Chapter 12

Towards a Shallow Groundwater Routine for Modeling Infiltration BMPs in Urban Stormwater Models

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Groundwater flow is an important component of the hydrologic cycle in urban areas. However, few urban runoff models realistically simulate shallow groundwater routing. Most are either too simplistic or too difficult to use. Objectives of this chapter are to examine the utility of shallow groundwater routing routines in SWMM4.3 (and HSPF) and to suggest an approach pertinent to infiltration best management practices (BMPs) for urban areas. A fundamental 4-unit element named JUGRND is tested, which may be suitable for building integrated dendritic surface and subsurface stormwater routing models. Conceptually, the idea is provide a basis for building a coupled model for those limited situations where groundwater routing directions are predictable and unlikely to change dynamically.

Although water is supplied to the subcatchments by infiltration, the proposed element was developed as a stand-alone program. The four fixed units in the array are: two up-gradient, an intermediate and one down-gradient subsurface subcatchment, so that the general planform promises to be useful as a building block for larger models. Current limitations include: only uni-directional down-gradient groundwater flow is allowed, groundwater flow is not allowed between the two up-gradient subcatchments, and unrestrained gravity flow of moisture from the unsaturated zone to the saturated zone is allowed as long as moisture content in the unsaturated zone is greater than field capacity.

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12.1 Introduction

Groundwater is an essential and important resource, the primary source of water for nearly 26% of all Canadians (Environment Canada, 1990). Groundwater-stormwater interaction must be properly modeled in order to make rational management decisions about infiltration BMPs (Ahmed, 1994) such as porous pavement (Shahin, 1994; Thompson, 1994; Kresin, 1996).

This study is restricted to the physical groundwater movement processes of water entering or leaving the unsaturated and shallow saturated zones of urban subcatchments. Only liquid-phase transport of water is dealt with - vapour-phase transport is excluded. Detailed descriptions of processes at or near the surface (such as capillary transport, soil moisture-plant interactions, and infiltration) are not discussed beyond the primary components of the water budget. Likewise, contaminant and chemical transport, and heat or freezing processes are not dealt with. The terms *soil-moisture* and *moisture content* are used rather than *soil-water* and *water content*, because the former terms are typically used in urban stormwater modeling.

For the subsurface routing, a fundamental tree-structure layout is used, which allows only unidirectional down gradient flow and requires a boundary condition water table elevation at the terminal subsurface subcatchment.

12.2 Background Review

In areas with permeable soil, the drainage path may be via infiltration down to the water table, whence the water moves laterally either to an adjacent subcatchment or to a channel or stream. Under certain conditions, surface runoff occurs only when the soil reaches saturation (Gagliardo and Huber, 1985). In many urban stormwater models, subsurface flow is ignored or represented as an external function that represents loss by infiltration or gain by base flow. But, in reality, groundwater discharge rates regulate the volume of water flowing from the saturated zone to the channel/stream while the rate of recharge to the shallow subsurface regime directly affects the volume of surface runoff (Environment Canada, 1990). As our understanding and modeling of stormwater runoff in urban watersheds has improved, the interaction of shallow groundwater flow with the surface flow regime has been clarified. Whipple (1991) emphatically states that although surface runoff and groundwater are separable, co-ordination between the two is essential. Freeze (1972) points out that surface runoff in base-flow-dominant channels is greatly influenced by characteristics of the subsurface regime such as the saturated and unsaturated soil properties, porosity and water table level. At any time in the year, but more specifically during dry periods, flow of some channels or streams may be entirely groundwater supported.

Effects of increased urbanization on surface stormwater runoff are well known. They have been reported by Kindler (1992), and Malmquist and Hard (1981). Kindler (1992) states that urbanization has three major impacts on water regimes:

1. less water infiltrates in urbanized areas due to increased impervious and paved roof surfaces than original surfaces; an increase in floods through larger runoff volumes is the expected result.decreased infiltration makes ground
2. water recharge smaller than prior to urbanization; base flow in urban streams and channels is reduced.
3. urban areas are sources of various types of pollutants; this usually increases the variety and loads of surface and subsurface water pollutants.

In addition, Malmquist and Hard (1981) state that, with urbanization, the average groundwater table lowers and pore pressure in the soil decreases. Consequently, damage to vegetation as well as subsidence and damage to buildings may occur in some areas.

With respect to the influence of urbanization on water temperature, it is well known that summer stream temperature increases. Anthropogenic factors such as removal of riparian vegetation, micro-climate changes, and more importantly (particularly to this study) reduction of groundwater inflow, add to watershed stream temperature increase in summer periods (MWCOG, 1990). Pluhowski (1970, cited by Xie, 1993) stated that there is a relationship between increased average urban stream temperature and groundwater inflow to the stream. As urbanization in an area increases, removal of vegetation from stream banks and storm runoff to streams also increases. In addition to this, there is a reduction in the amount of groundwater inflow to the stream (Xie, 1993). These results of urbanization, in turn, cause an increase in urban stream temperature in the summer, which may have adverse effects on aquatic ecosystems.

Surface non-point source (NPS) water pollution control preceded groundwater pollution control by many years. Due to this un-integrated approach, surface water and groundwater regimes have been handled separately in the past. Problems have arisen, such as runoff from commercial areas containing hydrocarbons reaching an aquifer which is a source of potable water. In an attempt to control such NPS pollution, a BMP involving stormwater and groundwater control should be linked to other BMPs (Whipple, 1991), in other words groundwater/surface water interactions must be studied in detail.

Infiltration basins store the incoming stormwater runoff until it gradually exfiltrates through the soil (MWCOG, 1992). Base flow can be attributed to infiltration from pervious areas of the watershed; therefore the minimum volume of water required for base flow augmentation in a BMP can be assumed to be equal to the volume of infiltration lost due to urbanization (MOE, 1991). In many countries infiltration is an essential component of stormwater management and is legislated by government. For example in the United States, in the state of Maryland, legislation was introduced in 1982 which made it mandatory to control peak discharge rate, runoff volume, water quality and subsequently, the use of infiltration practices (Shaver, 1986). Numerous benefits of infiltration practices make stormwater management processes important for maintaining pre-development runoff characteristics. Shaver (1986) further states that infiltration practices have proceeded slowly due to the following concerns:

1. polluting groundwater via entry of contaminated surface runoff,
2. clogging of infiltration facilities by sediments, and
3. difficult or neglected maintenance of the infiltration facilities.

The Maryland Department of Natural Resources recommended that infiltration of the first half inch (12 mm) of surface runoff be provided for water quality benefits. Maintaining this minimum level of infiltration significantly benefitted stream baseflow enhancement. On-site maintenance of the basins to prevent sediment clogging or sealing must be practiced (Shaver, 1986). According to a Metropolitan Washington Council of Governments document (MWCOG, 1992), when infiltration basins are implemented properly, they replicate pre-development hydrology more closely than any other BMP option.

With regard to water quality control in the infiltration process, pollutant removal is accomplished by adsorption, straining and microbial decomposition in the basin subsoil as well as trapping of particulate matter (MWCOG, 1992). In 1978, the United States Environmental Protection Agency (USEPA) initiated the Nationwide Urban Runoff Program (NURP). In response to this, a project named Fresno-NURP was conducted in Fresno, California (Nightingale, 1987). The main objective of the project was to determine the environmental impacts of the current retention practices and conservation of urban stormwater runoff by groundwater recharge (Nightingale, 1987). No significant contamination of infiltrating soil water or groundwater beneath any of the studied retention/recharge basins occurred for the contaminants studied, viz. selected trace elements (As, Cd, Cr, Cu, Fe, Pb, Hg, Ni, Zn), salinity and organics such as chlorinated pesticides, organophosphorus pesticides, chlorophenoxy herbicides, phenolic compounds, organic carbon and oil and grease (Nightingale, 1987). Diazanon was the only pesticide detected (0.3 micrograms/litre), and this in only three of the 334 subsurface water samples. These results are important to the conservation of stormwater runoff and the development of BMPs for stormwater management using retention/recharge basins (Nightingale, 1987). Nightingale suggests that groundwater contamination due to infiltration of stormwater via retention and infiltration basins is not always the end result. It should be noted that Nightingale's study was site-specific and variations between land use, soil type, runoff water quality characteristics, and groundwater flow regime were not investigated. Nonetheless, infiltration basin BMPs should be an important consideration for stormwater management. Malmquist and Hard (1981) studied the effects of stormwater infiltration on groundwater quality in three locations (residential, industrial and highway areas) in mid-western Sweden. Their studies indicated that there was no significant increase in nitrogen and phosphorous in groundwater downstream from the infiltration points. With the exception of copper, the concentration of heavy metals in the groundwater was not influenced (Malmquist and Hard, 1981). Malmquist and Hard concluded that infiltration of stormwater affects groundwater quality only to a small extent. However, Niemczynowicz (1990) cautiously stated that obvious hydrological, environmental and economic benefits which are acceptable on a short time scale of a few years, must be weighed against potential groundwater contamination risks on a longer time scale. We must be certain that infiltration of stormwater is not detrimental to the groundwater.

In this study we have proceeded on the assumption that the SWMM code is fixable. Conceptually, the SWMM configuration is simple, has high computation speed, and requires few input parameters. However, simplistic models like SWMM do not provide feedback from unsaturated zone hydraulic conductivity to surface infiltration. Many existing models, especially those especially written for groundwater simulation, do provide a more realistic coupling between surface infiltration and flow through the vadose zone. But these more complex approaches have not been considered here, because our first concern was to dovetail with existing SWMM code, rather than to rewrite the groundwater routine Unfortunately it seems unlikely that future versions of the official release will include more complex groundwater routines. So it remains a task for an enterprising, bright graduate student, and highly to be encouraged.

12.3 Review of Groundwater Routines in SWMM4.3

SWMM4.3 is a physically-based model that calculates surface runoff quantity by an iterative solution of the coupled continuity and Manning equations and uses the Green and Ampt or integrated Horton equation to handle infiltration into the subsurface. SWMM4.3 allows modeling of a large number of connected surface subcatchments. Larger catchments may be discretized and modeled sequentially using the COMBINE block, or by changing and re-compiling the source code. Surface runoff quantity modeling requires either the Horton or Green and Ampt infiltration parameters; infiltration is the only source of water into the subsurface. Subsurface quantity modeling requires parameters such as: porosity; field capacity; wilting point; hydraulic conductivity; initial water table level; evapotranspiration parameters; coefficients for groundwater outflow as a function of stage and tailwater elevation. If surface runoff is routed through the subsurface, the polluted water is modeled as if 100% removal of pollutants occurs in the subsurface (which is certainly not true in the real system).

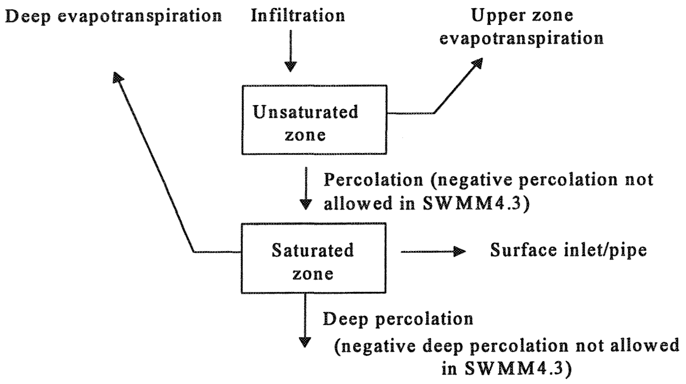

Figure 12.1 Interacting components of SWMM4.3 subsurface system.

Figure 12.1 is a schematic of the interacting components of the subsurface system. Infiltrated water may be routed through the subsurface system (quantity only) via the unsaturated storage zone and then by percolation to the saturated lower storage zone. Both of the storage zones are treated as single, spatially-averaged zones. Groundwater outflow from the saturated zone may be routed to a surface inlet or channel/pipe or is lost from the system to the deep groundwater system via deep percolation. SWMM4.3 does not allow groundwater routing between subsurface subcatchments (SS) to SS. The groundwater outflow does not have to be routed to the same channel/pipe system as the surface runoff. SWMM4.3 does not account for dry weather baseflow or interflow (lateral movement of water through the upper unsaturated soil layers).

Subsurface flow simulation strongly reflects soil properties of the SS parameters such as porosity, wilting point and field capacity are considered in the SWMM4.3 groundwater routine because they are threshold values at which point processes change in the simulation. Wilting range extends from the ultimate wilting point (lower) to the permanent wilting point (upper). Permanent wilting point is the soil moisture content at which plants no longer obtain enough moisture to meet transpiration requirements (Bedient and Huber, 1988). Field capacity is the amount of soil moisture that a well-drained soil still holds after all the free water has drained away. This occurs at soil moisture tensions of -0.1 to -0.3 atmospheres depending on soil-texture (Brady, 1990). The groundwater table is dynamic, therefore if the water table rises to the surface, the unsaturated zone disappears, infiltration ceases and excess water is calculated as surface runoff. If the groundwater table drops below the elevation of the bottom of the effluent channel/pipe, groundwater discharge stops. Groundwater discharge refers to the lateral flow of water from the saturated zone to a surface inlet/pipe.

Subroutine GROUND simulates an upper unsaturated (aeration) zone and a lower saturated zone where flow from the upper to lower zone is controlled by a percolation equation. Storms may cause a rise in the water table due to infiltration of water, and a subsequent slow release of groundwater from the saturated zone to the receiving water. By modifying infiltration parameters to account for subsurface storage, SWMM4.3 can deal with the infiltrated water. Infiltration is calculated in the subroutine WSHED. Evapotranspiration is the only loss from the upper unsaturated zone; losses from the lower saturated zone are via evapotranspiration, deep percolation and groundwater flow out of the system. Groundwater outflow from the saturated zone is positive only and can only be routed to a surface inlet. Calculation of groundwater flow is a power-function of the water table elevation and, if chosen, the depth of the water in the discharge channel. Water lost by deep percolation cannot contribute flow to the surface inlet, but is accounted for in the continuity check.

Continuity equations for each zone (saturated and unsaturated) are calculated for end-of-time stage, groundwater flow, deep percolation and upper zone moisture content. The unsaturated zone continuity equation is:

$$\begin{aligned}&\mathrm{TH2}=\\&\{[(\mathrm{ENFIL}-\mathrm{ETU})*\mathrm{PAREA}-\mathrm{PERC}]*\mathrm{DELT}+(\mathrm{D1}-\mathrm{D2})*\mathrm{TH2}+\mathrm{TH}*\mathrm{DWT1}\}/\\&(\mathrm{DTOT}-\mathrm{D2})\end{aligned}$$

Equation of continuity for the saturated zone for a rising water table is:

$$\begin{aligned}&\mathrm{D2}\ =\\&\{[\mathrm{PERC}-\mathrm{ETD}*\mathrm{PAREA}\text{-}0.5*(\mathrm{GWFLW}+\mathrm{A1}*(\mathrm{D2}\text{-}\mathrm{BC})^{\mathrm{B1}}+\mathrm{A3}*\mathrm{D2}*\mathrm{TW}\\&+\mathrm{DEPPRC}+\mathrm{DP}*\mathrm{D2}/\mathrm{DTOT})\text{-}\mathrm{TWFLW}]*\mathrm{DELT}+(\mathrm{D2}\text{-}\mathrm{D1})*(\mathrm{TH}\text{-}\mathrm{TH2})\}/\\&(\mathrm{PR}\text{-}\mathrm{TH2})+\mathrm{D1}\end{aligned}$$

and for a falling water table:

$$\begin{aligned}&\mathrm{D2}\ =\\&\{[\mathrm{PERC}-\mathrm{ETD}*\mathrm{PAREA}\text{-}0.5*(\mathrm{GWFLW}+\mathrm{A1}*(\mathrm{D2}\text{-}\mathrm{BC})^{\mathrm{B1}}+\mathrm{A3}*\mathrm{D2}*\mathrm{TW}+\\&\mathrm{DEPPRC}+\mathrm{DP}*\mathrm{D2}/\mathrm{DTOT})\text{-}\mathrm{TWFLW}]*\mathrm{DELT}\}/(\mathrm{PR}\text{-}\mathrm{TH2})+\mathrm{D1}\end{aligned}$$

where:

TH2 = end-of-time-step unsaturated zone moisture content
ENFIL = infiltration rate calculated in subroutine WSHED [m/hr]
ETU = unsaturated zone evapotranspiration rate [m/hr]
PERC = percolation rate [m/hr]
PAREA = pervious area divided by the total area
DELT = time step value set by user [hr]

D1 = beginning-of-time-step saturated zone depth [m]
D2 = end-of-time-step saturated zone depth [m]
TH = beginning-of-time-step unsaturated zone moisture content
DWT1 = beginning-of-time-step unsaturated zone depth [m]
DTOT = total depth of unsaturated and saturated zone (D1+DWT1) [m]
ETD = saturated zone evapotranspiration rate [m]
GWFLW = beginning-of-time-step groundwater flow rate [m^3/hr]
= $A1*(D1-BC)^{B1}$ -TWFLW + A3*D1*TW
A1, A2 = groundwater flow coefficient [unstated]
BC = bottom of channel elevation above datum [m]
B1, B2 = groundwater flow exponent [dimensionless]
DEPPRC = beginning-of-time-step deep percolation rate [m/hr]
DP = a recession coefficient derived from inter-event declines in the water table [m/hr]
PR = porosity
TWFLW = channel water influence rate [m^3/hr]
= $A2 * (TW-BC)^{B2}$
A3 = groundwater flow coefficient [unstated]
TW = depth of water in the channel (above datum) [m]

Conceptual problems that arise from this formulation include: the term A3*D2*TW has inconsistent units; units for A1 and A3 are unstated; and A1 is not defined relative to A3. Figure 12.2 (Huber and Dickinson, 1988) illustrates many of the above variables.

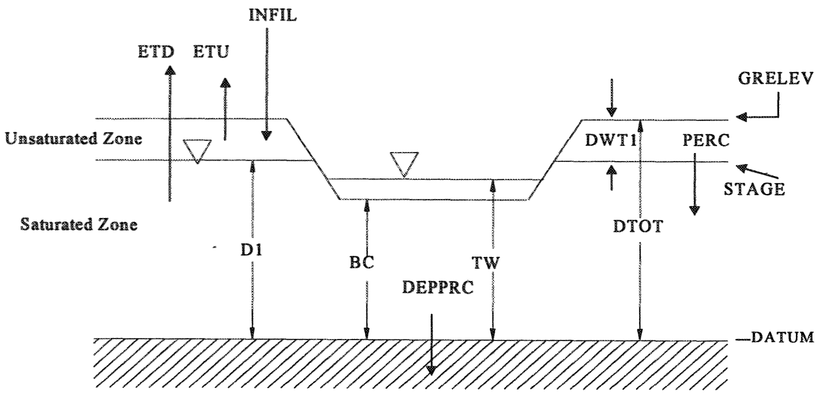

Figure 12.2 SWMM4.3 Variables in subroutine GROUND (Huber and Dickinson, 1988).

12.3.1 Processes Involved in Routing of Subsurface Flow

Infiltration

Surface infiltration is the movement of water through the soil surface into the soil profile, subject to the forces of gravity and capillarity. Infiltration rates are measured in units of volume per area-time, which reduces to length per unit time (e.g. m/hr), and are dependent on the spatial distribution of soil moisture, precipitation and permeability. Subroutine WSHED uses either the Green-Ampt or Horton equation to calculate the amount of infiltrated water input into subroutine GROUND. The Green-Ampt equation is a simple representation of infiltration under a ponded surface, with the assumptions of a homogeneous soil profile, a uniform distribution of antecedent soil moisture and that the movement of water in the soil takes the form of an advancing wetting front. Mein and Larson (1973) modified the equation to determine the time when surface ponding starts and modeled infiltration during steady rain. Chu (1978) divided infiltration into two stages: (i) a stage with surface ponding, and; (ii) a stage without surface ponding, applying the equation to determine the time that separates these two stages so that the infiltration for each stage can be treated separately. Thus he was able to model infiltration during unsteady rainfall events. When the water table approaches the surface, the end-of-time-step moisture content (TH2) approaches the porosity thus making the denominator of the continuity equations for saturated flow approach zero. This, in turn, produces anomalous values for the end-of-time-step saturated zone depth (D2), a situation that must be treated carefully. When the amount of infiltration is approximately equal to the amount of available infiltration capacity, four assumptions are made:

- End-of-time-step groundwater flow and deep percolation (which are normally found by iteration) are assumed to be equal to their respective beginning-of-time-step values to ensure that the final volume available for storage remains in the 0-0.0001 ft. range.
- TH2 is set to 90% of porosity in order to force the denominator to be non-zero.
- D2 is set close to the end-of-time-step saturated zone depth.
- Amount of infiltration that causes the final available volume of storage to exceed 0.0001 ft. is calculated and is sent back to the surface in the form of a reduction from RLOSS (infiltration + surface evaporation) in the subroutine WSHED.

Computations of infiltration inflow in the TRANSPORT block are not reconciled with the groundwater budget in the RUNOFF block.

Unsaturated (Upper) Zone Evapotranspiration (ETU)

Evapotranspiration from the unsaturated zone represents soil moisture lost due to transpiration from vegetative cover and direct evaporation from the soil surface of the pervious area. Wilting point represents the soil moisture condition at which plants can no longer extract moisture from the soil to meet transpiration requirements; thus, if moisture content is less than wilting point, and/or if infiltration rate is greater than zero, ETU is set to zero.

Saturated (Lower) Zone Evapotranspiration (ETD)

ETD represents the evapotranspiration from the saturated zone of the pervious area. In general, all quantities are assumed to be constant over the time-step.

Percolation

SWMM uses the term percolation to represent the flow of water from the upper unsaturated zone to the lower saturated zone. Negative percolation values are not allowed. Percolation is the only inflow to the saturated zone. Darcy's Law for one-dimensional, vertical flow is the basis for the percolation equation used in the model. If moisture content becomes less than or equal to field capacity, percolation is set to zero. Percolation is assumed to be constant for each time-step.

Deep Percolation

Deep percolation is a lumped-parameter term for unquantified losses from the saturated zone. Deep percolation cannot be a negative value. The two major losses considered in the model are percolation through the confining layer and lateral outflow from the zone to somewhere other than receiving water. Deep percolation is a function of static pressure head above the confining layer. Deep percolation is small in most cases and is averaged over the time-step.

Groundwater Flow

This component of the subsurface flow routing scheme represents groundwater flow from the saturated zone to the receiving surface outlet or channel/pipe. In SWMM4.3, groundwater flow cannot be a negative value and cannot be routed to another subcatchment via the subsurface. If the elevation of water in the channel equals the elevation of the bottom of the channel (i.e. no channel tailwater) then TWFLW is zero. Iterations are done to calculate the average flow for each time-step. Groundwater flow should be routed to a previously defined channel/pipe, inlet, etc. as long as the routing is physically realistic; it does not have to be routed to the same outlet as the overland flow for the subcatchment. Under-drains can be simulated, but since groundwater flow from subsurface subcatchments can only be routed to one pipe, a network of under-drains must be replaced by one equivalent pipe for simulation purposes. Channel water can be handled in two ways:

- Set TW to a constant value greater than or equal to BC and coefficients A2, B2 and/or A3 greater than zero, or

- Set TW equal to the elevation in a real channel. The groundwater must be routed to a drain (not an inlet). The depth of water in the channel (TW-BC) at each time-step is calculated as the depth in the channel from the previous time-step.

Groundwater flow should never be a negative value; this represents bank recharge from the channel into the groundwater system. This recharge flow would have to be subtracted from the channel flow in the model calculations. Bank recharge is possible in an actual system, however in SWMM4.3 there is no means of subtracting flow from the channel/pipes since the channel/pipe flow routing is not coupled to the groundwater flow routing. To ensure a positive GWFLW value, set A1 greater than or equal to A2, B1 greater than or equal to B2 and A3 equal to zero.

12.3.2 Limitations of Subsurface Flow Modeling in SWMM4.3

Although SWMM does route subsurface flow, it has a number of shortcomings (Huber and Dickinson, 1988):

- In the RUNOFF block, groundwater flow cannot be routed from one subsurface subcatchment to another. Groundwater flow must be routed to a surface channel/pipe or outlet. Only one subsurface subcatchment system can be modeled at a time.
- Subsurface subcatchment boundaries must coincide with the surface subcatchment boundary. In reality, this is not always the case and may cause problems when routing groundwater flow in the subsurface regime.
- Groundwater flow cannot be a negative value. Although negative flow may occur in real systems (such as bank recharge or flow back into an upstream subsurface subcatchment), it is not allowed since there is no means in SWMM4.3 of subtracting flow from the channel because the channel flow routing is not coupled to the groundwater flow routing in the code.
- Water quality is not modeled in the subsurface routines. Any pollutant load entering the soil will disappear as if the soil provides 100% treatment.
- Moisture content is taken as an average over the entire zone, therefore the moisture profile is lost and the infiltrating water is not modeled as a diffusing slug moving down to the saturated zone.
- Unsaturated and saturated zones are represented as simple 'tanks', thus non-uniform soil columns cannot be modeled.
- Model assumes that the infiltrated water is spread uniformly over the entire subcatchment, not just the pervious area, which may be a serious limitation for large impervious areas.

- Diffusion or suction of water from the capillary fringe of the saturated zone up into the unsaturated zone is not simulated in the model.
- There is no communication between the groundwater budget in the RUNOFF block and the computation of sewer infiltration inflow (e.g. due to high groundwater elevations) in the TRANSPORT block.
- If the infiltration rate is greater than zero, upper zone evapotranspiration is set to zero. In reality, this is not representative of true evapotranspiration processes.

12.4 Background Theory for Urban Groundwater Flow

Objectives here are to discuss processes rather than equations and code pertinent to JUGRND, a routine for a Y-shaped groundwater flow element. Some equations used in JUGRND are borrowed directly from SWMM4.3 while others are based (in part) on equations from HSPF11. An explicit rather than implicit numerical method is used, since the numerical manipulation and coding is simpler. Secondary equations to the groundwater flow equations (such as infiltration, percolation, evapotranspiration and deep percolation) were taken from the existing SWMM4.3 source code (Huber and Dickinson, 1988).

The basic idea is that connectivity of the subsurface subcatchments (SSs) is similar to the surface subcatchments, and delineation of the SSs directly conform to the surface subcatchments. The subsurface subcatchments have a tree-structure with subcatchments *UP1* and *UP2* being upstream from, and the groundwater flowing into, subcatchment *I*. Subcatchment *I* is upstream from and flows into subsurface subcatchment *DN*. In turn, subcatchment *DN* is upstream from and flows into subsurface subcatchment *X*. This planform of the subcatchments promises to be useful in further work as it can be used as a building block for larger models. Water table elevation of subsurface subcatchment *X* is constant for the calculations and is input by the user. Subsurface conditions of upstream SSs *UP1* and *UP2* will affect the processes occurring in intermediary *I* and vice versa. Likewise, subsurface conditions of *I* will affect the processes occurring in downstream *DN* and vice versa. Connectivity of the subsurface subcatchments is illustrated in Figure 12.3.

Calculation of groundwater flow for a given control volume and time period is based on two equations: conservation of mass (continuity) and Darcy's Law. Continuity may be written:

$$\Sigma(I-O) = \Delta S/\Delta t \qquad (12.1)$$

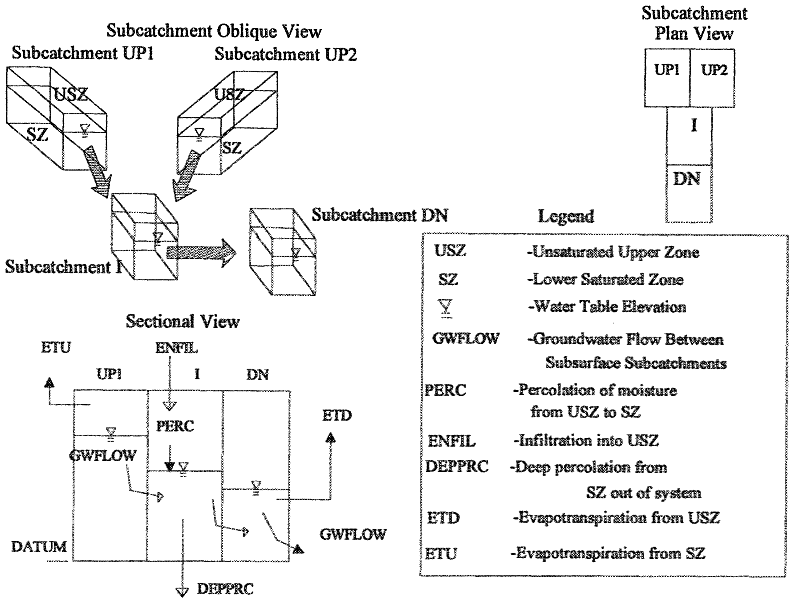

Figure 12.3 Subsurface subcatchment configurations.

where:

I = flows to the control volume [m^3/min]
O = flows from the control volume [m^3/min]
ΔS = change of moisture storage in the control volume [m^3]
Δt = time period specified [min]

The two sides of Equation 12.1 are:

1. Change in water stored in the control volume for a given time-step. This change is based on a mass balance account of moisture content in both the saturated and unsaturated zones as illustrated in Figure 12.4.
2. Fluxes into and out of both the unsaturated and saturated zones of the control volume for each subsurface subcatchment.

Moisture content changes in the unsaturated zone are calculated differently from those in the saturated zone. Change in storage based on moisture content can be written:

$$\Delta S = \Delta V_s + \Delta V_u \tag{12.2}$$

where:

ΔV_s = change in volume of water in the saturated zone [m^3]
ΔV_u = change in volume of water in the unsaturated zone [m^3]

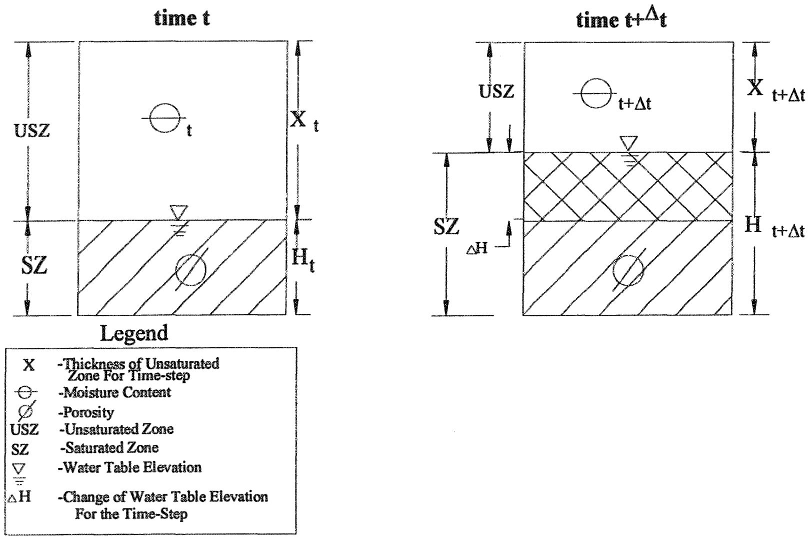

Figure 12.4 Changes in moisture content of saturated and unsaturated zones.

Equations for ΔV_s and ΔV_u can be formulated:

$$\Delta V_s = (\phi - \theta_t) * \Delta H * A \tag{12.3}$$

$$\Delta V_u = (\theta_{t+\Delta t} - \theta_t) * ((X_t * A) - (\Delta H * A)) \tag{12.4}$$

where:

ϕ = porosity of the soil
θ_t = beginning of time-step moisture content
$\theta_{t+\Delta t}$ = end of time-step moisture content
ΔH = change of water table elevation for the time-step [m]
A = surface area of subcatchment [m^2]
X_t = thickness of the unsaturated zone as a function of time [m];
X_t = ground elevation [m] - water table elevation [m]

Substituting Equations 12.3 and 12.4 into Equation 12.2:

$$\Delta S = \{(\phi - \theta_t) * (\Delta H * A)\} + \{(\theta_{t+\Delta t} - \theta_t) * (V_t - (\Delta H * A))\} \tag{12.5}$$

where:

V_t = total volume of unsaturated zone as a function of time [m^3]
i.e. V_t = $X_t * A$

The first term of Equation 12.5 deals with the moisture content of the saturated zone while the second term of the equation deals with moisture content of the unsaturated zone. With regard to moisture content, two important assumptions were made in developing the equations for the groundwater flow model:

1. Below the water table, moisture content is saturated i.e. moisture content = porosity (ϕ)
2. Above the water table, moisture content is set by the user (at the beginning of the simulation) and is homogeneous throughout the unsaturated zone.

The change in storage of Equation12.5 developed above simulates the following conditions:

1. Complete saturation of the subsurface subcatchment where
   $$\theta_{t+\Delta t} = \phi$$
2. Unsaturated conditions in which the moisture content changes, but the water table elevation does not necessarily change (i.e. $\Delta h = 0$). In this situation, change in storage becomes a function of change in moisture content of the unsaturated zone and volume of the unsaturated zone such that:
   $$\Sigma(\text{I-O}) = (\theta_{t+\Delta t} - \theta_t) * (V_t) \tag{12.6}$$
3. Unsaturated conditions in which the water table rises or falls as the moisture content changes.

Fluxes into and out of the unsaturated and saturated zones are illustrated in Figure 12.5.

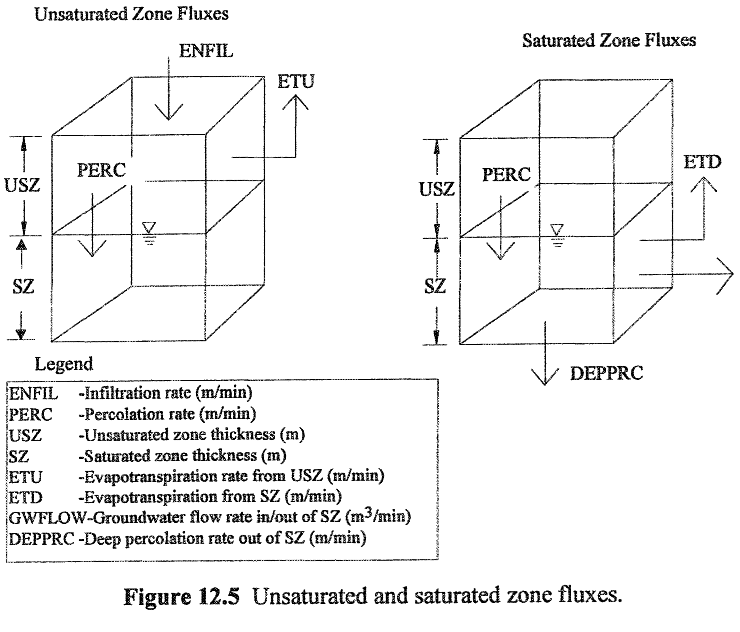

Figure 12.5 Unsaturated and saturated zone fluxes.

The types of inflows and outflows are the same for subsurface subcatchments *UP1* and *UP2* (Figure 12.3). Mass balance accounts of inflows and outflows for subsurface subcatchments *I* and *DN* differ.

12.5 New Groundwater Flow Model (JUGRND)

New code for simulating groundwater flow in the subcatchments was written to compute groundwater flow from the upstream to the downstream subsurface subcatchment (for each time-step). These calculations are based on a mass balance of the subsurface subcatchments (SS) as well as an account of the fluxes into and out of the SS for each time-step.

The new code was written in FORTRAN77. Program JUGRND was structured to facilitate easier integration back into the RUNOFF block in the future. As many of the original variable names as possible were maintained in the new source code of JUGRND to simplify such integration. Figure 12.6 depicts the logical structure of JUGRND.

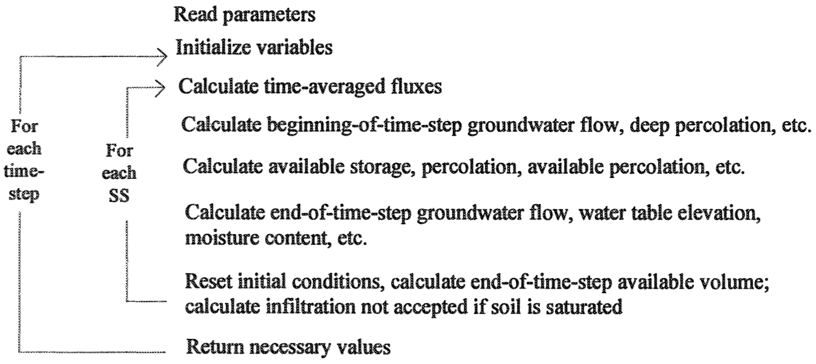

Figure 12.6 Flow chart for JUGRND.

12.5.1 Control Points for Calculation of Groundwater Flow

In JUGRND, the calculation of groundwater flow for a SS is a function of the water table elevation of that subcatchment as well as that of the adjacent SSs. Hydraulic gradients are calculated based on the water table elevations and flow distance between adjacent SSs. With respect to SS *DN*, the downstream SS is *X*; this SS has a constant water table elevation. This water table elevation acts as a control point for calculation of groundwater flow out of *DN*. In turn, the water table elevation of *DN* acts as a control point for calculation of groundwater flow out of *I* and so on. Different types of control points exist: (i) channels such as rivers and lakes with constant or variable water table elevations; and (ii) artificial controls such as pumping water wells. Thus, control points external to the downstream SS controls the groundwater table or longitudinal profile, and the flow of groundwater from upstream SSs. JUGRND permits groundwater flow, due to hydraulic gradient, from: *UP1* to *I*; from *UP2* to *I*; from *I* to *DN* and from *DN* to *X*. SS *X* represents a fixed water table condition in JUGRND. Program JUGRND does not allow groundwater flow between *UP1* and *UP2*.

12.5.2 Sensitivity analysis of selected parameters in JUGRND

The code was extensively tested and a sensitivity analysis was conducted using selected input parameters, which were varied by ±5% and ±10%. For each parameter used, the value for *UP1* was set equal to that of *UP2*, *I* and *DN* (e.g. L1=L2=L3=L4); therefore, the percent change in parameter value maintained uniform input values for the analysis. This was done to isolate the effect that change of the parameter values, for all SSs, had on groundwater flow and end-of-time-step water table elevation. Resulting groundwater flow and end-of-time water table elevation of *I*, at 180 minutes, were recorded to determine their sensitivity to the input parameters. SS *I* was chosen since it relies on the greatest number of SSs; *I* relies on groundwater flow from *UP1* and *UP2* as well as the water table elevation of *DN*. The datafile used represents a situation of relatively low infiltration rate; evapotranspiration and deep percolation are also simulated. Projected horizontal area of the SSs is uniform (10000 m^2) as is the porosity (0.43) (James et al, 1992); initial moisture content (0.35); field capacity (0.26) (Huber and Dickinson, 1988); wilting point (0.13) (Huber and Dickinson, 1988); saturated hydraulic conductivity (1.1E-4 m/min) (James et al, 1992); percent pervious area (75%); ground elevation (5.0 m); evapotranspiration rate (1E-6 m/min); groundwater flow length (100 m) and all other input parameters. The porosity, field capacity, wilting point and saturated hydraulic conductivity values used in the simulations are typical for common loam soils. The water table decreased in a downstream direction from *UP1* to *X* (4.50 m, 3.50 m, 2.50 m, 2.00 m, 1.00 m). The sensitivity analysis results are only relevant for this one case; it is suggested that each modeler perform a sensitivity analysis for the conditions being simulated.

As noted, not all input parameters were used in the analysis. Those input parameters which describe the physical characteristics of the SSs were included in the sensitivity analysis along with the time-step for the simulation (DELT) and infiltration rate (ENFIL). Eighteen parameters were used:

HKSAT - saturated hydraulic conductivity
POR - porosity of the soil
FC - field capacity
TH1 - initial moisture content of the unsaturated zone

WP - wilting point
HCO - calibration parameter for calculating hydraulic conductivity
PCO - calibration parameter for calculating percolation
DP - parameter used to calculate deep percolation
PERV - percent pervious area of the surface subcatchment
GRELEV - ground elevation of the surface subcatchments
L1, L2, L3, L4 - groundwater flow lengths of the SSs
AREA, SAX - horizontal area of the SSs
EVAP - evapotranspiration rate
DET - depth over which evapotranspiration can occur
CET - fraction of evapotranspiration apportioned to the unsaturated zone
DATUM - datum elevation for all SSs
DELT - time-step for the simulation
ENFIL - infiltration rate for the simulation

Parameters not used:

WT1 - initial water table elevations
MAX - maximum simulation time

Using a threshold for sensitivity of ± 2%, results indicate that for this case, groundwater flow is sensitive to changes in seven of eighteen parameters while end-of-time water table elevation is sensitive to four of eighteen parameters.

12.6 Conclusions

Urban stormwater runoff models are commonly used to analyze movement of water through the numerous facets of the hydrologic cycle in urban areas. Groundwater flow is an integral component of that hydrologic cycle; however, at the time of this study (1996), most urban surface water models ignore urban groundwater hydrology and most groundwater models ignore urban surface water hydraulics and hydrology. There is a need for improved shallow groundwater-stormwater interaction modeling for rational urban stormwater runoff management.

A stormwater management model that incorporates shallow groundwater processes is SWMM4. The main limitation of SWMM4.3 is that groundwater flow cannot be routed from one subsurface subcatchment to another - groundwater flow must be routed to a surface channel/pipe or outlet. In addition, only one subsurface subcatchment system can be modeled per RUNOFF run. SWMM4.3 was chosen as the base model from which to work, and a new fundamental subsurface 4-unit element called JUGRND was written to test a new approach to the routing of shallow groundwater flow through subsurface subcatchments.

As many of the SWMM4.3 variables as possible were used in JUGRND with the intention that code from JUGRND may eventually be incorporated back into SWMM4.3. The main improvement in modeling capability that JUGRND offers is the subsurface connectivity of adjacent subcatchments - shallow groundwater can potentially be routed dendritically through the subsurface from up-gradient subcatchments to down-gradient subcatchments, and the low water table elevation control boundary. In addition, JUGRND can handle extreme unsaturated and saturated conditions. Although JUGRND does provide relatively reliable routing of shallow groundwater from up-gradient to down-gradient subcatchments, the model still has limitations. Variable geometries have not been tested The JUGRND element is restricted to a fixed configuration of four subcatchments such that there are two up-gradient subcatchments with groundwater flowing into an intermediate subcatchment. In turn, the groundwater from the intermediate subcatchment flows into a down-gradient subcatchment. Located down-gradient is another subcatchment which has a fixed water table elevation at its lowest boundary. Another limitation is that the code allows unrestrained gravity flow of water from the unsaturated zone to the saturated zone (percolation) as long as the moisture content in the unsaturated zone is greater than field capacity. At present the code does not preserve moisture content in the unsaturated zone as may occur in reality. Perhaps related to this, it was found that, for certain conditions, the moisture content decreased below field capacity in the first upstream subcatchment; so the model requires further tuning. Other limitations are described in the chapter.

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