement to the normal Excel Solver, Premium Solver. Upon every iteration of the optimization, the SCS model is updated, updating the objective function.

## Development of Costs

In order to evaluate different water management options, cost data are essential to determine the cost effectiveness of the different approaches. When evaluating costs at the micro level, it is essentially evaluating costs from a consumer's perspective. This viewpoint is seldom studied. Typically costs are evaluated in aggregate from as those borne by the utility in servicing customers. From a customer's point of view, the outdoor cost structure is composed of these main components:

1. water use
2. onsite water management
3. water pollution control

These components are listed in order of how important they may seem to the average consumer. Costs of water tend to be the dominant item. Costs of onsite water management may be most appropriate for homeowners who have investments in maintaining a large irrigated area. Investments made in onsite water management usually will have the impact of reducing water use costs. Costs of water pollution control are typically not borne by the average consumer except for wastewater discharges based upon indoor flow needs. Excessive outdoor use can lead to an indirect rise in what the consumer pays for water pollution control. Ideally, runoff from lawn irrigation would be charged some rate so that there would be a disincentive to produce it. The cost model includes this charge for illustrative purposes.

For costs of water use, an inclining block rate is used in many communities. Water use per month is charged according to a set amount for the first *x* liters, then at a higher rate for the next *x+a* liters, and so on. An example set of rates according to an inclining block rate is provided in Table 1.

**Table 1. Cost Structure (assumed) for Calculation of Costs of Water**

| $/k gal. | | K gal. | $/liter | | Liters |
|---|---|---|---|---|---|
| 1 | ≤ | 10 | 0.26 | ≤ | 37850 |
| 2 | ≤ | 15 | 0.53 | ≤ | 56775 |
| 3 | ≤ | 20 | 0.79 | ≤ | 75700 |
| 4 | ≤ | 50 | 1.06 | ≤ | 189250 |
| 5 | > | 50 | 1.32 | > | 189250 |

For this example approach, a simple water management device is installed on an existing automatic sprinkling system that provides an estimate of ET for the previous day, and provides water based upon 80% of that amount on the following day. This device is estimated to cost approximately $200.

Costs of water pollution control are provided for illustrative purposes, as they are based only upon outdoor irrigation runoff. A value of $0.40/liter of runoff is used.

## Discussion of Results

The block shown in Figure 2 consists of approximately 0.4 hectares, with an average slope of 4.15%, generally running downwards to the swale to the South and more gently to the East. The water budget calculated from July 1, 1999 through September 30, 1999 for Parcel #1 is provided in Figure 3. As is typical of Front Range summers, few rainfall events occur during this period; so irrigation is constant. The type of soils used on this site have very little soil moisture storage available, so soil moisture in the top layer remains relatively constant, mainly due to the constant irrigation applied. The second soil moisture layer is more variable and dependent upon infiltration. Only eight runoff events occur during this time period. One of these events was selected for calibration purposes. After optimization using the Premium Solver, the root mean square difference was 0.0614, with a *CN* value of 37 and a $t_c$ value of 0.16 hours, and the curves for each are shown in Figure 4. The fitted model falls short of the peak, and lags slightly in time, but approximates the volume reasonably well.

The costs to parcel #1 during this time period are shown in Figure 5. Water management costs are insignificant when compared with the other costs. The inclining block rate has the effect of causing the later irrigation events to be more costly, as the rate is cumulative and is based upon the total water use in the month. The consumer may respond by shifting his demand, i.e., "loading" up his irrigation in the earlier parts of the month. This is not the desired outcome of using an inclining block rate structure from the perspective of a water utility. At the rate of $0.40/liter, the runoff events result in some significant charges in terms of "spikes" to the consumer; if the consumer could actually be charged for these events. Charging for water on the front end has a similar effect, however, because of the way it is charged, i.e., block rates based on monthly use, it has limitations on how it can affect a consumer in terms of an individual irrigation event.

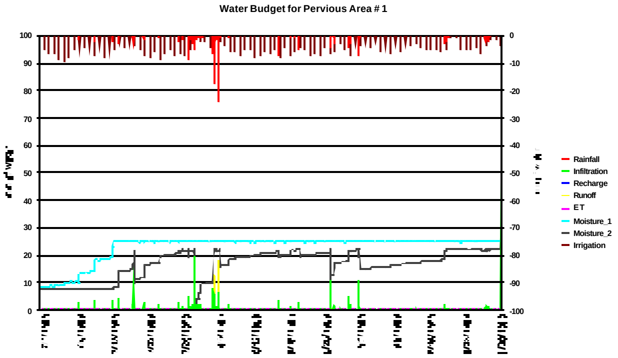

Figure 3. Urban water budget.

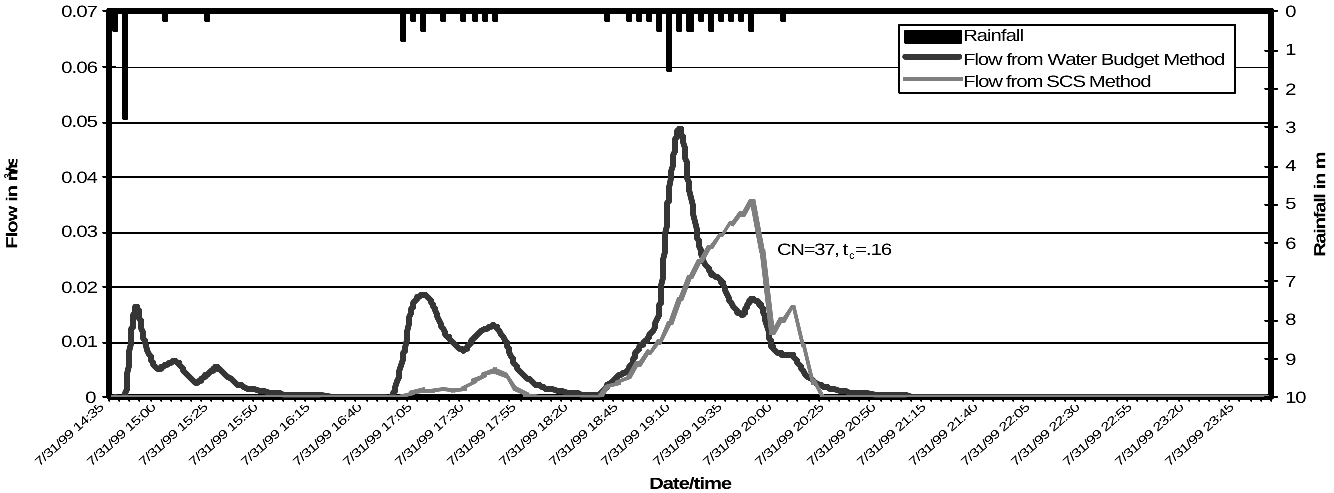

**Figure 4. Comparison of hydrograph of total water budget model and SCS model.**

## CONCLUSION

An approach has been outlined here for integrating irrigation into urban stormwater modeling. If the system being evaluated is too large to incorporate the TWBM, it could be run on selected parcels from the group, with a given irrigation management scheme, and then calibrated using the metamodel approach outlined in this paper. These selected parcels metamodels could then be aggregated into systemwide hydrologic model for the watershed that has the different irrigation management options implicitly incorporated.

Aggregating the costs for such an approach would be much easier than the hydrology, as the costs would be simple multiples of the number of lots of each type.

The methods outlined herein can be extended in the following ways:

1. Evaluation of *CN* and $t_c$ for various water management options, the effect different options may have on the various parameters.
2. Cost optimization; is rainwater harvesting cost effective? Minimize the total cost function on a single parcel, and select the least cost water management options first. Determine the most cost effective package for each lot. This may depend upon size of the lot and/or irrigation demand.
3. Include a penalty function for extended dry periods.
4. Incorporate a level of storage so that water pollution control needs can be met, i.e., runoff is minimized.

## REFERENCES

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998) Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements, United Nations Food and Agricultural Organization (FAO), Irrigation and Drainage Paper 56, Rome, Italy.

Butler, D. and Parkinson, J. (1997) Towards Sustainable Urban Drainage. *Water Sci. Technol. (G.B.)*, 35 (9): 53-63.

CH$_2$M Hill (2001) Pierce County Low Impact Development Study, Final Report, Bellevue, WA.

Chow, V.T., Maidment, D.R. and Mays, L.W. (1988) *Applied Hydrology* McGraw-Hill, New York NY.

Coombes, P.J., Kuczera, G., Kalma, J.D., and Argue, J.R. (2002) An Evaluation of the Benefits of Source Control Measures at the Regional Scale, *Urban Water* 4 (4): 307-320.

Courtney (1997) An Integrated Approach to Urban Irrigation: the Role of Shading, Scheduling, and Directly Connected Imperviousness, Master's Thesis, University of Colorado, Boulder, CO.

Frontline (2002) Premium Excel Solver User's Manual.

Grimmond and Oke (1986a) Urban Water Balance, 1. A Model for Daily Totals, *Water Resources Research*, 22 (10): 1397-1403.

Grimmond and Oke (1986b) Urban Water Balance, 2, Results from a Suburb of Vancouver, British Columbia, *Water Resources Research*, 22 (10): 1404-1412.

Harpring (1997) Nature of Indoor Residential Water Use, Master's Thesis, University of Colorado, Boulder, CO.

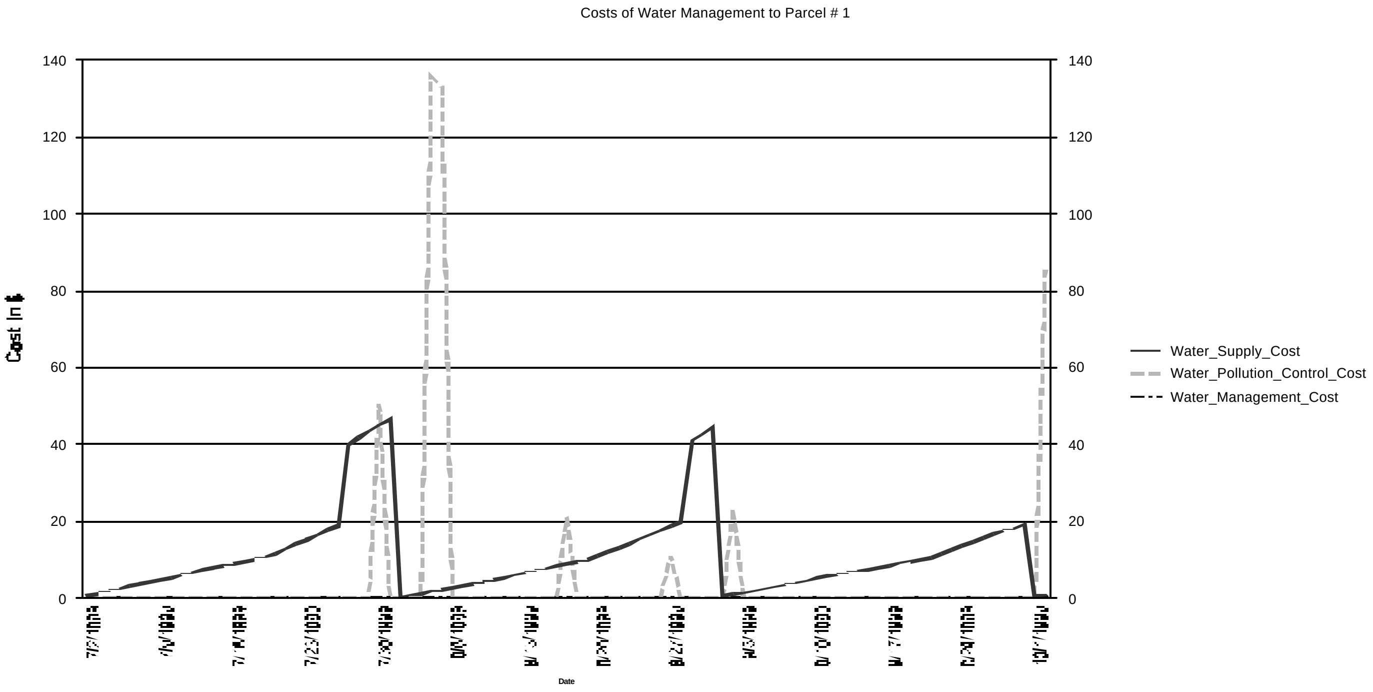

**Figure 5. Costs of Water.**

Heaney, J., Wright, L, Sample, D. (1999) Chapter 3: Sustainable Urban Water Management, in Heaney, J., Field, R., and Pitt, R. (Eds.) “Innovative Wet-Weather Flow Collection/Control/Treatment Systems For Newly Urbanizing Areas In The 21st Century”, Technomics, Lancaster, PA.

Huber, W.C., Dickinson, R.E., Roesner, L.A., and Aldrich, J.A. (1988) Stormwater Management Model User’s Manual, Version 4. EPA/600/3-88-001, U.S. EPA, Athens, GA.

Lee, J.G. and Heaney, J.P. (2003) Estimation of Urban Imperviousness and its Impacts on Stormwater Systems, accepted for publication in *Journal of Water Resources Planning and Management*.

Mayer, P.W., DeOreo, W.B., Opitz, E.M., Kiefer, J.C., Davis, W.Y., and Dziegielewski, B. (1999) Residential End Uses of Water, AWWA Research Foundation, Denver, CO.

Meeks, P. (2002) Finding Solutions to Landscape Irrigation Runoff, *Stormwater*, September/October, p. 12-21.

Mitchell, V.G. (1998) Development of an Urban Water Balance Model to Assess the Re-use Potential of Stormwater and Wastewater, Doctoral Dissertation, Monash University, Australia.

Mitchell, V.G.; Mein, R.G.; McMahon, T.A. (1998) Stormwater and Wastewater Use Within an Urban Catchment, *Int. Water Irrig. Rev.*, 18, (3): 11-15.

Moreland, D.C. (1975) Soil Survey of Boulder County Area, Colorado, Natural Resources Conservation Service (formerly SCS), Washington, DC.

Pilgrim, D.H. and Cordery, I. (1993) Flood Runoff, Chapter 9 in Maidment, D.R. (Ed.) Handbook *of Hydrology*, McGraw-Hill, New York, NY.

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., and Shirmohammadi, A. (1993) Infiltration and Soil Water Movement, Chapter 5 in Maidment, D.R. (Ed.) *Handbook of Hydrology*, McGraw-Hill, New York, NY.

Sample, D., Heaney, J., Wright, L., and Koustas, R. (2001) Geographic Information Systems, Decision Support Systems, and Urban Stormwater Management, *Journal*, *Water Resources Planning and Management*, ASCE, 127 (3): 155-161.

Stadjuhar, L. (1998) Outdoor Residential Water Use, Master’s Thesis, University of Colorado, Boulder, CO.

Veldkamp. R. G., Hermann, T., Colandini, V., Terwel, L, and Geldof, G. D. (1997) A Decision Network for Urban Water Management, *Water Sci. Technol. (G.B.),* 36: (8-9): 111-115.