FIPR Hydrologic Model

Users Manual
and
Technical Documentation

Prepared for:

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and
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University of South Florida
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FHM Users Manual & Technical Documentation

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PREFACE

To assist the phosphate industry in satisfying environmental/hydrological requirements of phosphate mine reclamation, the Florida Institute of Phosphate Research (FIPR) sponsored a research project to develop an advanced hydrologic model. The research project team, consisting of geologists, hydrologists, and water resources engineers, was charged with developing a "user-friendly" computer tool that would integrate a comprehensive surface water and ground water model to better predict ground water and surface water interactions. In addition, a Geographic Information System (GIS) was to be utilized as an integral data storage, preparation, output display and analysis feature. The original model code (FHM Version 1.0) and documentation was prepared as a collaboration between the University of South Florida, Bromwell & Carrier, Inc., and Schreuder & Davis, Inc. Maintenance and significant advancement of the model (Versions 1.2 - 3.01) have been the responsibility of University of South Florida/Center for Modeling Hydrologic and Aquatic Systems through various cooperative agreements with the Florida Institute of Phosphate Research, as well as sponsorship provided by the U.S. Fish and Wildlife Service, the Southwest Florida Water Management District, and feedback from the user community.

The present version of the documentation for the FIPR Hydrologic Model (FHM) is divided into four parts.

Part I: **Model Components and Integration** - Review of Part I is essential for user understanding of the mechanics, assumptions, parameters and theory involved in the development of FHM.

Part II: **HydroGIS: ARC/INFO Utilities** - This document presents a comprehensive technical documentation and application details to the GIS interface using ARC/INFO.

Part III: **Users Guide** - This working section presents an abbreviated quick reference users guide with data gathering, parameter estimation, model interface, and function.

Part IV: **Application: SWFWMD Regional Database** - A reference guide to using FHM with the SWFWMD District-scale model domain data base.

The overall documentation relies on a user familiarity with Part I. Part I essentially presents the "engine" of FHM and includes: Chapter 1, Model Development and Background; Chapter 2, Hydrologic Model Components; Chapter 3, Integrating Components; and Chapter 4, Geographic Information System Component. Chapter 1 describes the purpose for developing FHM, and provides a brief overview of FHM components and how each work together. Chapter 1 also has a brief overview of the capabilities, features, costs and limitations of the model. Chapter 2 explains each hydrologic model component of FHM: surface water, ground water, and evapotranspiration. This chapter includes details of the equations and assumptions specific to the model. Chapter 2 is designed to be used in conjunction with the individual component model documentations. Chapter 3 explains the integrating algorithms required to link the hydrologic components. Chapter 4 introduces the Geographic Information System Interface and the role it plays in providing spatial relationships between the hydrologic components and hydrologic data analysis. However, details of individual GIS interfaces and features are provided in Part II and stand alone documentation.

FHM is an advanced hydrologic system analysis concept as much as it is a model. FHM provides for efficient model data handling (e.g., preparing input and synthesizing output). However, perhaps more importantly, it provides for advanced archival, prioritization and implementation of new hydrologic information including that gleaned from model investigation and that derived from basic data gathering. As is the case with any analysis tool, FHM should be used in conjunction with other well established procedures including other models and sound basic hydrologic investigation. However, a well trained, multi-disciplinary team (ground water and surface water hydrologists as well as GIS technicians) could prove essential to properly conceptualize and calibrate the hydrologic components of FHM to a region.

From a "calibrated" model condition, the resultant product is "user friendly" enough to provide for significant advancement in analysis and cost savings for day-to-day water management and/or permitting investigations. With the multi-scale modeling capability of FHM, it is conceived by the present model authors that regionally calibrated models will be developed, maintained and made available to the industry much like basic hydrologic data is made available now. From regionally (e.g., a major river basin) calibrated models, local refined scale (near-field) calibrated models can be readily derived for tailored, individual investigations.

The considerable benefits to be derived from the investment in integrated modeling unfold from a holistic water balance which, in most applications, is completely rainfall driven. Ground water recharge is constrained by rainfall infiltration which must be compatible with measurable runoff rates. Ground water evapotranspiration (ET) rates are constrained by surface ET fluxes which exist in a higher potential (more readily available) form. Surface water features including lakes, wetlands and streams include both surface and ground water influences, the sum of which are constrained by measurable flow rates and stages. Complex cause and effect stresses from rainfall variations, ground water pumping, surface water diversions, land use changes, and surficial drainage features can be individually quantified. Innovative potential remedial water management actions such as purified waste water return, recharge augmentation (artificial recharge), aquifer storage and recovery (ASR), high flow scavenging and brackish aquifer desalination can be ideally evaluated with integrated model technology.

Finally, the authors wish to acknowledge the significant support and input provided by the Florida Institute of Phosphate Research, most notably, Dr. Steve Richardson; Leslie Cunningham formerly of the US Fish and Wildlife Service; and the Southwest Florida Water Management District, most notably, Kathleen Coates, Steve Dicks, Mike Kelley, Axel Griener and Andy Smith. Considerable contributions have been made over the years by graduate students at the University of South Florida. Credit must be given to Jodi Baudean, Carl Fielland, Julie Baker and the late Jeffrey Burdge.

FIPR Hydrologic Model

Part I:

MODEL COMPONENTS AND INTEGRATION

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CHAPTER 1. MODEL DEVELOPMENT AND BACKGROUND

Introduction

In 1988, the Florida Institute of Phosphate Research funded a research project to develop an advanced hydrologic model, to be used for phosphate mine reclamation in West-Central Florida. The intended product was to include a dynamically coupled comprehensive surface water and ground water model. The model components were to represent, individually, state-of-the-art capabilities, use public domain, widely accepted and validated codes and be compatible for integration. Extensive data needs for this model would be provided by a geographic information systems (GIS) data base, as well as online hydrologic and meteorological data sources (Powers et al. 1989). The model was to possess sufficiently simple user interfaces to provide for rapid applications and assessment of model results (Ross and Fielland 1991; Ross and Tara 1993). Several years later, the U.S. Fish and Wildlife Service (USFWS) contributed funding to the further development of the model to provide for regional scale hydrologic investigations of conjunctive water use issues associated with alluvial aquifers in the arid west (Cunningham and Ross 1993). In 1994, the Southwest Florida Water Management District initiated research to adapt the model to the complex urbanizing basins of West-Central Florida on a regional scale. The SWFWMD West-Central Florida regional applications represent a milestone in hydrologic simulation. An extensive topological, meteorological and hydrological data base has been developed and is substantially supported. Potential applications of the model include online day-to-day permitting evaluations, as well as complete regional resource management assessments. This evolution provides for both up-to-date and sufficiently detailed assessment capability as well as further contributing to the understanding and development of a complete hydrologic data base of the region.

The FIPR hydrologic model (FHM) provides an advanced predictive capability of the complex interactions of surface water and ground water features in shallow water table environments. The model can generally be characterized as a deterministic, semi-implicit real time simulation model, with variable timesteps and spatial discretization. All significant hydrologic processes including precipitation, interception, evaporation, runoff, recharge, stream flow, base flow, as well as all the component storages are explicitly accounted for in the model components. Input requirements include precipitation and potential evapotranspiration time series, surface topologic features (i.e., land use, soils, topography, and derived slopes), hydrography and rating conditions as well as hydrogeology of the ground water system and information about well pumping and surface water diversions. Output includes detailed water balance information on all major hydrologic processes, including surface water and ground water flows to wetlands, streams and lakes, evaporative losses from all storages, and detailed storage heads and flows in the ground water system.

FHM includes extensive graphical user interfaces, error trapping, and output assessment capabilities. The model exists entirely in the public domain, as do the component models, HSPF and MODFLOW. The model also possesses extensive geographical information system capabilities. A GIS interface has been written for ARC/INFO to support FHM. ARC/INFO is proprietary. Where adequate data exist, a GIS can provide considerable time savings and analysis benefits over conventional means of developing model data sets. Because model parameters of integrated models are more constrained, the potential exists for the results from an independent surface water or ground water model to be improved with an integrated model strategy (Geurink et al. 1995). However, FHM requires extensive data to be correctly applied and calibrated. Significant costs can be incurred in collecting this detailed data, and this must be understood before embarking on any integrated modeling strategy. Further discussion of the costs and implications of integrated modeling can be found in Geurink et al. 1997.

FHM Overview

FHM consists of a comprehensive surface water model, a ground water model, integration and vadose zone components. The surface water modeling component is satisfied by the EPA-supported Hydrological Simulation Program -- Fortran, HSPF. This model is distributed and supported by the EPA and has widespread application for both regional and urbanized hydrologic basin investigations in the U.S. The ground water component model, MODFLOW, supported by the U.S. Geological Survey, is also widely used and supported. Much of FHM is, in fact, integration software to provide for the interaction of the two component models, HSPF and MODFLOW.

Within FHM, the user can elect to perform simplistic surface water only simulations with full implementation of HSPF, or alternatively, ground water only simulations with user-defined recharge using MODFLOW. In fact, a typical application is to pre-calibrate the surface water and ground water applications in this stepwise fashion prior to performing comprehensive integrated simulations. For a calibrated, integrated hydrologic model, the only input specifications are precipitation and evapotranspiration time series, and surface and ground water diversions (pumping and releases). FHM is intended for the complete assessment of surface/ground water interactions.

Surface Water

HSPF was developed to simulate the hydrologic and water quality processes on pervious and impervious land surfaces, and transport within streams and reservoirs. While the complete HSPF code comprises hundreds of subroutines, FHM utilizes only those subroutines relevant to the particular simulation. The subroutines most commonly used in FHM are listed in Chapter 2 under the appropriate processes. Chapter 2 also contains more detailed information on the HSPF model.

Ground Water

MODFLOW was developed to simulate ground water flow in three dimensions using a block-centered, finite-difference approach. It provides for simulation of unconfined and confined ground water flow conditions. The model includes a stream package which is used in conjunction with the HSPF stream reach feature to include base flow dependent on stream stage. All capabilities of MODFLOW are included in FHM. Within FHM, wells, springs, rivers, drains, and variable hydrogeologic conditions can be defined for multi-aquifer systems, subject to the limitations of MODFLOW.

Evapotranspiration

Evapotranspiration is an important element of the hydrologic cycle and is the dominant component of the annual rainfall of a region (as high as 70 or 80% in Florida). It is believed that evapotranspiration can be the most difficult to analyze. While both HSPF and MODFLOW have evapotranspiration (ET) subroutines which could be used by themselves, FHM actually employs both in a unique hierarchical fashion. Evapotranspiration is accounted for in FHM by first specifying a potential rate time series based on pan data or other information. Under surface water only simulations, the HSPF ET module is used exclusively to develop ET values. For the integrated simulations, HSPF is used to derive the distribution of ET among principal surface water sources but ET is also satisfied from available MODFLOW ground water sources, including vegetation (root zone) variation. There is a significant departure of FHM ET algorithms from the original (Version 1.0) form following extensive critical user and peer review and identified problems with the modified Thornthwaite (1957) method as it was applied within FHM V1.0. Chapter 2 contains detailed information on simulation of the ET budget.

Integrating Software

Typically surface and ground water models can not be integrated directly because the two models use two different spatial frameworks. Such is the case with HSPF and MODFLOW. HSPF uses watershed subbasins as the basic spatial descriptive unit, while MODFLOW uses specified data points in a gridded, nodal network. For integration, HSPF results (e.g., recharge) must be allocated to a nodal network for use by MODFLOW, while MODFLOW results must be regrouped by subbasin for use by HSPF. In FHM, recharge and ET fluxes use both regular grids and irregular subbasins. Therefore, the results from each discretization domain must be manipulated prior to transfer to the other domain.

In addition, HSPF and MODFLOW operate with different time steps, characteristic of the different time scales of surface and ground water processes. Typically, surface water runoff simulations are performed on hourly (or less) increments, while ground water response time scales are much longer, requiring time steps of days to weeks. To provide time step compatibility, FHM integrating software translates HSPF results (e.g., in hourly increments) into stress periods (time steps) used by MODFLOW (e.g., daily or weekly), and MODFLOW results are partitioned into appropriate periods for HSPF.

The integrating software provides the linkage between the three hydrologic models used in FHM. Output data is formatted from one hydrologic model into the input for another. Also, input data sets are modified based on the output of the other hydrologic model components (e.g. HSPF lower zone storage parameters are modified based on water table heads from MODFLOW when the water table is near the surface). There are numerous software checks for internal errors and warnings and halts are provided during the simulation when they are found. Software also has been written to summarize and insure a water balance for the model components. Chapter 3 contains detailed information on the integrating software.

Geographic Information System (GIS)

A very important element of FHM is the GIS interface. The GIS utility of FHM is called HydroGIS which provides for the storage and analysis of all spatial data, including land use, vegetation type, soil type, topography, hydrography and hydrogeology. HydroGIS is a public domain interface with spatial analysis features that use UNIX ARC/INFO as the GIS. Existing GIS data can be used and utilities are available to create new digital map and attribute data for a modeling project. The results of spatial analysis completed with HydroGIS include a series of characteristic files which contain model input data for HSPF, MODFLOW and FHM integration. The integration data facilitate dynamic data sharing between HSPF and MODFLOW during an integrated simulation. The characteristic files from HydroGIS combined with other data entered through FHM pre-processors are used to develop the initial input data sets for the hydrologic model components. FHM output facilitates limited applications of GIS to perform post-processing and graphic display of model results, which assists user evaluation and perception of the results. Chapter 4 summarizes the significant function of the GIS interface for FHM. Part II contains technical and application details for HydroGIS/ARC/INFO. Outdated utilities from FHM using SPANS (Tydac 1990) and PC ARC/INFO exist but are no longer supported for Version 3.0 FHM.

Interfacing Software

The interfacing software is divided into four groups: overall model interface, pre-processing, post-processing and GIS interface (HydroGIS). The objective of the interfacing software is to provide the model user with a tool to more efficiently use the model and to more effectively analyze hydrologic and hydrogeologic relationships. The overall model interface performs file management functions and error trapping, and allows the user to execute the pre and post-processing analysis. The GIS interface is a separate, stand-alone module which is discussed in Part II. See Part 3, Users Guide, for details on interfacing within FHM.

FHM Operation

FHM is a complex hydrologic model which is intended to be easy to use, operated through a user friendly menu driven interface. Prior to running the model, the user gathers background data including existing GIS datasets or digitized maps, hydrological and meteorological data. As discussed in Part II, all GIS data must be available a priori except for project-specific data. If digital data or a GIS is not available, the user can collect and perform the preparation of data manually.

Scenarios which can be run through FHM include design storm event simulations or continuous seasonal or annual simulations in surface water only, ground water only or integrated surface/ground water modes. Figure 1.1 depicts the three available paths within FHM depending on the simulation type.

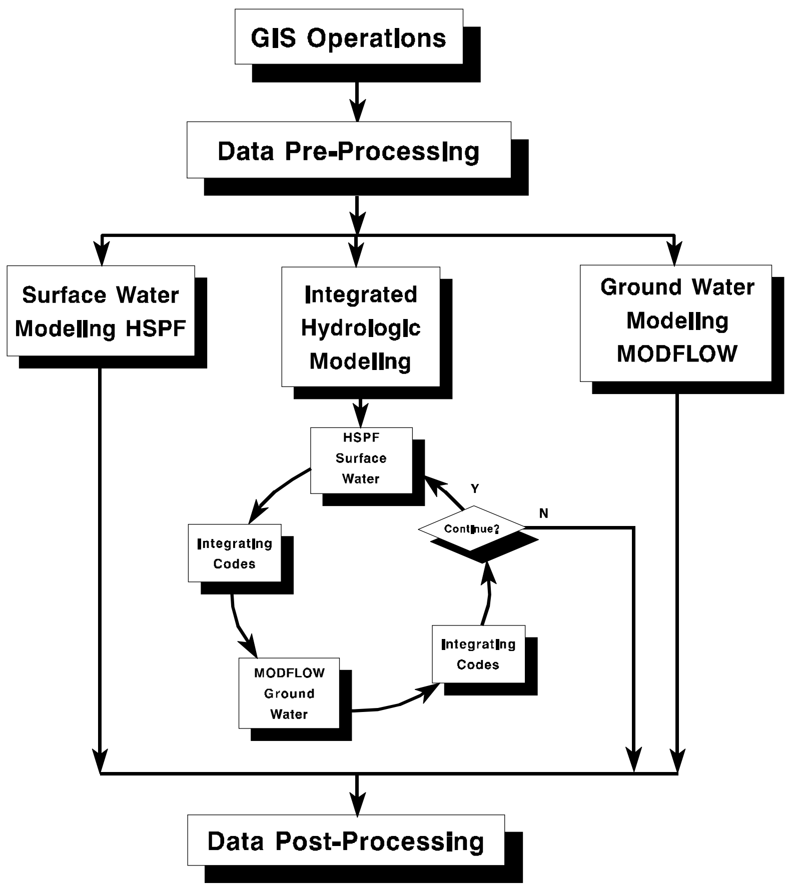

Figure 1.1 FHM Application Paths Within the User Interface

For surface water or ground water only simulation, the user utilizes the pre-processors of FHM to apply the individual models, HSPF or MODFLOW. After the user has built a data set and runs FHM, post-processing is available to aid output assessment. Furthermore, the data prepared for the individual model applications can be used later for an integrated application.

For an integrated seasonal or annual simulation, the hydrologic models HSPF and MODFLOW are run sequentially on a variable time interval as shown in Figure 1.1. Prior to the run, the user specifies initial conditions for all FHM components. The simulation begins with HSPF which calculates runoff, infiltration, recharge, surface ET and its distribution, and all surface water storages including soil moisture conditions on an hourly basis. MODFLOW is then employed to perform the ground water simulation for the same time period, typically using daily time steps. Updated values for recharge, base flow, stream-stage relationships, soil moisture, and remaining potential evapotranspiration are passed to various integrating software components throughout the loop. Integration software prepares files for the next hydrologic model loop. The looping sequence is repeated until the simulation is completed.

Limitations

Each application of FHM version 3.0 is limited to the following constraints:

Pre-processing:

1. 10 rainfall stations
2. 10 potential ET stations
3. 10 surface water diversions
4. 50 subbasins
5. 50 reaches (each reach can include dynamic and static hydrography elements, refer to Part I, Chapter 2, Reaches section)
6. MODFLOW grid: 106 rows, 60 columns
7. calendar or water year run lengths for integrated
8. multiple year run lengths for independent surface or ground water
9. MODFLOW X-ARRAY: 1,500,000

Overall:

1. Full capabilities of MODFLOW (1984)
2. Full capabilities of HSPF (v. 10.1)
3. Limitations of UNIX ARC/INFO (v. 6.11)

Integrated Simulation:

1. Integration timestep is set to one week

Details concerning model limitations and capabilities and circumventing the above can be found in Part III.

CHAPTER 2. HYDROLOGIC MODEL COMPONENTS

Introduction

This chapter discusses the components of the FIPR Hydrologic Model (FHM) in terms of individual hydrologic processes. The chapter is divided into four sections: surface water system (basins), reaches, ground water system and ET. Each section discusses the relationship of the individual hydrologic processes to the specific model components (HSPF, MODFLOW) of FHM. The discussion includes the specific assumptions, parameters, and changes employed within each model component. The surface water section discusses the utility of the surface water model HSPF. HSPF is used within FHM for both surface water only simulation or integrated modeling. Presently, for the typical application, the period of simulation for either application is limited to one year. However, the model can be run sequentially for any number of years. There are also advanced methods to run the model consecutively for multiple years.

The ground water model section discusses the ground water model MODFLOW, which simulates the flow of water in the saturated system, surficial and confined aquifers. Within FHM, MODFLOW can be run either stand-alone or in integrated mode employing most of the same data sets. The ET section discusses how potential ET is used in the model. Tables of input parameters, ranges, and suggested values for a model simulation are included for each model component in the respective section.

In an effort to identify different types of acronyms used for variables, subroutines, and programs, the documentation uses the following type style conventions:

	Type Style Examples
Programs:	HSPF
Subroutines:	*UZONE*
Variables:	**CEPSC**

Surface Water System (Runoff Flow Planes)

The surface water system of the hydrologic cycle is hereby defined to extend to the saturated zone of the ground water system (water table aquifer) as illustrated in Figure 2.1.

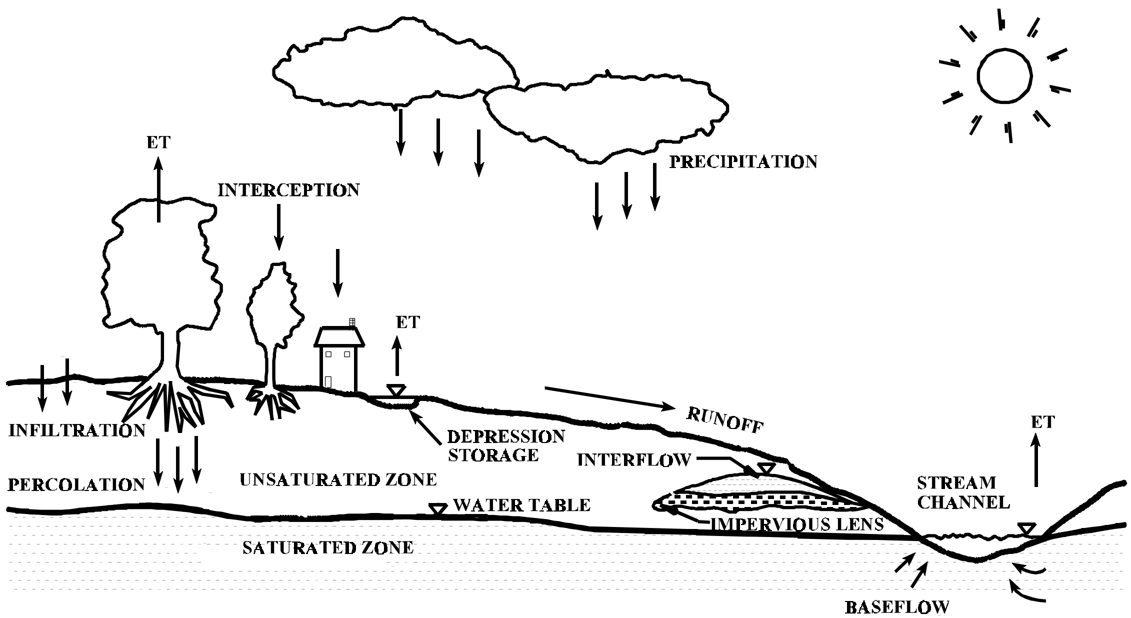

Figure 2.1 Primary Components of the Surface Water System Simulated by HSPF Within FHM

For the surface water only simulation, the simplistic ground water algorithms within HSPF are employed to account for surficial aquifer influences on streamflow and runoff. HSPF divides the unsaturated zone into two zones--the upper zone and the lower zone. These two zones will be referred to throughout the Surface Water Section; it is essential to understand what the zones represent. The upper zone is primarily depression storage which consists of micro storage features not explicitly included in attenuation routing in the model. Micro-depression storage includes cracks, potholes, depressions, etc. on the land surface which can hold water and remove water from runoff and direct infiltration. For regional (larger basin) applications, depressed storage can include macro-features such as isolated wetlands, ponds, and small lakes not included explicitly in the surface water model routing. The lower zone is the remainder of the unsaturated zone between the upper zone and the water table. The lower zone accounts for soil moisture influences on infiltration and root zone ET. Below the lower zone in HSPF is the “active” and inactive ground water storage units which are not used in an integrated simulation, but can be used for surface water only modeling.

Overview of HSPF Operation

HSPF operates on a watershed or catchment basin framework which typically consists of many subbasins. This is commonly referred to as a "lumped" parameter approach; however, the catchments can be quite small. Herein, lumped parameter refers to assignment of one value (i.e., weighted mean) for a model parameter within a subbasin. Figure 2.2 shows a simple example watershed with five subbasins. The figure also shows two reach elements representing a lake and a stream channel with a discharge to the watershed outfall (discharge point). Rivers and streams within HSPF are assumed to have negligible hysteresis in flow characteristics. In applying HSPF the user must specify the sequence of flow between reaches and subbasins, referred to as routing. HSPF simulates discharge from streams and lakes through a simplistic technique using pre-specified rating conditions (stage-storage-discharge).

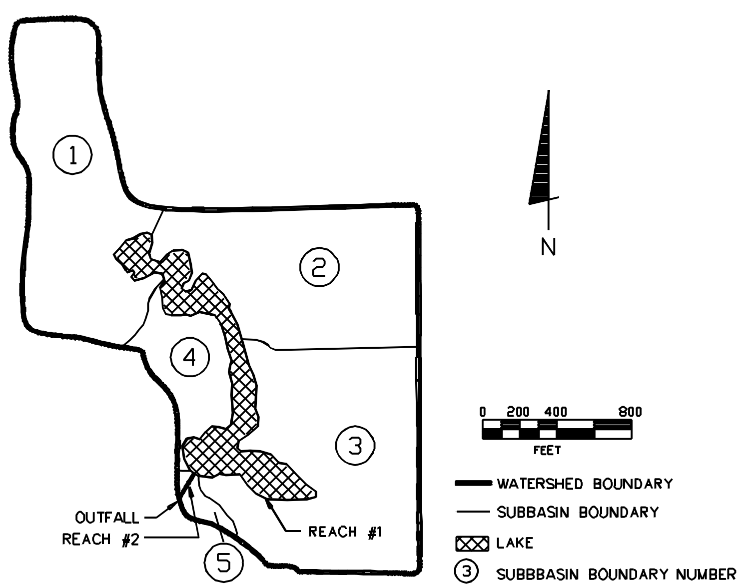

Figure 2.2 Simple Watershed Concepts

Each subbasin is normally composed of many unique areas which represent uniform characteristics such as soil type and vegetation cover. However, HSPF uses one area-weighted mean value for each storage or flux parameter to represent conditions within a subbasin. Figure 2.3 shows the example area with two soil type distributions. These zones are spatially averaged within each subbasin either manually or more typically within the GIS interface to determine average characteristic values (e.g., infiltration capacity) for each subbasin.

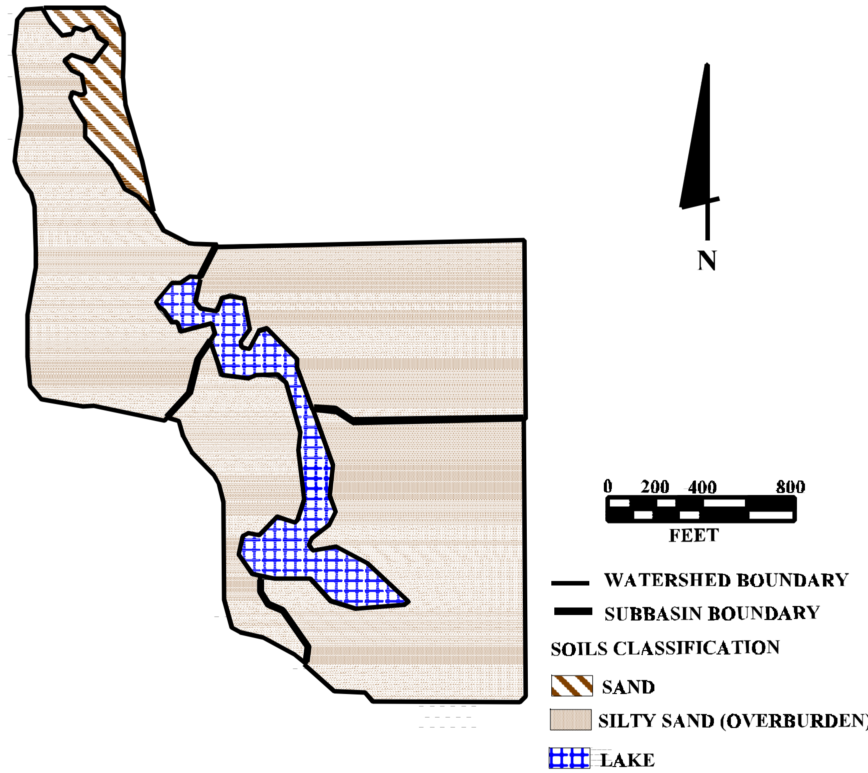

Figure 2.3 Sample Study Area

As stated earlier, HSPF defines storages and fluxes from simplistic elements to represent the principal surface water processes. Figure 2.4 demonstrates the temporal sequence HSPF uses to distribute rainfall to storages and fluxes in relationship to time and depth of a storm. Interception is assumed to occur first during a storm and can be a significant loss if the basin possesses substantial vegetative cover. As the interception storage capacity is filled, precipitation begins filling depressions and infiltrates. Depending on antecedent conditions, depression storage (upper zone storage) may also reach capacity relatively quickly. As rainfall proceeds soil infiltration capacity diminishes with increasing soil moisture, and overland flow can occur. Water which infiltrates the soil surface and is not retained as soil moisture in the lower zone either moves to a stream as interflow, percolates to the water table where it may contribute to a stream as base flow, or too deep aquifer recharge.

The hydrologic processes described above are highly interrelated, and in HSPF, are modeled with physical and empirical algorithms. To assist the user in understanding how HSPF within FHM treats these processes, a flowchart of the operations of the model is provided in Figures A.1(a) to A.1(c) in Appendix A. This flowchart is modified from the flowchart contained within the HSPF User's Manual for Release 10.0. Additional details have been provided in the flowchart for FHM for the surface detention storage process (unchanged in FHM) and the method used in FHM of handling inactive/active ground water storage and baseflow with MODFLOW.

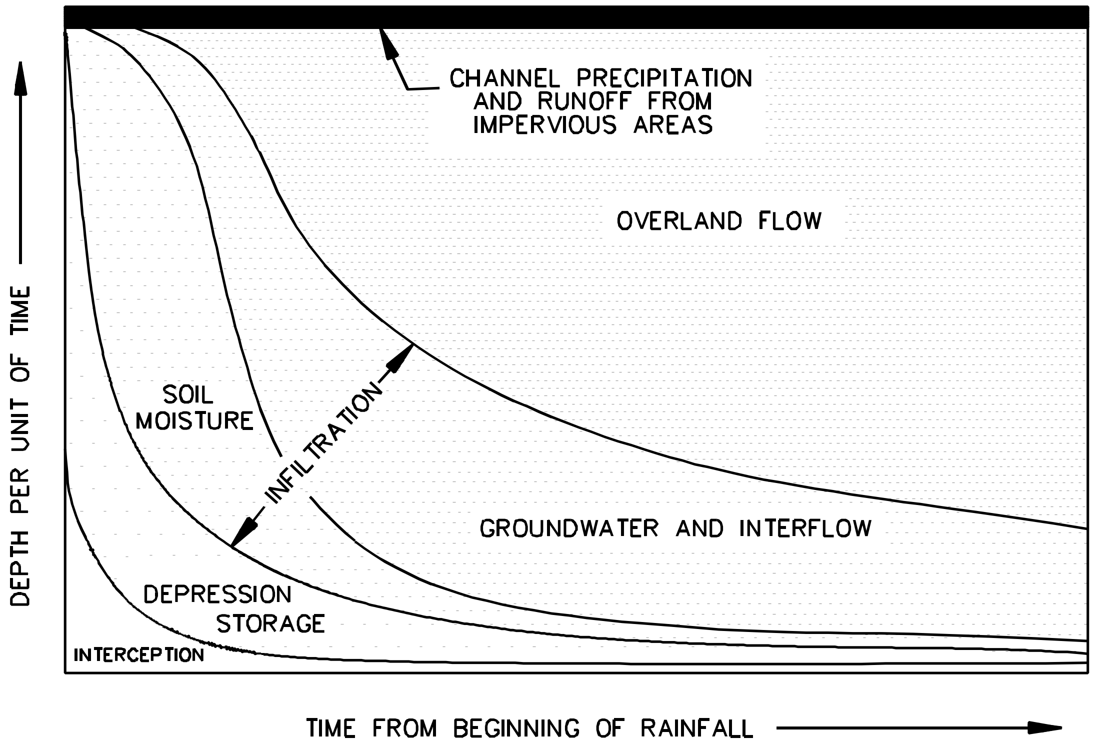

Figure 2.4 HSPF Rainfall Distribution Sequence

The flowchart is organized from top to bottom in the order in which HSPF and FHM perform operations. Storages and fluxes are denoted by rectangles and ovals respectively. Intermediate operations (e.g. summation of storages and fluxes to enter another storage or flux) are symbolized with hexagons. Decision points are depicted with diamonds and the results of decisions are denoted by parallelograms. The dashed box around the center portion of the flowchart represents storages and fluxes within a subbasin; fluxes or storages outside the dashed box represent water which is entering or leaving the subbasin. Within parenthesis, FORTRAN variable names from the source code are provided. Those storages and fluxes which are shaded are not available within the current FHM version. The processes which are unavailable are related to lateral fluxes. Basin to basin lateral flow should be limited to a distance which is smaller than the distance necessary for runoff to form rivulets. Basins of strictly overland flow will be very small in comparison to other basins in the model.

The surface detention storage process contained within the double-lined box presents one of HSPF's most complicated operations. This process effects various components of the hydrologic system as simulated by HSPF. The relationships will be explained in detail later in this chapter. Because the surface detention storage process, as used here, effects so many components of the hydrologic system, it is appropriate to provide a brief overview. Available surface water (**SURI**) enters the top of the box (precipitation after interception and external basin overland flow), then surface detention storage (**SURS**) from the previous model time interval is added to it, represented by the dashed arrow from **SURS** to moisture supply (**MSUPY**). In a counterclockwise direction, the various fluxes and storages are removed from **MSUPY** in the order in which HSPF removes them until the water remaining is surface detention storage. Fluxes and storages leaving the box represent water that is no longer part of the surface detention storage process.

As shown, the hydrologic processes in HSPF are interrelated and must be discussed in relation with one another. Within this section is a discussion of hydrologic unsaturated and saturated zone processes in terms of HSPF storages and fluxes. HSPF processes are discussed in this order:

1. precipitation

2. surface storages--interception, depression storage and surface detention storage (water that is in runoff)

3. surface fluxes--infiltration, overland flow and stream flow

4. subsurface storages--upper zone storage, lower zone storage, interflow storage, and ground water storage

5. subsurface fluxes--percolation, interflow, recharge, and ground water flux.

For further information, refer to the HSPF manual for Release 10.0 (Bicknell et al. 1993). All HSPF input formats and equations are documented there.

Precipitation

Only precipitation in the form of rainfall is considered in the present version of FHM. However, HSPF has snowfall/snowmelt subroutines that can be employed by the advanced user. Snowfall/snowmelt can be applied to an independent surface water model or to an integrated model.

Precipitation data must be gathered from available meteorologic sources, validated and prepared into proper input file format for FHM. If multiple rainfall stations are used, a weighted spatial distribution must be defined for each subbasin. The default spatial distribution for rainfall represents an even distribution of all rainfall stations for each subbasin.

FHM requires hourly (or shorter) increment rainfall distribution to model runoff. For details concerning the preparation, selection, available options and requirements for rainfall input to the model, refer to Part III Users Guide.

Surface Storages: Interception, Depression, and Surface Detention

Storage components used by HSPF to model rainfall that reaches the surface are shown in Figure 2.5. Interception storage, water stored on vegetative cover and on building roofs and other surfaces, is primarily a function of land use. Depression storage, upper zone storage (UZS) in HSPF, includes micro-depression features such as cracks, potholes, small yard depressions, and water required to wet ground litter. For regional scale basins (subbasins more than 1 mi^2 in area), depression storage may also include ponds, lakes, non-flowing ditches, and other wetlands not directly connected to the principal drainage system. Depression storage is primarily a function of surface conditions such as land use, topography, and time of year. Surface detention storage is water contained in rainfall excess which is available for runoff:rainfall which is not infiltration or captured in interception or depressions. The amount of water in surface detention storage is a function of rainfall intensity, infiltration capacity, hydraulic slope, hydraulic length and Manning's roughness coefficient. The unsaturated zone storage, lower zone storage (LZS) in HSPF, refers to the volume of water stored in the soil above the water table.

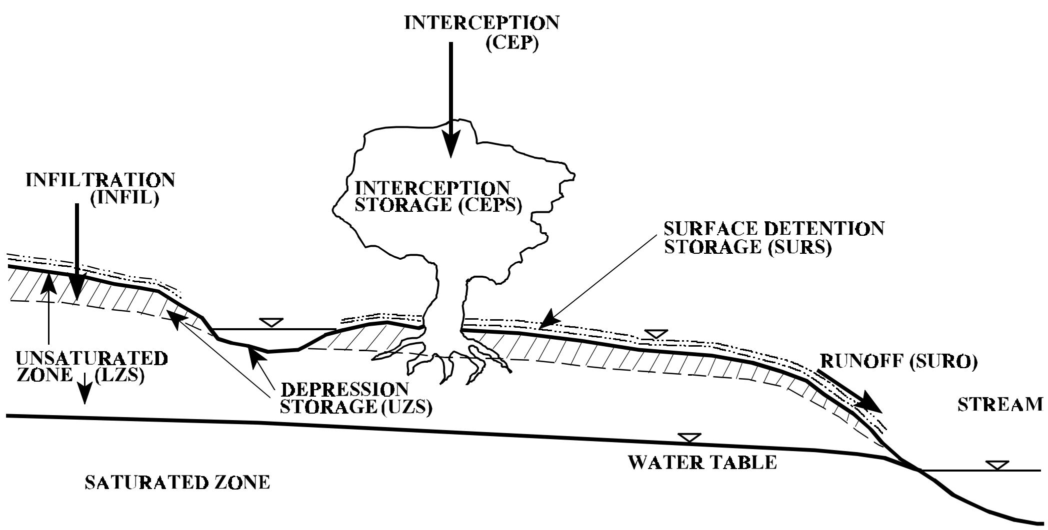

Figure 2.5 Surface Storages and Fluxes Used in HSPF

Assumptions and Equations

Within FHM, interception storage is removed from total precipitation first. Refer to the operations flowchart in Appendix A. HSPF considers interception storage to be any water retained on or above the overland flow plane. Within pervious areas, most interception storage occurs on vegetation and man-made structures. When the interception storage capacity (maximum potential interception) is reached, any additional precipitation is allocated to the other surface storages and fluxes. Water can be removed from interception storage only by evapotranspiration (see ET section).

Depression storage is influenced greatly by the land use and surface antecedent moisture conditions. Both depression and surface soil wetting storage are allocated in HSPF to upper zone storage, one of two unsaturated storage zones (see Figure 2.5). HSPF determines upper zone storage after calculating infiltration (**INFIL**) and potential direct runoff (**PDRO**), or Q as used below. Refer to the Infiltration section for further details on **INFIL** and **PDRO** calculations. Potential direct runoff is the water available for surface inflow to interflow storage, inflow to upper zone storage, and surface detention storage, which goes to overland flow and runoff.

The fraction of potential direct runoff (**UZFRAC**) symbolized by F_{uz}, which becomes upper zone storage (both depression and surface soil moisture storage), is a function of the ratio of the upper zone storage to the upper zone nominal storage (an arbitrary value). The two equations below represent the method of subroutine *UZINF2* (*UZINF* is not used in FHM). The equation for F_{uz} when $U_r \leq 2$ is:

$$F_{uz} = 1 - \left(\frac{U_r}{2}\right) \times \left(\frac{1}{4-U_r}\right)^{3-U_r} \quad \textbf{(1)}$$

When $U_r > 2$, the equation is:

$$F_{uz} = \left(\frac{1}{2x\left(U_r - 1\right)}\right)^{2U_r-3} \quad \textbf{(2)}$$

The inflow to upper zone storage (**UZI**) or Q_{ui}, is determined by:

$$Q_{ui} = F_{uz} \times Q \quad \textbf{(3)}$$

Upper zone storage can then be calculated as:

$$V_{uz}^{t} = Q_{ui} + V_{uz}^{t-1} - I_p \qquad \textbf{(4)}$$

where:

V_{uz}^{t-1} = upper zone storage in inches (**UZS**); the (t) and (t-1) superscripts refer to current and prior model time interval respectively

I_p = percolation in inches (**PERC**), refer to subsurface section

Q_{ui} = inflow to upper zone storage in inches (**UZI**)

Q = potential direct runoff in inches (**PDRO**)

F_{uz} = the fraction of potential direct runoff retained by upper zone storage (**UZFRAC**)

U_r = the ratio (**UZRAT**) of upper zone storage (**UZS**) to the upper zone nominal storage (**UZSN**).

The only avenues for water to move out of upper zone storage are percolation to lower zone storage and evapotranspiration.

Surface detention storage is the volume of water stored on the subbasin as temporary rainfall excess (instantaneous depth of the kinematic overland flow wave). Surface detention storage (**SURS**) is a temporary land surface storage which can become overland flow or infiltration. In HSPF, surface detention storage is determined after adding precipitation and subtracting infiltration, upper zone storage, interflow, and overland runoff outflows. The operations flowchart in Appendix A depicts the surface detention storage process. For each model time interval, the variable SURS, known as V_d below, is determined by:

$$V_d = V_{dp} - Q_{so} \qquad \textbf{(5)}$$

where:

V_d = surface detention storage in inches (**SURS**)

V_{dp} = potential surface detention storage in inches (**PSURS**)

Q_{so} = overland runoff flow in inches (**SURO**)

Note: The Overland Flow section describes the development of V_{dp} and Q_{so}.

Components

Interception is handled by subroutine *ICEPT*. Subroutine *SURFAC* and its subordinate subroutines *DISPOS, DIVISN, UZINF2,* and *PROUTE* determine the allocation for moisture not used for interception. Subroutine *DIVISN* determines infiltration and the components of potential direct runoff. Subroutine *DISPOS* determines the total potential direct runoff, *UZINF2, UZONE* and *UZONES* determine the upper storage, and *PROUTE* determines surface detention storage. For other information on interception, upper zone storage and surface detention storage, see the HSPF Manual.

Infiltration

Infiltration is the movement of water from the soil surface into the unsaturated zone (Figure 2.5). Infiltration units are those of a flux (flow/unit area/unit time, *i.e.,* inches per hour over the subbasin). Infiltration is a function of many factors including soil type, moisture content, vegetative cover and depth to water table. Infiltration also depends upon percolation (vertical downward movement of water within the soil). When infiltration exceeds the unsaturated zone percolation for extended periods, surface saturation occurs.

Assumptions and Equations

HSPF considers infiltration (**INFIL**), symbolized by Q_i in this document, to be the loss of water from the surface detention storage to the lower zone storage. Thus, infiltration in HSPF "bypasses" the upper zone and is transferred immediately into lower zone storage. Refer to the HSPF operations flowchart in Appendix A. In HSPF, infiltration is a function of infiltration capacity (the maximum rate at which soil will accept infiltration) and lower zone storage parameters (**LZS** and **LZSN**) which are discussed in the Subsurface Storage section of this chapter. Infiltration capacity is a spatially varying parameter which is discussed below. When rainfall supply exceeds the infiltration capacity, water is allocated to other storages and fluxes. Infiltration capacity is a function of both fixed and variable characteristics of the watershed. Fixed characteristics include such parameters as soil type and land surface cover, variable characteristics including soil surface conditions, soil moisture content and depth to water table. Fixed and variable characteristics vary spatially over the subbasin. HSPF uses a linear probability density function (Figure 2.6) to account for areal variation of infiltration over the subbasin.

The linear probability density function relates maximum to mean infiltration capacity, using algorithms to represent the continuous variation of the infiltration capacity with time as a function of the soil moisture in the unsaturated zone. The equations, representing the dependence of infiltration on soil moisture, are based on the work of Phillip (1957) as interpreted by Crawford (1964) and later adapted in the Standford Watershed Model (Crawford and Linsley 1966).

The assumption of a linear distribution of infiltration over a subbasin is implemented in HSPF in the following manner. The mean infiltration capacity (**IBAR**), denoted by I_c below, is determined. I_c is then multiplied by the ratio of maximum to mean infiltration capacity to determine **IMAX**, the maximum infiltration capacity, represented in the following equations by I_x. The minimum infiltration capacity (**IMIN**), corresponding to I_n, is then calculated using I_c and I_x.

$$I_c = \frac{I}{(V_{LZS} \ / \ V_{LZSN})^p} \tag{6}$$

$$I_x = I_r \times I_c \tag{7}$$

$$I_n = 2 \times I_c - I_x \tag{8}$$

where:

I	=	infiltration index in inches/hr. (**INFILT**)
I_c	=	mean infiltration capacity over the subbasin in inches/hr. (**IBAR**)
V_{LZS}	=	lower zone storage in inches (**LZS**)
V_{LZSN}	=	lower zone nominal storage in inches (**LZSN**)
p	=	exponent (greater than 1) (**INFEXP**)
I_n	=	minimum infiltration capacity in inches/hr. (**IMIN**)
I_x	=	maximum infiltration capacity in inches/hr. (**IMAX**)
I_r	=	ratio of maximum to mean infiltration capacity over the subbasin (**INFILD**)

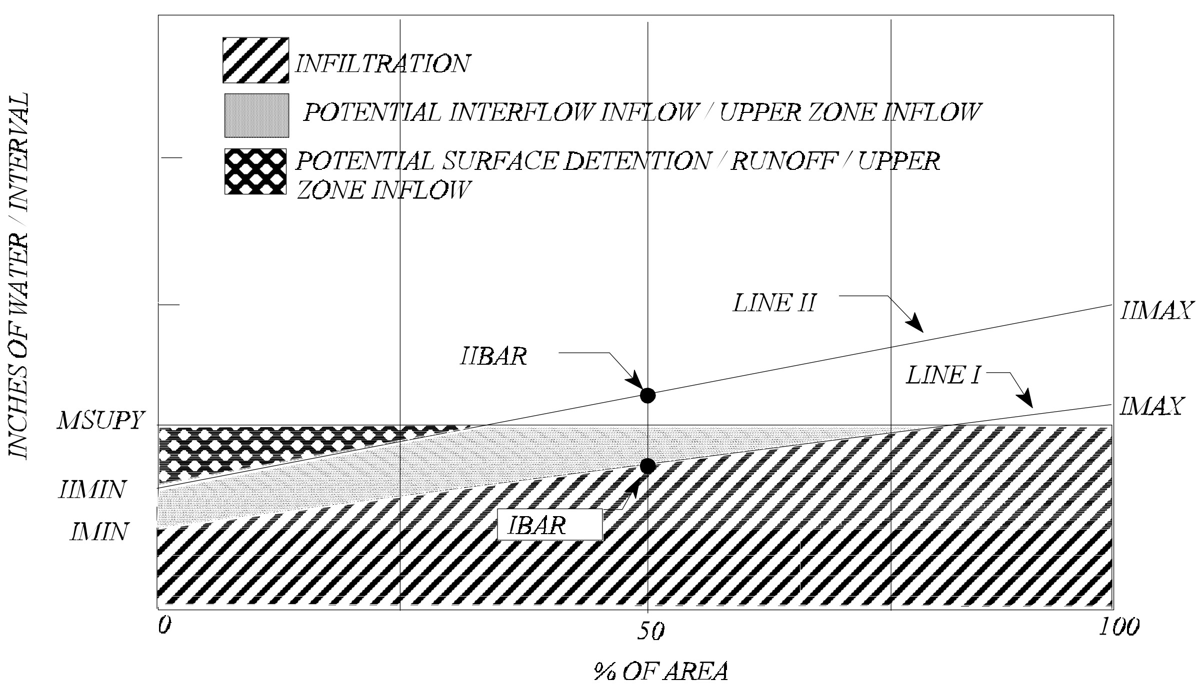

Figure 2.6 HSPF Linear Probability Density Function (after Bicknell et al. 1993)

The I_n, I_c, and I_x points represent the infiltration line (Line I) (see Figure 2.6). All moisture supply (**MSUPY**), denoted by M_s, below the infiltration line is considered as infiltration or Q_i. Above the infiltration line, M_s is considered to be potential direct runoff (**PDRO**), symbolized by Q_R. M_s consists of the water remaining after interception storage is determined, plus lateral overland inflow from an adjacent subbasin (which is not currently supported in FHM) for the current model time interval, plus the surface detention storage from the prior model time interval. Depending upon the amount of moisture M_s available, one of the following three cases are used by HSPF to determine Q_i and Q_R.

$$if\ M_s \le I_n :\ \ Q_i = M_s\ ,\ \ Q_R = 0 \tag{9}$$

$$if\ M_s > I_x :\ \ Q_i = \frac{(I_n + I_x)}{2}\ ,\ \ Q_R = M_s - Q_i \tag{10}$$

otherwise

$$if\ I_n < M_s \le I_x :\ \ \ Q_i = M_s - Q_R\ ,\ \ Q_R = \frac{(M_s - I_n)^2}{2\ (I_x - I_n)} \tag{11}$$

where:

I_n	=	minimum infiltration capacity in inches/hr. **(IMIN)**
I_x	=	maximum infiltration capacity in inches/hr. (**IMAX**)
M_s	=	moisture supply in inches (**MSUPY**)
Q_i	=	infiltration (**INFIL**) in inches
Q_R	=	potential direct runoff (**PDRO**) in inches

The prior three equations are contained within the *DIVISN* subroutine and are interpreted as follows. If the moisture supply is less than the minimum infiltration capacity, then all moisture is assigned to infiltration. If the moisture supply is greater than the maximum infiltration capacity, then infiltration is the mean infiltration capacity, and potential direct runoff is the remaining moisture supply. When the moisture supply is greater than the minimum infiltration capacity but less than or equal to the maximum infiltration capacity, infiltration and potential direct runoff take the form of Equation 11. In all cases, the infiltration line is established prior to calculation of the infiltration and the potential direct runoff depths.

Water which is infiltrating combines with water which is percolating in lower zone storage. This process will be explored in a subsequent section of this chapter.

Components

The subroutines *SURFAC, DISPOS,* and *DIVISN* determine the routing of water for infiltration. For more information about how HSPF handles infiltration, please see the HSPF manual.

Runoff

Surface runoff is the water that travels over the ground surface to a waterway or basin discharge point and includes the initial stages of runoff which occurs as sheetflow and the shallow concentrated flows of primary collectors such as small ditches. For storm event analysis, this process governs the subbasin peak discharge and volume.

Assumptions and Equations

In HSPF, overland flow is determined from potential direct runoff (**PDRO**) following infiltration, upper zone inflow, and interflow inflow calculations. The operations flowchart for FHM in Appendix A illustrates the sequence. However, prior to describing the overland flow calculation procedures, it is necessary to attain the amount of water available for routing.

In the infiltration section, it was stated that HSPF assumes a linear probability density function to describe the spatial variability of infiltration across a subbasin. HSPF also assumes a linear distribution in spatial variability for surface inflow to interflow storage (**IFWI**), or Q_{fs} as used below, and potential surface detention storage (**PSUR**), symbolized by V_{dp}. V_{dp} ultimately becomes overland flow (**SURO**) or Q_{so} and surface detention storage (**SURS**) or V_d.

The assumption of a linear distribution of Q_{fs} and V_{dp} over a subbasin is implemented in HSPF in a manner similar to that of infiltration. A second line (Line II), above the infiltration line (Line I) described in the infiltration section, is constructed to separate Q_{fs} from V_{dp} depths. Also, flux to the upper zone is derived from portions of the Q_{fs} and V_{dp} depths. The line is established by the minimum and maximum values of the line, which are calculated in the following manner:

$$II_n = I_n \times II_r \quad \textbf{(12)}$$

$$II_x = I_x \times II_r \quad \textbf{(13)}$$

where:

I_n	=	minimum infiltration capacity in inches/hr. (**IMIN**)
I_x	=	maximum infiltration capacity in inches/hr. (**IMAX**)
II_n	=	minimum value of line II in inches/hr. (**IIMIN**)
II_x	=	maximum value of line II in inches/hr. (**IIMAX**)
II_r	=	parameter relating infiltration, lower zone storage, and interflow to determine minimum and maximum values for line II (**RATIO**)
I_{fw}	=	interflow inflow parameter (**INTFW**)
L_r	=	ratio of lower zone storage to lower zone nominal storage (**LZRAT**)

The I_{fw} parameter is input by the user and is usually used where there is known to be significant lateral saturated flow above a low permeability lens within the unsaturated zone. Refer to the subsurface storage section for a description of L_r.

The II_n and II_x points represent line II for purposes of separating Q_{fs} from V_{dp} depths. The moisture supply (M_s) above line II is considered to be V_{dp} except for a component of flux to upper zone storage. The moisture supply between the infiltration line and line II is considered to be surface inflow to interflow storage (Q_{fs}), and a component of flux to upper zone storage (**UZI**) or Q_{ui}. The flux to upper zone storage is the first component of potential direct runoff to be determined. Thus, Q_{fs} and V_{dp} depths must be adjusted for Q_{ui}. Refer to the surface storage and subsurface storage sections for an explanation of upper zone storage. Depending upon the amount of moisture supply (M_s) available, one of the following three cases are used by HSPF to determine V_{dp}.

$$\text{if } M_s \le II_n: \quad V_{dp} = 0 \quad \textbf{(14)}$$

$$\text{if } M_s > II_x: \quad V_{dp} = M_s - \left(\frac{II_n + II_x}{2}\right) \quad \textbf{(15)}$$

$$\text{if } II_n < M_s \le II_x: \quad V_{dp} = \frac{(M_s - II_n)^2}{2 \times (II_x - II_n)} \quad \textbf{(16)}$$

The prior three equations are contained within the *DIVISN* subroutine and are applied in a similar way to that described in the infiltration section. If the moisture supply is less than II_n, then potential surface detention storage is zero. When the moisture supply is greater than II_x, then potential surface detention is equal to the moisture supply minus the mean of II_n and II_x. For cases where the moisture supply is between II_n and II_x, potential surface detention takes the form of Equation 16. The value of potential surface detention (V_{dp}) is used to determine overland flow. However, the values of V_{dp} in Equations 14 to 16 are uncorrected for flux to the upper zone. The following corrections must be made prior to employing the results above.

$$corrected\ V_{dp} = uncorrected\ V_{dp} \times (1 - F_{uz}) \qquad \textbf{(17)}$$

where:

V_{dp} = potential surface detention storage (**PSUR**) for the current model time interval; **PSUR** includes the **SURS** moisture from the previous model time interval.

F_{uz} = fraction of potential direct runoff that is flux to upper zone storage (**UZFRAC**)

Note: Refer to Surface Storage and Infiltration sections for a description of the terms used above.

Overland flow is treated as a turbulent flow process. It is simulated using Manning's equation and an equation for continuity, together known as the kinematic wave equation. HSPF uses an internal range of appropriate time steps in simulating overland flow to increase stability in solving the 1-dimensional kinematic wave equations.

The relationships used to calculate the rate of overland flow discharge for the ARM/NPS method are determined by one of two equations. The equation used is dependent upon whether the rate of moisture supply to the overland flow surface (**SSUPR**), or M_r as used below, is decreasing or is at equilibrium ($M_r \leq 0$), or is increasing ($M_r > 0$). M_r is determined by the following:

$$M_r = V_{dp} - V_d^{(t-1)} \qquad \textbf{(18)}$$

where:

V_{dp} = potential surface detention storage (**PSUR**) for the current model time interval; **PSUR** includes the **SURS** moisture from the previous model time interval.

$V_d^{(t-1)}$ = surface detention storage (**SURS**) from the previous model time interval

When the rate of moisture supply to the overland flow surface is increasing, the rate of overland flow (**SURO**), symbolized by Q_{so}, is determined by:

$$Q_{so} = \Delta_{60} \times K_r \times \left(D_m \times \left(1.0 + 0.6 \times \left(\frac{D_m}{D_e} \right)^3 \right) \right)^{1.67} \qquad \textbf{(19)}$$

The equilibrium surface detention storage (**SURSE**), denoted by D_e, for Equation 19 is determined by:

$$D_e = K_v \times (M_r)^{0.6} \qquad \textbf{(20)}$$

When M_r is at equilibrium or is decreasing, Q_{so} is determined by:

$$Q_{so} = \Delta_{60} \times K_r \times (1.6 \times D_m)^{1.67} \qquad \textbf{(21)}$$

The mean surface detention storage (D_m) for the current model time interval is determined by the following equation:

$$D_m = \frac{\left(V_{dp} + V_d^{(t-1)} \right)}{2} \qquad \textbf{(22)}$$

where:

Q_{so}	=	overland flow rate in inches/hr. (**SURO**)
Δ_{60}	=	number of hour/interval (**DELT60**)
K_r	=	calculated routing variable (**SRC**)
D_m	=	mean surface detention storage for current model time interval in inches (**SURSM**)
D_e	=	equilibrium surface detention storage for current model time interval in inches (**SURSE**)
K_v	=	calculated routing variable (**DEC**)
M_r	=	rate of moisture supply to the overland flow surface in inches/hr (**SSUPR**)

The variables K_v and K_r are calculated daily as:

$$K_v = 0.00982 \times \left(\frac{n \times L}{\sqrt{S_L}} \right)^{0.6} \quad \textbf{(23)}$$

$$K_r = 1020.0 \times \left(\frac{\sqrt{S_L}}{n \times L} \right) \quad \textbf{(24)}$$

where:

n	=	Manning's n for the overland flow plane (**NSUR**)
L	=	length of the overland flow plane in feet (**LSUR**)
S_L	=	slope of the overland flow plane in feet/feet (**SLSUR**)

Components

Overland flow is calculated in the *PROUTE* subroutine of the HSPF model. For more information about overland flow, see the HSPF Manual.

Subsurface Storages: Upper Zone, Lower Zone, Interflow, Ground Water

When precipitation infiltrates the soil, it travels into the unsaturated or vadose zone. The moisture then percolates vertically downward through the unsaturated zone until it either contributes to soil moisture (for soil moistures below the field capacity), contributes to interflow, transpires through vegetation, evaporates through the soil, or reaches the water table or saturated zone where it becomes ground water storage. The volume of water that reaches the water table is recharge. Evapotranspiration occurs from the vadose zone through soil evaporation and vegetative osmotic pumping. Shallow (water table) ground water can also contribute baseflow to streams, leakage to deeper aquifers, or move with the water table gradient to other subbasins. Within the unsaturated zone, interflow occurs as horizontal variably saturated flow above relatively lower permeability layers where water moves laterally, also contributing to receiving streams. Interflow is, generally, a more responsive process than water table baseflow.

Assumptions and Equations

In HSPF, the water within the unsaturated zone is calculated by three storages (Figure 2.7): upper zone storage, lower zone storage, and interflow storage. Upper zone storage, as stated earlier, includes moisture within depression storage and surface soil moisture. Lower zone storage is moisture in the remaining unsaturated zone with the exception of moisture held within interflow storage.

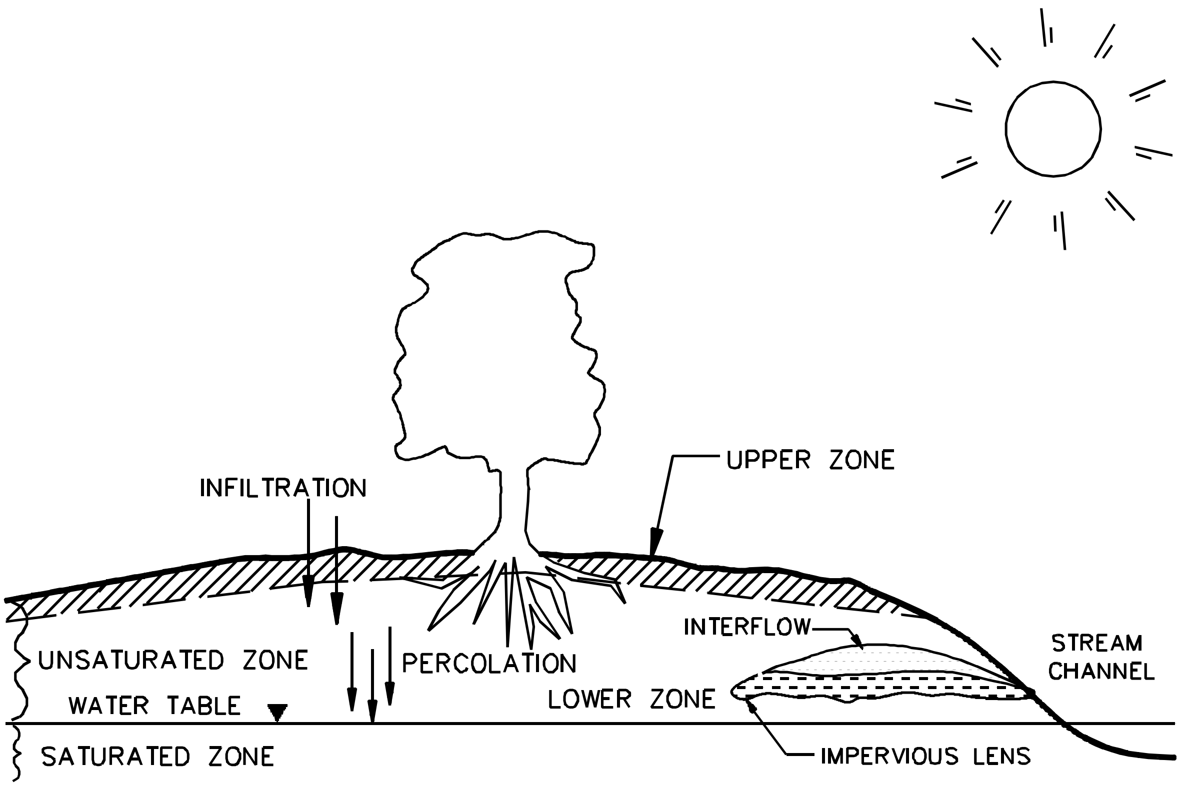

Figure 2.7 Subsurface Fluxes and Storages Used in HSPF

Flux to interflow storage is the next component of **PDRO** to be determined. This moisture is allocated to interflow storage or to interflow outflow, which is discussed in the next section. Following the determination of interflow outflow, interflow storage (**IFWS**), symbolized by V_f, is calculated as the difference of potential interflow storage and interflow outflow.

HSPF allocates water to subsurface storages after it accounts for interception losses and lateral overland flow inflow from adjacent basins. The HSPF process flowchart in Appendix A graphically depicts how subsurface storages are updated. In the Infiltration section of this document, the allocation of water to infiltration and potential direct runoff (**PDRO**) is discussed. As stated earlier, **PDRO** consists of surface inflow to upper zone storage inflow, interflow inflow from surface, surface detention storage, and overland outflow components.

From the surface storage section, flux to upper zone storage is the first storage/flux to be satisfied from **PDRO**. Upper zone storage is eventually allocated to evapotranspiration or percolation. Percolation eventually rejoins infiltration as a source for other unsaturated and saturated storages and fluxes. Refer to the surface storage section for an explanation of how upper zone storage is treated in HSPF.

$$V_f = Q_{fp} - Q_{fo} \tag{25}$$

where:

V_f = interflow storage for the model time interval in inches (**IFWS**)
Q_{fp} = potential interflow storage for the model time interval in inches (**VALUE**)
Q_{fo} = interflow outflow for the model time interval in inches (**IFWO**)

The fraction of infiltration plus percolation (**IPERC**) which enters the lower zone (**LZFRAC**) is denoted by L_f. The remainder of **IPERC** or I_{pt} as used here, is subsequently allocated to saturated zone storages and fluxes or to evapotranspiration. Lower zone storage is calculated from the ratio **LZRAT**, or (L_r) as used below, which is lower zone storage (**LZS**) to lower zone nominal storage capacity (**LZSN**), I_{pt}, and the previous model time interval lower zone storage ($V_l^{(t-1)}$).

$$Q_{li} = L_f \times I_{pt} \tag{26}$$

When $L_r \leq 1$:

$$L_f = 1 - L_r \times \left(\frac{1}{1 + \delta} \right)^{\delta} \tag{27}$$

When $L_r > 1$:

$$L_f = \left(\frac{1}{1 + \delta} \right)^{\delta} \tag{28}$$

For:

$$\delta = 1.5 \times |L_r - 1| + 1 \tag{29}$$

Resulting in:

$$V_l^{(t)} = V_l^{(t-1)} + Q_{li} \qquad \textbf{(30)}$$

where:

V_l^t	=	lower zone storage for the current model time interval in inches (**LZS**); the (t) and (t-1) superscripts refer to the current and previous model time intervals respectively
Q_{li}	=	lower zone inflow in inches (**LZI**)
I_{pt}	=	sum of infiltration and percolation in inches (**IPERC**)
L_f	=	the fraction of infiltration plus percolation entering lower zone storage (**LZFRAC**)
L_r	=	the ratio of **LZS/LZSN**, which is **LZRAT**
δ	=	an index

Moisture in lower zone storage is removed only by evapotranspiration. After lower zone storage is satisfied for the current model time interval, all unsaturated storages and fluxes have been satisfied and the remaining moisture is sent to saturated storages and fluxes.

In the integrated FHM application the lower zone moisture (**LZS**) and nominal capacity (**LZSN**) are updated periodically (at integration time steps). This is to provide for changes in water table influences on the storage capacity and thus the infiltration and recharge capacities. Water balances must be observed and smoothness in infiltration and percolation must be maintained. Specific details on how this is done in FHM are provided in Chapter 3.

The procedures used within FHM to account for ground water storage in the saturated zone differ depending upon whether the simulation is surface water only or integrated. HSPF breaks ground water storage into two groups: inactive and active. Inactive storage is assumed to go to a deeper aquifer and is not available to contribute to the baseflow. Inactive storage is used in FHM continuous simulations and is discussed later. In FHM active ground water storage is available only for event simulations to better represent ET and baseflow.

In the event simulation, HSPF uses the water sent to saturated storages (**GWI**) to calculate inactive ground water storage (**IGWI**) and active ground water storage (**AGWI**). The user specifies the fraction (**DEEPFR**) of water to be assigned to inactive ground water storage. This water is deep aquifer recharge and can no longer be used within HSPF (to satisfy ET or baseflow) once it reaches this storage. The remaining fraction is used to update active ground water storage after active ground water outflow is determined. The outflow process is explained in the Subsurface Flux section. From that section, the following equation can be derived to update active ground water storage.

$$V_g^{(t)} = V_g^{(t-1)} + (Q_{ga} + Q_{gl} - Q_{go}) \quad \textbf{(31)}$$

where:

$V_g^{\ t}$	=	active ground water storage in inches (**AGWS**); the (t) and the (t-1) superscripts refer to the current and previous model time intervals respectively
Q_{ga}	=	active ground water inflow in inches (**AGWI**)
Q_{gl}	=	active ground water lateral inflow in inches (**AGWLI**)
Q_{go}	=	active ground water outflow in inches (**AGWO**)

For the continuous simulation in FHM, HSPF transfers all moisture which reaches the saturated zone to inactive ground water storage which is used as recharge input to MODFLOW for saturated zone calculations. MODFLOW determines the water table elevation for each time interval and thus the saturated zone storage is also determined in MODFLOW. This is explained in the ground water system sections.

Components

The subroutine *LZONE* in HSPF determines the quantity of infiltrated and percolated water which enters the lower zone. The infiltrated moisture supply is determined by the subroutines *SURFAC, DISPOS*, and *DIVISN*. The percolated moisture from the upper zone is determined in subroutines *UZONE* and *UZONES*. The subroutine *INTFLW* calculates the moisture directed to interflow storage. Ground water storages are calculated in *GWATER*. See the HSPF manual for more information.

Subsurface Fluxes: Percolation, Interflow, Recharge, Ground Water Flow

Percolation is the vertical movement of water within the unsaturated soil toward the saturated zone. Percolated water fills available unsaturated soil moisture (to field capacity) with excess going to recharge. Interflow, which may add to stream flow, is the horizontal movement of water above an impervious layer in the unsaturated zone. For an event simulation, HSPF calculates both interflow and ground water flow. Recharge is the water that reaches the saturated zone. This section will describe how recharge is used to determine ground water outflow for event simulations. For continuous simulations, MODFLOW is employed to determine the effect of recharge on ground water flow. See Appendix A for the HSPF operations flowchart.

Percolation

In HSPF, percolation only occurs when the ratio of the upper zone storage to the upper zone nominal storage (**UZRAT**) minus the ratio of the lower zone storage to the lower zone nominal storage (**LZRAT**) is greater than 0.01. Percolation is a division of upper zone storage along with ET. Percolation can only occur if there is sufficient water in upper zone storage. Percolation which does occur eventually rejoins direct infiltration as a source for storages and fluxes from the lower zone downward and ET (see Figure 2.7).

Percolation (I_p) is calculated by the following empirical expression:

$$I_p = 0.1 \times I \times U_n \times (U_r - L_r)^3 \tag{32}$$

However, if

$$if\ I_p > V_u,\ then\ I_p = V_u \tag{33}$$

where:

I_p	=	percolation from the upper zone in inches/hr (**PERC**)
I	=	infiltration index in inches/hr (**INFILT**)
U_n	=	upper zone nominal storage in inches (**UZSN**)
U_r	=	ratio of upper zone storage (**UZS**) to upper zone nominal storage (**UZSN**), which is **UZRAT**
L_r	=	ratio of lower zone storage (**LZS**) to lower zone nominal storage (**LZSN**), which is **LZRAT**
V_u	=	upper zone storage for the current model time interval in inches (**UZS**)

Interflow

Interflow has a linear relationship to interflow storage and to inflow to interflow storage. In HSPF, interflow is a function of a recession parameter, total inflow to interflow storage (from surface and lateral sources), and interflow storage from the previous model time interval. To calculate the interflow outflow (Q_{fo}) which contributes to stream base flow or lateral interflow to adjacent basins (not available in current FHM version), HSPF uses the following procedure:

Surface inflow to interflow storage (Q_{fs}) is determined by:

$$Q_{fs} = (Q - V_{dp}) \times (1 - F_{uz}) \quad \textbf{(34)}$$

The value of Q_{fs} above is corrected for the upper zone inflow component (UZI) by the (1 - F_{uz}) factor. Refer to the Overland Flow section for further details on the correction factor.
Total inflow to interflow storage (Q_{fi}) is calculated as:

$$Q_{fi} = Q_{fs} + Q_{fl} \quad \textbf{(35)}$$

Potential interflow storage (Q_{fp}) is determined by:

$$Q_{fp} = Q_{fi} + V_f^{(t-1)} \quad \textbf{(36)}$$

From total inflow (flux) to interflow storage for the current model time interval, interflow storage from prior model time interval, and a recession parameter, the interflow outflow (Q_{fo}) is calculated.

$$Q_{fo} = (K_1 \times Q_{fi}) + \left(K_2 \times V_f^{(t-1)}\right) \quad \textbf{(37)}$$

where:

Q_{fi}	=	total inflow to interflow storage for the current model time interval in inches (**INFLO**)
Q_{fs}	=	surface component of inflow to interflow storage for the model time interval in inches (**IFWI**)
Q_{fl}	=	lateral component of inflow to interflow storage for the model time interval in inches (**IFWLI**)
V_f^{t-1}	=	interflow storage from previous model time interval in inches (**IFWS**); the (t-1) superscript refers to the previous model time interval

$$K_1 = 1 - \left(\frac{K_2}{K_f}\right) \quad \textbf{(38)}$$

K_1 and K_2 are variables determined by

$$K_f = \frac{\Delta_{60} \ln I_r}{24} \qquad \textbf{(39)}$$

$$K_2 = 1 - e^{-K_f} \qquad \textbf{(40)}$$

where:

I_r	=	interflow recession per day (**IRC**)
Δ_{60}	=	number of hours/interval (**DELT60**)
24	=	number of hours/day

The interflow recession parameter (**IRC**), used as (I_r) above, is the ratio of the present rate of interflow outflow(Q_{fo}) to the value 24 hours earlier, if there was no inflow. The user must enter values for both **IRC** and initial **IFWS** in the pre-processor.

Ground Water Inflow (HSPF "Recharge")

Ground water inflow (GWI) in HSPF is the amount of direct infiltration and percolation which does not remain in the lower zone (unsaturated) storage. This water represents an outflow flux from HSPF and can be thought of as the water which reaches the water table (see Figure 2.7). GWI in HSPF, referred to here as "recharge" or R for convenience, is calculated the same for surface water only and integrated simulations. HSPF "recharge" is determined by:

$$R = I_{pt} - Q_{li} \qquad \textbf{(41)}$$

where:

R	=	volume of water moving to the water table
I_{pt}	=	infiltration and percolation (**IPERC**)
Q_{li}	=	volume of water staying in lower zone storage

Ground Water Flow (Surface Water Only Simulation)

Ground water flow is handled differently in FHM for surface water only and integrated simulations. For integrated simulations, all ground water storage and flow calculations are performed in MODFLOW; refer to the Ground Water System sections for more details.

HSPF performs ground water calculations for surface water only simulations in the following manner (see Figure 2.7). As stated in the ground water storage section, the fraction of infiltration and percolation going to inactive ground water storage, which is water "lost" from the system, is determined by the value of DEEPFR. The remaining water goes to active ground water storage. The following equations illustrate inactive and active ground water storage inflows:

$$Q_{gi} = K_f \times R \quad \textbf{(42)}$$

$$Q_{ga} = R - Q_{gi} \quad \textbf{(43)}$$

where:

Q_{gi}	=	inflow to inactive ground water storage in inches (**IGWI**)
Q_{ga}	=	inflow to active ground water storage in inches (**AGWI**)
K_f	=	fraction of ground water inflow sent to inactive ground water storage (**DEEPFR**)
R	=	recharge to the water table in inches (**GWI**)

To determine base flow from active ground water storage, HSPF uses a relationship which assumes that the aquifer discharge is proportional to the product of the cross-sectional area and the energy gradient of the flow. This relationship also assumes that a representative cross sectional area of flow is related to the ground water storage level at the start of the interval. The energy gradient is estimated as a basic gradient plus a variable gradient that depends upon past active ground water accumulation. For event simulations, ground water outflow (**AGWO**) from active ground water storage (Q_{go}) is estimated in the following manner:

$$Q_{go} = K_g \times (1.0 + K_v \times \delta_s) \times V_g^{(t-1)} \quad \textbf{(44)}$$

otherwise,

$$\mathit{If}\ K_v = 0 \ \ \mathit{then}\ \ Q_{go} = K_g \times V_g^{(t-1)} \quad \textbf{(45)}$$

$$K_g = 1.0 - (K_r)^{\frac{\Delta_{60}}{24}} \quad \textbf{(46)}$$

where:

K_g	=	ground water outflow recession parameter, per interval
K_v	=	non-linear outflow parameter in inches (**KVARY**)
δ_s	=	ground water slope index for current model time interval in inches (**GWVS**)
V_g^{t-1}	=	active ground water storage at start of model time interval in inches (**AGWS**)
K_r	=	daily ground water recession parameter (**AGWRC**)
Δ_{60}	=	hour/interval

The ground water slope index δ_s is increased each model time interval by the inflow to active ground water, but it is also decreased by three percent each day. The index is a measure of antecedent active ground water inflow. K_v allows variable ground water recession rates.

Components

Percolation from the upper zone is calculated by the subroutines *UZONE* and *UZONES*. Interflow is calculated in subroutines *DISPOS, DIVISN*, and *INTFLW*. Active ground water flow is calculated in subroutine *GWATER*.

Assumptions and Equations

For integrated FHM simulations, HSPF determines the amount of recharge which reaches the water table as ground water inflow. For ground water only simulation recharge must be defined by the user, cell by cell, using the pre-processor of FHM. Refer to Part III for details on this application. Although the method of determining the amount of recharge is the same for surface water only and integrated simulations, only the integrated transfer of recharge is discussed here. The reader is directed to the Subsurface Flow Section of this Chapter for details on surface water only simulation. For integrated simulation, the **DEEPFR** variable of HSPF is always set to 1.0 to direct all water to go to inactive ground water storage (**IGWI**). Allowing any water to go to active storage in HSPF will cause base flow to occur in HSPF and in MODFLOW, which will produce erroneous results. The interfacing software of FHM places the recharge determined by HSPF into a MODFLOW recharge package for use in the ground water. The recharge is apportioned uniformly to all cells by subbasin designation. MODFLOW uses the recharge, along with other output data from HSPF, to update water table and stream reach heads and fluxes.

Components

Percolation from the upper zone is calculated by the HSPF subroutines *UZONE* and *UZONES*. Interflow is calculated in HSPF subroutines *DISPOS*, *DIVISN*, and *INTFLW*. Active ground water flow is calculated in HSPF subroutine *GWATER*.

Within MODFLOW assignment of recharge to the water table is provided by the Recharge (RCH) package. Recharge data is either specified by the user through the pre-processor (ground water only) or generated by the HSPF surface water model as **IGWI** in the PERLND module.

Ground Water System

By definition for FHM the ground water system is that portion of the hydrologic system that occurs below the water table in soils and hydrogeologic units which are fully saturated. The ground water system may consist of multiple hydrogeologic units: e.g., a surficial (water table) aquifer, a semi-confining bed, and a semi-confined aquifer (see Figure 2.8). Lateral head gradients result in the movement or flow of ground water horizontally through an aquifer. Movement of water vertically through a semi-confining layer is leakage. In any application, the user must specify the number of layers needed to represent the aquifer(s) and confining unit(s) of interest and the hydraulic properties of each.

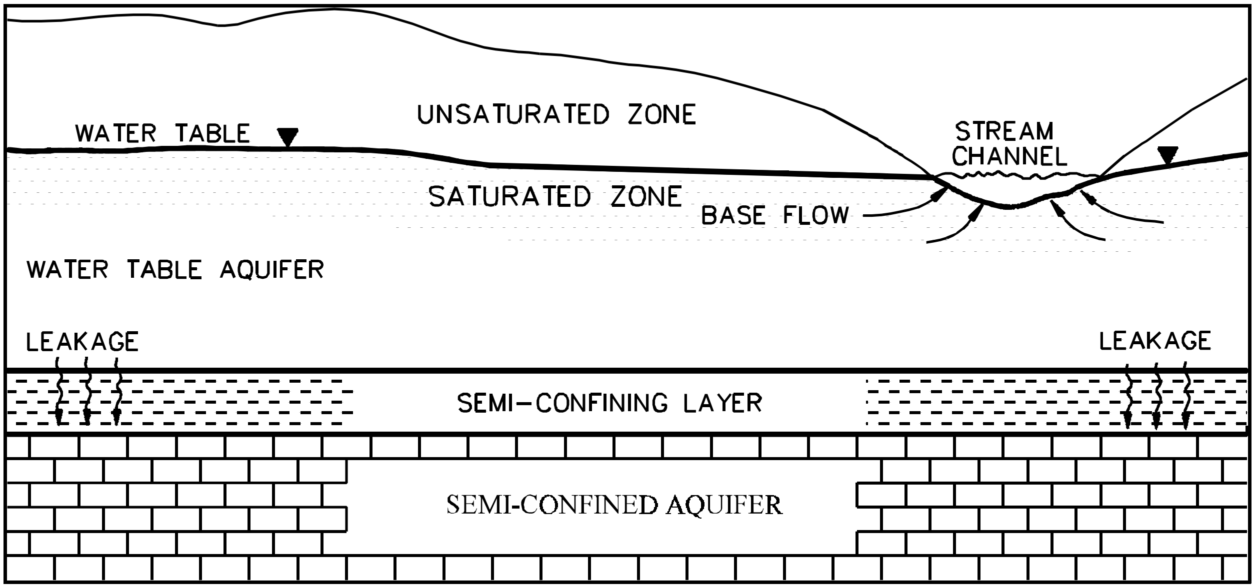

Figure 2.8 Simple Conceptual Ground Water System

Overview of MODFLOW Operation

As stated earlier, MODFLOW, developed by the U.S. Geological Survey, is used both for ground water only and integrated simulations in FHM. HSPF performs ground water calculations for surface water only simulations. All capabilities of MODFLOW are available for applications in FHM.

A series of implicit finite-difference equations are produced by MODFLOW and solved simultaneously. The procedure requires multiple iterations to converge on the solution which is the resultant head and flow distribution.

MODFLOW operates upon a different spatial discretization than HSPF. HSPF uses watersheds and stream reaches as a base; MODFLOW uses an equally-spaced grid of cells, with interior nodes to express the difference equations for each layer. The equal spacing is a limitation of FHM V3.0. The rows, columns and layers are defined with an i, j, k system of coordinates. The layers are the representation of hydrogeologic units in the vertical direction which typically have significant water bearing potential. However, in certain applications, it may be necessary to represent a confining layer with multiple model layers. Other specialized applications may also warrant additional model layers. Each hydrogeologic unit is conceptualized to behave distinctly differently from adjacent units (layers). Each node is centered in a cell, not located at the intersection of cell boundaries. Each cell represents a block of porous material which has uniform hydraulic properties (e.g., hydraulic conductivity) for each layer. Figure 2.9 shows a MODFLOW grid and cell structure in relation to an HSPF subbasin structure for a study area. The size of the grid spacing and area covered varies depending upon the areal size of the watershed and the degree of resolution required.

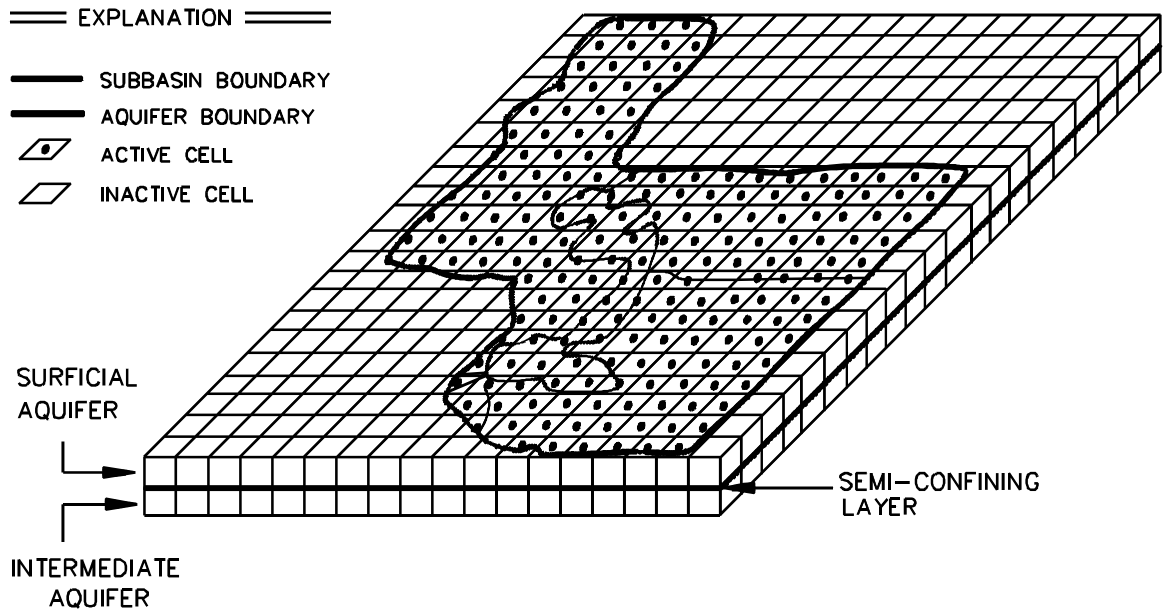

Figure 2.9 Example MODFLOW Grid Superimposed With HSPF Subbasins

The FHM application of MODFLOW uses a generic multi-layer conceptual system to represent the hydrogeologic units of interest which are present within the modeled area. The layers are associated with the aquifer(s) (and potentially confining units) which are "connected" to each other by a leakance term. Representation of a semi-confining bed as a leakance term is valid, provided: there is approximately two orders of magnitude difference in hydraulic conductivity between the semi-confining bed and the aquifers above and below, and the semi-confining bed provides minimal release of water from the confining bed storage. FHM does not place any limits on how the hydrologic system is conceptualized into layers.

FHM uses the following assumptions with respect to ground water flow:

1. Moisture which reaches inactive storage within HSPF represents recharge to the surficial aquifer layer.
2. The sum of all flow into and out of the cell per time step equals the rate of change in storage within the cell which is dependent on the storage coefficient.
3. The model simulates horizontal flow in all model layers.
4. Water movement between significant water bodies (e.g. streams, lakes, wetlands) and model layers is vertical only.
5. "Static" streams do not experience significant stage variations relative to ground water timescales. Temporal stage variation is pre-determined by the user for each stress period for independent ground water and integrated simulations.

6. “Dynamic” streams have stage-dependent ground water connectivity warranting temporal updates considering surface water flows. For independent ground water simulations, temporal stage variation is pre-determined by the user. For integrated simulations, the simulated reach stage from HSPF determines the temporal variation.

To allow HSPF and MODFLOW to communicate, data must be transferred into a format that each model can use. Basin to grid linkages are made using the basin array file. This data provides the spatial linkage between basins and grids periodically accessed by the integration software during the run sequence. Details concerning data transfer are provided in Chapter 3.

Figure 2.9 shows a MODFLOW grid and cell system used for a typical study area. The figure superimposes the grid system over HSPF subbasins, which allows the two models to pass data between each other. This is one of the GIS operations described in the GIS Section (see Chapter 4 and Parts II and III). Without GIS, the user will have to manually create a grid system and provide all parameters manually using the pre-processor (refer to Part III).

Boundary conditions can take the form of constant or specified heads or fluxes or are unconstrained by either an external head or flux condition. Boundary conditions are modeled using different types of cells in MODFLOW. Cells which are unconstrained by boundary conditions, in which water level change occurs, are called active cells and are designated by a positive integer in the **IBOUND** array. Those cells which correspond to areas outside the active ground water domain are designated as inactive cells or no flow boundaries, symbolized by a zero in the **IBOUND** array. In FHM, large bodies of water along the boundary which would operate as a constant sink or source are designated constant-head cells, and are denoted by a negative integer. Constant head cells interior of an active domain should be avoided as water balance errors will result. Within FHM, the full capabilities of MODFLOW (1984) are provided. All standard MODFLOW packages can be used during a ground water only or integrated simulation. However, pre-processors within FHM provide easy data preparation for 10 commonly used packages.

FHM incorporates ten packages of MODFLOW for integrated simulations. These include: Basic (BAS) , Block Centered Flow (BCF), Recharge (RCH), River (RIV), Wells (WEL), Drains (DRN), General Head Boundaries (GHB), Evapotranspiration (EVT), Output Control (OC), and Strongly Implicit Procedure (SIP). The MODFLOW documentation explains the theory, equations, and application of each of these subroutines thoroughly, the user is referred to it for greater detail. In the following sections, the topics listed below will be explored in relation to MODFLOW within FHM:

1. Saturated Flow
2. Recharge
3. River Base flow and Surface Water Body Flux
4. Leakage
5. Wells

Lateral Flow

Lateral flow in an aquifer occurs from horizontal head gradients and is controlled by the hydraulic conductivity in the direction of flow and the thickness of the aquifer.

Assumptions and Equations

An elementary discussion of Darcian flow is provided here. However, the MODFLOW users manual is sufficiently well written and detailed to suffice for FHM application. The reader is directed to McDonald and Harbaugh (1984) for further reference.

Saturated flow is calculated by using Darcy's Law which defines 1-dimensional flow as:

$$Q = \frac{KA(h_2 - h_1)}{L} \tag{47}$$

where:

Q	=	ground water flow in ft^3/day
K	=	hydraulic conductivity in the direction of flow in ft/day
A	=	cross sectional area perpendicular to flow in ft^2
h_2-h_1	=	the head difference across the prism parallel to the flow in ft
L	=	length of flow path in ft

For unconfined aquifers, such as the surficial (water table), the calculated heads are a function of changes to the saturated aquifer thickness among other factors. Transmissivity, the ability of the aquifer to transmit water, is equal to: aquifer hydraulic conductivity times saturated thickness. Therefore, the transmissivity of the surficial aquifer varies temporally and the saturated thickness must be tracked by MODFLOW through time.

The ground water parameters are determined as follows. For the surficial aquifer, the hydraulic conductivity (K) is assigned from soil and slug tests, as well as aquifer (pumping) tests. The area (A) is determined by cell dimension and the saturated thickness of the aquifer. The saturated thickness is the elevation difference between the water table head and the top of the aquitard for the surficial aquifer and defined by the upper and lower confining unit elevations for a confined aquifer. Because the water table elevation varies spatially and temporally, and the top of the aquitard varies spatially, the saturated thickness is variable. Where adequate digital hydrogeologic data exists, the GIS provides a convenient and rapid means to define this data. The length of the flow path (L) is determined from the cell dimensions. The head difference (h_2 - h_1) is determined through finite-difference techniques.

For confined aquifers, the saturated thickness is assumed to be a constant value (distance between confining beds); thus, the hydraulic conductivity and the saturated thickness are combined into a temporally constant transmissivity term, which is input to MODFLOW through the pre-processor. For deeper aquifers hydraulic conductivities and/or transmissivities have been determined by pump tests and previous model calibration.

Aquifers which oscillate between confined and unconfined conditions can be simulated by FHM. MODFLOW allows two types of convertible aquifers which have different input requirements.

Leakage

Leakage is the vertical movement of ground water from one aquifer to another. Leakage is a function of the vertical hydraulic conductivities of confining unit and underlying/overlying aquifers, the thickness of a semi-confining bed, and the vertical head difference between two aquifers. Leakage can occur either upward or downward.

Assumptions and Equations

Leakage is the volume of water that moves through a semi-confining bed from one aquifer to another. It is defined as leakance multiplied by the head difference. Leakance is the vertical hydraulic conductivity divided by the thickness of the semi-confining materials.

$$L_g = L \times (h_e - h_a) \quad \textbf{(48)}$$

$$L = \frac{K}{m} \quad \textbf{(49)}$$

where:

L_g	=	leakage in ft/day
L	=	leakance in day^{-1}
h_e	=	head in the aquifer located across the confining bed from where heads are currently being calculated by MODFLOW in ft
h_a	=	head in the aquifer in which heads are currently being calculated by MODFLOW in ft
K	=	vertical hydraulic conductivity in ft/day
m	=	thickness of confining bed in ft

Within MODFLOW, the unit represented by a leakance term is associated with the unit above represented by a model layer. The assumption of vertical flow through a confining bed relies on maintaining at least two orders of magnitude difference in hydraulic conductivity between the semi-confining bed and the aquifers above and below it.

Reaches (Wetlands, Lakes and Streams)

Basin hydrology is strongly influenced by the "condition" of the receiving hydrography (surface water bodies: wetlands, lakes and streams). The condition of a water body includes the storage capacity, the contributing drainage basin, the connection to the ground water system, the ET losses, and the downstream conveyance ability. It is a primary objective of integrated modeling to be able to quantify these components. Within a basin, especially a regional basin, there are many hydrography features, both ephemeral (seasonal) and perennial (wet all year). This includes ditches, multi-ordered streams, interconnected wetlands, lakes, and man-made conveyance structures. The combined storage and friction attenuation of these conveyance features completely define the character of storm runoff response at any downstream flow station. Also, the major natural discharge mechanism for the ground water system is the combined contributed base flow to the conveyance system which becomes open water and wetland ET and downstream sustained flows.

Within FHM, basin hydrography is considered to fall under one of three categories: isolated, "static" or "dynamic" connected. If a wetland, pond or lake is not directly connected and contributing to the downstream flow response of the system it is considered hydraulically isolated. If it is not of sufficient interest to warrant the assignment of its own reach element and thereby requiring the determination of its own contribution basin area, it must be combined into the overall depression storage capacity of the basin. This is considered a "macro-depressional" feature. All other hydrography that does contribute directly to the downstream discharge of a receiving body must be accounted for and classified as either "static" or "dynamic" for the integrated model. It is presently beyond the capabilities of FHM and/or not cost effective to model every connected hydrography segment individually.

Static versus dynamic streams refer to their interaction and simulation within the surface and ground water system within the structure of FHM. The designation is based on the following assumptions. The base flow of a stream is largely derived from the combined small contributions of the many miles of contributing low-order (Strahler method, Viessman and Lewis 1996) streams. Base flow response in these streams is relatively unaffected (over ground water time scales) by the storm response stream stage variation but instead mostly influenced by the local water table stage variation from a recent or historical infiltration event. Where base flow is mostly affected by aquifer variation, the hydrography element can be classified as "static".

For larger water bodies (e.g., rivers, lakes and reservoirs), the magnitude (and in some cases direction) of base flow is strongly dependent on not just the head in the aquifer but the stage of the hydrography element. Extended periods of elevated stage can occur in these water bodies due to the greater contributing drainage basin area and increased storage capacity. Routing elements that exhibit significant base flow variation due to relative stage in the feature must be classified as “dynamic”. More on how to designate static and dynamic hydrography elements can be found in Parts II and III.

Within FHM, static hydrography elements receive base flow from MODFLOW based on constant stage assignments determined from the “average” stage of each hydrography element. For ephemeral streams that are commonly dry, the “average” stage may be near or equal to the bed elevation. For dynamic hydrography elements, the base flow is always determined by considering the periodic stage of the element which is updated from the surface water model.

All hydrography elements receiving basin runoff inflows that directly contribute to the downstream flow response must be included in the rating (storage attenuation) condition of the modeled surface water reach. Every basin should have at least one reach with the assigned surface storage volume of all interior contributing hydrography elements. This volume must be expressed with respect to the outlet stage of the principal discharge outlet. Basins can have one or more reaches to represent storage attenuation depending on the level of detail desired. The following section describes how HSPF, the surface water component model, uses reaches within FHM.

HSPF Reach/Reservoir Routing

Stream flows, wetland and lake discharges are modeled in HSPF as reach routing elements (RCHRES). Figure 2.10 depicts the water balance terms for reach/reservoir segments. Reaches receive surface water runoff (overland flow) from adjacent basins, interflow, ground water base flow, upstream reach inflows, diversions, precipitation, and ET. Runoff contributes to stream flow for short periods and is usually discharged from the basin within days. Base flow varies gradually with rising and falling water table elevations and may vary monthly or seasonally.

Assumptions and Equations

The stream flow and stream routing subroutines are portions of FHM that require user-defined values (i.e., rating) for the stage-storage-discharge-area relationship. These values must be measured at the site or carefully estimated by a hydrologist.

HSPF uses a fixed relationship (single valued rating) between the volume of water in a reach versus stage. Discharge at each cross-section or node is a function of a fixed stage-storage/discharge table (referred to as an F-Table in HSPF, refer to Part III, Appendix C for an example) for each routing reach. The rating curve is fixed, but the discharge varies in time as a function of the variation in stage. The rating contains no provision for hysteresis. HSPF uses the following continuity equation:

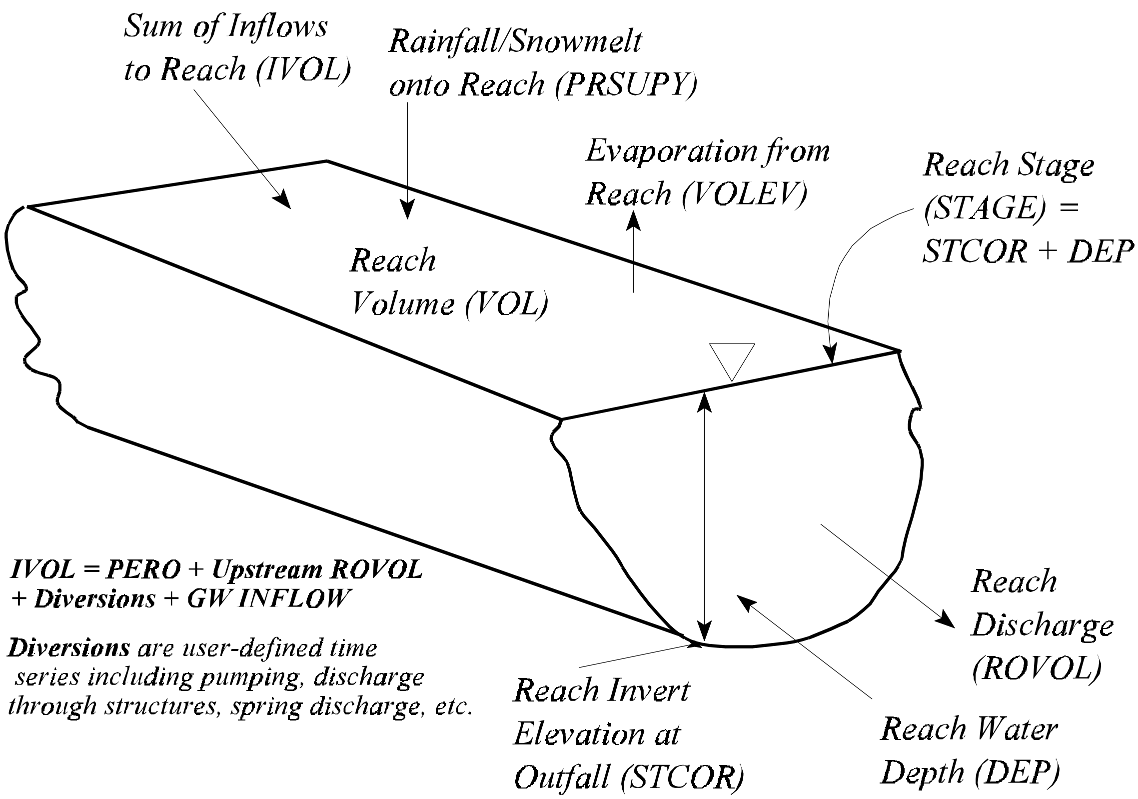

Figure 2.10 Water Balance Terms Included in FHM/HSPF Reach Reservoir Segment

$$V = V_s + V_i + P_s - V_e - V_o \tag{50}$$

where:

V	=	volume at the end of the model time interval (**VOL**)
V_s	=	volume at the start of the model time interval (**VOLS**)
V_i	=	water inflow from upstream reaches and subbasins (**IVOL**)
P_s	=	precipitation on the surface of the reach (**PRSUPY**)
V_e	=	water lost to evaporation from water surface (**VOLEV**)
V_o	=	water leaving reach as outflow (**ROVOL**)

The volume of water inflow (V_i) is the summation of overland flow, interflow, base flow from ground water and the upstream reach outflow. Refer to earlier sections of this document for more information on basin discharge components.

The mean rate of outflow (**ROVOL** discharge) is assumed to be a weighted mean of the rates determined by the stages at the start and end of the interval, yielding an implicit solution. A weighting factor (K_s), is provided by the user to determine the degree of implicitness of the solution. The equation for the mean rate of outflow, Q, is:

$$Q = (K_s \times Q_s + K_c \times Q_o) \times \Delta t \qquad \textbf{(51)}$$

where:

K_s	=	weighting factor [$0 \leq K_s \leq 0.99$] (**KS**)
K_c	=	complement of K_s [$1.0 - K_s$] (**COKS**)
Q_s	=	total rate of outflow from reach at start of model time interval (**ROS**)
Q_o	=	total rate of demanded outflow from reach at end of model time interval (**ROD**)
Δt	=	simulation interval in sec. (**DELTS**)

By combining Equations 50 and 51 the following equation is produced:

$$V = V_s + V_i + P_s - V_e - (K_s \times Q_s + K_c \times Q_o) \times \Delta t \qquad \textbf{(52)}$$

Equation 52 leaves HSPF with two unknown values, Q_o and V. HSPF then uses the user defined F-tables, which are the stage-storage/discharge tables, and solves for Q_o, V and stage iteratively using linear interpolation of the tabulated listings.

Components

Reach reservoir modeling in HSPF uses the RCHRES module. Stream flow components are located in subroutine *HYDR* of HSPF. For more information on stream flow and routing, see the HSPF Manual.

Base Flow

Base flow occurs when an aquifer contributes flow to streams and rivers because of a head gradient between the aquifer and stream. Ground water flux to other surface water bodies (i.e., to lakes and wetlands) occurs in a similar manner. If the water table aquifer is higher in elevation than the stream/lake, the aquifer contributes water to the stream/lake; if the water table is lower in elevation than the stream/lake, the stream/lake loses water to the water table. During a storm hydrograph passage in a stream, the base flow may temporarily halt or reverse as the head gradient reverses. For large water bodies, this may be significant. The magnitude of flux for streams/lakes is dependent upon the hydraulic conductivity and thickness of the bottom sediments and the head difference between the adjacent water table and the stream/lake.

Assumptions and Equations

FHM can simulate base flow or stream leakage, which is flux to or from surface water bodies (gaining or losing streams, respectively). Surface water bodies are designated as reaches in HSPF and MODFLOW, although the definition of a reach is different between the two models. A reach in HSPF is a defined water conveyance entity which has a single-valued discharge relationship for all defined depths. In MODFLOW, a reach is that section of a stream or water body that falls into a particular cell of the grid. It may take more than one cell to represent the surface water body, and a particular cell may contain more than one reach from different streams. The two equations used to calculate base flow, stream losses or surface water body flux are based upon Darcy's Law. Ordinarily, water table heads are above the bottom of streams and the corresponding base flow depends on the head gradient (Equation 53). When the aquifer head (H_a) falls below the bottom elevation (Z_{bot}) of the stream/lake sediments, the flow out of the surface water body is limited to the conductance times the head difference between the stage of the surface water body and the sediment bottom elevation (Equation 54). MODFLOW representation of hydrography/aquifer interaction is illustrated in Figure 2.11.

$$\text{If } H_a > Z_{bot}: \quad Q_b = C_{sb} \times (H_s - H_a) \tag{53}$$

$$\text{If } H_a \leq Z_{bot}: \quad Q_b = C_{sb} \times (H_s - Z_{bot}) \tag{54}$$

where:

Q_b	=	the quantity of base flow or surface water body flux entering/leaving stream flow through the grid-cell reach in ft^3/day
H_s	=	the elevation head (stage) of the stream or lake in ft
H_a	=	the elevation head of the aquifer in ft
Z_{bot}	=	the elevation of the stream/lake bottom sediments in ft
C_{sb}	=	stream/lake bed conductance in ft^2/day

Conductance is the ratio of the vertical hydraulic conductivity of the stream/lake bed to the thickness of the stream/lake bed multiplied by the cross-sectional area of flow (grid-cell reach length multiplied by the stream/lake bed width)

NOTE: The grid-cell reach length is different than the reach length as defined for HSPF. Also, the grid-cell reach length could be greater than the cell dimensions if the stream is winding.

Thus:

$$C_{sb} = \frac{K_{sb} \times L_r \times W}{m_{sb}} \tag{55}$$

where:

C_{sb}	=	stream/lake bed conductance in ft^2/day
K_{sb}	=	vertical hydraulic conductivity of the stream/lake bed in ft/day
m_{sb}	=	thickness of the stream/lake bed in ft
L_r	=	length of the grid-cell reach in ft
W	=	width of stream/lake bed in ft

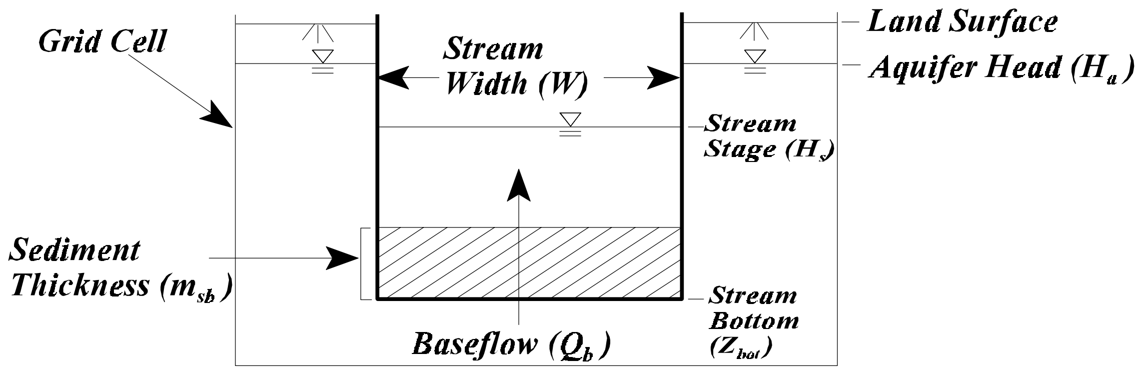

Figure 2.11 Hydrography Representation in MODFLOW

As discussed previously, FHM provides for "static" and "dynamic" reaches. Static reaches have a constant stage and are not updated by the surface water model. "Dynamic" reaches have variable stages updated by the surface water model during integration time steps.

Components

For continuous simulations, base flow and flux to other surface water bodies is calculated through the MODFLOW river package. Prior to MODFLOW simulation, HSPF determines the surface contribution to all surface water bodies, calculates surface flows between reaches, and determines updated stream/lake stages due to surface water inflows. The new stream/lake stages are transferred to MODFLOW via FHM integrating software. MODFLOW uses the updated stages, along with other output from HSPF, to update the water table heads and to determine the base flow, stream leakage, and flux for other surface water bodies due to ground water influences.

There is a base flow component in HSPF; however, in order to avoid duplication within FHM, the HSPF base flow component is not used in integrated simulations. Refer to the Subsurface Flux Section for further details on base flow calculation procedures for surface water only simulations.

Hydrography Scale Dependence

The interaction between hydrography and the ground water system is locally and sometimes regionally significant. The interaction is also scale-dependent. In the physical system, hydrography elements possess both highly variable surface water stage and bed bottom elevations. The variability in these elevations can be demonstrated with topographic elevations near a stream as shown in Figure 2.12. In the illustration, topography elevation contours are shown in gray with bold stream arcs and a ground water grid cell overlaying the contours. The illustration shows that the two legs of the stream above the confluence are represented in the ground water model as many stream segments (i.e., four segments for the upper leg and two segments for the lower leg). Each stream segment requires assignment of model values for stage and bed bottom elevations and conductance. The variability in the physical elevation data along the stream must be captured in the model data. In the illustration, there is greater than 40 feet of elevation difference in land surface from the upper end of each leg to the confluence.

It is also understood that the bed leakance, or magnitude of connection with the ground water system, varies along the course of a stream or from one lake or wetland to another. Ground water base flow is a measure of the degree of connection but the flow rate varies along the stream. From the perspective of a hydrography element and using the HSPF sign convention, when base flow is positive the ground water system discharges into the stream or lake (gaining reach), and when base flow is negative the stream or lake loses water to the aquifer (losing reach). A set of multi-scale models which produce simulated base flow at a consistent rate regardless of model scale is considered scale-independent with respect to hydrography.

To acquire consistent base flow rates across all management scales, the model must incorporate an appropriate level of detail in hydrography representation which is consistent for all scales, employ shifted elevations to overcome problems attributed to hydrography gradients and absolute or physical elevations, and weight the elevations by bed hydraulic characteristics when hydrography aggregation is necessary. The following paragraphs expand on these concepts.

Hydrography must be represented with an appropriate level of detail to attain scale-independence across all management scales. The hydrography elements which significantly affect or are significantly affected by the ground water system at the smallest conceivable management scale should be included in the ground water model at all scales. For example, a good start might include all perennial streams, lakes, wetlands, etc. which are connected through the tributary network to the main stream channel in the watershed. Physical attributes must be assigned to each hydrography element to permit development of model data.

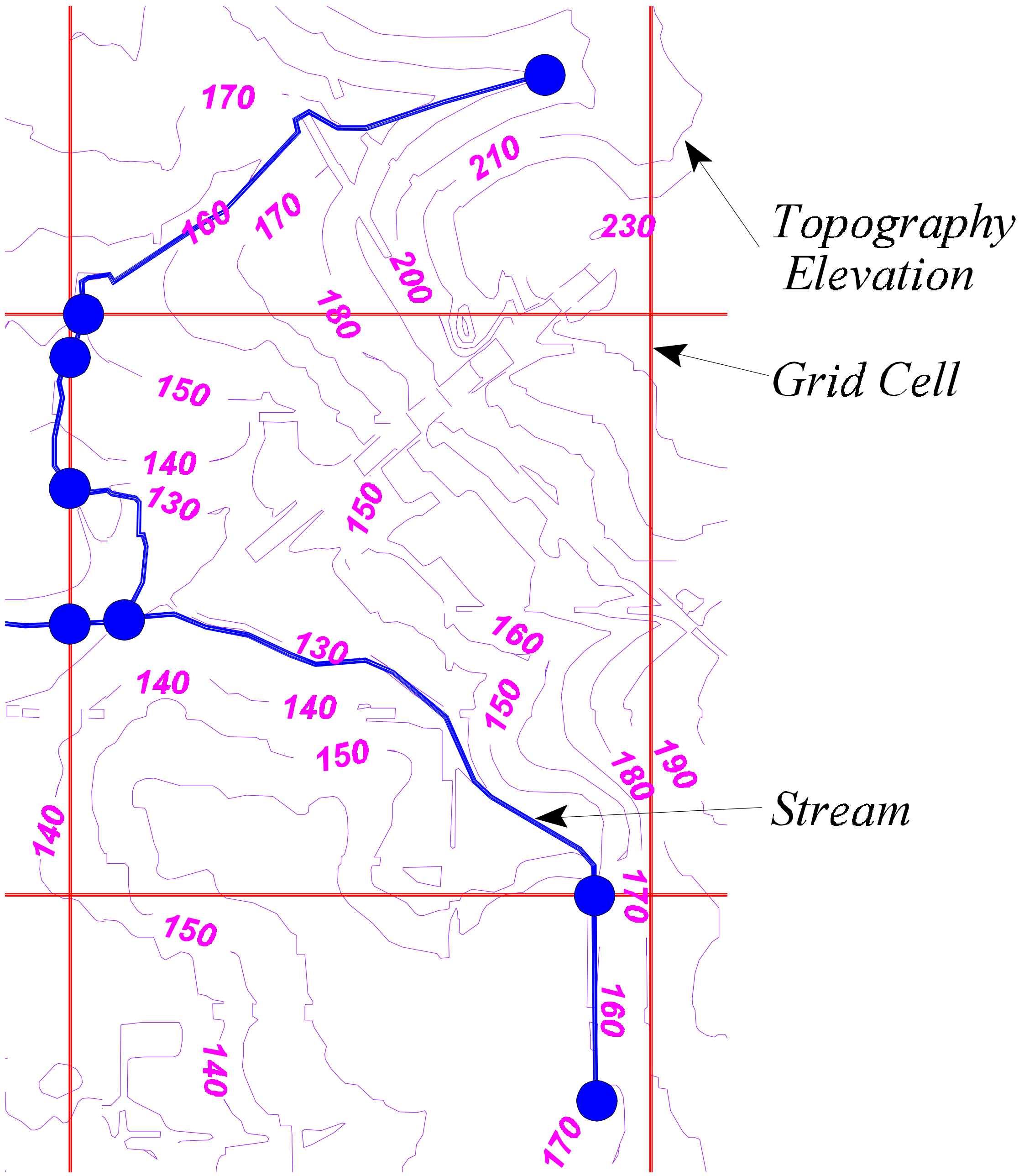

Figure 2.12 Elevation Gradients for Hydrography Within a One-Mile Grid Cell

The problems associated with incorporating absolute or physical hydrography stage and bed bottom elevations into a model are illustrated in Figure 2.13. Displayed in Figure 2.13(a) is a regional cross section showing the aquifer water level relative to the surface water stage of two streams as in the natural system. For this example, both streams are shown as gaining streams. For clarity of a two-dimensional presentation, the cross section is located at the midpoint of a model grid cell. Illustrated in Figure 2.13(b) is the model representation of the stream when utilizing the physical elevations from the natural system, as shown in Figure 2.13(a). The head difference between model stage and the mean aquifer water level elevation within the grid cell results in stream 1 representing a gaining stream while stream 2 represents a losing stream. Model calibration would require adjustment of conductances for both streams such that the combined baseflow would be gaining to attain the target baseflow value downstream of streams 1 and 2. The resulting streambed conductances would be completely scale-dependent and the simulated baseflow contribution from the individual stream elements would be quite different from the natural system.

An alternative approach requires the elevations of each of the streams to be “shifted” to an appropriate elevation which allows the driving head to be representative of the relationship in the natural system between the local aquifer head and stage. As illustrated in Figure 2.13(c), the “shifted” elevations allow the driving head in the model representation to be similar to the natural system conditions. With the driving head appropriately represented in the model, baseflow magnitude and direction are appropriately maintained. As illustrated in Figure 2.13(c), steams 1 and 2 would be correctly represented as gaining streams with “shifted” elevations for stream stage and bed bottom. As the grid scale is reduced, the elevation “shift” is dimensioned until the local influence of the aquifer on the stream is represented by the cell dimensions (i.e., about the width of the stream channel or slightly larger). Elevation “shifting” applies to all types of hydrography.

“Shifting” of hydrography elevations also provides benefits when applying hydrography data to models which span multiple management scales. Figure 2.14 is used to illustrate this benefit. Two management scales are represented in Figure 2.14 which includes a large-scale cell dimension of 2 miles and a smaller-scale cell dimension of 0.5 miles. The head difference between the local aquifer water level and the stream stage (i.e., physical driving head), in conjunction with scale-independent bed hydraulic properties produces the correct base flow magnitude and direction. Note that the local aquifer water level elevations for streams 1 and 2 may be very different, however, the driving head for base flow may be very similar. As the model scale is reduced, the simulated water level within the cell more closely approximates the local aquifer water level associated with the driving head of each hydrography element. Because it is necessary to work with multiple management scales, maintaining only small-scale models is not the solution to the problems presented above. In addition, the process of recalibrating the magnitude of bed hydraulic characteristics for each new model scale is equally problematic and inefficient.

In a model, “shifted” elevations are a substitute for, but are constrained by, physical absolute elevations which are acquired through field surveys using benchmarks. Since ground water models cannot effectively use physical hydrography gradients as is shown above, a substitute or proxy topographic datum is established for each hydrography element. The proxy datum can

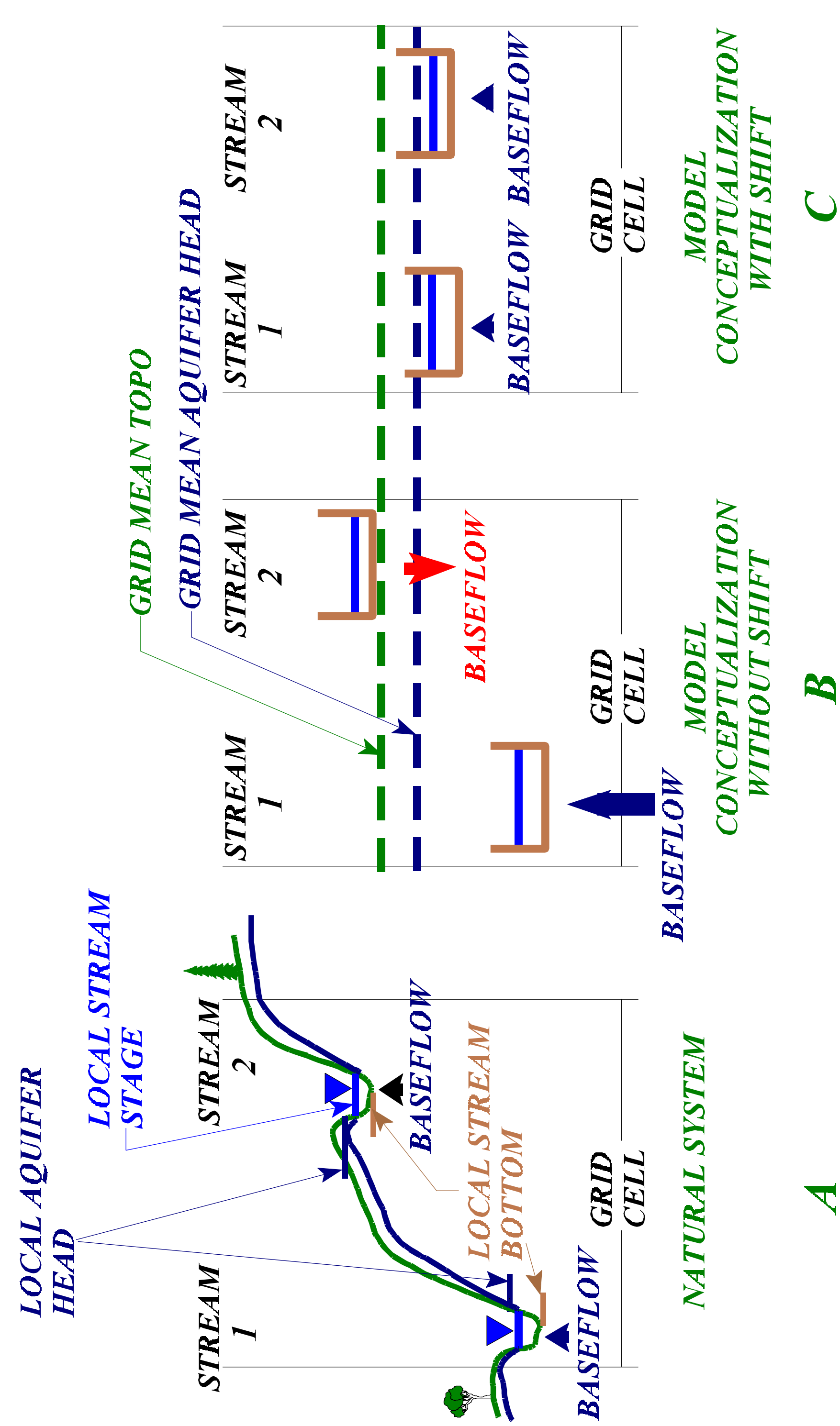

Figure 2.13 Two Model Representations of Hydrography Compared to the Natural System.

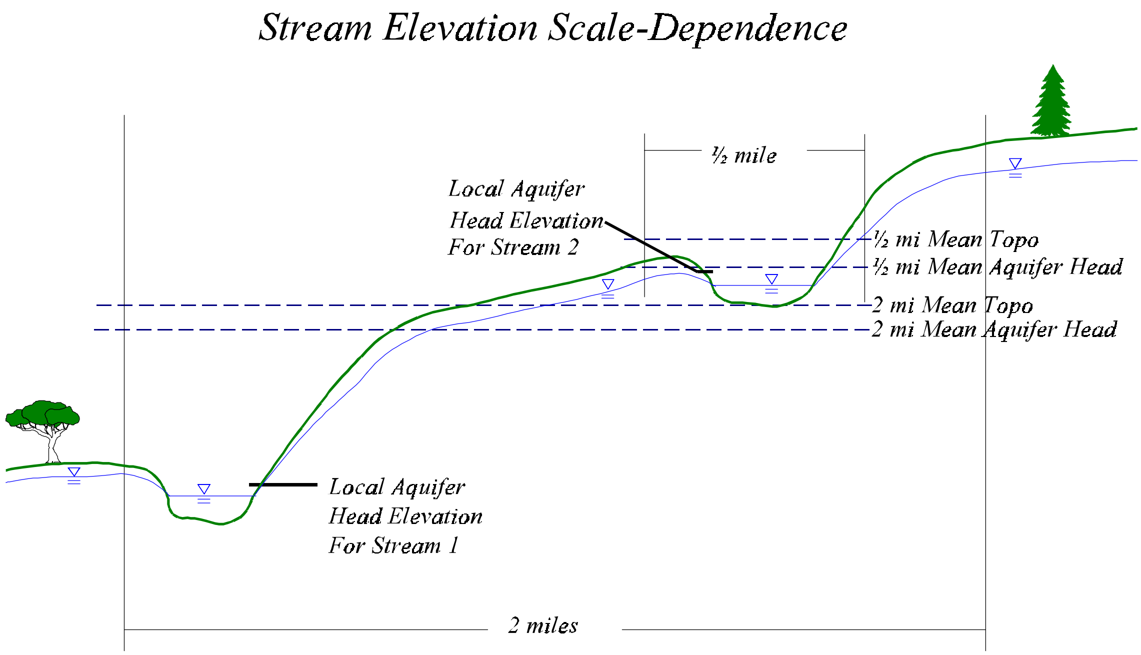

Figure 2.14 Physical Hydrography and Aquifer Water Level Elevations Compared for Two Model Scales

range from the top of bank elevation to the 100-year flood plain elevation along the course of a stream or associated with a lake or wetland. As illustrated in Figure 2.15, each hydrography element is assigned a proxy datum which is used in conjunction with the mean topographic elevation of a grid cell for the current grid scale to determine an elevation correction value (i.e., **ELCOR**, the subscript in Figure 2.15 refers to the model scale). Depending upon the position of the hydrography element within the cell relative to the mean topographic value, the elevation correction value is negative (upstream) or positive (downstream). The elevation correction value for each hydrography element converts the physical elevations of stage and bed bottom to "shifted" elevations for the current model scale. The elevations have absolute elevation magnitude but they are relative to the mean topographic elevation of the grid cell and model scale.

By employing "shifted" elevations for hydrography stage and bed bottom in a ground water model, scale-independent hydrography model data is maintained. The hydrography driving head magnitude is the most critical of the hydrography elevation issues to maintain in the model. Shifted elevations provide the opportunity to maintain a consistent driving head magnitude across all management scales. However, it is believed that the method does not provide complete scale-independence for hydrography data. With this method, the proxy datum and the mean topographic elevation of the grid cell coincide, and the elevation differences between the proxy datum and the hydrography stage and bed bottom are constant for all scales. Typically, near a hydrography feature, the depth to water (D2W) within a cell will decrease with decreasing model scale, which brings the aquifer water level closer to the proxy datum. This change in depth to water due to model scale is believed to relate increasing base flow and decreasing model scale when employing "shifted" elevations. Various factors may influence or mitigate this relationship including topographic gradients, the position of the proxy datum, and the head difference between hydrography, stage, and aquifer head from largest to smallest scale. Although the method described in the preceding paragraphs does not provide a full realization of scale-independent hydrography data, the concept should function well in coastal plains due to the relatively small driving heads.

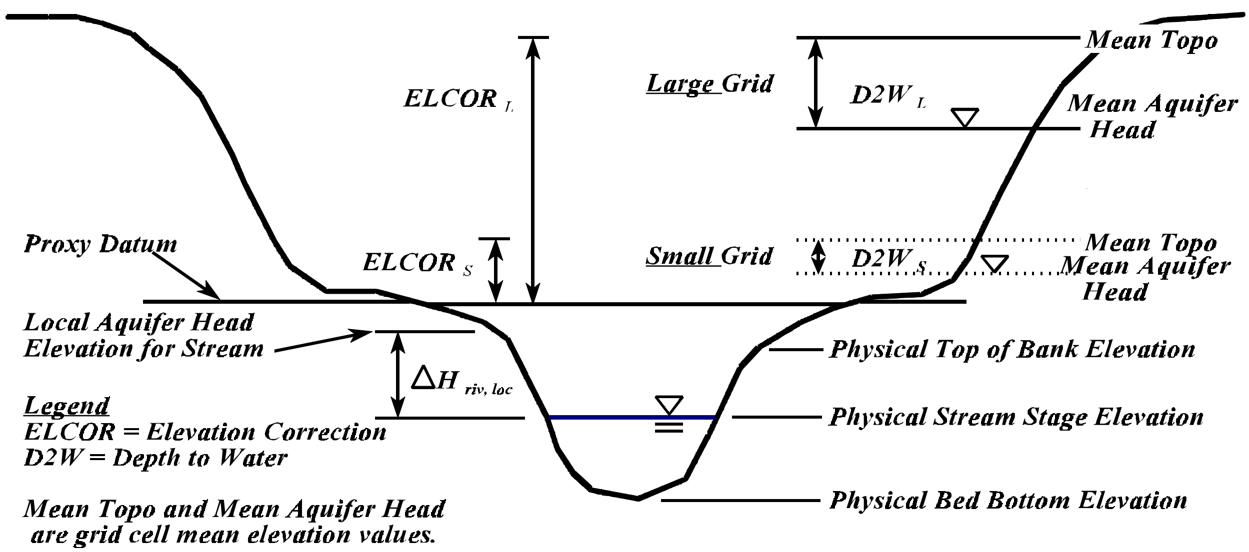

Figure 2.15 Ground Water Model Shifted Elevations for Hydrography

Aggregation of hydrography elements is also scale-dependent. The MODFLOW river (RIV) package can represent each unique hydrography element as separate model elements. However, where high density hydrography elements exist, it may become necessary to aggregate hydrography elements within a grid cell. Aggregation refers to combining physically separate elements into one or several model elements within a grid cell. Refer to Part II for more discussion of hydrography aggregation in GIS analyses. It is recommended to maintain the unique hydrography elements in the model data to ascertain the baseflow contribution from each element. In summary, to properly aggregate hydrography elements within a grid cell, the following procedures must be followed.

1. The conductance (C_{ag}) of the aggregated element is equal to the sum of the conductances (C_j) of the individual elements or:

$$C_{ag} = \sum_{j=1}^{n} C_j \qquad \textbf{(56)}$$

where:

j = individual hydrography element number within a cell

n = total number of hydrography elements to be aggregated within a cell

2. The surface water stage (H_{as}) and bed bottom (Z_{abot}) elevations of the aggregated element are conductance weighted as follows:

$$H_{as} = \frac{\sum_{j=1}^{n} (C\,H_s)_j}{\sum_{j=1}^{n} C_j} \qquad Z_{abot} = \frac{\sum_{j=1}^{n} (C\,Z_{bot})_j}{\sum_{j=1}^{n} C_j} \tag{57}$$

where:

H_{as}	=	aggregated hydrography model element stage elevation
H_s	=	individual hydrography element stage elevation
Z_{abot}	=	aggregated hydrography model element bed bottom elevation
Z_{bot}	=	individual hydrography element bed bottom elevation
j	=	individual hydrography element number within a cell
n	=	total number of hydrography elements to be aggregated within a cell

Evapotranspiration

Evapotranspiration (ET) plays a large role within the hydrologic cycle over seasonal or annual time scales. Evapotranspiration can account for as much as 70 percent of precipitation losses in Florida. In arid regions with significant surface water inflows or ground water pumping it can be greater than the annual precipitation.

Evapotranspiration (ET) is water lost to the atmosphere, and thus is no longer available for recharge or runoff. In FHM evaporation is calculated from surface and ground water sources in a hierarchal fashion. In HSPF, evapotranspiration is from surface evaporation and vegetative transpiration from the vadose zone. MODFLOW ET is based on the proximity of the water table within the root zone.

Potential Evapotranspiration

Evaporation is based on the total rate made possible by the prevailing atmospheric conditions (i.e., temperature, humidity, wind speed, insolation), and the available moisture at and near the land surface. The maximum rate defined by purely atmospheric conditions is the potential evapotranspiration (PET). Actual ET is generally less than PET and is dependent on vegetation land cover and antecedent moisture conditions.

Surface Water Only Simulation

Evapotranspiration occurs during a design storm (e.g., 25-year/24-hour) rainfall event, but it does not significantly impact runoff. However, ET loss is a significant term in continuous simulation. Evapotranspiration is calculated hourly by HSPF for event and continuous surface water only simulations based on a user-specified potential rate and available water sources documented in HSPF (Bicknell et al. 1993) and discussed below.

Ground Water Only Simulation

Ground water only simulations, (using MODFLOW) within FHM allows the use of the MODFLOW Evapotranspiration (EVT) package. The EVT package requires a user defined "PET" rate. The actual (ground water) ET is then determined by the proximity of the water table within a user-defined "extinction depth". The resultant ground water ET rate is zero when the water table is at or below the extinction depth and equal to the "PET" when at the land surface. Ground water ET rates are assumed to vary linearly from the maximum (PET) to zero for water table elevations between the two limits.

Integrated Simulation

As alluded to previously, evapotranspiration is a function of temperature, humidity, insulation, precipitation, vegetative type, and available moisture. ET occurs throughout the hydrologic cycle from many sources including interception, detention storage, water in depression storage, and moisture in the unsaturated and saturated zones. Largely, evapotranspiration draws moisture from the rhizosphere (the root zone in the soil), and varies according to season and depth of the water table.

In FHM, simulation of ET first requires the determination of atmospheric potential evapotranspiration. FHM subtracts the actual ET from the appropriate storages, based on available water in a hierarchal fashion. Potential evapotranspiration can be estimated from energy budget methods or diffusion methods, but the most practical estimate can be derived from open pan measurements and the application of a reasonable pan coefficient. In West-Central Florida, pan ET rates range between 70 and 80 inches as an annual total. Estimates of open water evaporation rates based on numerous studies indicate that open water evaporation is on the order of 50-55 inches. This lends credibility to the use of a pan coefficient of 0.7, a common estimate. Because potential evaporation is rarely satisfied, the model is not terribly sensitive to the annual total (Baudean 1996).

Referring to Figure 2.16, FHM ET model concept, ET rates occur from various sources based on their relative energy level. For example, if surface features are wetted, very little plant transpiration can occur until this intercepted water can be removed. Therefore, in model hierarchy interception storage is assumed to occur first. Plant transpiration can occur after the surfaces of leaves are dried, pulling water from the lower (unsaturated) zone and potentially from the water table if it is in close proximity to the root zone. At the same time, upper zone ET can occur from depressional storage, in surface detritus, and shallow rooted vegetation. Open water evaporation is assumed to occur at the potential ET rate. Within HSPF, ET losses in the upper and lower zone are assumed to occur at a rate proportional to the relative moisture content of each of the systems. See the HSPF manual for details on the flux rates from these storages. A brief discussion of the formulation is provided below. Refer to Figure 2.17 for a flow chart depicting the order of removal from the various HSPF storages. In HSPF, base flow ET is primarily an artifact of the original Stanford Watershed Model (Crawford and Linsley 1966).

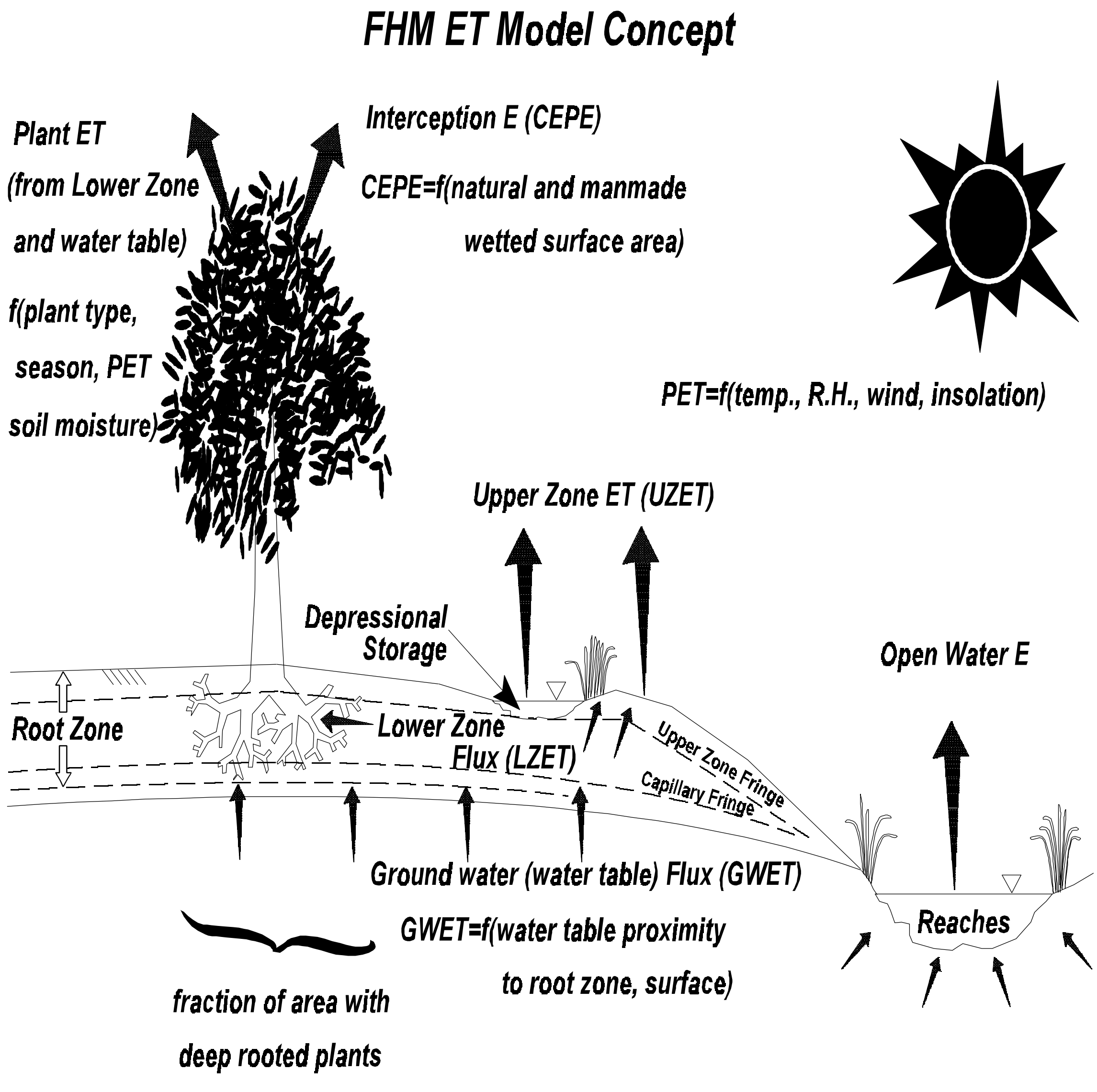

Figure 2.16 FHM ET Model Concept

HSPF EVAPOTRANSPIRATION SIMULATION HIERARCHY

(Adapted from Bicknell et al. 1993)

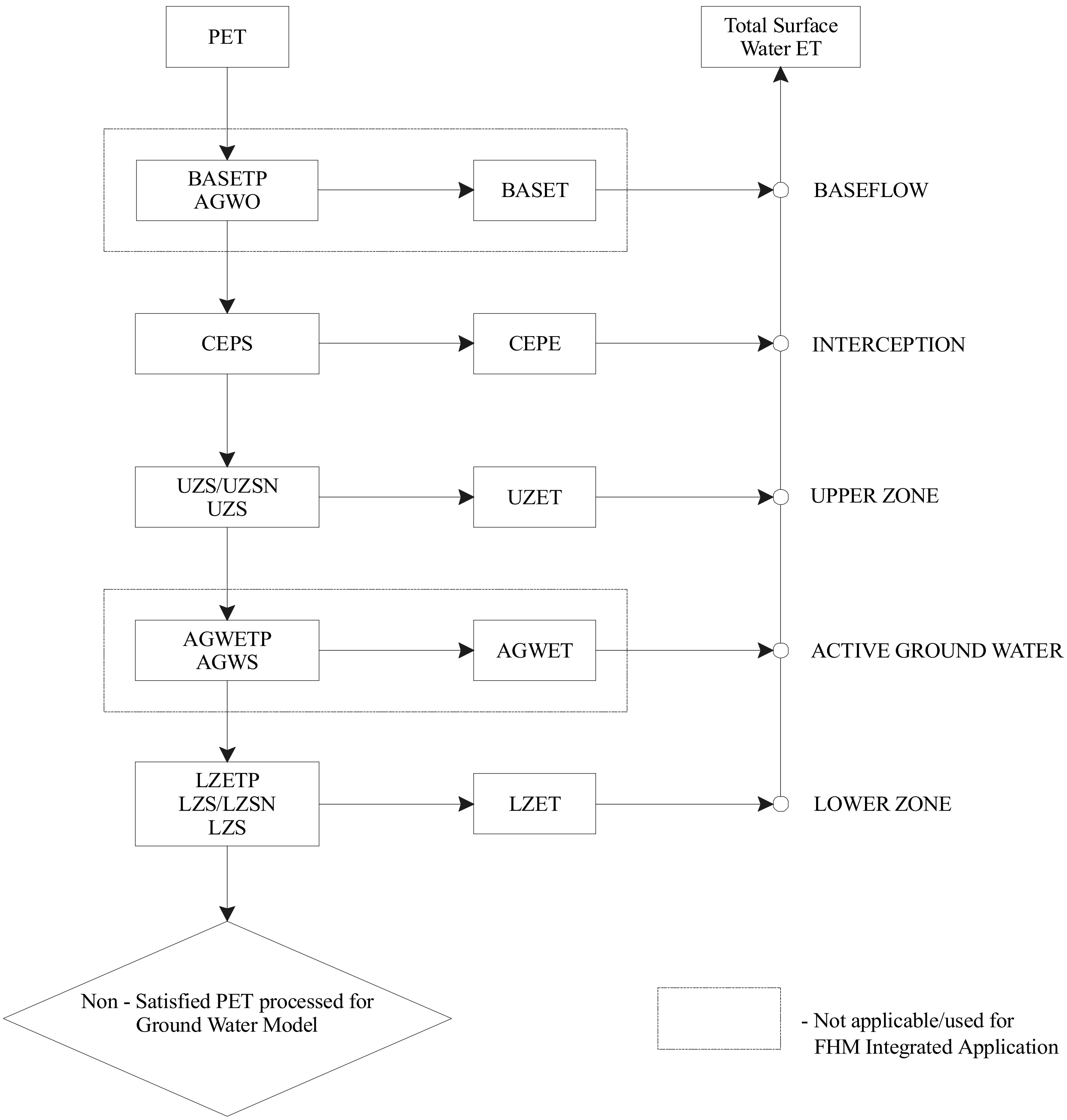

Figure 2.17 HSPF Evapotranspiration Simulation Hierarchy

Surface Water ET

The following section is a summary of surface water ET from the HSPF manual, the user is also directed to Part III for specific information on parameter selection.

Base flow

The first source from which ET can be taken is the active ground water outflow or base flow. This is intended to provide for ET from riparian vegetation in which ground water is withdrawn as it enters the stream. The user specifies the fraction, if any, of the potential ET that can be sought from the base flow. That portion can only be fulfilled if outflow exists. Any remaining potential not met by actual base flow evaporation will be sought from other surface water sources. Due to the manner in which HSPF is coupled to stream flow this source should not be used.

Interception

Remaining potential ET demand is placed on water in interception storage. The demand can be completely satisfied by interception storage if enough available wetted surface moisture exists (e.g. after a storm). When the demand is greater than the storage, the remaining demand will try to be satisfied in subroutine ETUZON.

Upper Zone

Actual evapotranspiration will occur from the upper zone storage at the remaining potential demand if the ratio of upper zone storage to nominal capacity, is greater than 2.0. Otherwise, the remaining potential ET demand on the upper zone storage is reduced.

Active Ground Water

Like ET from base flow, actual evapotranspiration from active ground water is regulated by a parameter. The parameter AGWETP is the fraction of the remaining potential ET that can be sought from the active ground water storage. This parameter is dependent on the water table proximity to the surface and the root zone, which is crudely modeled in HSPF. Also, for the particular application of HSPF within FHM, this source is not used during integrated modeling. Ground water ET is calculated differently as discussed below.

Lower Zone

The lower zone is the last surface water storage from which PET is sought. ET from the lower zone depends upon vegetation transpiration and vadose zone soil moisture. Evapotranspiration opportunity will vary with the vegetation type, the depth of the rooting, density of the vegetation cover, and the stage of plant growth along with the moisture profile of the soil zone. Unlike the other storages, lower zone ET can be varied on a monthly basis to account for temporal changes in plant transpiration.

HSPF uses a lower zone ET parameter, **LZETP** to calculate losses from this storage. If the **LZETP** parameter is at its maximum value of one, representing near complete areal coverage of deep rooted vegetation, then the potential ET for the lower zone is equal to the demand that remains. However, this is normally not the case. Usually vegetation type and/or rooting depths will vary over the land segment. To simulate this, a linear probability density function for ET opportunity is assumed. This approach is similar to that used to handle areal variations in infiltration/percolation capacity. More details on the **LZETP** parameter can be found in Part III. Details on GIS analysis to determine root zone depths can be found in Part II.

Ground Water ET

ET can occur indirectly from the water table (ground water system), due to unsaturated soil potential (capillary suction) and osmotic pumping in the root zone. MODFLOW has an ET package that assumes linearly decreasing ET losses for water table heads within a user-defined extinction depth. The FHM concept requires the extinction depth to be defined from the maximum rooting depth for each land use classification. The root zone is also referred to as the rhizosphere. Satisfaction of potential ET is first checked within the surface water system. Any remaining potential ET is passed to the ground water module as ground water potential ET.

The MODFLOW extinction package is employed whereby remaining potential ET is assumed to be completely satisfied if the water table is at or near the land surface. Ground water ET is assumed to be zero if the water table falls below the extinction depth, and it varies linearly from between these two values depending on the elevation within the root zone. The rate of ground water potential evaporation is also moderated by two factors. One factor is the plant community type which has a particular ET efficiency. For example, a broad, leafy plant community may have higher ET rates than a particular coniferous type. Each plant community also has seasonal variations (e.g., a cypress dome is deciduous in winter). Therefore, the PET rate passed to MODFLOW is first multiplied by a plant ET coefficient. Typical values for the plant ET coefficient can be found in Part III, Users Guide.

Within a basin, different land use categories have predominant vegetative communities with different rhizosphere depths. Rhizosphere depths are, therefore, conveniently assigned by land use classification, although this is a gross simplification. For example, in Florida, it is common to use FLUCFCS (1990) codes classification even though the plant community type might vary widely within a particular category (e.g., plant types vary appreciably for different single family residential communities). Also, not all the plants in a landform community have deep roots; therefore, it is also important to determine the fraction of area associated with deep-rooted plants. Within a basin, these values are usually found from GIS assessments of area-weighted mean values of the maximum rooting depth. Details of GIS operations for average root zone depth can be found in Part II. Further information about the various root zone depths for West Central Florida landform communities can be found in Part IV.

CHAPTER 3. INTEGRATION COMPONENTS

Introduction

The FHM model components described in Chapter 2 can operate independently of each other. However, to meet the goals of FHM development, the various model components were dynamically linked. To accomplish linkage of the models, appropriate data is extracted from one code, prepared and passed to another code in sequential fashion. This linkage is accomplished by the integrating software of FHM. The flow chart in Figure 3.1 depicts the order of various operations that were incorporated into FHM to accomplish an integrated simulation of the complete hydrologic system. FHM operating in integrated mode uses a timestep based (typically weekly) looping starting with HSPF (surface water system), followed by MODFLOW (ground water). The sequence is repeated until the simulation is complete. The integrating software between the hydrologic model components perform the following functions:

1. Modify input data files of model components based on the output of other model components
2. Partition PET to the various components
3. Provide compatible data sets for input to model components
4. Check for errors or warnings from model components
5. Insure continuity (water balance) in flux transfers
6. Formulate a water budget summary for the various model components

INTSTART

Purpose

The integration program, INTSTART, performs several integration operations. INTSTART initializes HSPF parameters, lower zone nominal storage (**LZSN**) and lower zone storage (**LZS**), for the integrated simulation. For definitions of **LZSN** and **LZS**, refer to the Subsurface Storages section in Chapter 2. INTSTART maintains the water balance in transfers from surface and ground water systems. Lastly, the program converts the MODFLOW base flow output into a format compatible with HSPF.

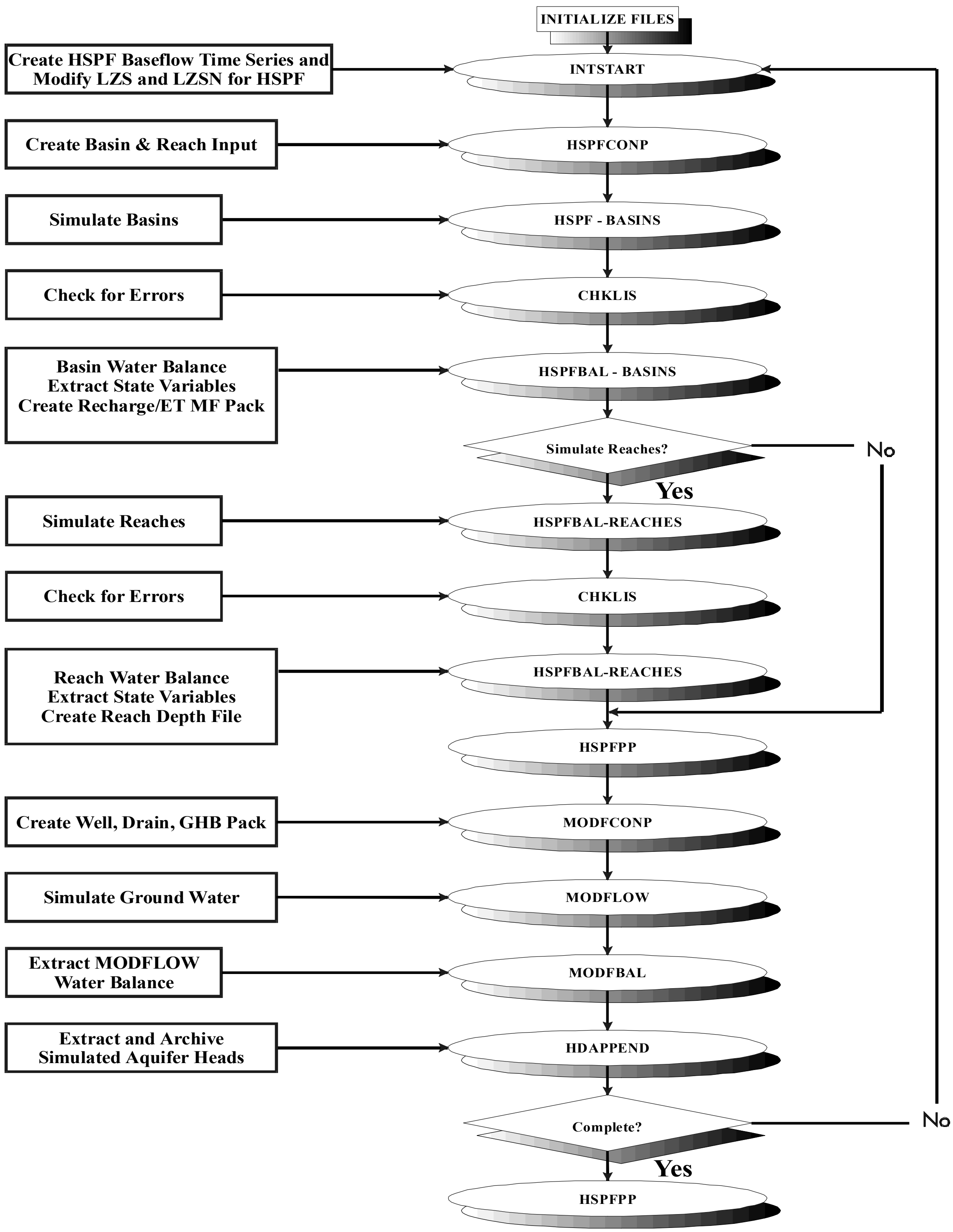

Figure 3.1 FHM Integration Looping Process

Assumptions and Equations

INTSTART first converts baseflow from MODFLOW for the previous integration timestep and creates a baseflow input file(s) for HSPF. For water balance, the baseflow input is represented by the time series from the previous integration timestep. The baseflow calculated in MODFLOW is the same baseflow input to HSPF. However, baseflow in surface water flows is always one integration timestep delayed. The time series of baseflow processed for HSPF varies temporally at the MODFLOW timestep. The MODFLOW timestep, which could be variable within a stress period, is always less than the integration timestep.

INTSTART reads the current aquifer heads (aquifer heads updated throughout the integrated simulation) and the input data for the first MODFLOW layer (BCF package). INSTART also reads the basin array and field capacity from the overall integration data set. For integrated modeling, the first layer is required to be a MODFLOW layer type (LAYCON) 3 which is assumed to be an unconfined surficial aquifer. Layer type 3 requires the specification of aquifer top to compute the thickness of the unsaturated zone and the storage coefficient required for maintaining water balance. The basin array is used for spatial linking between the basins and cells. The sum of storage coefficient and field capacity is equal to the porosity which defines the maximum storage potential of the soil.

The HSPF parameter **LZSN** which must be defined by basin is derived from the values determined for the cells (results of Equation 58). The denominator of 2.5 is used because inflows can occur up to a value of **LZS** 2.5 times the nominal storage **LZSN**. Therefore, the nominal storage is assumed to be 2.5 times less than the total allowable storage. The **LZSN** calculations are performed for every active cell. The results for each cell are tested and adjusted to conform to the allowable HSPF range of 0.01 ≤ **LZSN** ≤ 100. Adjusting the **LZSN** parameter to the allowable HSPF range does not produce a water balance error because **LZSN** is not a quantity of water. **LZSN** is a storage index, a storage region of soil that influences infiltration. The cell based **LZSN** array is averaged using the basin array to determine the average **LZSN** for each basin.

The **LZSN** calculation made for each cell is as follows:

$$V_{LZSN} = \frac{\eta * (E_S - H_{W.T.}) * 12}{2.5} \qquad \textbf{(58)}$$

where:

V_{LZSN} = nominal volume capacity of lower zone storage by cell (inches)
η = weighted average soil porosity for the cell
E_S = average elevation of land surface within cell (ft)
$H_{W.T.}$ = ending integration period head of surficial aquifer (ft)

The value of actual storage, **LZS**, by grid is then found based on the assumption that the change in moisture content that influences infiltration should be smooth (smoothness in infiltration) and it must conform to the new storage index. The resulting formulation for new (next timestep starting value) **LZS** determination by cell is:

$$V_{LZS_{new}} = \frac{V_{LZS_{old}}}{V_{LZSN_{old}}} * V_{LZSN_{new}} \tag{59}$$

where:

$V_{LZS_{new}}$	= the initial lower zone storage for the next iteration
$V_{LZS_{old}}$	= the lower zone storage at the end of the previous iteration
$V_{LZSN_{old}}$	= the nominal storage capacity for the previous loop
$V_{LZSN_{new}}$	= the grid averaged new **LZSN** for the next loop

The HSPF lower zone storage from the end of the previous integration timestep (prior to performing Equation 59, a single value for the entire basin) is first distributed to the individual cells within each basin. The distribution is based on the storage potential of each cell.

The storage potential is weighted by the relative field capacity by grid cell as:

$$V_{LZS_{new}} = V_{LZS_{old}} \cdot \frac{V_{FC_{cell}}}{V_{FC_{basin}}} \cdot \frac{A_b}{A_c} \tag{60}$$

where:

$V_{LZS_{old}}$	= previous integration timestep ending value of **LZS** by basin
A_b	= total area of cells assigned to basin
A_c	= area of cell
$V_{FC_{cell}}$	= volume of field capacity storage for cell = F.C. * (E_S - $H_{W.T.}$) * 12 * A_C
$V_{FC_{basin}}$	= $\sum V_{FC_{cell}}$ for all cells assigned to basin

The **LZS** is then modified maintaining the same **LZRAT**, which is the ratio **LZS/LZSN**. The computed grid based **LZS** is tested and adjusted to remain within the HSPF limits of 0.001 and 100. Unlike **LZSN**, **LZS** is a storage quantity and adjustment to conform to permissible HSPF limits introduces water balance errors. To maintain water balance, a term is introduced to correct for this adjustment, which is termed "error recharge" (when it occurs). Error recharge is the difference between the original computed **LZS** and the adjusted **LZS** for each grid summed for the basin. Values of **LZS** approaching the lower limit correspond to water table elevations at land surface. **LZS** values greater than 100 correspond to extreme water table depths (e.g., 40 feet from land surface). Fortunately, for regional scale basins in coastal plain applications, the latter rarely occurs. Therefore, the water balance adjustment is typically very small.

Another correction to the water balance must be made to account for variability in vadose zone moisture. In ground water only simulation, MODFLOW assumes that the storage coefficient is a constant value which determines the loss or gain from storage due to a rising or falling water table elevation respectively. In the integrated system, the surface water model accounts for variable soil moisture. Therefore, the storage coefficient in the ground water system should also be variable. Recall rising water table in MODFLOW is a loss to storage (accumulated into aquifer storage). For a particular water level rise, the loss to storage is much less if the soil is already partially saturated and conversely much greater if the soil is substantially less than the field capacity. Instead of modifying the ground water component (MODFLOW directly) (e.g., modifying the specific yield of the surficial aquifer every timestep), in the integrated model it was more convenient and desirable to modify the transfers by adjusting recharge. Unsaturated zone transfers, conveniently termed additional recharge, AR, are calculated cell by cell as:

$$AR^{t+\frac{1}{2}} = \left(\frac{V^{t}_{LZS}}{\left(E_S - H^{t}_{w.t.}\right) * 12} - F.C. \right) * \left(H^{t}_{w.t.} - H^{t-1}_{w.t.}\right) \qquad \textbf{(61)}$$

where:

V^{t}_{LZS}	=	cell lower zone storage volume (**LZS**) at end of previous timestep
F.C.	=	field capacity of soil (volume ratio)
E_S	=	elevation of land surface
$H^{t}_{w.t.}$	=	cell water table head at end of the previous timestep
$H^{t-1}_{w.t.}$	=	cell water table head at beginning of previous timestep

Additional recharge is then summed for all grids by basin and applied in the next timestep (t+ ½), between the HSPF and MODFLOW loop.

A report is generated describing the changes in the **LZSN** and **LZS** for each integration loop. It also reports the total water budget corrections of additional and error recharge. The additional and error recharge are transferred to the HSPFBAL code which then generates the recharge package for MODFLOW. The additional recharge and error recharge are archived in file ADDRCH.ARC

INTSTART also converts the MODFLOW river flux output into a format accepted by HSPF. The MODFLOW river fluxes are accumulated for each reach id (seventh column in the river package). The accumulated flow rate is the base flow that will be added to each HSPF reach. The fluxes are output from MODFLOW using the stress period timesteps (e.g., daily). The timestep variation is preserved when creating HSPF input files. The base flow time series are stored in HSPF plot files HSPFBF1.DAT to HSPFBF5.DAT.

HSPFCONP

Purpose

This program modifies HSPF input for the next integration timestep. It also creates the initial base flow data for the first integration timestep (prior to MODFLOW results).

Description

HSPFCONP is the continuous processor for HSPF. This program modifies the input data files *.ICS (input for basin simulation) and *.ICR (input for reach simulation). The modifications applied to the input files consist of the simulation dates and the initial conditions. The start and stop dates are advanced to reflect the next integration loop. The loop counter is stored in RUN.MOD. The initial variables are updated to reflect the storages from the end of the previous loop. Modifying the initial storages every week is an important step in the looping integration to avoid significant water balance discrepancies.

In the integration loop, HSPF is executed before MODFLOW. Therefore, the base flow used in HSPF is actually the result from the previous integration timestep. This is a relatively safe assumption because base flow and aquifer heads do not change rapidly. Because HSPF is executed before MODFLOW, base flow must be approximated during the first integration timestep. The approximations can be made from the measured hydrographs and recorded in a data file HSPFBF0.DAT. If no approximations are made, base flows of 0.0 will be used. Starting with base flows of 0.0 may be appropriate for very small reaches but transients will be introduced for large reaches resulting in errors in discharge hydrographs early in the simulation. For the first week HSPFCONP creates the base flow files used in the HSPF simulation (HSPFBF1.DAT through HSPFBF5.DAT). Each file contains the base flow time series for 10 reaches. After the first integration timestep, base flow files are created by INTSTART described above.

CHKLIS

Purpose

The integration file CHKLIS searches HSPF output for errors or warnings. When errors are encountered the integrated simulation is halted. Warning and error statements are attached to files.

Description

HSPF provides error and warning messages in an extensive and difficult to use “list-file” named with the run name and .LIS extension. HSPF closes normally when this occurs. As a consequence, the FHM integration loop would not halt if the HSPF simulation where to encounter an error. For this reason CHKLIS was developed to interrupt the loop upon detection of a fatal error. Error messages are extracted and recorded in the ASCII file ERROR.DAT. If non-fatal warnings are encountered, they are extracted and reported in the ASCII file WARNING.DAT. Warnings will not halt the integrated simulation; instead, it is the user's responsibility to review any warnings produced to insure no major problem in the simulation of the model occurred.

HSPFBAL

Purpose

HSPFBAL performs two major tasks; it extracts water budget summaries for the surface water system (basins and reaches) and it prepares data for the ground water simulation.

Description

After it is determined that the surface water simulation was successful (see CHKLIS) HSPFBAL is executed. This program extracts and stores the balance information in a random access file to be sorted upon completion of the integration timestep by HSPFPP. The surface water simulation is divided into two separate simulations to increase the number of possible basins and reaches. HSPFBAL is executed twice in the integration loop, once for basins and once for reaches. HSPFBAL is executed after each execution of HSPF (basins or reaches) with flags ('s' for subbasins 'r' for reaches) to determine the processes to perform. The balance output of HSPF is overwritten by the consecutive execution. Therefore, the balance data must be extracted before it is lost. The water balance extraction procedures are identical for both surface water only and integrated simulations. HSPFBAL produces binary files *.UBS, *.UBY, *.UBR, which are used by the program HSPFPP to prepare daily, monthly, and annual summary water budget reports (described below).

The second task is the compiling of the HSPF output to prepare data for the ground water component of the integrated model. First the inactive ground water inflow (IGWI) is summed for every day of the integration timestep for each basin. The total IGWI term is then scaled by an area factor which is the ratio of areas between the surface water component and the ground water component. The area factor required to maintain water balance is:

$$A_f = \frac{(A_{Grid})}{(A_{Basin} - A_{Outside\ Grid})} \qquad \textbf{(62)}$$

where

A_f	=	Area factor used to adjust recharge from the surface water model to the ground water model
A_{Grid}	=	Total area of grid elements associated with the basin
A_{Basin}	=	Area of the catchment used in surface water model
$A_{OutsideGrid}$	=	Area of basin falling outside the grid boundaries

The units are converted from inches per integration timestep to feet per day. The factored IGWI term for each basin is used as the recharge rate for the cells that are assigned to the basin (see basin array in the integration pre-processor). HSPFBAL produces the recharge package used by MODFLOW for the current integration timestep (the recharge package is over-written each integration timestep and contains the data for the current integration timestep only). The potential ground water evapotranspiration rate is then calculated. First, the sum of the remaining potential after all surface water ET has been extracted is found for each basin as:

$$RPET = \Sigma PET - \Sigma TAET \qquad \textbf{(63)}$$

Next, the remaining potential (RPET) is factored by the area factor discussed above and units are again converted to feet per day. The RPET is then factored by the plant ET coefficient. This factoring is performed cell by cell based on the plant ET coefficient array. The plant ET coefficient is a factor based on land use/land cover which reduces the potential ET rate passed to the ground water component of the integration. Refer to Chapter 2 and to Part III for more details on plant ET coefficients. HSPFBAL then modifies the given MODFLOW EVT package updating only the ET rate for the current integration timestep, both the ET surface and ET extinction depth remain constant for the entire simulation.

HSPFBAL also extracts ending storages for each basin for use as initial conditions for the following integration loop. The river stages and volumes are also prepared for use in the ground water base flow calculations and initial conditions. The stage is averaged over the integration timestep for each reach and stored in the RUNB.DAT file. The inflow volume is summed for the integration timestep and the ending volume is also extracted and stored in the RUNB.DAT file. The RUNB.DAT data file is used in the modified MODFLOW ground water model, MODFRUN.EXE, (see description of modifications below).

MODFCONP

Purpose

MODFCONP is a continuous processor for MODFLOW. This program extracts the stress period data for the general head boundaries, drains, and wells.

Description

MODFLOW is executed once every integration timestep. For each integration timestep, the simulation is one stress period with multiple timesteps. For example, stress periods may be weekly and timesteps daily. This program modifies the various stress period related packages (wells, general head boundaries, and drains) every integration timestep. The user-defined stress periods are typically much greater than the integration timestep, therefore, updating the packages may not be required for the current integration timestep. For the integrated simulation there are actually two different MODFLOW basic packages. These basic packages are created in the MODFLOW pre-processor. The first basic package (*.BAS) is the standard multi-stress period, transient data set that is used for ground water only simulations. The stress period data (number of stress periods, stress period lengths) are completely user-defined. The user-defined stress period data must account for the entire HSPF simulation period otherwise the data in the last stress period will continue to be used until the integrated simulation is completed. The integrated version of the basic package (*.IBA) is predefined as one stress period with daily timesteps. The integrated basic package is used for ground water simulations in the integration loop while the standard basic package is used to define the stress period data. MODFCONP is controlled from the standard basic package of MODFLOW. This program creates a file named MODICP.INP. This file contains the stress period number that is currently extracted for the ground water simulations in the integration loop. MODFCONP calculates the time into the simulation based on the integrated timestep counter (found in RUN.MOD) multiplied by the integration timestep length. If the calculated stress period is the same as that stored in the MODICP.INP file then nothing is done. Otherwise the individual packages (drain, well, and GHB) are opened to extract the stress period data associated with the current integration timestep. This program expects that all stress period data are available in the drain, well and GHB packages. These same packages are also used in ground water only simulations. **The MODFLOW practice of utilizing a -1 flag for the MODFLOW variable *ITMP* to reuse the last stress period data is not allowed in the integrated simulations because of a limitation in MODFCONP.**

MODFRUN

Purpose

MODFRUN is the actual MODFLOW execution during the integrated sequence.

Description

MODFRUN is basically MODFLOW (McDonald and Harbaugh, 1984) with modifications to allow full integration with HSPF. The modifications are only made to the river modules. First, a seventh column was added to the standard river package of MODFLOW. This seventh column associates each MODFLOW river cell to a HSPF reach. The association allows the defined HSPF reach stage (now stored in the RUNB.DAT data file, see HSPFBAL) to be assigned to each "dynamic" river cell. The river stage as reported by HSPF is converted to depth by subtracting **STCOR**. The computed depth is then added to the individual **RBOT** for each river cell to calculate the river stage. This process is performed only if the reach id is greater than zero denoting that the reach is dynamic. All reaches with an id less than zero (negative) use the fixed stage defined in the first stress period of the river package. These are the so-called "static" reaches defined in Chapter 2. The base flow rates of each river cell are accumulated using the reach id. If the aggregate rate equates to a negative volume for the MODFLOW timestep which is greater than the volume reported by HSPF, the base flow for the reach cannot be less than zero for the remainder of the current integration timestep. No mass balance errors occur as a result of this baseflow transfer.

MODFBAL

Purpose

MODFBAL produces archived MODFLOW water balance in a tabular format and a base flow report for each HSPF reach.

Description

The ground water simulation (MODFLOW) produces water balance reports for each integration timestep. MODFBAL reads the MODFLOW output file and produces an archive of the water balance. All terms in the ground water balance (e.g., recharge, drains, wells, etc.) include total flows in and out of the aquifer system. Separating the fluxes into the rates into and out of the aquifer system enables the user to identify a flow through system. The second process MODFBAL performs is the accumulation of base flow rates from the river fluxes. The accumulation utilizes the additional entry in the MODFLOW river package (the seventh column reach id) to sort the base flow rates. Baseflow from river cells is accumulated by reach id and is reported for each integration timestep. Again, both fluxes in and out of the aquifer systems are accumulated. In addition, the reach id can be a positive reach number or a negative reach number. "Dynamic" river cells are represented by a positive reach id. The stages for the dynamic river cells are adjusted using the reach depths reported from HSPF. A negative reach id represents the "static" portion of the reach. The stages to the static river cells are set to a constant value reported in the first stress period of the standard MODFLOW river package. The base flow water balance is stored in the *.CDR file. This water balance file contains the base flow fluxes in and out of the dynamic elements, the static elements, and total base flow flux sorted by reach id and by stress period.

HDAPPEND

Purpose

HDAPPEND reads the binary head files produced by MODFLOW, writes the head arrays into an archive file and writes the heads to an ASCII file used by MODFLOW as input.

Description

HDAPPEND is executed after the completion of MODFLOW in the integrated loop. MODFLOW writes the heads in each layer upon completion of the simulation. These heads are in binary format. HDAPPEND reads the binary file and writes an ASCII file which can be used as input for the next integration loop. This program uses a format similar to the MODFLOW basic package. HDAPPEND insures that the next ground water simulation will be executed with the ending heads of the previous iteration. The aquifer heads at the end of every week are archived, for later retrieval and analysis, in a binary file similar in format to the MODFLOW produced head file (instead of stress periods there are week numbers). A post-processor program was developed to process the archived head file into data files for creating either well hydrographs or surface plots.

HSPFPP

Purpose

HSPFPP converts the random access files into sorted ASCII files and averages the hourly stream flow hydrographs into daily values.

Description

This program is called in two different locations. Once every integration timestep after both HSPF simulations are completed successfully and again at the completion of the entire simulation. HSPFPP performs two separate tasks: (1) it averages the hourly discharge hydrographs into sorted daily formats, and (2) it stores the binary random access file into ASCII output files. The first task is performed every integration timestep. The hourly output of HSPF is processed into daily averages. The hourly output is overwritten every integration loop and is not available in integrated simulations (the hourly output is available in surface water only simulations). The daily formatted discharge hydrographs are made available in the *.S91-*.S95 files for the basins and *.R91- *.R95 files for the reaches (10 columns per file for the 50 basins and reaches). The second task is performed at the completion of the entire integrated simulation. During the simulation HSPFBAL archived the water balance data in binary random access files. The files cannot be read until they are converted into ASCII formatted files. The random access files are also unsorted containing data for each basin/reach for each integration timestep. This program sorts the output by basin or reach. Within each basin or reach, the file is further sorted by integration time step number. The converted files are named *.IBS for daily basin output, *.IBM for monthly basin output, *.IBY for annual basin output, and *.IBR for daily reach output. This program is also used for surface water only simulations.

CHAPTER 4. GEOGRAPHIC INFORMATION SYSTEM COMPONENT

Overview of GIS Functions

This chapter discusses the elements of the GIS which are key to FHM. In fact, the GIS is what makes FHM unique. As stated earlier, multiple GIS have been used with FHM including Tydac Technologies Spatial Analysis System (SPANS) and ESRI ARC/INFO and ESRI PC ARC/INFO. Presently, only one GIS, ESRI ARC/INFO, is supported in FHM Version 3.0 (see Part II). For FHM, the GIS performs the following functions:

1. Geo-Referencing for varied topological data
2. Model Linking for varied spatial discretization
3. Spatial Analysis for model parameter input
4. Output Processing and further analysis of select model results
5. Archiving Model Results and collected data for future model development
6. Visual Inspection of Input and Output data for error trapping

Geo-Referencing

Geo-referencing relates to the manner by which landform features are described on a paper or digital image. Geo-referencing also requires mathematical algorithms to transform irregular surfaces into planar representations. Geo-referencing involves projection and transformation operations by which the coordinates of a flat map are transformed into the spherical coordinates of the Earth, e.g., latitude and longitude, or vice versa. When the digital topological (land form) data are entered into a GIS, a projection and origin must be specified for that map. The GIS will translate the coordinate system used by the digital map into the coordinate system of the project area. When all maps are referenced to a common coordinate system, e.g., latitude and longitude coordinates, they can be compared with one another (via overlays or models) without the errors caused by differences in projection, scale, or reference point.

Model Linking

The surface water model HSPF, as with most surface water models, uses variably shaped and sized subbasins as spatial description units for model input and output. Subbasins have arbitrary shapes defined by surface elevation contours, flow patterns and divides. Input parameters are averaged and reported for each subbasin area (lumped parameter analysis). The ground water model and some ET components of FHM work with a uniform grid spatial description. This means these model components require input parameters to be averaged and reported for each grid cell. Alternatively, parameters can be assigned as point values to the "nodes" or center of the grid.

The GIS handles the model linking using a simple overlay of the grid map and the subbasin map. Each grid node is tagged with the associated subbasin number. The FHM integration programs use this linking information to create the proper data transfer and sharing paths.

Additionally, the GIS provides for key linkage and specific parameter assignments for the various model scales that may be employed. The GIS greatly facilitates near field/far field modeling (multi-scale) providing boundary linkages between models and appropriate manipulation of the shared scale-dependent stresses. More details concerning GIS features for multi-scale modeling can be found in Part II.

Spatial Analysis

The spatial analyses or map overlays are performed on each of the spatial descriptions (grids, points, reaches, and subbasins). This function of the GIS develops the required input and integration data for each of the model components.

The grid map is actually a series of equally spaced points (nodes). These nodes represent the centers of the MODFLOW grid cells. Grid nodes are used to assign data for the ground water and integration components. The grid map is overlaid with the maps containing the attribute information used by the ground water model and integration codes. The data is tagged to the grid map and exported to characteristic files so the ground water model pre-processor can read, sort, and extract the data.

GIS modeling for the surface water model, HSPF, determines average input parameters within subbasin boundaries. The most elementary parameter needed by HSPF is the subbasin area. The basin areas are derived from the basin map and the line and polygon hydrography maps. The hydrography maps are used to remove reach routing surface area from the basin area. The next group of parameters are the surface hydraulic characteristics, including average values of slope, interception and depression storages, Manning's n, and various soil properties for vadose zone dynamics. The GIS overlays the individual maps with the subbasins map and averages each attribute for each basin. The subbasin data are then organized into a characteristic file used by the surface water pre-processors.

The last type of GIS modeling is used to obtain data for the stream reaches, wetlands and lakes (i.e., hydrography). Hydrography coverages include vector (arc) data (e.g., steam center-lines), polygon features (e.g., wetland boundaries or lake edges), and point data (e.g., springs).

Unique spatial analyses are required for the particular GIS used and for the particular data requirements of the integrated model.

Output Processing

After the completion of a surface water only simulation the output to be analyzed is simply discharge hydrograph(s) and detailed water budget summaries. Within the post-processor of FHM, utilities are provided for this purpose, or the data can be loaded into commercial spreadsheet packages. However, for ground water only and fully integrated simulations with FHM, an enormous amount of output can be produced which is difficult to assimilate. For this reason, there is a great deal of output processing capability provided in the post-processor of FHM. In addition a GIS is capable of importing a portion of the output from the ground water model and displaying graphical representations of the water table at various periods. The output (water table elevations at every grid node by integration timestep) can be read into the GIS and interpolated into contoured maps. The maps can then be overlaid with other maps such as the initial water table elevations for a comparison of the change in elevation. From the model, the user can calculate averages, maximums, or minimums of the water table. The GIS can define differences and annual or seasonal low water elevation that can be compared to the surface elevation and land use maps giving wetland definitions.

Landform Data Requirements for the GIS

For the GIS operations, thematic maps for the site must be compiled. Thirteen types of thematic landform maps are required to perform the GIS operations.

1. Watershed and subbasin boundaries
2. Land use/land cover
3. Soils coverage
4. Continuous surface for topographic elevations
5. Basin slope
6. Line, polygon and point hydrography with reach numbers
7. Ground water grid
8. Continuous surfaces for aquifer water level elevations
9. Continuous surfaces for aquifer top and bottom elevations
10. Aquifer hydraulic properties
11. Pumping wells
12. Station locations for temporal data
13. Ground water boundary conditions

While the procedures describing the GIS operations are possible with any GIS capable of complex attribute modeling, FHM has interfaces available for three GIS systems (ARC/INFO, PC ARC/INFO, and SPANS). This supporting software was written in a menu driven format. The menus facilitate the development of characteristic files (model data) through GIS operations (see Part II, HydroGIS: ARC/INFO GIS Utilities). The GIS interfaces for PC ARC/INFO and SPANS cannot be used with FHM V3.0.

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APPENDIX A

The following flowchart is an adaptation of the flowchart found in the HSPF documentation. This flowchart was modified to better describe the infiltration and surface detention processes. It also gives more details of the integration or linking of the HSPF PERLND module to the other FHM components.

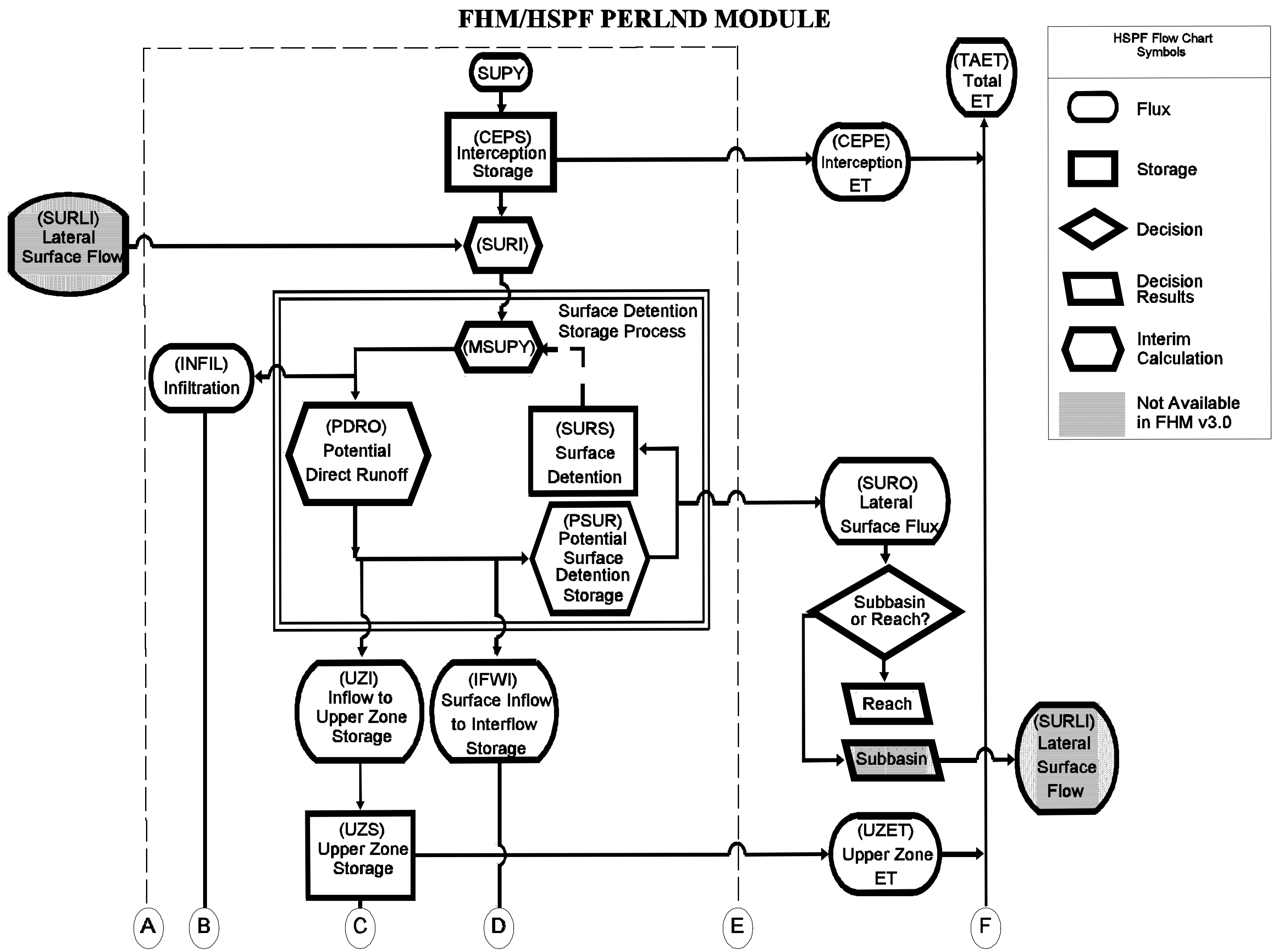

Figure A.1(a) HSPF Operations Flowchart (Moisture Supply to Upper Zone)

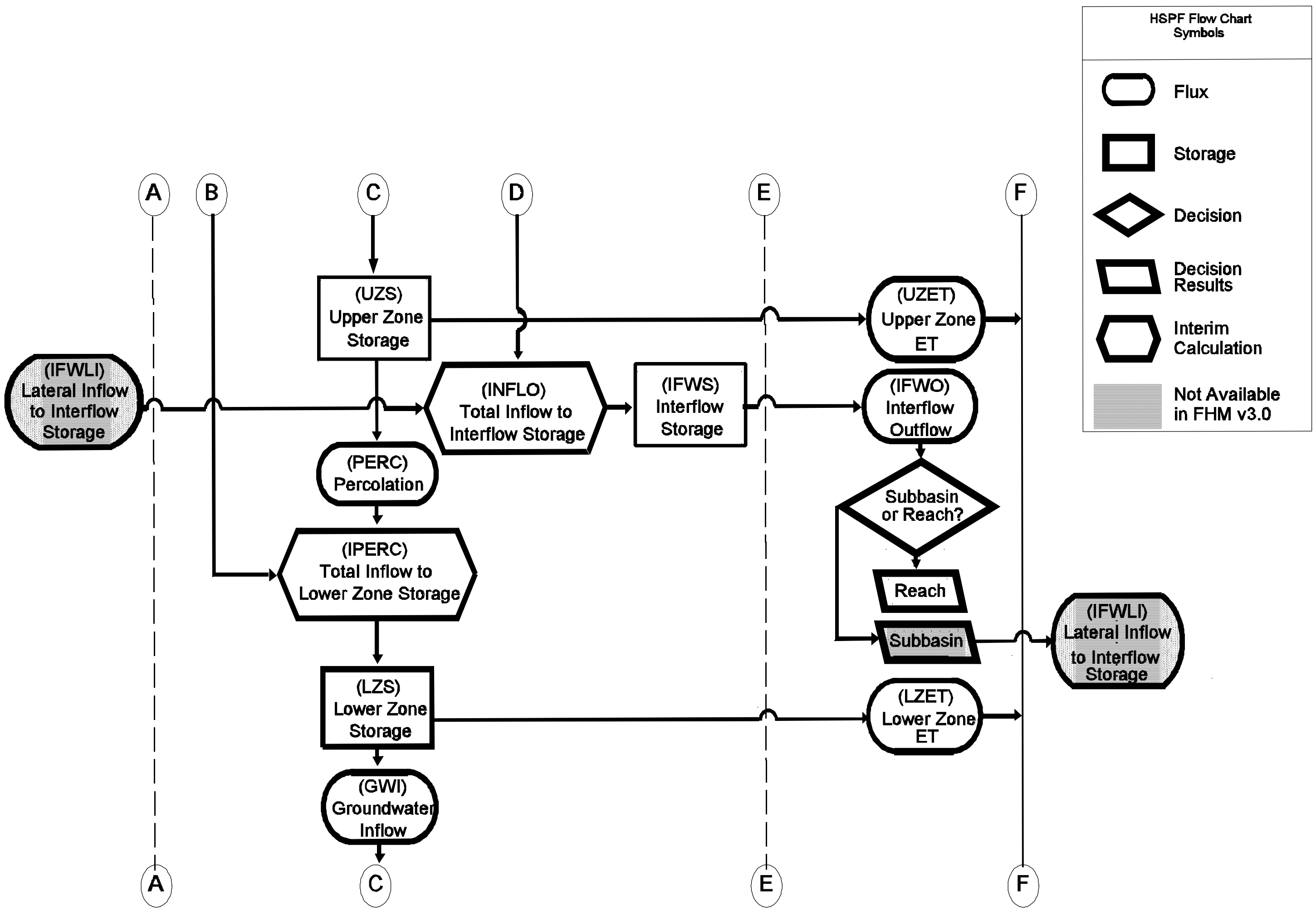

Figure A.1(b) **HSPF Operations Flowchart (Upper Zone to Ground Water)**

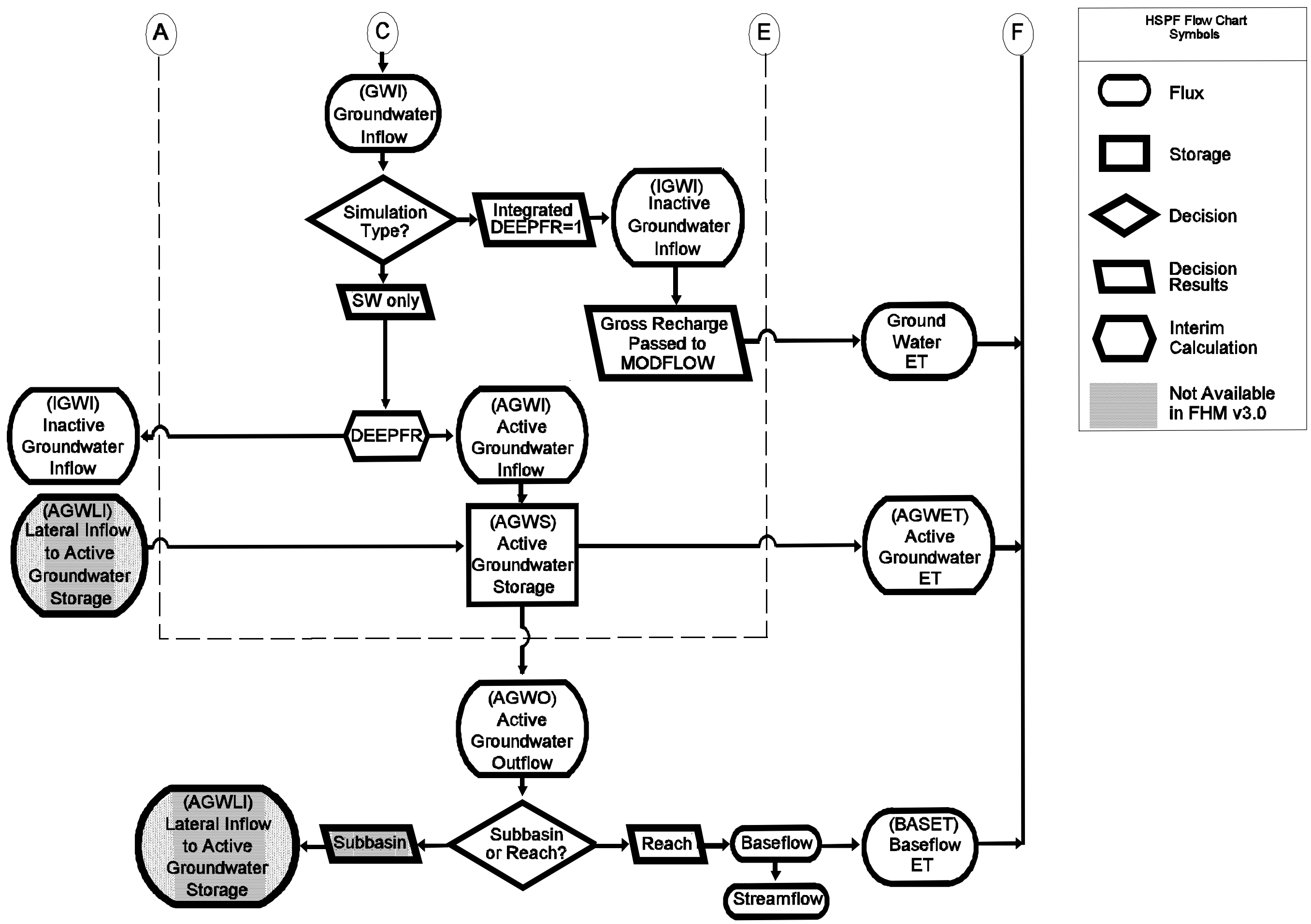

Figure A.1(c) HSPF Operations Flowchart (Ground Water)

GLOSSARY

active cell: in MODFLOW, cells or blocks of porous material (aquifer), through which ground water flow occurs.

active ground water outflow: the volume of water that HSPF sends to base flow in event simulations.

active ground water storage: the volume of water that HSPF stores in saturated storage and eventually becomes base flow in event simulations.

aquifer: geologic formation which contains water and transmits it from one point to another.

available moisture: the difference between the moisture content at field capacity and at the wilting point. It represents the useful storage capacity of the soil.

depression storage: rainwater retained in puddles, ditches, wetlands, and other depressions.

effluent streams: streams intersecting the water table and receiving flow from the ground water.

flux: transfer rate.

field capacity: the moisture content of soil after gravity drainage is complete.

head: potentiometric level of ground water in a confined aquifer.

hydraulic conductivity: the measure of the ease of movement of ground water through an aquifer.

hydraulic length: effective length of the overland flow plane in a subbasin or reach.

hydraulic slope: effective difference in elevation of the overland flow plane in a subbasin or reach.

hydroperiod: the duration of inundation in a wetland.

impervious layer: a formation that has no interconnected openings and cannot transmit water.

inactive cells: in MODFLOW, cells or blocks of non-porous material through which no ground water flow occurs.

index infiltration capacity: saturated vertical hydraulic conductivity of soil.

infiltration: passage of water through the soil surface into the soil.

infiltration capacity: maximum rate at which water can enter the soil at a particular point under a given set of conditions.

infiltration equation exponent: an exponent which is a function of soil type, moisture content and vegetative cover, and approximates the infiltration rate curve.

influent streams: streams contributing to the ground water.

initial interception storage: in HSPF, the amount of water stored by vegetative cover at the start of a simulation.

initial interflow storage: in HSPF, the volume of water stored as interflow at the start of a simulation.

initial lower zone storage: in HSPF, the volume of water stored in the lower zone at the start of a simulation.

initial surface storage: in HSPF, the volume of water stored as depression storage at the start of a simulation; the amount of precipitation that is not infiltration or surface runoff.

initial upper zone storage: in HSPF, the volume of water stored in the upper zone at the start of a simulation.

initial water table elevation: in MODFLOW, the water table elevation above datum (NGVD) at the start of a simulation.

interception: rainfall water which wets the surface of vegetation.

interception storage: the precipitation stored in vegetation.

interflow: the combined horizontal movement of water in the unsaturated zone, often an impervious layer associated with vadose zone stratigraphy, that ultimately contributes to stream flow.

interflow inflow parameter: parameter to allow variation of interflow inflow rates.

interflow recession: an HSPF value, the rate at which interflow depletes the amount of water in interflow storage.

leakage: ground water moving vertically through a semi-confining layer.

leakance: vertical hydraulic conductivity divided by the thickness of semi-confining layer.

lower zone: one of two soil zones in the unsaturated zone used in HSPF.

lower zone nominal storage: in HSPF, the storage which limits the maximum storage in the lower zone, defined as one-half of the storage potential at field capacity.

Manning's n: a roughness coefficient to determine overland flow or open channel flow.

overland flow: water that travels over the ground surface to a channel; also called surface runoff.

perched ground water: local zone of saturation above a locally impervious stratum. Called interflow within HSPF.

percolation: movement of water vertically through the soil.

porosity: the ratio of the pore volume to the total volume of the formation. The original porosity of a material is that which existed when the material was formed. Secondary porosity results from fractures and solution channels.

potential direct runoff: an HSPF term defining the moisture which will be divided into different storages and fluxes before being allocated to direct runoff.

reach: section of a stream channel.

recharge: water that enters the ground water system.

saturation zone: below the unsaturated zone where the pores are filled with water; also called ground water zone.

semi-confining layer: a formation which contains water and resists vertical movement of water; a formation which cannot transmit water rapidly enough to furnish a significant supply to a well or a spring.

specific yield: the ratio of water which will drain freely from the material to the total volume of the formation. This is always less than the porosity.

stage-storage/discharge: relationship between stage and stream storage and stage and stream discharge.

storativity: the water-yielding capacity of an aquifer. Equal to specific yield for a water table aquifer.

streambed elevation: the elevation of the surface of the streambed.

streambed leakance: the vertical hydraulic conductivity of the streambed divided by the thickness of the streambed.

streambed vertical hydraulic conductivity: the measure of the ease of water movement vertically through streambed material.

streamflow routing: the technique used to compute the effect of channel storage on the shape of a movement of a flood wave.

stream stage: the elevation of the stream or river surface at a given point.

surface detention: the portion of precipitation retained on or above the ground surface. Includes interception, depression storage, and evaporation during a storm.

surficial aquifer bottom elevation: the bottom elevation of the surficial aquifer.

upper zone nominal storage: in HSPF, the storage which limits the maximum storage in the upper zone.

unsaturated zone: soil having pore spaces containing both air and water, sometimes known as zone of aeration.

vertical hydraulic conductivity: the measure of the ease of water movement vertically through a semi-confining layer.

water table: the surface separating the unsaturated zone from the saturated zone. Also called phreatic surface.

wilting point: the soil moisture at the time that plants cannot extract water from the soil. The moisture is held at a tension equivalent to the osmotic pressure exerted by the plant roots.

NOTES: