Hydrologic Process Modules of the Regional Simulation Model: An Overview

Eric Flaig, Randy VanZee and Wasantha Lal

Office of Modeling

South Florida Water Management District, USA

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Abstract

The Regional Simulation Model is a regional finite-volume, aquifer-stream-surface hydrology model under development by the South Florida Water Management District. The Hydrologic Process Modules (HPM) are designed to solve the local surface water hydrology for RSM, where an HPM is assigned to each cell in the irregular mesh. The HPMs are solved explicitly at the beginning of each model time step and the results are provided as known flows to the upper boundary condition of the regional implicit finite-volume flow model. The architecture of the RSM source code is flexible and allows for the development and implementation of new and more specialized HPMs as additional functionality is required.

There are several HPM types available for use with RSM that provide simple to complex descriptions of surface hydrology. Different HPMs are available to simulate natural and man-made hydrology, both urban and agricultural. HPMs process rain and evapotranspiration to produce runoff and recharge. Where there is irrigation, HPMs produce a water supply demand. Demand can also be generated by urban consumptive use. There are simple HPMs that contain the hydrologic processes for one land use type such as native, urban, or agricultural lands. There are Hubs that contain one or more HPMs, where water supply and runoff are directed to a single water body in the regional model. Hubs are used to model complex urban and agricultural landscapes. In this paper, the HPM concepts and governing equations are developed and the hydrology of the individual HPMs are described.

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1 Introduction

The Regional Simulation Model (RSM) is a large-scale hydrologic model created by the South Florida Water Management District (SFWMD) as a tool for planning and managing the water resources of south Florida including regional water supply, flood control and environmental enhancement (SFWMD, 2005). The RSM is composed of two components, the Hydrologic Simulation Engine (HSE) and the Management Simulation Engine (MSE). The HSE is a 2D-3D, regional, saturated-flow, finite-volume numerical model that solves the diffusive wave equation over an irregular triangular mesh using an implicit solver. The implicit solution for saturated flow is referred to as the regional solution. An integral part of the HSE is a canal network that solves the 1D diffusive wave equation and simulates hydraulic structures. The MSE is a set of controllers, controller-supervisors and filters that provide hydrologic and system information to the controllers. The controllers set the operational characteristics of the hydraulic structures in the HSE network and mesh to achieve regional water management objectives.

The Hydrologic Process Modules (HPMs) were developed to simulate the small-scale, local hydrology and vertical processes for the RSM. The primary function of HPMs is to provide the surface boundary condition for the regional solution; HPMs are used to process rainfall and potential evapotranspiration (PET) and provide net recharge to the mesh cells of the HSE. Structurally, the foot print for the HPMs matches the cell boundaries of the irregular triangular 2D mesh. HPMs can be constructed to model vertical flow in the soil as well as complex flow in the landscape including surface runoff, interflow, baseflow, and water management systems including stormwater routing and detention/retention ponds. It is possible to combine simple HPM types to form Hubs that can be used to model complex landscapes within a single mesh cell or a collection of mesh cells. The unconditional stability of the regional solution allows the implementation of a variety of HPMs throughout the mesh as necessary to best model the characteristics of the landscape.

Some models have simulated surface hydrologic processes as simple functions (Pandy and Huyahorn, 2004), while others have included surface water management processes (DHI, 2001). Simple analytical functions describing surface processes can be incorporated into the implicit solution. However, complex processes including water management have not been incorporated into implicit 2D hydrologic models. The HPMs within RSM provide greater flexibility in selection and application of hydrologic processes to different landuse types and landscapes.

The HPMs are one set of process modules linked to the HSE. Other process modules include Water Quality Process Modules (WQPM) and Ecological Process Modules (EPM). The WQPMs use the advective flow calculated by HSE to provide transport for the biogeochemical processes modeled in the WQPMs. EPMs are being developed to simulate landscape and habitat processes that use the hydrology from the HSE to simulate functional changes in the environment.

In this paper, we present HPM concepts and describe HPM types that are currently available in the RSM. Available types include simple or single HPMs and hubs that include one or more HPMs.

2 Governing Equation

The governing equation for the HPM in context of HSE is the conservation of mass. Mass is conserved within each time step within each HPM and the regional solution. The water budget within the HPM is developed to maintain the mass balance within the RSM model. In the most general case the governing equation of conservation of mass, expressed as depth per unit area of the HPM, can be expresses as follows:

$$S_t = S_{t-1} + P_t - ET_t + CellDelta_{t-1} + hpmInflow_t - \sum_{j=0}^{n} WS_{jt} - \sum_{j=0}^{n} RO_{jt} - Rec_{jt} \qquad (1)$$

where S is the volumetric water storage in the HPM at time step (t) and the previous time step $(t-1)$, P is precipitation, ET is evapotranspiration, $CellDelta_{t-1}$ is the change in water volume for the underlying mesh cell, referred to as the homecell, as determined by the regional implicit solution from the previous time step, $hpmInflow_t$ is water exchange with adjacent HPMs within a Hub, ΣWS_{jt} is the sum of the demands for water supply applied to the jth selected water body, ΣRO_{jt} is the sum of the surface runoff outlets directed to the jth specific water body and Rec_{jt} is recharge to the homecell. Depending on how a specific HPM is constructed, one or more of these terms may not be included in the mass balance. For example, hpmInflow does not occur with simple HPMs but only in a Hub. The details of the mass balance (Equation 1) are explained below.

Several components on the right hand side of Equation 1 for the conservation of mass for an HPM can be expressed as the following:

$$
\begin{aligned}
\Sigma WS_t \quad &= Q_{irr} + Q_{cu} \\
\Sigma RO_t \quad &= Q_{sur} + Q_{int} + Q_{det} + Q_{base} + Q_{sew} \\
Rec_t \quad &= Q_{rchg} + Q_{sep} + Q_{seep} + Q_{imp} \\
S_{t-1} \quad &= S_{soil} + S_{det} + S_{imp}
\end{aligned}
\qquad (2)
$$

in which Q_{irr} is irrigation; Q_{cu} is urban water supply; Q_{sur} is surface runoff; Q_{int} is interflow, Q_{det} is discharge from detention storage, Q_{base} is baseflow, Q_{sew} is sewer discharge; Q_{rchg} is direct recharge, Q_{sep} is water discharged to onsite disposal systems; Q_{seep} is water lost through seepage, Q_{imp} is the discharge from stormwater detention impoundment systems, S_{soil} is soil water storage, S_{det} is detention storage and S_{imp} is water stored in impoundment systems. Some of the optional terms may not be applicable to some of the processes. Although there are several processes that generate discharge from an HPM, such as seepage, impoundment discharge, sewage and over-land flow, for the exchange with the system of water bodies (Fig. 1) these flows are resolved into WS, RO or Rec. For a simple HPM, there can only be one connection each for WS, RO and Rec. The water supply demand, or withdrawal, can be applied to one or more water bodies depending on how the HPM is specified. Similarly, runoff and discharge can be applied to one

or more water bodies; water bodies include mesh cells, network segments and lakes. The flows that resolve to recharge are summed and directed only to the homecell. The HPM provides the surface boundary condition for the water bodies of the regional solution.

For each mesh cell there is an HPM that contains one or more hydrologic processes that process rain and PET and calculates water movement through the soil, over the landscape and through surface water management systems (Fig. 1). The HPM may be a simple HPM consisting of a single HPM or a Hub that contains more than one HPM. The Hub provides the structure for directing the runoff from all of the HPMs within the Hub to a single water body and directing the water supply requirement, or irrigation demand as illustrated in the example in Figure 1, to a single water body such as a canal segment (Fig. 1). Water may flow between the HPMs within a Hub (hpmInflow) in a structured, explicitly define progression. The HSE provides the functions by which the HPM can exchange water with selected water bodies (mesh cells, network segments or lakes) in the regional system. Each HPM, simple or Hub, provides flows to the regional system of water bodies through the three possible components; runoff, recharge and water supply.
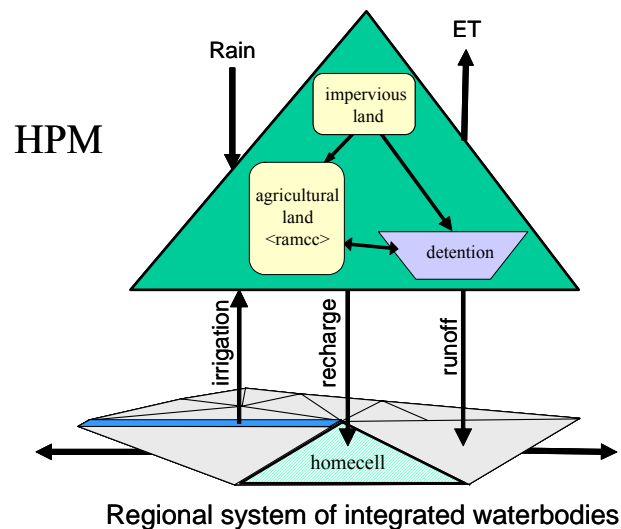

Figure 1. Coupling between Hydrologic Process Modules and the HSE mesh.

The interaction between the HPMs and the regional solution is based on the conservation of mass. However, the processes formulated within an HPM may be designed to include routing and thus the conservation of momentum. An HPM can be created to use the momentum to solve hydrologic processes within an HPM such as unsaturated flow through soil, discharge from impoundments and routing of overland flow. These processes may be solved within an HPM using a small time step or an analytical solution. The resulting mass flow for each HSE time step within the HPM is applied to the water bodies in the regional solution.

2.1.1 HPM Control Volume

The calculation of the mass balance for HPMs and the HSE regional solution occurs over two control volumes during each time step. The mass balance for each water body and HPM is calculated for the appropriate control volume during the specified time slice of the numerical process (Fig. 2). During each time step of the model simulation, the mass balance for the HPMs

is solved explicitly and the resulting flows (WS, RO and Rec) are applied as source/sink terms on the right hand side of the implicit matrix (see SFWMD, 2005), and the implicit solver for the finite-volume matrix provides the solution of water movement within the mesh, lake and network.

In the explicit slice of the HSE time step, the various inputs and outputs are calculated (Eqn. 2). The hydrologic processes are typically solved in two steps during the explicit solution. First, water from all sources is combined and added to the HPM creating a temporary value for HPM head:

$$H_{temp} = H_{t-1} + (P_t + CellDelta_{t-1} + hpmInflow_t) / Sy \tag{3}$$

where H_{t-1} is the head at the beginning of the time step and Sy is the specific yield for the surficial aquifer that allows conversion of the inflow volumes into head. Where there are no inputs from rain or other HPMs, H_{temp} is the head in the mesh cell at the end of the previous time step. The HPM head for the explicit solution is calculated by completing the hydrologic processes of the HPM and adjusting the HPM water balance as follows;

$$H_t = H_{temp} + S_{t-1} - ET_t - \sum_{j=0}^{n} WS_{jt} - \sum_{j=0}^{n} RO_{jt} - Rec_{jt} \tag{4}$$

The mass balance of the HPM is calculated for the control volume that may include the saturated water to the base of the aquifer, the unsaturated zone water and water held in local detention storage components. The water storages and processes of the control volume depend on the physical characteristics of the selected HPM and the processes includes in the HPM. These are described for each HPM type in the other sections of this paper.

In the implicit slice of the HSE time step, the outputs from the HPMs are entered into the implicit regional solution as known flows (Fig. 2). The control volume for the underlying water body, typically a mesh cell, includes only the saturated zone water. The regional solution includes flows from adjacent water bodies, mesh cells, lakes and segment. The result of the implicit solution is the change in water body storage, CellDelta (t). The RSM model produces water budgets for the HPMs and mesh cells separately. Because of the different phases in the water budget calculation, the HPM water budget and the Mesh Cell water budgets are calculated separately. The CellDelta from the previous time step is used to calculate the HPM water balance for the current time step. The new CellDelta is calculated as part of the implicit solution during the current time step.

The control volume used for each HPM depends on the specific HPM selected for each mesh cell. The control volumes for HPMs and Water bodies illustrated in Figure 2 represents the most connected combination of control volumes used in RSM. Other HPMs describe different local hydrologic processes that do not include the saturated zone and do not require information from the water bodies to complete the water balance. The control volumes for each HPM are provided with the description of the HPMs in the following sections.
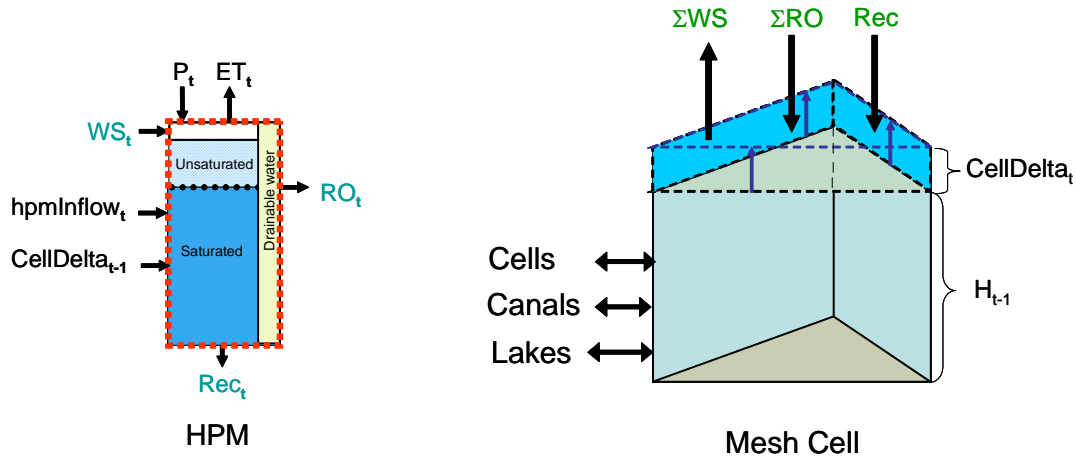
Figure 2. Control volumes and water balance components for HPM and Mesh Cell.

3 HPM Concepts

The HPM approach provides a method for modeling the local surface hydrology of a mesh cell or a collection of mesh cells. Each mesh cell has an HPM assigned to that cell to provide the upper boundary condition for the implicit solution. The explicit solution of the local hydrology at the beginning of the time step provides the opportunity to simulate a range of possible modules depending on dominant hydrologic processes or important water management practices. The HPMs are typically designed to model the simplified vertical or surface processes. As a solution to local hydrology in a regional water management model, the HPMs are generally not designed to simulate small-scale hydrologic processes such as unsteady flow or hydraulics, although these could be simulated under the appropriate circumstances. The HPMs provide the solution for aggregate hydrologic behavior of the local landscape. HPMs have been designed to simulate the following processes:

- Unsaturated flow in soil,
- Interception and detention of flow,
- Interflow and field drainage,
- Urban hydrology and stormwater management practices,
- Rainfall-Runoff simulation,
- Agricultural irrigation and drainage practices,
- Anisotropic surface hydrology,
- Small creek and tributary flow,
- Discharge, seepage and aquifer recharge from detention and retention ponds.

The HPM concept provides an opportunity for hydrologic modelers outside the SFWMD development group to develop new HPMs. The RSM is written in an object-oriented framework and the HPM class is setup to accommodate additional HPMs by simple addition of new objectives of the HPM class following the inheritance rules to create the appropriate interface

with HSE. Additional HPMs can be added that provide new or more detailed processes for simulating surface hydrology and water management practices.

Within the architecture and design of HSE, it is possible to have many HPM types that are selectable as part of the input XML. Besides the HPMs that model necessary processes, it is possible to have HPMs that model local hydrology by using different methods. This is useful, when different hydrologic processes dominate water movement for different soil, landuse and landscape types. It is also useful when different users want to select specific methods to simulate local hydrology. For example, agricultural consumptive use may be estimated using different methods. HSE allows for the creation of multiple agricultural land HPMs and the users can select the appropriate HPMs by changing the XML specifications.

In this architecture, it is possible and common that the different HPMs are constructed in very different ways. For example, the layer1nsm HPM (presented below) is a very simple C++ program, while the layer5 HPM has multiple layers of objects and depends strongly on inheritance. Other HPMs can be constructed by creating a C++ wrapper around FORTRAN code. This allows the use of known and accepted legacy code to be implemented as a local hydrologic process module in HSE. With this level of flexibility, it is common to have different parameters for different HPMs that describe essentially the same processes. It is also possible to have the same parameter, e.g. shallow root depth, used in different processes in different HPMs. As such, each HPM should be interpreted as a unique entity.

3.1 Simple HPM types

The area simulated by the RSM may include native lands as well as developed land, both urban and agricultural. The natural areas are modeled by hydrologic processes representing wetlands and low gradient upland. Developed land, both agricultural and urban, is characterized by intensive surface water management systems. Agricultural areas include irrigation systems that are managed in conjunction with water table management, constructed drainage ditches to capture field drainage and impoundments to hold water and release it at a controlled rate. Urban developments contain large areas of impervious surfaces, constructed drainage systems, and retention/detention ponds.

The HPMs in the RSM have been designed to simulate the hydrology for each of these types of land uses. These are simple hydrologic process modules that may be used to simulate local hydrologic processes for a single mesh cell. There is also a "no action" HPM that is used to turn off hydrologic processes in selected areas for model testing and development.

In the following discussion, simple HPM descriptions are classified into these three general types. The term in brackets such as <layer1nsm> is the RSM input element identified by its XML tag that creates the environment for specifying the attributes of the HPM.

- Natural System HPMs
  - Natural Wetland System <layer1nsm>
  - Unsaturated Soil <unsat>
  - Five Layer <layer5>
  - Precipitation Runoff Routing <prr>
  - No Action <layerpc>

- Agricultural HPMs
  - Agricultural Irrigation Requirements <ramcc>
  - Drainage Collector Ditch <pumpedditch>
  - Agricultural Impoundment <agimp>
- Urban HPMs
  - Impervious Area <imperv>
  - Multi-Basin Routing <mbrcell>
  - Consumptive Use <cu>
  - Urban/Stormwater Retention/Detention <urbandet>

3.2 Hubs

The simplest implementation of HPMs occurs as a single simple HPM associated with each mesh cell to simulate the local hydrology for that area. It is possible that a small number of generic HPMs could provide adequate local hydrology for the entire domain of an RSM implementation. Often, it is not possible or appropriate to model the RSM domain with simple, single-purpose HPMs. In most water management applications, water managers need to simulate areas with more complex processes than application of single, simple HPMs allow. Although simple HPMs may typically be used in large areas of a model domain, they do not adequately represent regions where the landscape is complex and one mesh cell may include a combination of natural, agricultural, and urban areas; or several mesh cells may cover a partially urbanized area, interspersed with agricultural areas. To simulate such areas without unduly complicated arrangements of mesh cells or water movers, a Hub is used.

The Hub provides two additional functions to local hydrology; the area-weighted hydrologic response for water supply demand, runoff or recharge for the HPMs within a Hub, and the capability to direct the hydrologic response of the HPMs within the Hub to selected water bodies other than the homecell. In the first case, where more than one HPM is necessary to describe the local hydrology of a mesh cell, a Hub can be used to calculate the area-weighted hydrologic response of the surface hydrology. This commonly occurs in mixed landuse watersheds where agricultural land or native land is adjacent to urban developments and each of the different landuses is described by one or more HPMs. In the second case, a Hub can be used to model a local stormwater management system that covers several mesh cells, and more than one HPM is commonly used to describe the local hydrology within the Hub. Each of the HPMs within a Hub is allowed to interact with other HPMs as may occur in a typical surface water management system. The Hub covers the group of mesh cells and the hydrologic response of the Hub can be redirected to a single well or canal. In this case, the area-weighted recharge is directed uniformly as recharge to all mesh cells under the Hub. There is the facility for the individual HPMs within the Hub to interact with any water body in the RSM mesh.

The additional functionality provided by the Hub construct allows for considerable flexibility in the combination of process specific HPMs and implementation of simple HPMs in complex landscapes. The Hub is particularly useful in modeling agricultural and urban development that has multiple hydrologic connections to the regional water management system.

3.3 Limitations of HPMs

HPMs are the means by which local hydrology is simulated in the RSM. They contribute to the governing equations through the source/sink term on the right hand side of the HSE matrix solution (SFWMD, 2005). Furthermore, the solution of HPMs is designed as an explicit solution for convenience and stability; this provides a means to introduce considerable complexity in the modeling of surface hydrology without introducing nonlinearity into the regional solution. Since HPMs are open for user development, the explicit option is the only one available, as this protects the user from making the equations in the overall HSE solution matrix stiff, or unstable. HPMs are also assumed to be non-interactive with HPMs of other mesh cells, and HPMs within Hubs interactive in only a linear way. This preserves the stability of the regional solution and the integrity of both the HPM and the regional solution water budgets.

4 Natural System HPMs

The natural system HPMs are designed to simulate local hydrology in natural areas that can be classified as wetlands and uplands. The principal distinction in terms of hydrologic processes is the interaction with the surficial aquifer. In wetlands and other areas where the water table is in the root zone for most of the year, the local hydrology is largely controlled by the depth to the water table. In upland areas there is substantial water storage in the unsaturated zone above the water table but below the root zone. Water will drain from saturated soil over extended periods contributing to surface water and regional groundwater. Natural areas differ from developed areas in that the hydrology is controlled by the native landscape features, and water moves relatively slowly through the landscape. In developed areas, man-made features move water quickly to maintain and manage water levels. The natural systems HPMs are briefly described below followed by more detailed descriptions of each natural system HPM type:

- The natural wetland system <layer1nsm> HPM is used to represent the local hydrology of wetlands and high water table soils where the water table is in the root zone for extended periods every year. The available soil water for evapotranspiration is determined by the location of the water table. When the water table is below the root zone the simple algorithm used in this HPM will not accurately describe evapotranspiration and the water budget will not be accurately simulated.

- The unsaturated soil HPM <unsat> an extension of the <layer1nsm> HPM type. Whereas the <layer1nsm> HPM assumes that there is no unsaturated soil and all of the water for evapotranspiration is extracted from the water table, <unsat> maintains moisture accounting in the unsaturated zone as well as tracking the water table. The available moisture in the unsaturated zone is extracted for evapotranspiration demand before water is removed from the water table.

- The five-layer HPM <layer5> is an extension of the <unsat> HPM. The <layer5> HPM is composed of two water layers above the ground surface, the shallow root zone, the deep root zone, and a deeper soil layer below the root zone. The <layer5> HPM tracks the unsaturated zone soil moisture and gravimetric soil water. In addition, the <layer5> HPM has the capability of tracking the soil moisture of multiple soil horizons within the soil profile.

- The precipitation-runoff routing HPM <prr> is a deterministic lumped parameter conceptual model with moderate input data requirements. Water is stored in various compartments; interception, upper zone and lower zone from where is apportioned to runoff, groundwater recharge, evapotranspiration, and interflow.

- The no action HPM <layerpc> performs no calculations and uses none of the HPM access functions. It is used as a place-holder when the simulation of local hydrology is not desired. This may occur during the calibration process to test limited sections of the model domain; either to conduct testing of HPMs in a limited area or testing of other model components without HPMs. It may also be used with lower layer cells in a three dimensional groundwater simulation to maintain mass balance.

4.1 Natural Wetland System <layer1nsm>

The natural wetland system HPM satisfies the need to simulate hydrologic processes in natural systems where the unsaturated zone processes are not significant. This HPM calculates a simple water budget for the soil with a water table that closely follows the water level in the mesh cell. A sequence of computations occur to process the hydrology. Evaporation (Evap) occurs from the IntSto at the rate of the potential evapotranspiration rate (PET) until IntSto is depleted or the PET is satisfied. Rain (P) is applied to the surface and after interception storage (IntSto) is satisfied, the remaining water infiltrates directly to the water table. The volume of infiltration and inflow from other mesh cells (CellDelta) is added to the water table. The change in the position of the water table is determined by the amount of water added, where Sy is the specific yield of the aquifer in the mesh cell if the water table is below the ground surface and is 1.0 if the water table is above the ground surface.

$$H_{temp} = H_{t-1} + (P_t + CellDelta_{t-1} - \Delta IntSto_t - Evap_t) / Sy \qquad (5)$$

where H_{t-1} is the head at the beginning of the time step and H_{temp} is a temporary head from which additional ET occurs to produce the head at the end of the time step. Evapotranspiration depth is removed from the re-computed water table according to equation (7).

$$H_t = H_{temp} - Kc (PET_t - Evap_t) / Sy \qquad (6)$$

The amount of water added to the homecell from the <layer1nsm> HPM is recharge;

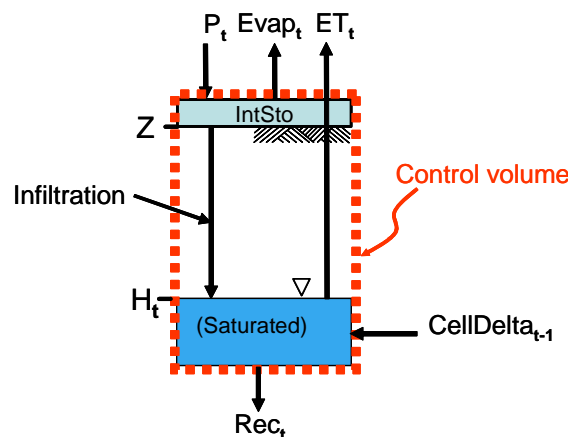$$Rec_t = P_t + \Delta IntSto_t - ET \qquad (7)$$

Figure 3. Control volume and water budget components for the <layer1nsm> HPM.

Where actual evapotranspiration (ET) is calculated as the remaining PET after evaporation from interception storage times a PET correction coefficient (Kc). The value of Kc depends on the location of the water table in Figure 4 relative to the ponding depth (Pd), land surface (Z), rooting depth (Rd) and ET extinction depth (Xd). The linear decrease of Kc with depth below the root zone reflects the influence of capillary upflux from the water table into the root zone (Eqn. 7). The values for Xd, were quantified as calibration coefficients for producing reasonable dry season ET budgets. Kveg is the reference vegetation PET correction coefficient for a specified instance of the HPM identified by landuse type, Kw is the PET correction coefficient for ponded condition.

The generic crop correction factor for wetland reference crop potential evapotranspiration data is as follows:

$$
Kc = \begin{cases}
Kw & H \geq Z + Pd \\[2mm]
(Kw - Kveg)\dfrac{H - Z}{Pd} + Kveg & Z \leq H < Z + Pd \\[2mm]
Kveg & Z - Rd \leq H < Z \\[2mm]
Kveg\dfrac{Xd - (Z - H)}{Xd - Rd} & Z - Xd \leq H < Z - Rd \\[2mm]
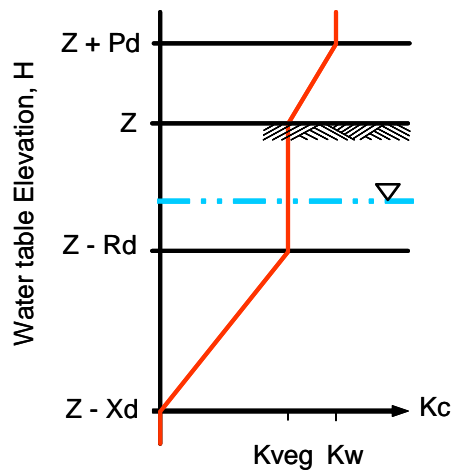0 & H < Z - Xd
\end{cases} \tag{8}
$$

Figure 4. Variation of the PET correction coefficient Kc with water depth.

It is assumed that the Actual Evapotranspiration (AET) from open ponded water is greater than the ET from the vegetation. When the water table is below the root zone, AET decreases linearly with depth, which mimics the effect of capillary upflux from the water table. ET in these cells is

completely cut off when the water level falls below the extinction depth, Xd. As a result, when the water level is low as in upland areas, this HPM can underestimate the ET and overestimate the runoff. This HPM may be better configured to simulate upland areas if Xd is set to a relatively large value. The attributes for the <layer1nsm> HPM are provided in Table 1.

Table 1. Attributes for the <layer1nsm> HPM.

Attribute	Definition	Suggested range	Typical value
Kw	Maximum PET correction coefficient for open water	0.0 – 1.2	1.00
Rd	Shallow root zone depth, (m)	0.0 – 1.0	0.60
Xd	Extinction depth below which no ET occurs (m)	0.0 – 3.0	2.00
Pd	Open water ponding depth (m)	0.0 – 2.0	0.40
Kveg	Vegetation reference crop PET correction coefficient	0.0 – 1.2	0.76
Imax	Maximum interception (m)	0.0 – 0.2	0.02

4.2 Unsaturated Soil HPM <unsat>

The unsaturated soil HPM <unsat> computes a simple water budget for a single-layer soil (Fig. 5). This HPM is similar to the <layer1nsm> HPM except it considers water in the unsaturated soil above the water table in the water balance, whereas <layer1nsm> does not. Because the water budget accounts for the water content of the unsaturated zone, this can be a useful option to use in areas where the water table may be well below ground for a significant portion of the year and ET is not influenced by the water table. The control volume for <unsat> tracks the volume of water in the unsaturated soil and has a variable size with the bottom set by the location of the water table.
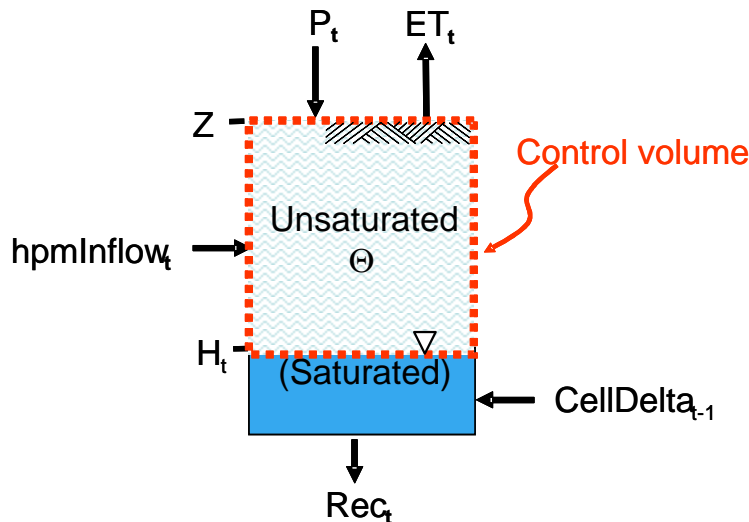

Figure 5. Control volume and water budget components for <unsat> HPM.

At the beginning of each time step, the depth to the water table (wtdepth) is updated. Water is added to or subtracted from the HPM by the horizontal inflows from adjacent mesh cells (CellDelta), from other HPMs (hpmInflow) and rainfall.

$$\text{addwater} = \text{CellDelta}_{t-1} + \text{hpmInflow}_t + P_t \tag{9}$$

$$\text{wtdepth}_{temp} = \text{wtdepth}_{t-1} + \text{addwater} / Sy \tag{10}$$

The total water in the HPM, all of the water above wtdepth$_{t-1}$, is then redistributed to fill the soil profile from bottom to top and determine the water table depth (wtdepth) and addwater.

$$\text{wtdepth}_t = \text{wtdepth}_{temp} - \Theta - (Kc * PET) / Sy \tag{11}$$

where wtdepth$_t$ is depth to the water table at the end of the time step, wtdepth$_{t-1}$ is depth to the water table at the end of the previous time step, wtdepth$_{temp}$ is water table depth adjusted for inflows. The water content in the unsaturated zone (Θ) is calculated as a function of the added water where Ew is the extractable water between field capacity and wilting point.

$$\Theta = \begin{cases} Ew & \text{addwater} > Ew \\ P + \text{CellDelta} + \text{hpmInflow} & \text{Xthres} < \text{addwater} < Ew \\ \text{Xthres} & \text{addwater} < \text{Xthres} \end{cases} \tag{12}$$

The water content in the unsaturated soil is determined by the amount of available water. Kc is the PET correction coefficient. The vegetation specific reference vegetation PET correction coefficient varies as a function of the water table depth and the water content in the unsaturated zone as described below.

Evapotranspiration is a function of the wtdepth and Θ. When the wtdepth is less than the surface elevation (Z) or greater than the rooting depth (Rd), the PET correction coefficient is a function of water table depth. When wtdepth is less than Rd, Kc is a function of the water content of the soil in the unsaturated root zone. Where Θ is greater than a threshold value, Pthres, which is typically equal to one half of extractable water content, Kc equals Kveg. Once Θ drops below Pthres, ET decreases linearly until wilting point, Xthres, below which ET ceases.

$$Kc = \begin{cases} Kw & \text{wtdepth} < 0 \\ (Kw - Kveg)\dfrac{Pd - H}{Pd} + Kveg & 0 > \text{wtdepth} > Pd \\ \left. \begin{array}{ll} Kveg & \Theta > \text{Pthres} \\ Kveg\dfrac{\Theta - \text{Xthres}}{\text{Pthres} - \text{Xthres}} & \text{Xthres} < \Theta < \text{Pthres} \\ 0 & \Theta < \text{Xthres} \end{array} \right\} \text{wtdepth} < Rd \\ 0 & \text{wtdepth} > Rd \end{cases} \tag{13}$$

After ET occurs, the water is again redistributed in the vertical soil column. Recharge to the homecell is a function of rain, HPM inflows and ET.

$$Rec = P_t + hpmInflow_t - Kc * PET \qquad\qquad (14)$$

The elements and attributes used to describe the <unsat> HPM are presented in Table 2. The specific yield is determined by the soil properties of the underlying mesh cell.

Table 2. Attributes for the <unsat> HPM.

Attribute	Definition	Allowable Range	Typical value
Kw	Maximum PET correction coefficient for open water	0.5 - 1.0	1.00
Rd	Root zone depth, (m)	0.0 - 2.0	1.60
Pd	Ponding depth (m) above which open water occurs	0.0 - 2.0	0.50
Xthresh	Soil water content when ET ceases, wilting point (m)	0.0 - 0.3	0.07
Pthresh	Soil water content when Kc decreases from Kveg (m)	0.0 - 0.5	0.14
Kveg	Vegetation reference crop PET correction coefficient	0.5 - 1.0	0.75

4.3 Five Layer HPM <layer5>

The five layer HPM <layer5> simulates the water budget for a soil column with multiple soil horizons (Fig. 6). The total length of this column is divided into five layers defined by the reference elevations; Pd, Z, Rd and Xd as defined in Section 4.1 for estimating ET. The HPM is designed to model several soil horizons that have different soil water characteristic values, extractable water and gravitational water. Extractable water (Θ_{cap}) is the amount of water retained in soil capillaries and is the difference between field capacity and wilting point. Gravitational water (Θ_{grav}) is the amount of water that will drain freely from the soil (specific yield). In this example, the soil is divided into four horizons; surface soil, horizon 2, horizon 3 and the subsoil (Fig. 6). Soil water content is tracked in each soil horizon during the simulation.

The <layer5> HPM is coupled to the mesh cell in that the head is obtained from the mesh cell at the beginning of the simulation. At the beginning of each time step the amount of extractable water and gravitational water in each soil layer is adjusted by the amount of lateral inflow or outflow from adjacent mesh cells (CellDelta) and adjusted by inflows from other HPMs (hpmInflow) if <layer5> is part of a Hub. Inflow water is added to the soil from the water table upward and outflow water (Recharge) is removed from the water table downward. Rainfall fills the extractable water and then the gravitational water from the surface to the bottom of the cell and then from the surface upward as required:

$$WaterContent_{t,i} = InitialWC_{t-1,i} + CellDelta_{t-1} + hpmInflow_t + P_t \qquad \text{for layer i = 1,5} \qquad (15)$$

where CellDelta$_{t-1}$ is the net inflow from adjacent cells as a result of the regional solution and hpmInflow is inflow from other HPMs.

Evapotranspiration occurs from the top layer downward through the soil. The amount of potential ET that can be removed from each layer is calculated using the vegetation reference crop PET correction coefficients for each layer in the using Equation (16).

$$\text{WaterContent}_t = \text{WaterContent}_{t-1} - \sum_{i=0}^{3} Kc_{ti}\, PET_i \qquad (16)$$

where i is the index for each layer, Kc_{ti} is the PET coefficient, and PET_i is the PET remaining for layer i.
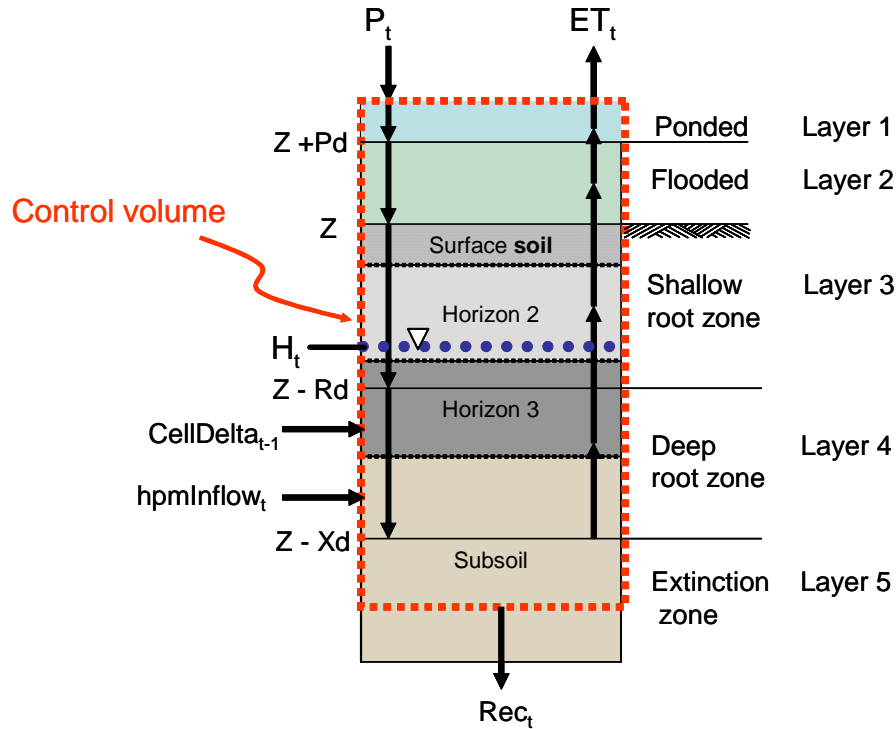

Figure 6. Control volume, water budget components and soil layers for <layer5> HPM.

The actual amount of ET removed from each layer is limited by the amount of gravitational water and extractable water. The fraction of potential ET demand satisfied by each layer is calculated progressively from the ponded layer downward. For each layer the available water is removed from the gravitational water and then from the extractable water (Ew). The Ew values are tabulated by depth for each soil horizon. Currently, only one soil horizon is implemented in RSM. After ET is complete, the water is redistributed by removing all gravitational water and then filling the soil column from the bottom to the top, first filling the capillary storage in all the layers and then the gravitational storage.

The input parameter values for the <layer5> HPM are limited to the description of the five layers in the column and the Ew for each of the soil horizons (Fig. 6). The elements and attributes used to define a <layer5> HPM are described in (Table 3). The extractable water is a depth of water equivalent to field capacity minus wilting point. The gravitational water that is equal to saturation minus field capacity is equivalent to the specific yield. The specific yield is obtained from the properties of the mesh cell to which the HPM is attached.

$$Kc = \begin{cases} Kw & H \geq Z + Pd \\\\ Kveg + (Kw - Kveg) * \left(\dfrac{\Theta i}{\Theta_{grav}}\right) & Z \leq H < Z + Pd \\\\ Kveg & Z - Rd \leq H < Z \qquad (17) \\\\ Kveg \dfrac{\Theta i}{(\Theta_{cap} + \Theta_{grav})} & Z - Xd \leq H < Z - Rd \\\\ 0 & H < Z - Xd \end{cases}$$

Table 3. Attributes for the <layer5> HPM.

Attribute	Definition	Suggested range	Typical value
Ew_i	Maximum Extractable water for soil horizon(i) i = 1, n	0.0 – 0.5	0.20
Kw	Maximum PET correction coefficient for open water	0.5 – 1.2	1.00
Pd	Ponding depth, (m)	0.0 – 2.0	0.50
Rd	Shallow root zone depth, (m)	0.2 – 2.0	0.50
Xd	Extinction depth below which there is no ET, (m)	1.0 – 10.0	2.00
Kveg	Vegetation reference crop PET correction coefficient	0.0 – 1.0	0.85

4.4 Precipitation-Runoff Routing HPM <prr>

The precipitation-runoff routing HPM <prr> is a modified version of a model originally developed by the Technical University of Denmark and which is now used by the Danish Hydraulic Institute (DHI) in the MIKE 11 model (DHI, 2000). It is characterized as a "deterministic lumped parameter conceptual model with moderate input data requirements."

In the conceptual diagram of the model (Fig. 7), Pn is excess rainfall, QOF is overland flow, ROF is routed overland flow, QIF is interflow, I is interception storage, U is upper zone storage, L is lower zone storage, G is groundwater recharge and RG is routed groundwater recharge.

In the model, water is stored as interception storage and in an upper storage zone denoted by U and a lower storage zone denoted by L (Fig. 7). Meteorological input data are precipitation, and potential evapotranspiration. On this basis, it produces catchment runoff, and groundwater recharge. The resulting catchment runoff is split conceptually into overland flow, interflow and baseflow components.
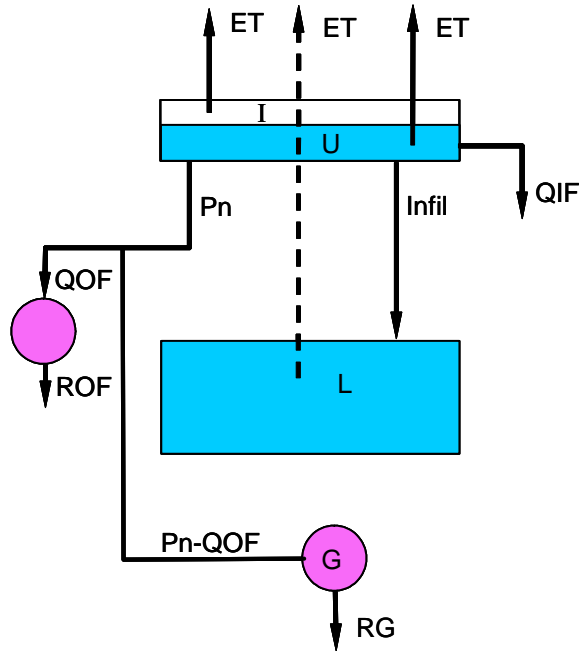
Figure 7. Conceptual diagram and water budget components of the <PRR> HPM.

Moisture intercepted on vegetation is stored as interception storage (I) with a maximum value of Imax. The upper zone storage (U) is water trapped in depressions in the soil surface and in the uppermost, cultivated part of the ground. Umax denotes the upper limit to the amount of water in the upper zone storage. Water in interception storage and in the upper zone storage is continuously depleted by evaporation. The upper zone storage is also diminished by horizontal leakage (interflow) and by infiltration into the lower zone. When the upper zone storage exceeds the maximum value, a portion of the excess water, will enter the streams as overland flow, whereas the remainder is diverted as infiltration into lower zone and groundwater storage.

When the surface storage spills, i.e. when U > Umax, the excess water, Pn = U - Umax gives rise to overland flow. QOF denotes the portion of Pn that contributes to overland flow while the remainder goes to the lower layer. Overland flow is assumed to be proportional to Pn and to vary linearly with the relative soil moisture content (L/Lmax) of the lower zone storage.

$$QOF = Pn*CQOF \frac{\dfrac{L}{Lmax} - TOF}{1 - TOF} \qquad \text{for} \quad \frac{L}{Lmax} > TOF \qquad (18)$$

$QOF = 0$ otherwise,

where CQOF is the overland flow runoff coefficient, $0 \leq CQOF \leq 1$ and TOF is the threshold value of L/Lmax for overland flow where $0 \leq TOF \leq 1$.

A portion of the remaining upper zone storage infiltrates to the lower zone storage. Infiltration is computed as

$$\text{Infil} = (1.0 - \frac{L}{\text{Lmax}})(K_{0\text{inf}})dt \tag{19}$$

where $K_{0\text{inf}}$ is the maximum infiltration rate and dt is the model time step. Infiltration is added to lower zone storage after the remaining hydrologic processes have occurred.

The interflow contribution, QIF, is assumed to be proportional to the remaining upper zone storage, U, and vary linearly with the relative moisture content of the lower zone storage.

$$\text{QIF} = \frac{dt}{\text{CKIF}} \frac{\frac{L}{\text{Lmax}} - \text{TIF}}{1 - \text{TIF}} U \qquad \frac{L}{\text{Lmax}} > \text{TIF} \tag{20}$$

$$\text{QIF} = 0 \qquad \text{otherwise,}$$

where CKIF is the time constant for interflow, and TIF is the root zone threshold value for interflow $(0 \leq TIF \leq 1)$.

The soil moisture in the root zone is stored in the soil lower zone. The maximum possible value of lower zone moisture content L is Lmax. L is subject to consumptive loss from transpiration and recharge to the groundwater.

Evapotranspiration demands are first met at the potential rate from interception storage, I, and then from the upper zone storage, U. If the total moisture content in I and U is less than these requirements, the remaining fraction is assumed to be withdrawn by root activity from the lower zone storage at the rate (Ea).

$$E_a = E_p \frac{L}{\text{Lmax}} \tag{21}$$

where E_p is remaining potential evapotranspiration after ET from I and U.

The amount of water G recharging the groundwater storage depends on the soil moisture content in the root zone and the remaining excess upper zone storage after surface runoff is subtracted.

$$G = (Pn - QOF)\frac{\frac{L}{\text{Lmax}} - \text{TG}}{1 - \text{TG}} \qquad \frac{L}{\text{Lmax}} > \text{TG} \tag{22}$$

$$G = 0 \qquad \text{otherwise,}$$

where TG is the root zone threshold value for groundwater recharge $(0 \leq TG \leq 1)$.

The lower zone storage represents the water content within the root zone. After apportioning the net rainfall (Pn) between overland flow and groundwater recharge, the remainder of the net rainfall and the infiltration increases the moisture content L within the lower zone storage.

$$L = L + Pn + Infil - QOF - G \qquad (23)$$

If L > Lmax the excess lower zone storage L - Lmax is added to the routed surface runoff. If the resulting value of L is < 0, L is set = 0. The depth of water remaining in the upper and lower zone storages are the beginning values for the next model time step.

The overland flow is routed through a linear reservoir with time constant, KOF, and the baseflow is routed through a linear reservoir with time constant, KBF. Routing can be suppressed by assigning very small values such as 1.0×10^{-13} to these parameters so that the water partitioned to overland flow or base flow is instantaneously routed from the linear reservoir storage. The equations for routing through a linear reservoir are

$$Sout = KS \frac{Sin + 2.0Sto}{1 + KS} \qquad (24)$$

$$Sto_i = Sto_{i-1} + Sin_{i-1} - Sout_{i-1} \qquad (25)$$

where KS is 0.5dt/K, the linear reservoir time constant, Sin is water added to the reservoir in the time step, Sout is water leaving the reservoir during the time step, Sto is water stored in the reservoir at the beginning of the time step, and dt is the model time step.

The data needed for the <prr> HPM are defined in Table 4. The simplified version of <prr> HPM contains nine parameters to be determined by calibration. Some of the less important parameters can be set to default values. In particular, TOF, TIF, and TG can often be set to zero.

Table 4. Attributes of the <prr> HPM

Attribute	Definition	Suggested Range	Typical values
etcoef	ET crop coefficient	0.0 – 1.0	0.8
K_{0inf}	Maximum infiltration rate, m/s	0.0 – 1.0	0.4
Imax	Maximum interception storage, m	0.0 – 1.0	0.05
Umax	Maximum upper zone moisture content, m	0.0 – 1.0	0.5
Lmax	Maximum lower zone moisture content, m	0.0 – 2.0	1.3
TOF	Threshold value of lower zone storage L for overland flow	0.0 – 1.0	0.3
TIF	Threshold value of lower zone storage L for interflow	0.0 – 1.0	0.3
TG	Threshold value of lower zone storage L for groundwater recharge	0.0 – 1.0	0.3
CQOF	Overland flow runoff coefficient	0.0 – 1.0	0.3
CKOL	Time constant for overland flow routing, hrs	0.0 – 200	47.0
CKIF	Time constant for interflow, hrs	0.0 – 2000	48.3
CKBF	Time constant for groundwater routing, hrs	0.0 – 5000	567.8

4.5 No-Action HPM <layerpc>

The no-action HPM <layerpc> simulates no hydrologic processes and requires no attributes in the XML input. When simulating three-dimensional flow under both confined and unconfined conditions there is no need to carry out hydrologic functions, but there is a need to maintain mass balance. This HPM acts as a placeholder for this function in a three-dimensional groundwater simulation.

5 Agricultural Land HPMs

The primary hydrologic characteristic of agricultural land is the use of irrigation and surface water management of excess water. Available HPMs for agricultural land model soil water, irrigation, surface water and stormwater detention. The <ramcc> HPM is a general purpose module for modeling agricultural land as simple agricultural fields. It is customizable for specific crops and irrigation schedules and computes drainage and runoff from the soil as well as irrigation demands. Several HPMs are in development for specific crops, soils and landscapes.

Additional agricultural land HPMs include <pumpedditch> and <agimp>. The <pumpedditch> HPM simulates a ditch or system of ditches that is maintained at a nearly constant water level by pumping. The water budget includes inflow, evaporation, pumping and seepage between the ditch and the aquifer. The <agimp> HPM simulates an agricultural impoundment constructed to meet local environmental and flood control requirements. It first computes the size of the impoundment and the outlet structure and then routes inflow through the impoundment to a designated water body.

The <pumpedditch> HPM can be used for urban land as well as for agricultural land. The <agimp> differs from the <urbandet> HPM described in Section 6.5 in that the agricultural impoundment typically dries out while the urban detention ponds are deep and never dry out. Typically, <pumpedditch> and <agimp> HPMs are used with <ramcc> HPM within a Hub to model agricultural land (see Section 7.1).

5.1 Agricultural Irrigation Requirement HPM <ramcc>

The RSM agricultural module HPM <ramcc> is the primary HPM used to simulate field-scale hydrology on agricultural land, including estimation of irrigation demand and drainage from agricultural land. The <ramcc> HPM is an adaptation of the Agricultural Field-Scale Irrigation Requirement System (AFSIRS) model (Smajstrla, 1990). The <ramcc> HPM is a C++ implementation of the essential components of AFSIRS Fortran model. It was designed to use the same inputs as AFSIRS and with exceptions discussed below, the <ramcc> HPM follows the AFSIRS model and the reader is referred to the AFSIRS model documentation for details on model structure, components and parameters. The details of the <ramcc> HPM processes are presented in the Ramcc Design Document (Flaig, 2005).

The <ramcc> HPM estimates gross and net irrigation requirements for selected crop type, soil, irrigation method and irrigation management type for a given daily reference crop potential evapotranspiration and rainfall time series. The model accounts for conveyance and for irrigation application efficiencies. The <ramcc> HPM has been modified to provide a more accurate accounting of crop ET and a more detailed soil moisture accounting, while AFSIRS maintains a soil water budget in the root zone. Whereas AFSIRS tracked irrigated soil moisture

and non-irrigation soil moisture, <ramcc> tracks the soil moisture in the non-irrigated root zone and non-root zone soil (Fig. 8). Rainfall is captured in interception and surface detention storage, which may infiltrate into the soil, evaporate or become surface runoff. The soil moisture is changed by rainfall, irrigation, evapotranspiration, percolation to the groundwater, upflux from the water table and lateral redistribution to adjacent soil zones (Eqn. 26).

The AFSIRS model assumes that the agricultural land is well drained. This works reasonably well for agriculture in South Florida where there is adequate drainage. When the soil water content falls below a set threshold, irrigation water is requested from a water source. The water source can be designated as the home cell, a specific well or a canal segment. The AFSIRS model calculates drainage as excess soil water that simply drains off-site, the model does not specify whether the drainage becomes runoff or aquifer recharge. In the <ramcc> HPM, excess soil water is directed to surface runoff, field drainage or aquifer recharge depending on the crop type, irrigation method and season. The surface runoff can be directed to the home cell, a well, a canal segment, a specific cell or a specific HPM. Typically the runoff is directed to an agricultural impoundment or pumped ditch when placed in a Hub. Where there is no impoundment, runoff may be directed to an adjacent canal segment or adjacent cell. The selection of the destination can be determined based on the drainage characteristics of the watershed and the time step for the RSM implementation. Where the watershed has a large volume of drainage and runoff is expected to drain to the canal network within a daily time step, the drainage destination for the runoff is set to the nearest canal segment.
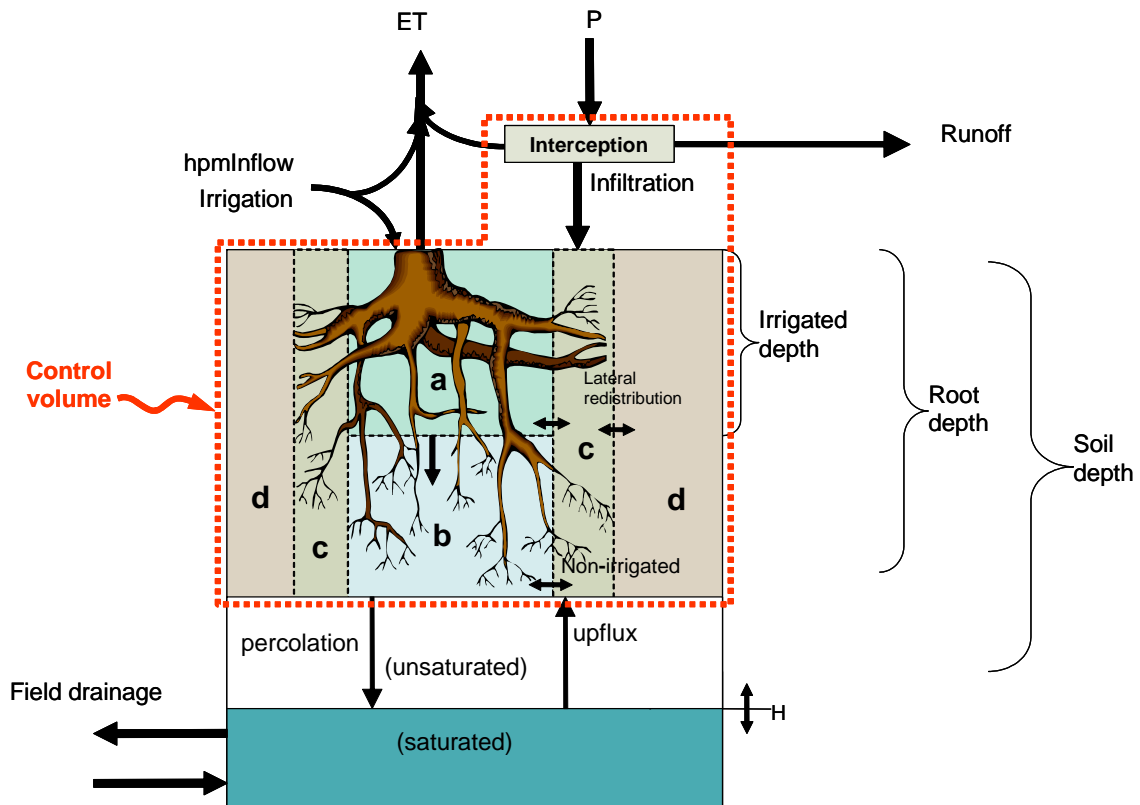
Figure 8. The conceptual scheme for water budget for soil zones (a, b, c & d) and control volume for the <ramcc> HPM.

The <ramcc> HPM calculates a daily water budget for each soil zone (i) to determine irrigation requirements.

$$STO_{t,i} = STO_{t-1,i} + P_t + IRR_t - ET_{t,i} -/+ Redist_{t,i} - Perc_{t,i} - Upflux_{t,i} \quad \text{for zone } i = a,b,c,d \qquad (26)$$

where STO is the soil water storage for each soil zone (i), P is rainfall, IRR is net irrigation, ET is crop evapotranspiration for the ith soil zone, Redist is lateral redistribution with adjacent soil zones, Perc is percolation to lower soil layers and Upflux is upward movement by soil water due to capillarity. Rainfall and irrigation are processed through surface interception storage (Fig. 8). Where typical Florida soils are not infiltration rate limited, surface detention storage is seldom exceeded. Surface runoff may occur when the water table elevation exceeds the ground elevation and the surface storage has been exceeded.

For the typical solution of optimal irrigation, IRR is the required water necessary to bring the available soil water (ASW) storage to field capacity after the ASW has fallen below a minimum soil water deficit (AWD) set for each crop. For drought conditions or fixed frequency irrigation, IRR may be reduced. The gross irrigation requirement is the net irrigation divided by the efficiency. This efficiency, which ranges from 0.5 to 0.9 for various irrigation methods, accounts for atmospheric losses and field-scale conveyance losses to drainage. The amount of ET is determined by the crop specific, reference-crop PET correction coefficient (Kc), the areal extent and depth of rooting zone and ASW. The amount of percolation is determined by soil water content and an exponential decrease in water content over time. Similarly, lateral redistribution between soil zones is modeled as an exponential decay function for water moving from the zone of high water content, typically irrigated soil, to the zone of lower soil water content. Soil water upflux from the water table into the root zone is modeled as wedge of water placed into the root zone due to the placement of the water table at the beginning of each time step.

The <ramcc> HPM requires parameters to describe crop, soil, irrigation system and irrigation management plan. The detailed description of these data can be found in Smajstrla (1990) and the HPM User's Manual (SFWMD, 2005b). The crop information includes crop correction coefficients for wetland reference crop potential evapotranspiration. These are monthly values for perennial crops and crop growth stage values for annual crops. There are allowable soil moisture deficit values for determining the allowable soil water deficit that can occur prior to irrigation. Other parameters include the root depth for the crop and the depth of irrigation for selected crops. The <ramcc> HPM uses the data for 26 perennial crops and 44 annual crops compiled by Smajstrla (1990) for Florida crops.

The crop irrigation is defined by several parameters that describe the irrigation method. The area of land irrigated (arzi) determines the areal extent of zone "a" soil (Fig. 8); for low volume irrigation it is typically 40 percent coverage while 100 percent for sprinkler irrigation of turf. The amount of water the crop gets from the irrigated soil is set by variable (exir). The irrigation efficiency determines the amount of water that is lost to the atmosphere and conveyance loss. Other parameters characterize the location of the water table that in turn affects soil zone definitions and soil water content, e.g. the depth of flood irrigation for rice and the target depth of the water table for crown flood irrigation. There is a trigger code that permits a percent reduction in irrigation during droughts as determined by the MSE. The soil zones are each described by the depth and maximum water holding capacity (maxwc).

5.2 Drainage Collector Ditch HPM <pumpedditch>

The drainage collector ditch HPM <pumpedditch> simulates canal storage where the inflow for water supply and outflow for flood control is controlled by a pump. The canal storage can be a series of collector ditches or a detention storage area internal to a farm or a canal in a water control district. The prototype is a large citrus grove or vegetable farm where runoff from the field flows to a large collector ditch system (Fig. 9).
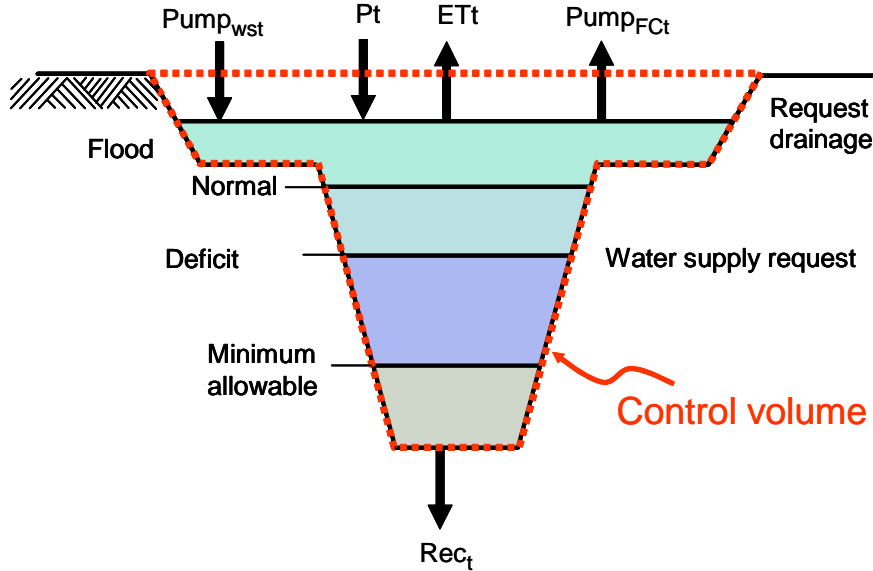

Figure 9. Schematic representation and control volume of a <pumpedditch> HPM.

The collector ditches are typically large enough to have a large storage volume as much as ten percent of the area of the agricultural parcel and are sufficiently deep to contain a substantial volume of runoff and provide a sump for the "throwout" pump. Because the collector ditch occupies a substantial area of a farm, a water budget is calculated for the ditch

$$\text{Stage}_t = \text{Stage}_{t-1} + P_t - ET_t \pm \text{Seepage}_t - \text{Pumpage}_t \tag{27}$$

where Stage_t and Stage_{t-1} are the stages at the end of time step t and t-1 respectively, P is precipitation depth, Pumpage is the inflow of water from other HPMs converted from a volume to depth as a function of the stage-volume relationship, ET is evapotranspiration at the PET rate, Seepage is seepage from the ditch to the mesh cell or into the ditch from the mesh cell and pumpage is the depth of water pumped from the ditch. The Seepage is computed as a Darcy flow between the <pumpedditch> head and the water body head (WBhead) where K is a user specified coefficient.

$$\text{Seepage} = K(\text{Stage} - \text{WBHead}) \tag{28}$$

The HPM tracks the ditch water level that is the storage divided by the area of the ditch. The ditch receives rainfall and runoff from the grove (hpmInflow). Water is lost from the ditch by evapotranspiration (ET), seepage and pumped discharge (Pumpage). This HPM interacts with the local water table only by seepage between the mesh cell and the ditch. Water is removed from the collector ditch by a throwout pump that can remove the water from the farm at a rate as high as six inches per day to a detention impoundment or an offsite drainage ditch. The pump is set to begin pumping at a specified high water level, fcPumpOn, and turn off when the collector ditch level drops below the off trigger stage, fcPumpOff (Table 9). The maximum pump rate during a time step is specified by the user. The <pumpedditch> HPM also serves as a water supply for local irrigation. Water can be removed down to a minlevel. The water supply inflow pump, wsPump, is turned on at a constant rate when the stage in the <pumpedditch> falls below fcPumpOn. When the stage rises to wsPumpoff, the water supply pump turns off. The attributes used in the <pumpedditch> HPM are provided in Table 6.

Table 6. Attributes and typical values used for the <pumpedditch> HPM.

Attribute	Definition	Suggested Range	Typical value
hpID	HPM ID	100000 – 200000	134768
percentarea	Percent area of farm occupied by collector ditches (%)	0.0 – 15.0	8.5
runoff	destination of runoff	Any water body	Homecell
rks	Seepage Coefficient (1/day)	0.001 – 0.1	0.025
wsPump	Pump rate for water supply pump (m^3/s)	0.0 – 4.0	2.0
fcPump	Pump rate for flood control pump (m^3/s)	0.0 – 4.0	2.0
fcPumpoff	Trigger elevation for water supply pump turn-on (m-NAGD)	1.0 – 6.0	3.8
fcPumpOn	Trigger elevation for water supply pump turn-on (m-NAGD)	<= 0	4.2
wsPumpOn	Trigger elevation for water supply pump turn-on (m-NAGD)	0 – 50	3.0
wsPumpoff	Trigger elevation for water supply pump turn-on (m-NAGD)	0 – 50	3.5
maxLevel	Trigger elevation for water supply pump turn-on (m-NAGD)	0 – 50	8.0
minLevel	Trigger elevation for water supply pump turn-on (m-NAGD)	0 – 50	2.0
bottom	Bottom Elevation of ditch (m-NAGD)	0 – 50	1.0

Although developed for large farms and groves, the pumped ditch can be used for golf courses, urban developments and internal canals of drainage districts where the discharge is controlled by a pump.

5.3 Agricultural Impoundment HPM <agimp>

The agricultural impoundment HPM <agimp> was created to simulate the impoundments required by the Surface Water Regulation permitting process developed by SFWMD. All agricultural operations constructed since the mid-1980s have been required to construct an impoundment to capture runoff such that post-development runoff does not exceed pre-development runoff. The Environmental Resource Permit Information Manual, Volume IV (SFWMD, 2000) provides the design specifications for agricultural impoundments. The design specifications provide criteria for the impoundment size and discharge structure (weir and bleeder) characteristics. Review of the agricultural permits from Caloosahatchee watershed indicates that the farms in that region have constructed the agricultural impoundments closely according to the specified criteria and thus the design criteria can reasonably be used to simulate agricultural impoundments in the model. The <agimp> HPM uses input parameters to compute the size of the impoundment and the design of the outlet structure, and then uses the resulting structure design to compute discharge from the impoundment as a function of stage.

The dimensions of the <agimp> HPM are determined by the design criteria presented in Volume IV (SFWMD, 2000). The crest elevation of the discharge weir is determined by the wet season water table elevation. The crest elevation of the rectangular discharge weir is set above the wet season water table to store the first inch of runoff. The invert of the bleeder is set at the wet season water table. If the impoundment is designed to protect enclosed wetlands, the crest may be raised an additional one or two feet. The storage volume of the impoundment is determined by the runoff created by the 25-year, 3-day, design-storm rainfall, r25y3d (Trimble, 1990). The amount of runoff is determined by the Natural Resources Conservation Service (NRCS) curve number method (USDA-NRCS, 1985):

$$Q = \frac{(r25y3d - 0.2S)^2}{r25y3d + 0.S}$$ (29)

where S is the available soil storage. The soil storage depends on the soil type and landscape and the depth to the wet season water table. The value for S is determined from the soil series. The design volume of the impoundment is determined by the design runoff times the parcel area. The maximum design head is set by dividing the required storage volume by the impoundment area. The length of the discharge weir is determined by considering the allowable basin discharge (Fig. 10).
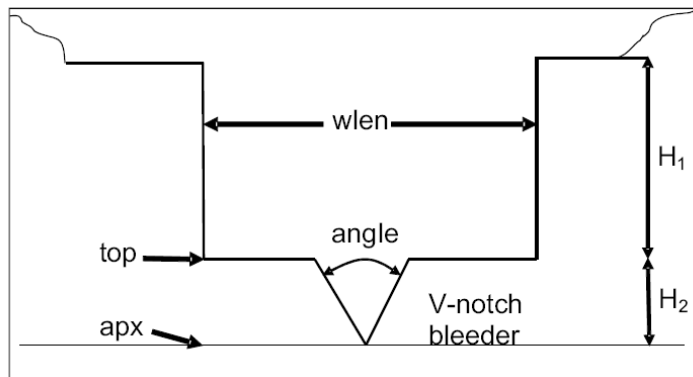

Figure 10. Dimensions of discharge weir with V-notch bleeder for agricultural impoundments <agimp> HPM and urban detention ponds <urbandet> HPM.

$$wlen = \frac{AllowableDischarge}{3.13 DesignHead^{1.5}}$$ (30)

There is a bleeder device below the crest that allows for the discharge of the first inch of runoff at a rate 0.5 inch/day or less for water quality protection. Typically, a V-notch bleeder is used to control this discharge. The discharge rate from the bleeder is calculated by the following equation:

$$Q = 2.5 \tan\left(\frac{\Theta}{2}\right) H^{2.5}$$ (31)

where Θ is the angle of the V-notch and H is the elevation of the pond stage behind the weir. Since the discharge decreases as the water level decreases, the time average of the discharge, as the first 0.5 inch of runoff is discharged, in 24 hours is

$$Q_{avg} = 0.41\left[2.5 \tan\left(\frac{\Theta}{2}\right) H_{max}^{2.5}\right]$$ (32)

where the factor 0.41 is computed from the time average of Q, and H_{max} is the head in the impoundment storing the first inch of runoff.

Since Q_{avg} and H_{max} are known, this equation is used to calculate the angle of the V-notch weir. When the head is above the crest of the rectangular weir, the V-notch weir is treated as an orifice and the discharge from the impoundment is calculated by the following equation.

$$Q = 4.8 H_2 \tan\left(\frac{\Theta}{2}\right)\left(H_1 + \frac{H_2}{3}\right)^{0.5} + 3.13 \, L \, H_1^{1.5}$$ (33)

where H_1 is the head above the weir crest, H_2 is the height of the V-notch bleeder, and L is the length of the rectangular weir.

The first term describes discharge through the V-notch bleeder and the second term describes discharge through the weir. When the head is at or below the top of the rectangular weir Equation 34 is used for flow through the V-notch weir where H is the head above the bottom of the V-notch weir.

The <agimp> HPM estimates the volume of the surface water runoff detention impoundment and the dimensions of the discharge structure. The impoundment is assumed to be constructed above grade so that the detention drains down to land surface. The storage in the impoundment includes water in the unsaturated zone between the land surface and the root depth. There is an option to provide a storage-volume converter that accounts for borrow ditches or other excavations within the impoundment. The design criteria include setting the discharge weir invert high enough to protect included wetlands. Unlike urban detention ponds, the <agimp> HPM is expected to dry out unless it is designed to protect wetlands.

Water loss from the <agimp> HPM occurs through evapotranspiration and seepage computed as a function of the head difference between the impoundment stage and the mesh cell head, and through flow from the discharge structure. Discharge from the impoundment is integrated over the time step of the RSM. It was originally assumed that RSM would use a daily time step. Unlike the <ramcc> HPM and the <pumpedditch> HPM that assume complete discharge for each day, the discharge from the <agimp> HPM occurs over several days. To accomplish this, the discharge for a given day is calculated by a loop that integrates the discharge at 30-minute intervals during each day. For time steps less than a day the discharge is calculated as a fraction of the expected daily discharge. The water volume of the impoundment is calculated for each time step so the mass balance is maintained.

The <agimp> HPM is useful for any water storage area that dries out and for which discharge is controlled by a weir/bleeder. It may be appropriate to treat the drainage canals and effective runoff detention of selected Water Control Districts that connect to the primary system as large <agimp> HPMs. The attributes for the <agimp> HPM are provided in Table 7.

Table 7. Elements, attributes and typical values used for the <agimp> HPM.

Attribute	Definition	Suggested range	Typical values
psID	HPM ID	100000 – 200000	157843
percentarea	Percent area of parcel in impoundment (%)	5.0 – 25.0	15
runoff	Destination of runoff	Any water body	Hub
rks	Seepage coefficient (1/day)	0.001 – 0.1	0.03
height	Wet season water table elevation (m – NVGD)	0.0 – 15.0	3.6
rd	root depth (bottom of storage) (m)	0.0 – 1.5	2.6
r25y3d	Rainfall depth for 25-year, 3-day return period storm (m)	0.08 – 0.32	5.2
allow	Allowable basin discharge (m^3/s)	0.1 – 1.0	1.5
s	Abstraction in the NRCS runoff method (m)	0.7 – 1.0	0.85

6 Urban HPMs

The key characteristic of simple urban HPMs is the amount of impervious land that results in greater runoff and reduces the amount of evapotranspiration. The simplest urban HPM is for impervious land. It is possible to represent a fraction of the urban land as turf grass representing lawns and landscaping, and model that land using <rsmcc>. Urban land can also be modeled using the precipitation-runoff routing HPM <prr>, which can be calibrated for stormwater detention and routing. The two simple HPMs designed for simulation of urban areas are

- The impervious land HPM <imperv> simulates impervious areas with rainfall, ET, surface storage and runoff. There is no recharge to the underlying soil.
- The multibasin routing HPM <mbrcell> provides a simple runoff model that combines the Natural Resources Conservation Service (NRCS) curve number runoff algorithm with simple linear reservoir routing.
- Consumptive use <cu> HPM allows the extraction of water from wells for domestic or other use and the return of used water through sewers or septic systems.

- Retention/detention storage and discharge is modeled using the <urbandet> HPM. Water is input from other HPMs and rainfall and leaves through ET, seepage, and discharge through the outlet structure.

6.1 Impervious Area HPM <imperv>

Specific hydrologic processes occurring on impervious areas include rainfall, evaporation, interception, surface detention and runoff. The control volume for the <imperv> HPM is presented in Figure 11. These processes are simulated by the <imperv> HPM, using Equations 34 through 37. Rain falls directly on the roofs and sidewalks where some is intercepted by plants, buildings, and other structures as well as stored as a thin layer over the surface that is a function of surface roughness. Inflow from other HPMs in the Hub is added to interception storage at this time. Evaporation removes water from the interception storage at the rate of PET.

$$IntSto_i = IntSto_{i-1} + Rain + hpmInflow - Evap \qquad (34)$$

If the remaining interception storage is greater than a user input maximum interception storage, the excess (IntRunoff) enters depression storage; depressions in the impervious surface such as holes and other low areas.

$$IntRunoff = IntSto - MaxIntSto \qquad (35)$$

Water is then evaporated from depression storage up to any remaining PET and the depression storage in excess of the user input maximum becomes runoff that is directed to a user designated water body such as a canal or a detention pond <urbandet> HPM, or to a pervious area of another HPM, or a pervious area within the Hub.

$$DetSto_i = DetSto_{i-1} + IntRunoff - DetET \qquad (36)$$

$$Runoff = DetSto - MaxDetSto \qquad (37)$$
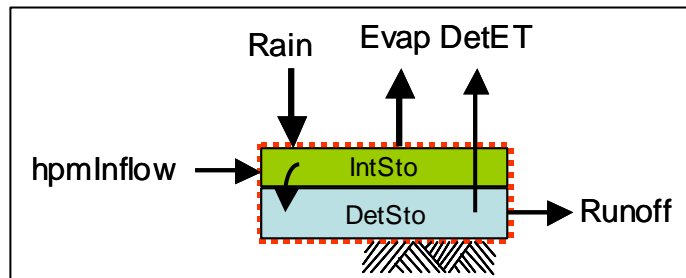

Figure 11. Conceptual water budget and control volume for impervious land <imperv> HPM.

The <imperv> HPM has two instances; undirectly connected impervious area, UCIA, representing roofs and sidewalks and directly connected impervious area, DCIA, representing roads and storm sewers. For DCIA the impervious area is directly connected and five percent of the runoff is lost as seepage from storm sewers and drainage ditches. The <imperv> HPM is implemented with the attributes shown in Table 8.

Table 8. Attributes for the <imperv> HPM.

Attribute	Definition	Range	Example
dirconn	Specifies directly or indirectly connected	0=DCIA, 1=UCIA	1
isto	Maximum interception storage depth, (m)	0.001 – 0.1	0.03
isto1	Initial interception storage depth, (m)	0.001 – 0.1	0.02
sdet	Maximum depressional surface storage depth, (m)	0.01 – 0.2	0.08
sdet1	Initial depressional surface storage depth, (m)	0.01 – 0.2	0.05

6.2 Multi-Basin Routing HPM <mbrcell>

The multibasin routing HPM <mbrcell> provides a simple HPM for modeling urban runoff and routing. Urban areas are different from natural areas mainly because of the more rapid runoff in urban areas with less infiltration and recharge. Much of this runoff occurs before the soil is fully saturated. For urban runoff, the time of concentration is short because of a high percentage of impervious land and numerous drainage canals and storm sewers. The runoff approach in the <mbrcell> is similar to the NRCS curve number method (USDA-NRCS, 1985) for calculating the volume of runoff. The runoff volume is routed through a linear reservoir to control the hydrograph timing. The NRCS method is used because of its simplicity and because the method accounts for unsaturated soil moisture and infiltration. The linear routing is based on the Multi-Basin Routing model (MBR) used in the South Florid Water Management Model (SFWMM) (SFWMD, 1998). The <mbrcell> HPM is different from the MBR model in the SFWMM because of the accounting of infiltration and treatment of flooding conditions.

The <mbrcell> HPM is an uncoupled HPM in that the water table head is not explicitly tracked. The change in head of the underlying mesh cell is not used to adjust the head in the saturated zone. The <mbrcell> assumes that the water table is always below the root zone. In the <mbrcell> HPM there are three water storages (Figure 12). The control volume for <mbrcell> accounts for water storage in compartments; saturated zone, unsaturated soil storage and urban detention.
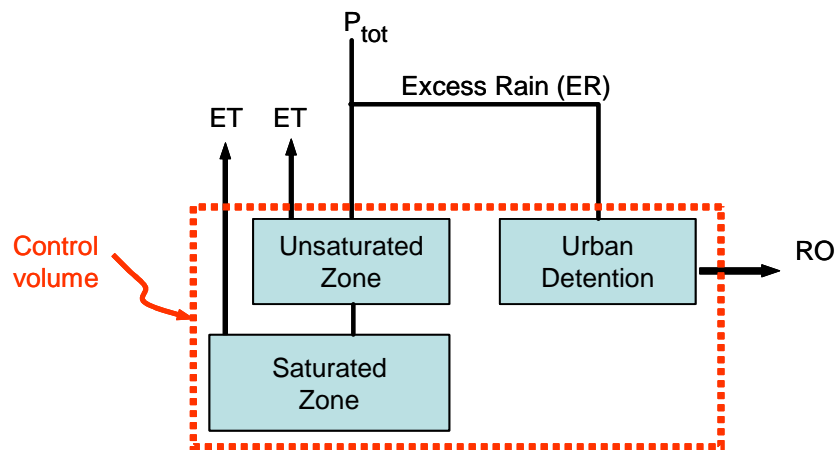

Figure 12. Control volume and water budget components for <mbrcell> HPM.

The unsaturated layer takes a fraction of the rainfall according to the NRCS curve number method. The excess rainfall (runoff) is directed to urban detention (linear reservoir). Any excess water from the unsaturated soil (greater than field capacity) enters the saturated layer. ET is withdrawn from the unsaturated layer first, and the saturated layer next. Urban detention storage retains the water that is not routed in the current time step.

The Natural Resources Conservation Service (NRCS) curve number (CN) method was developed to determine the volume of runoff from a given amount of precipitation. The method is based on the following relationship with all the quantities specified in units of depth.

$$\frac{F}{S_{pa}} = \frac{Q}{P_e} \tag{38}$$

where P_{tot} is accumulated total storm rainfall for each day, I_a is initial abstraction, P_e ($= P_{tot} - I_a$) is effective storm runoff, F ($= P_e - Q$) is infiltration occurring after the beginning of runoff, S_{pa} is potential abstraction and Q is runoff. Since it is normally assumed that $I_a = 0.2S$, runoff can be computed as

$$Q = \frac{(P_{tot} - 0.2S_{pa})^2}{P_{tot} + 0.8S_{pa}} \tag{39}$$

In the \<mbrcell\> the CN approach is modified by evaluating the potential abstraction at every time step and controlling the timing of direct runoff by using a linear reservoir routing approach. The use of a curve number is avoided by using soil moisture values from the model itself. The potential abstraction is computed as:

$$S_{pa} = (z - h)(Sy + Fld\_cap) - uns \tag{40}$$

Where Sy is specific yield, Fld_cap is field capacity (maximum soil water storage in unsaturated zone, uns is water storage in the unsaturated zone, z is land surface elevation and h is head. The \<mbrcell\> HPM maintains the head (h) in the soil, which is a combination of the saturated zone and the unsaturated zone

$$h_t = h_{t-1} + P - ER - ET \tag{41}$$

The water budget in \<mbrcell\> HPM is not connected to regional solution as other HPMs are connected; the saturated zone is expected to be well below the ground elevation for this HPM to work properly.

Excess rainfall (ER) is then computed as

$$ER = \frac{(P_{tot} - 0.2S_{pa})^2}{P_{tot} + 0.8S_{pa} + uns} \tag{42}$$

which differs from the standard NRCS curve number method by the addition of the variable "uns" in the denominator.

The second function of the <mbrcell> is to route the water using a linear reservoir model. If the urban catchment has a time of concentration of t_c, and if the time step used in the simulation is dt, then the amount of discharge (RO) leaving the catchment during one time step is

$$RO_t = ER(1.0 - K_S) + K_S RO_{t-1} \qquad (43)$$

in which,

$$K_S = \frac{t_c - 0.5\,dt}{t_c + 0.5\,dt} \qquad (44)$$

RO_{t-1} is the discharge at time step t-1, ER is the runoff during the current time step and K_s is surface routing parameter based on time of concentration.

Evapotranspiration (ET) is computed using the following equations with z being the elevation of the ground surface.

$$ET = Kc * PET \qquad (45)$$

where

$$Kc = \begin{cases} Kveg & h > D_{shallow} \\[2ex] \dfrac{[h - D\_deep)]}{[D\_deep - D\_shal]} * Kveg & D\_shal > h > D\_deep \\[2ex] 0 & h < D\_deep \end{cases} \qquad (46)$$

where D_shal and D_deep are depths of the shallow and deep root zones respectively and Kveg is a crop coefficient for ET.

Once runoff and ET are subtracted from rainfall, the remaining water is added to the unsaturated zone. When the unsaturated zone is filled to field capacity the remaining water is added to the water table, which increases the head. If there is enough water, ponding occurs. In the current implementation, the amount of runoff in excess of the routed runoff, Q - RO, remaining in the linear reservoir, is lost from detention as ET. The intent is to calibrate the runoff algorithm so there is no excess runoff. The attributes for the <mbrcell> HPM are provided in Table 9.

Table 9. Elements, attributes, and typical values used for the MBRcell HPM.

Attribute	Definition	Suggested range	Typical values
Route	waterbody ID for destination of discharge	Any valid water body ID	7
tc	Time of concentration (s)	900 – 50,000	3,600
Kveg	Evapotranspiration crop coefficient	0.0 – 1.0	0.85
D_shal	Shallow root zone depth (m)	0.5 – 3.0	1.0
D_deep	Deep root zone depth (m)	1.0 – 5.0	3.5
Fld_cap	Water content at field capacity (m)	0.0 – 2.0	0.2

6.3 Consumptive Use HPM <cu>

The consumptive use <cu> HPM is used to distribute water used in homes and other urban uses from water supply sources. The distinction between consumptive (CU) and non-consumptive use of water is a critical aspect of effective water management. Consumptive use of water means that water is not directly returned to the water source from which it was withdrawn. Non-consumptive water use means that, after use, the water is directly returned to the source for use by others. Urban consumptive use is an important component of surface and shallow water table aquifer hydrology, particularly during the dry season. During the dry season, water use for lawns and landscaping is high due to the lack of rainfall, and the higher population of seasonal residents. Although a portion of CU can be modeled as a stress on the aquifer at the locations of public water supply wells and a discharge at the sewage treatment plants, a substantial portion of CU does not return to treatment plants and is either used for landscaping or is discharged through septic fields. There are also several small water supply systems that provide water for individual mobile home parks and other small developments. These systems have small package plants (POTWs) to handle the wastewater.

The volume of CU for each parcel is determined by the land use type. A lookup table provides the volume of water used by each of the primary Florida Land Unified Classification System (FLUCS level II) urban classes. This information is based on data obtained from the USACOE to determine overall urban water use. The volume of CU in a Hub is determined by the sum of the CU of each of the urban land uses.

The fate of CU water is determined by the areal extent of the public water supply coverage area and the areal extent of the sewage connections. Areas outside that boundary are assumed to have local disposal. Local disposal is through a seepage field, either individual or community. Although the design of most seepage fields is intended to have discharged water consumed by evapotranspiration, it is expected that the water will percolate to the water table aquifer.

Consumptive use is simulated by the <cu> HPM that is defined within the <Hub> environment. The attributes used to specify consumptive use are detailed in Table 10.

Table 10. Elements and attributes for the <cu> object.

Attribute	Definition	Suggested Range	Typical value
	<cu>		
label	High density or low density urban land use	HI or LI	HI
percentarea	Percent area of the Hub with the specified consumptive use (%)	0 – 100	50.0
wsupply	Water supply source	Any waterbody	Hub
	<sewer>		
fracloss	Fraction of water lost from sewer system to groundwater	0.0 – 1.0	0.1
septic	Discharge water from CU goes to homecell rather than directed waterbody		

6.3.1 Drought Management

Drought management is modeled as part of HPM water supply. For urban consumptive use the user inputs a reduced volume of consumptive use assigned to each urban land use and by a trigger value that reduces the volume of water used to irrigate the urban turf and landscaping. The CU reductions are based on the expected reduction identified by implementing the selected water conservation practices. The application of irrigation water is reduced by a known fraction according to the phase of water restrictions the basin is experiencing.

Phase I   = 15 percent irrigation reduction
Phase II   = 30 percent irrigation reduction
Phase III   = 45 percent irrigation reduction
Phase IV   = 60 percent irrigation reduction

For agricultural land, a trigger value is used to reduce the volume of irrigation calculated for each crop by the appropriate factor.

6.4 Urban Stormwater Retention/Detention HPM <urbandet>

Urban stormwater runoff may be collected and routed through a stormwater detention facility. This facility may include detention for water quality treatment, a retention pond or a stormwater detention pond. Typically, ditches, swales or storm sewers capture runoff that is discharged to a pond designed to meet the SFWMD stormwater permit requirements (SFWMD, 2000). The ponds are typically deep and not likely to dry out even during droughts. The area of the pond is typically determined by the type of urban land. The detention pond is simulated by the HPM <urbandet> in a Hub.

The storm water detention area is treated as a pond with a discharge weir. The storage (S) in the detention pond changes in a time step according to Equation 47.

$$S_i = S_{i-1} + \text{Rain} + \text{hpmInflow} - \text{ET} - \text{seepage} - \text{Discharge} \tag{47}$$

where hpmInflow is the inflow from other HPMs in the Hub, ET occurs at the PET rate, Discharge is the flow from the outlet structure on the pond and Seepage recharges the groundwater.

$$\text{Seepage} = \text{rks}(H_{pond} - H_{cell}) \tag{48}$$

where rks is a user specified seepage coefficient.

Because the <urbandet> HPM assumes that the RSM operates on a daily time step, a simple hydrologic routing is conducted during each day to calculate the daily water loss from each impoundment. The water budget is calculated for 48 intervals during each time-step, or at 30-minute intervals for a daily time step. Rainfall is added to the impoundment in equal values during the afternoon hours and ET is removed from the impoundment in equal values during daylight hours. Recharge to the shallow aquifer occurs as seepage based on the difference in head between the pond and the surficial aquifer.

The criteria for detention pond weirs are as follows: for water quality protection, the urban land is required to retain the first one-inch of runoff from the total parcel area or 2.5 times the area of impervious land. The pond is required to retain the runoff from the 25-year, 3-day design storm in the pond. The invert elevation for the bleeder on the discharge structure can be set no lower than the elevation of the average wet season water table. The discharge from the pond into waters of the state can not exceed one-half inch of runoff per day. The maximum allowable discharge for the pond can not exceed the allowable discharge rate for the subbasin in which the project is located. The allowable discharge for each sub-basin is determined based on the conveyance capacity of the ditches and canals. This information is all preprocessed and input by the modeler.

The discharge structure characteristics are determined using the methods in ERP Volume IV (SFWMD, 2000) using the parcel size, impervious area, pond area, allowable basin discharge, and the 25-year, 3-day return period rainfall volume. The characteristics of the discharge structure include the dimensions of the V-notch bleeder (angle and top elevation) and the length of the sharp-crested rectangular weir (wlen). Discharge from the detention pond through a small rectangular weir and V-notch bleeder as described for the Agricultural Impoundment.   The attributes used to specify an <urbandet> HPM in a Hub are presented in Table 11.

Table 11. Attributes for the <urbandet> HPM.

Attribute	Definition	Suggested range	Example
psID	HPM ID	10000-20000	157843
percentarea	Percent area of parcel in impoundment (%)	5.0 - 25.0	8.5
runoff	destination of runoff	Any waterbody	Hub
rks	Seepage coefficient	0.001- 0.1	.007
vnotchweir	Designates the <vnotch weir> outlet structure		
wlen	Length of rectangular weir (m)	0 – 10	7.5
angle	Angle of V-notch weir (deg)	0 – 120	75.0
top	Elevation of top of v-notch bleeder and invert of the rectangular weir (m NGVD)	0 – 20	13.6
apx	Elevation of invert of v-notch bleeder (m, NGVD)	0 – 20	11.4

7 Water Management Systems HPMs <Hub>

The simple HPMs described above are useful for modeling simple landscapes and uniform land use types with simple hydrology. In water management systems with complex landscapes or land use types with highly managed local hydrology, it is necessary to use complex HPMs to obtain an appropriate description of the hydrology. The principal tool for modeling the complex local hydrology is the Hub. The Hub allows the combination of several HPM types based on areal distribution. The Hub also allows for the implementation of additional HPM types that handle local routing.

Although simple urban (PRR) and agricultural (ramcc) HPMs can be used to simulate simple, relevant features of the landscape, such as irrigation demand and accelerated runoff, the landscape of South Florida is more complex and the local hydrology can be better represented by implementing water management systems. Water management systems can be represented by

the use of Hubs. Hubs have the capability of linking several HPM types together to model the hydrology of urban and agricultural developments.

The Hub is normally used to model an urban area or a large agricultural operation that has a mixture of land uses and a single water source and runoff destination. This is appropriate for citrus groves or vegetable farms that withdraw irrigation water from a single well or canal and discharge it through a pump or weir to an off-site canal. A single composite HPM is created for all of the mesh cells within the farm. The composite HPM identifies which HPM types are in the Hub, the percent of the total land in each type, water source for each HPM type and the destination for runoff from each HPM type. For example, in Figure 13 a citrus grove may have 60% ramcc-citrus, 15% wetlands, 10% pumped ditches and 15% agricultural impoundment. The water source is a single well for ramcc. The ramcc area drains to the pumped ditch and the pumped ditch drains to the <agimp> impoundment, which drains to a canal. The composite HPM is applied to each mesh cell in the grove. An alternative configuration could have the runoff from 40% of the ramcc drain to the pumped ditch and 20% of the ramcc drain to the isolated wetland. The wetland would drain to the home cell (immediately below the HPM). Use of a Hub simplifies the development of HPMs as well as creates a better representation of the farm operations.

A Hub is appropriate where the group of simple HPMs can be applied uniformly for all cells in the Hub and the resulting seepage and water use can be applied uniformly. However, where the location of the impoundment or pumped ditches is important an agricultural Hub and an <agimp> HPM can be linked to obtain the appropriate functionality. The attributes required to create a Hub are listed in Table 12.

Table 12. Elements and attributes for the <Hub> HPM.

Attribute	Definition	Suggested range	Example
wsupply	Source of the water supply	Any waterbody, well, HPM	well-342
sewer	Destination of sewer flow	Any waterbody, well, HPM	wb-3454
runoff	Destination of Hub runoff	Any waterbody, well, HPM	homecell
percentarea	Percent of the Hub covered by HPM	0.0 – 100.0	20.0

The preferred implementation of HPMs will be the utilization of a small number of simple HPM types applied throughout the domain, on a one HPM per mesh cell basis. For example, all cells with a greatest percent of any land use type within the cell become citrus cells. This is appropriate where the source of irrigation comes from the cell and runoff is directed to the cell. If each citrus cell requires a specific well or discharges to a specific canal segment, it is necessary to have a unique HPM for each mesh cell. Where there are large blocks of citrus that use the same well, these can be consolidated into a Hub and that unique HPM can be applied to several cells.

There are several HPMs that have been developed to work within the Hub construct. These HPMs interact with other HPMs to provide a better representation of the urban and agricultural landscape. These HPMs are listed here and described in detail in the following sections.

7.1 Large Agricultural Developments

Typically, the local hydrology for agriculture is conceptualized as a series of containers that represent the agricultural field including root zone soil, runoff collector ditch systems and stormwater detention impoundments. Water moves among the storage containers within the time step of the model such that the hydrodynamics of water movement are not simulated. Three HPMs are classified as agricultural HPMs: <rsmcc>, <pumpedditch> and <agimp>.

Water in the agricultural HPMs does not interact directly with the mesh cell water bodies except for seepage to/from groundwater. When the RSM is run on a daily time step this is adequate. When the time step is substantially shorter, the processes such as evapotranspiration, rain, runoff and irrigation can be adjusted to better reflect the appropriate time of occurrence of each event. For example, rain and runoff occur primarily during the afternoon while irrigation occurs primarily during the morning. Figure 13 shows an agricultural area. This area might be modeled by <ramcc> for the agricultural land and fields, <pumpedditch> for the drainage system, and <agimp> for the impoundment. These three agricultural HPMs are discussed in detail in the next section, except ramcc, which is described above in Section 5.1.
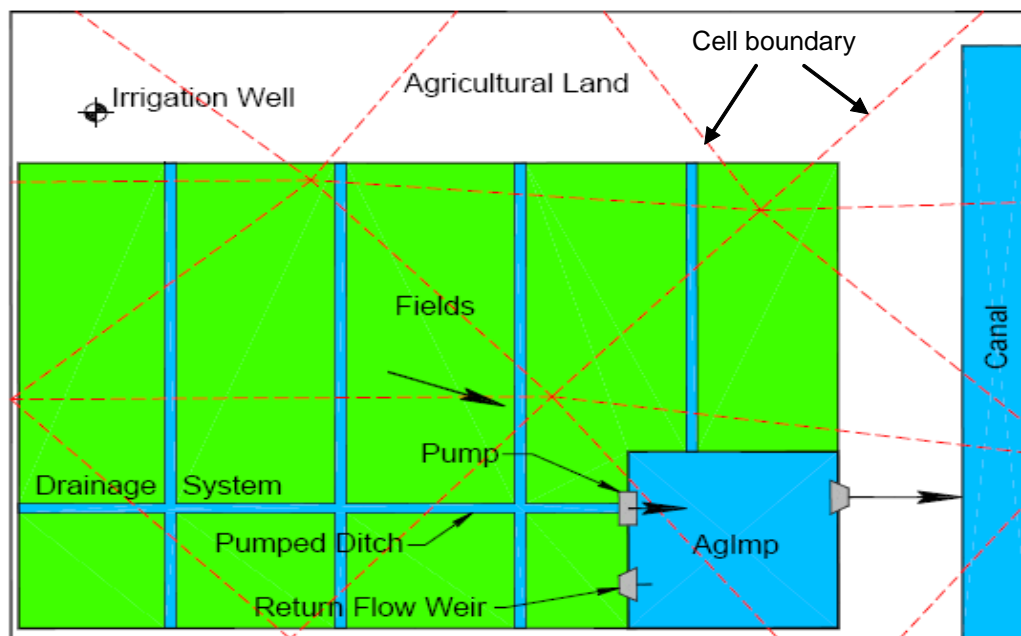

Figure 13. Schematic hydrology for agricultural land Hub.

7.2 Urban Developments

Urban developments have complex hydrology that can best be modeled using the Hub. This provides the mechanism to combine the hydrology of impervious land, pervious land, stormwater detention, urban consumptive use and disposal of septic water.

Urban hydrology differs from natural and agricultural hydrology in that significant areas are impervious and runoff is often routed through storm sewers and ditches to detention basins, canals, or other water bodies. Lawns, parks and other open areas are often irrigated, and water is withdrawn from the saturated zone for irrigation and domestic use and returned to the soil through septic drain fields, leaking ditches and sewers, and infiltration from irrigation. Urban areas can be simulated by associating several types of HPMs with the mesh cells in an urban area through the use of a <Hub>.

An urban area is shown schematically in Figure 14. The areas in the figure represent directly connected impervious areas (DCIA) such as parking lots, roads and storm sewers, unconnected impervious areas (UCIA) such as roofs and sidewalks, pervious areas (PA) such as lawns and landscaped areas, a detention pond (Det) and a canal. The UCIA and DCIA areas could be modeled with the <imperv> HPM, the PA area by <ramcc> and the detention area by <urbandet>. This is the urban landscape used in the Surface Water Management Model (Huber and Dickinson, 1988). In the typical urban development a large portion of the landscape is impervious area. The runoff from these areas either drains to the pervious area, to onsite detention or offsite to a secondary canal. Urban areas that have surface water permits will have onsite detention ponds. The urban developments receive water from offsite public water supply wells (PWS), are self-served or have both where landscape irrigation comes from a local source. The hydrologic characteristics of each of these areas is described below as well as consumptive use, <cu>, and the impacts of drought on the hydrology of an urban area.
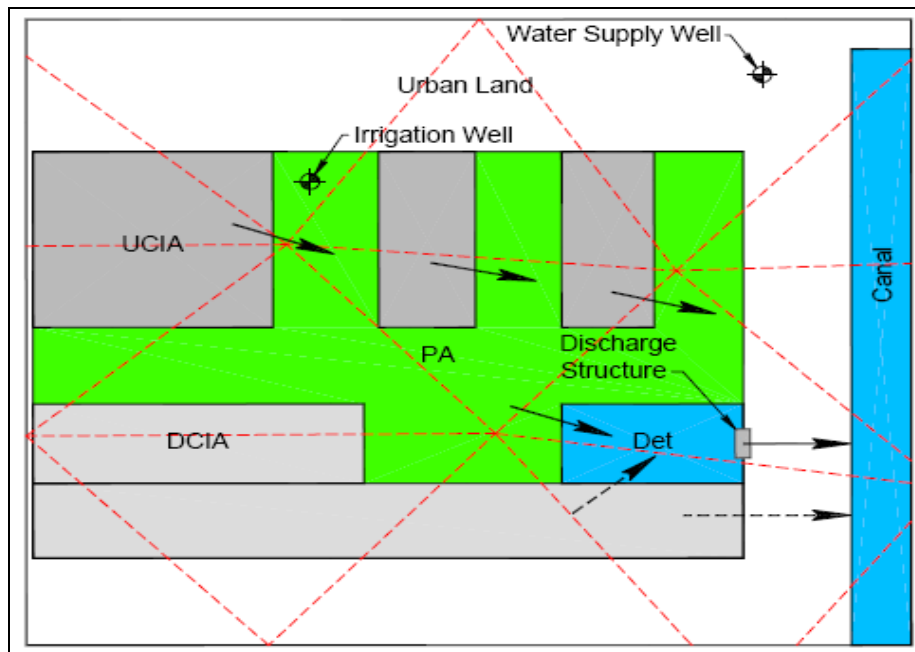

Figure 14. Schematic hydrology for urban land Hub.

In the urban area the pervious areas are typically covered with grass or landscaping shrubbery. The cover is assumed to be uniform turf or landscaping that is irrigated frequently. The pervious area is treated as agricultural land and simulated using the <ramcc>. This model simulates the water budget in the soil based on water storage capacity, rainfall, evapotranspiration, drainage

and irrigation. Evapotranspiration is estimated from potential ET modified by a crop coefficient. The infiltration rate is ignored in this application, since the RSM has a daily time step and infiltration is assumed to be complete within a day. The PA infiltration rate is generally similar to the rate of an open field but may be substantially lower depending on the amount of traffic on the site. Drainage is a simple excess inflow over soil water storage. The drainage from <ramcc> is divided into seepage or recharge to the cell and runoff contribution to a detention pond where appropriate, with off-site discharge to a canal.

8 Testing Hydrologic Process Modules

8.1 Numerical Experiments

8.1.1 PRR HPM

An experiment was carried out to understand the behavior of the PRR HPM to changing variables and parameters. The purpose of the experiment is to understand the use of HPMs in upland areas of completely unknown regions. A rainfall data set from the Kalawewa Basin of Sri Lanka was used for this purpose because this is a unique example of a basin where only the annual water budgets and the rainfall are known in terms of parameters. The basin has a tropical forest landuse type. About 26% of the rainfall is known to run off into the ocean. Starting with the parameters shown in Table 13 the influence of a number of parameters on the 1999 water budget was investigated in this experiment.

A 3x3 RSM mesh was used in the experiment to test the PRR HPMs. Figure 15 shows the mesh and the boundary conditions. In the mesh, the row of cells 2, 11, 5, 14, 8 and 17 is isolated by assigning no-flow boundary conditions along the node lists 2-6-10-14 and 3-7-11-15. Rain is applied on middle cells 5 and 14 while keeping cells 2, 8, 11 and 17 dry. The purpose is to monitor the behavior of cell 5 for the immediate rain impact and the downstream dry cell 11 for the movement of the flood peak. The output is analyzed for water budget components of rain, ET, runoff and seepage when various parameters and variables are changed. The purpose is also to understand the behavior of the level and the lag in the flood peak when various parameters are altered.
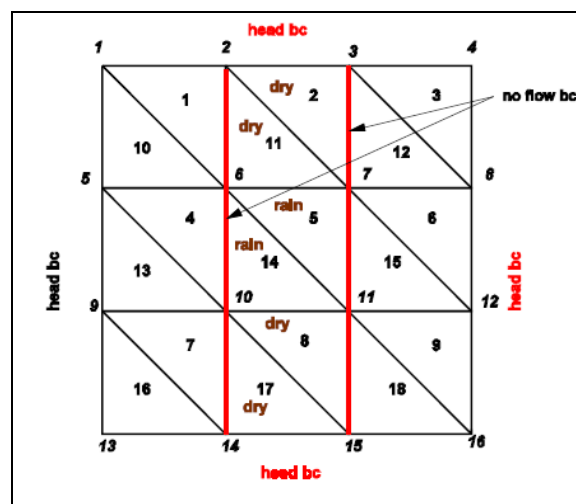

Figure 15. The mesh used to test the HPMs.

Behavior of the PRR Model with Variation of Selected Parameters

Sensitivity of the water budget to PET, water level, lmax, CQOF, CKOL, CKBF and routing is examined in this section.

Table 13. Values of PRR parameters obtained from a calibration.

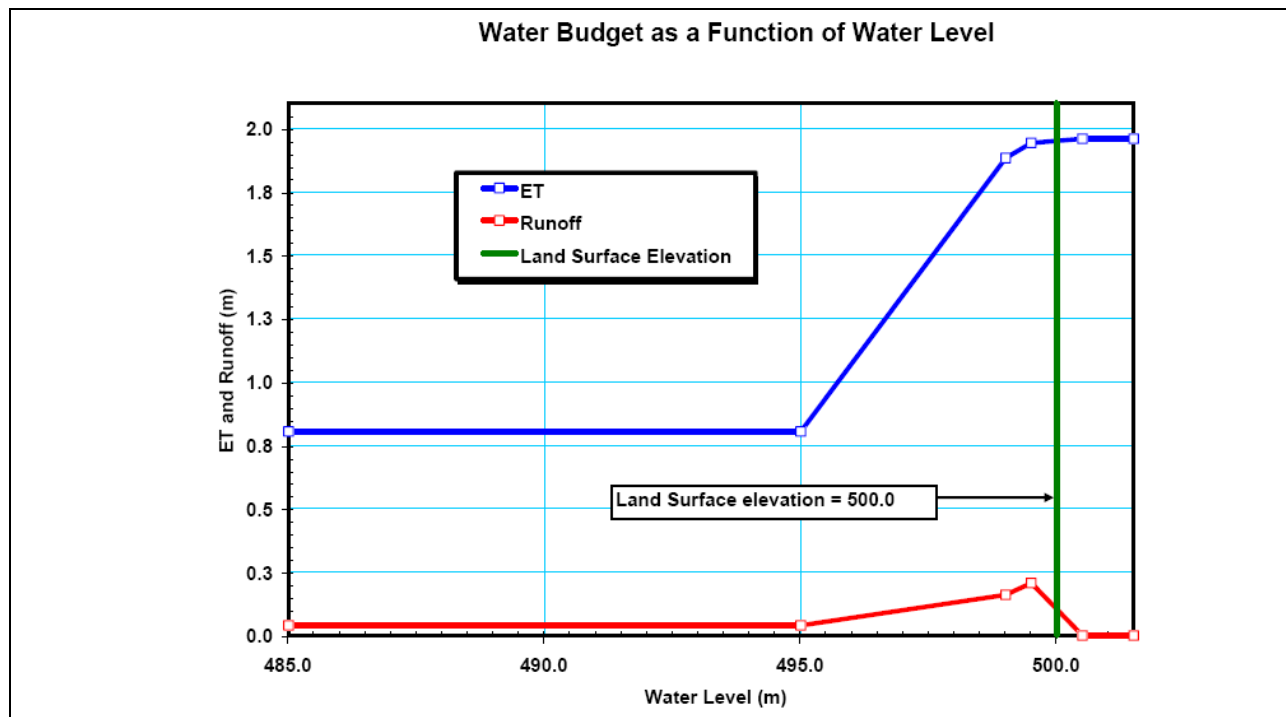| Parameter	Value
etcoef	0.7
k0inf	3.5×10^{-6} m/s
imax	0.05 m
umax	0.025 m
lmax	0.27 m
tof	0.01 m
tif	0.01 m
tg	0.01 m
cqof	0.5
ckif	460 hrs
ckol	52.8 hrs
ckbf	2784.0 hrs

Figure 16. Variation of water budget quantities with water levels.

Figure 16 depicts how the water budgets change with the water table elevation. The ground elevation for the problem is assumed as 500.0 m, and the bottom of the aquifer is assumed to be at 0.0 m. When the water level is much below the ground elevation, the ET is capped at about 0.8

m. As the water level gets closer to ground, the ET becomes larger until it reaches PET under flooded conditions. The runoff also increases as the water level gets closer to the ground surface. When it gets flooded (elevation 500.0), runoff becomes zero since runoff routing completely stops, and free overland flow begins. There is no runoff from the HPM since there is ponded water. When there is ponded water PET and the deficits in interception and upper and lower zone storages (imax, umax, and lmax) are subtracted from rainfall and the remainder becomes seepage that recharges the mesh cell.

ET varies with the maximum lower zone moisture. As lmax increases, overland flow runoff decreases because more water seeps into groundwater. ET also increases with increasing lmax because more water is available for evaporation from lower zone moisture.

The next experiment is used to understand the influence of the runoff coefficient. The volume of runoff is linearly proportional to the runoff coefficient CQOF. This coefficient can therefore be used as a calibration constant for water budgets. If hydrologic data are not available for a basin, a better approach to calibrate a model is to use the NRCS curve number to obtain a value for lmax.

The variation of water levels in cells 5 and 11 changes when the time constant for groundwater routing, CBKF, is changed from 2784 hrs to 1784 hrs (Fig. 17). The peak of the hydrograph remains relatively intact while the base flow gets somewhat delayed when the time constant is increased.

A portion of the water level hydrograph as a result of no routing (extremely small routing time constant) when compared to routing with ckol = 52.8 hrs and ckbf = 2784 hrs. The figure shows that there is some delay of the peak in the downstream cell 11, compared with the peak in cell 5, with no routing and that routing makes the delay longer.
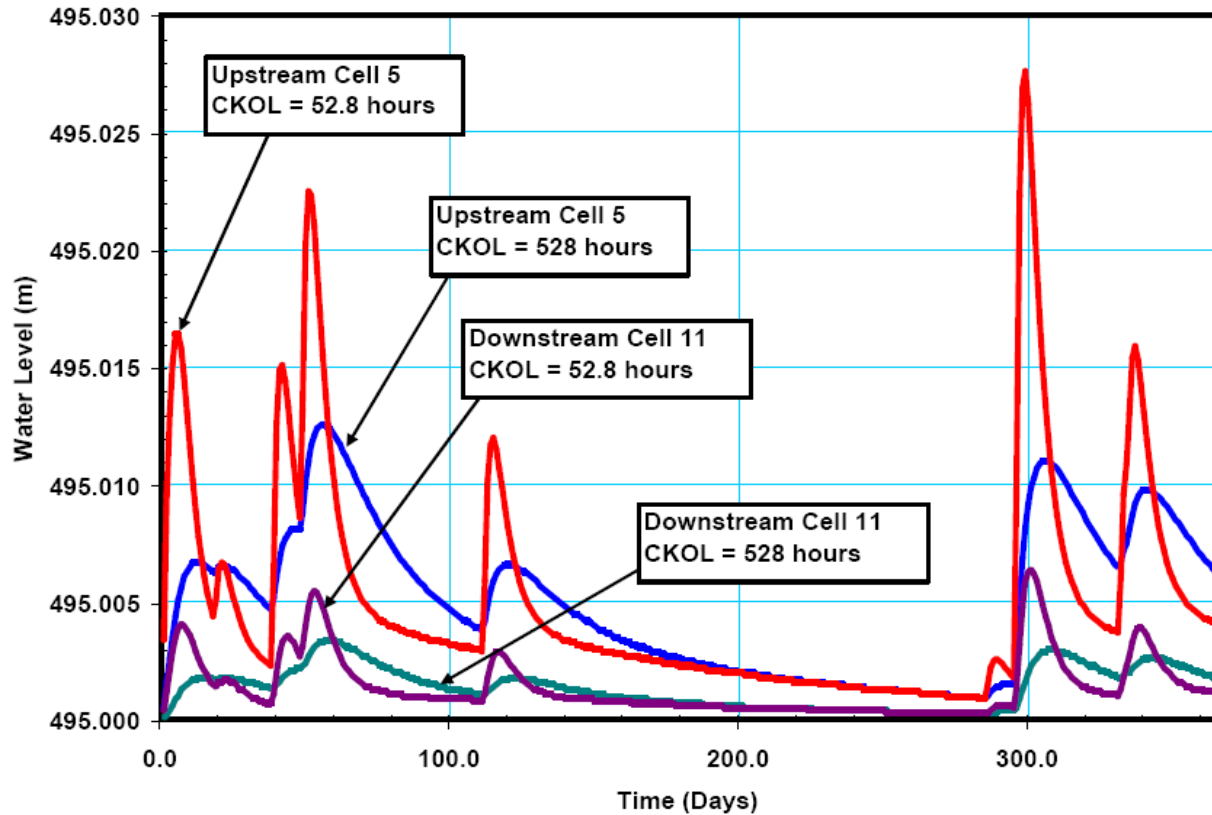
Figure 17. Variation in runoff hydrograph as a function of CKOL.

RSM and its HPMs utilize a number of parameters that can be used to explain many different hydrologic behaviors of the system. Some of these behaviors can be attributed to the regional hydrologic parameters, and some may be attributed to the HPM parameters. To prevent conflicts and obtain consistent values for parameters, the general calibration process must be based on simple rules.

For best results the parameters should be adjusted in a pre-determined order. Parameter Lmax, which strongly affects the annual volume of runoff is generally calibrated in an isolated HPM first. The NRCS curve number method is used to determine the maximum soil moisture capacity. This is done by choosing an appropriate curve number (CN) and computing Lmax as

$$L\max = \frac{1000}{CN} - 10 \qquad\qquad (50)$$

The overland flow runoff coefficient, CQOF, can also be used to fine tune the runoff volume, which essentially determines the water budget for the region. ET crop coefficient also has an effect on the runoff, but this value should be determined using independent experimental observations as opposed to model calibration to prevent the system from becoming over determined. Calibration of transmissivity and Manning's roughness parameters in the regional solution can take place next, in order to achieve proper redistribution of water. The time constants for routing overland and groundwater flow through linear reservoirs should be carried out last to match the peaks and timing of the flow hydrographs.

9 Future Work

Additional HPMs will be developed as necessary to present new and specialized functionality of for modeling local hydrology. Some examples include an HPM for agriculture on high water tables with thin soil on top of very porous surficial aquifer characteristic south Miami-Dade County, Florida and an HPM for seepage irrigation of sugar cane grown on organic muck soils in the Everglades Agricultural Area. An additional HPM may be created for detailed flow in sawgrass marsh /periphyton slough landscapes.

10 Conclusion

Hydrologic Process Modules have been developed to process rainfall and potential evapotranspiration to provide recharge to the implicit finite-volume solution for regional flow. There are many different types of HPMs that provide different levels of complexity in the implementation of hydrologic processes. The current HPMs range from simple vegetation ET modules to complex combinations of agricultural and urban HPMs. The RSM model is sufficiently flexible to allow for implementation of a highly heterogeneous arrangement of HPMs. The architecture of RSM model provides the opportunity to develop and implement additional HPMs as more functionality is necessary.

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