

## **INTRODUCTION TO THE INTEGRATED HYDROLOGIC MODEL (IHM)**

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**Abstract:** The public domain Integrated Hydrologic Model (IHM) combines the EPA surface water model HSPF and the USGS groundwater model MODFLOW with near simultaneous integration and fundamentally new interpretations of vadose zone process dynamics. The two model components are concurrently run, linked through an interface that provides a surface-water to groundwater transition that maintains strict water balance and smoothness in physical processes. The computational elements of the surface-water components are combinations of hydrologically distinct landforms made up of specific land use and soil types. Traditionally, HSPF has been a lumped-parameter model where parameters were averaged over a basin or smaller pervious area. The approach used in the IHM is to disaggregate basins into discrete landform elements that have similar hydrologic properties. These landforms can include impervious areas, irrigated areas, areas with different soils or significantly different depth-to-water table, and areas with different types of land (vegetative) cover or different land uses. Using discrete landforms within basins allows significant distributed parameter analysis. To facilitate this level of discretization for regional domains the model has been uniquely written to maintain efficient computational structure. IHM integration code interprets and manages fluxes and storages across the component model interfaces, accounting for disparate discretization of land segments, hydrography (HSPF) and ground water (MODFLOW).

### **INTRODUCTION**

Hydrologic modeling of areas where there is a significant temporal flux and storage connection between surface water and groundwater requires simultaneous modeling of both systems. This simultaneous or integrated surface and groundwater modeling is necessary to understand and capture the interaction between the surface and groundwater systems, to adequately evaluate the hydroperiod and stresses on wetlands, to reproduce saturation-excess runoff, and to add water balance constraints that are absent in single system models. Research is currently being completed to develop, test and apply a new integrated surface-groundwater model, called the Integrated Hydrologic Model (IHM) (Ross et al. 2004), which is intended to address weaknesses of previous models and extend the functionality of current integrated modeling to simulate coastal plain systems.

IHM is designed to provide an advanced predictive capability of the complex interactions of surface water and groundwater features in shallow water-table environments. The model can be characterized as deterministic, extremely-distributed-parameter, semi-implicit and real-time with variable time steps and feature specific spatial discretization. The model components explicitly account for all significant hydrologic processes including precipitation, interception, evapotranspiration, runoff, recharge, irrigation flux applied to land, stream flow, wetland hydroperiod, baseflow, interflow groundwater flow, and all the component storages of surface, vadose and saturated zone. Input requirements include precipitation and potential

evapotranspiration time series, surface topologic features (i.e. land use, soils, topography and derived slopes), irrigation fluxes, hydrography characteristics, rating conditions, hydrogeologic parameters of the groundwater 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 groundwater flows to wetlands, streams and lakes, evapotranspiration losses from all storages, reach stage, soil moisture, recharge to the groundwater system and storage, heads and fluxes in the groundwater system.

The integration codes of IHM exist entirely in the public domain, as do the component models, HSPF (Bicknell, et al., 2001) and MODFLOW (Harbaugh and McDonald, 1996). However, commercial database utilities Microsoft Access®, and user-preference model utilities (e.g., Groundwater Vistas® and WIN HSPF) for regional watershed applications are useful, necessary and facilitated by IHM for highly discretized model domains. The model also uses extensive geographical information system capabilities (e.g., ARCGIS). Where adequate data exist, a GIS can provide considerable time savings and analysis benefits over conventional means of developing model data sets (Ross and Tara, 1993). Because model parameters of integrated models are more constrained, the potential exists for the results from an independent surface water or groundwater model to be improved with an integrated model strategy (Geurink, et al., 1995). However, IHM requires extensive data to be correctly applied and calibrated. Significant costs can be incurred in collecting and manipulating this detailed data, and this must be understood before embarking on any integrated modeling strategy (Geurink, et al., 1997).

## **IHM OVERVIEW**

IHM version 1.0 consists of a comprehensive surface-water model, a groundwater model, integration and vadose zone components, and a supporting Microsoft Access database. Hydrological Simulation Program—FORTRAN, HSPF V. 12 (Bicknell, et al., 2001) satisfies the surface-water-modeling component, However, unique deterministic interpretations of parameters, especially in the vadose zone, and code changes have been made. This model is distributed and supported by the Environmental Protection Agency and Aqua Terra Consultants and has widespread application for regional, sub-regional and urbanized hydrologic basin investigations in the U.S. The groundwater component model, MODFLOW-96 (Harbaugh and McDonald, 1996) supported by the U.S. Geological Survey, has been widely used. Much of IHM is integration software to provide for the interaction of the two component models, HSPF and MODFLOW, as well as special interpretation and algorithms specific to the dynamic boundary at the interface between the vadose zone and the water table. Of great value is the maintenance of generic component codes HSPF and MODFLOW such that nearly full capabilities of both models are maintained and third party software is still applicable.

Within IHM, the user can elect to perform surface-water-only simulations with full implementation of HSPF, or alternatively, groundwater-only simulations using MODFLOW with pre-determined or post-HSPF user-defined recharge and potential groundwater ET. In fact, a typical application is to pre-calibrate the surface water and groundwater applications in this stepwise fashion prior to performing comprehensive integrated simulations. IHM is intended for the complete assessment of hydrologic water budgets for surface/groundwater interactions.

**Surface Water:** HSPF was developed to simulate the hydrologic and water quality processes on pervious and impervious land surfaces, and transport using reservoir routing within streams and reservoirs. HSPF uses irregularly shaped watershed sub-basins that can be discretized into multiple land segments with pervious and impervious land parcels (PERLNDS and IMPLNDS). IHM allows multiple land segment types, based on user-defined, similarly behaved, hydrologic response units (HRUs), to discretize land-based hydrologic processes within each sub-basin. Each land segment type in a sub-basin is comprised of many land parcels that form one pervious simulation unit (PERLND) which may include some disconnected (drains onto pervious surfaces) impervious areas. Connected or “effective” (draining contiguously over impervious surfaces) impervious areas across all land segment types within the sub-basin are aggregated into one or more IMPLND units. Hydrologic response from each sub-basin is then the aggregated response of the contributing PERLND and IMPLND simulation units.

Hydrologic response of all wetland and open water features is simulated with coupled HSPF reaches (RCHRES) and MODFLOW river package (RIV) reaches. Three general categories of reaches are supported including conditionally-connected, connected, and routing. Conditionally-connected reaches represent wetland or open water bodies that are usually isolated from downstream drainage features except on a seasonal basis or under extreme high-water levels. Connected reaches represent water bodies that consistently discharge to downstream water bodies. Routing reaches receive water from the conditionally-connected and connected reaches. Discharges from each land segment are routed to one or more reaches (on a percentage basis) based on the reach categories and conditions of the sub-basin.

While the complete HSPF and MODFLOW codes comprise hundreds of subroutines, IHM re-conceptualizes only those subroutines relevant to the hydrologic water balance integration of HSPF and MODFLOW. Other features of the component codes have been maintained.

**Groundwater:** MODFLOW (Harbaugh and McDonald, 1996) was developed to simulate groundwater flow in quasi-three dimensions using a block-centered, finite-difference approach to a variably discretized Cartesian space. It provides for simulation of unconfined and confined groundwater-flow conditions. The river package of MODFLOW is used in conjunction with the HSPF RCHRES module to simulate flux transfer between surface-water bodies and groundwater that is dependent on temporally-varying stage. Within IHM, wells, springs, rivers, lakes, wetlands, drains, boundary conditions, evapotranspiration and variable hydrogeologic conditions can be defined for multi-aquifer systems, subject to the limitations of MODFLOW. The RCHRES module of HSPF maintains water balance and determines heads considering the dynamic groundwater fluxes determined by the MODFLOW RIV package. The simulated depth from the RCHRES is used in part to determine stage for the MODFLOW RIV package which calculates the dynamic flux interaction between water bodies and groundwater.

**Evapotranspiration:** Evapotranspiration (ET) is an important element of the hydrologic cycle and is the dominant component of the annual rainfall of a region (e.g., ET return is as high as 70 or 80% of precipitation in Florida; (Bidlake, et al., 1993). ET can be the most difficult budget term to assess. While both HSPF and MODFLOW have ET subroutines, which are often used separately, IHM actually employs both in a unique interpretation and hierarchical approach with stricter adherence to the physics of ET. IHM accounts for evapotranspiration by first specifying a

potential atmospheric evaporation-rate time series based on open pan data or other meteorologic data.

For the integrated simulations, HSPF is used to simulate the distribution of ET among principal surface-water storages, including interception, depression and vadose zone storage. Both vadose zone and saturated groundwater ET are dictated by vegetative cover characteristics, including plant coefficient, root-zone (rhizosphere) depth, soil characteristics and depth to the water table. The extinction depth and maximum ET surface for the evapotranspiration package of MODFLOW are distinctively defined.

**Model Databases:** Management and analysis of the large volume of data which supports IHM requires GIS and other data base tools. These tools are used before, during and after a simulation.

Although the IHM can be run without the use of a GIS, the extensive spatial data requirements make that impracticable for all but the simplest of model conceptualizations. Areas of sub-basins, land segments, reaches and grid cells must be determined. Slopes must be calculated, topographic elevations must be assigned and data and observation points must be located. Plant communities and soil types must be mapped to estimate ET parameters (e.g. root zone, plant coefficients etc.) and recharge variation. Hydrography characteristics must be summarized for the appropriate discretization and coupling. Summaries of the spatial data are stored in a Microsoft Access® database. The Access® database has the capability to import data from many GIS applications, either directly or through intermediate text files.

The surface-water component, HSPF, utilizes a unique time series data structure for both model input and output. Time series data for HSPF are stored in a portable binary format called Watershed Data Management files or WDM files. Many public domain programs exist to import, export, analyze, graph, and transform data stored in WDM format (e.g., WDMUTIL, GENSCN, ANNIE, IOWDM, HYSEP, SWSTAT, and HSPEXP). IHM utilizes the WDM file format and a dynamic Access® database for efficient transfer of model input, output, and integration data.

The IHM integration database is implemented using Microsoft Access®. It has 13 tables, each containing multiple columns (fields). The integration database contains spatial data for land segments, water bodies and grid cells that are used for HSPF and MODFLOW input. The database also includes temporal input data for boundary conditions and pumping wells that are used for MODFLOW.

**Integrating Software:** Simulated results from HSPF and MODFLOW cannot be directly integrated with each other because these models use different spatial discretization concepts. As described earlier, HSPF uses irregularly shaped watershed sub-basins that are discretized into multiple land segments with pervious and impervious land parcels originating from HRUs. MODFLOW uses a block-centered, finite-difference approach to discretize space. 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 land segment within each sub-basin for use by HSPF. In IHM, recharge and ET fluxes use both regular grid cells and irregular land segments within sub-basins. Therefore, the results from each discretization domain must be manipulated prior to transfer to the other domain.

Temporal discretization also varies between HSPF and MODFLOW as a characteristic of the different time scales of surface and groundwater processes. The integration time step of IHM, the time interval over which time integrated model results are transferred from one component model to the other, is specified to be the same as the stress period length of MODFLOW. Physically-based surface-water runoff simulations are typically performed on hourly or less (15 minutes is preferred) increments, while groundwater response time scales are much longer, requiring time steps of a day to multiple days. Also, surface water features, including lakes, wetlands and streams, have a different characteristic timescale compared to rainfall/runoff processes. Therefore, HSPF reaches (RCHRES) can use a different time step length than what is used for the land segments (PERLND, IMPLND). To provide time-step compatibility, IHM integrating software aggregates HSPF results (e.g., in 15 minute, hourly or daily increments) into MODFLOW stress periods, and MODFLOW results are partitioned into appropriate periods for HSPF. Within a MODFLOW stress period, a time step length of less than the stress period length can be specified for MODFLOW simulation. Integration and component model time-step lengths are variable and user-specified.

The integrating software, including integral dynamic databases, provides the linkage between the component hydrologic models used in IHM. Component model results are processed (integrated or partitioned) and placed in the model dynamic database for use in the next time step. The codes also dynamically pass some integration data. For example, HSPF lower zone storage parameters are modified based on water-table heads from MODFLOW as the water table nears land surface. There are numerous software checks made for internal errors, with warnings and halts provided during the simulation when problems are found. Software also has been written to summarize and ensure a water balance for the model components.

**IHM Operation:** For surface-water or groundwater-only simulation, the user can utilize standard commercial pre-processors for the individual models, HSPF or MODFLOW mindful of the unique component and parameter interpretations for IHM, including WinHSPF, GENSCN, Groundwater Vistas, Visual MODFLOW, etc. After the user builds a data set and runs IHM, standard commercial or IHM unique post-processing software can be used to aid output assessment.

Updated values for recharge, baseflow, stream-stage relationships, soil moisture, depth-to-water table and remaining potential evapotranspiration are passed to various integrating software components throughout the numerical integration time step. Integration software updates dynamic memory data and archived database results for the next component model, the next integration time step, or for post-processing following a completed simulation. The integration looping sequence is repeated until the simulation is completed. The user sets the total length of integration, integration time step length, and time step/stress period length of all component models.

## LAND SEGMENTS/COMPUTATIONAL ELEMENTS

To better simulate the water balance and runoff/recharge processes of regional basins and maintain model parameters based on physical and not “lumped” properties, the IHM discretization of subbasins starts by subdividing areas into small hydrologic response units (HRUs). These HRUs incorporate hydrologically unique land-use categories and soil conditions combined with depth-to-water table consideration (ideally not combining shallow and deep environments). IHM requires categorizing the different HRUs into fewer hydrologically similar segments, usually by land use (e.g., typically 7-10 per basin). These subdivisions are referred to as land segments. Each land segment within each model basin is comprised of an aggregation of many discrete, unconnected HRUs. Unique to the IHM, full spatial resolution of HRUs (down to the grid dimension) is maintained in the model for groundwater association. The calibration process shifts from basin-by-basin to landform- (segment) based parameter adjustments thereby maintaining direct association to and predictive capability for land use issues.

Land segments and surface water bodies are distinctly discretized for the HSPF and MODFLOW components of IHM. An HSPF land segment (index  $j$ ) is comprised of multiple HRUs which exhibit similarity in hydrologic response over time for an applied stress. Stated earlier, an HRU can be a unique combination of land use, soils, slope, predominant depth to water table and possibly other characteristics. Model objectives, limitations on runtime, or other considerations constrain the number of land segments which form the basis for PERLND simulation units in HSPF. HRUs are aggregated in a consistent manner to maintain similarity in hydrologic response and to stay within the defined limits for land segments for the model application. Each HRU can contain imperviousness dependent on land use characteristics. As a consequence, each land segment can contain imperviousness. Unless there exists detailed mapping of impervious areas, only an area weighted percent imperviousness by land segment can be determined. Imperviousness from all land segments within a sub-basin are aggregated into one or more IMPLND elements in HSPF. However, the model is set up to accommodate a separate impervious element for each appropriate land use category. In such a manner, the model could be discretized down to the size of roof tops, driveways and grassed front lawns if warranted.

For MODFLOW, the entire model domain is discretized with rectangular or square, finite-difference cells (index  $i$ ). Intersection of HSPF land segments with MODFLOW cells form individual land fragments as shown in Figure 1 (HRUs inside & HRUs cut by the grid). In this example, aggregation of HRUs is based on five general categories of pervious land use including urban, irrigated, grass/pasture (non-irrigated), forested, and mined/disturbed. The wetland and open water categories are represented as reaches. In IHM, a land segment of a particular type (e.g. pasture grass land) is unique from one subbasin to the next. If, for no other reason, than it could be in different antecedent moisture condition or metrological stress region. It is not necessary for integration to maintain the individual land fragments of the same land segment within a cell as there is no intra-grid detail for depth-to-water table. Therefore, like fragments of the same land segment within a cell are grouped into aggregated land fragments referred to simply as grid land fragments (index  $ij$ ) within each cell as shown in Figure 2. Within a cell, the number of land segments is thus limited excepting that there can be multiple subbasins.

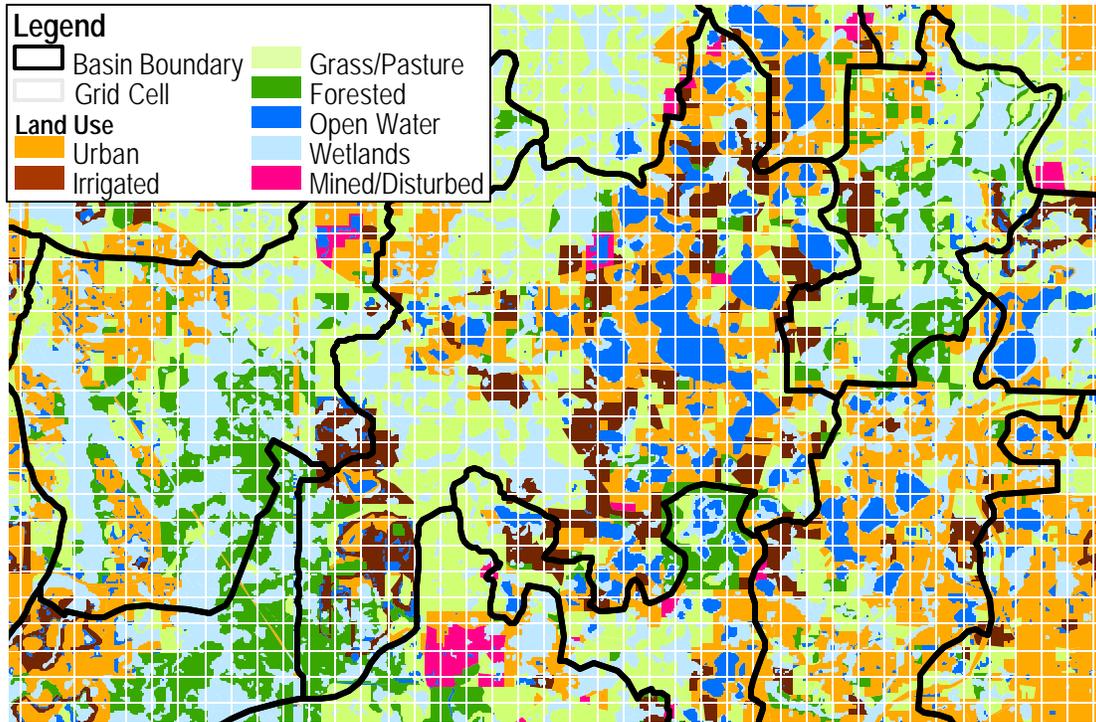


Figure 1 Example of land fragments within grid cells

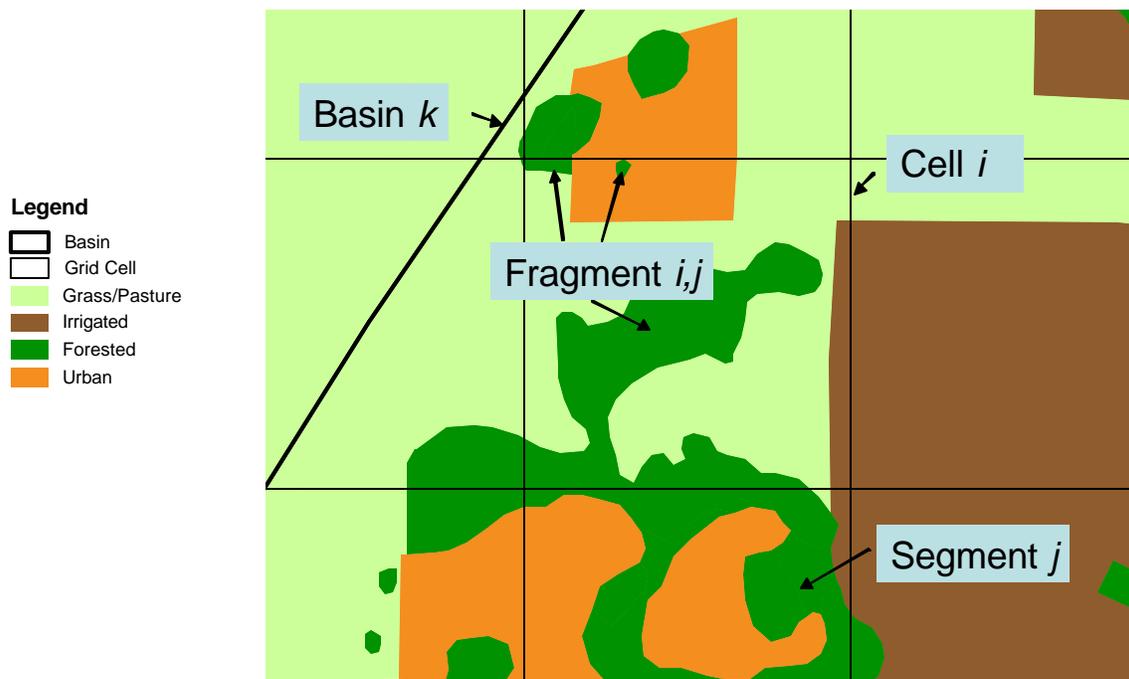


Figure 2 Example of sub-basins, land segments, land fragments and grid cells

## CONCLUSION

An integrated hydrologic model using HSPF and MODFLOW has been formulated using small hydrologically similar computational elements appropriate to the two models which provides for computational efficiency sufficient to handle large regional ( $\sim 10^3$  km<sup>2</sup>) applications and adequate distribution to maintain all parameter assignments within physical homogeneous landforms. Considerable discretization (e.g.,  $10^6$  HRU elements) is facilitated by GIS and integration database utilities. Consistency and conservation of fluxes and storages between the model components has been maintained. The model provides for better runoff/recharge prediction for both Hortonian and saturation excess mechanisms. The model insures consistent plant ET process distribution between surface storages and below ground storages and allows for smooth transition between soil moisture fluxes supporting surface evaporation and subsurface ET. Unique interpretation and code changes for a more physically-based vadose zone, plant and soil parameters and water fluxes and storage have been implemented in IHM. Variable time steps (including integration time steps) are provided in the model to streamline model simulation time. The model is being tested through calibration, verification and validation exercises on regional and detailed field scale applications as well as simple analytical comparisons and/or vadose zone solutions with Richard's Equation.

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