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Discretization Approach in Integrated Hydrologic Model for Surface and Groundwater Interaction

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Abstract: The commonly used discretization approaches for distributed hydrological models can be broadly categorized into four types, based on the nature of the discrete components: Regular Mesh, Triangular Irregular Networks (TINs), Representative Elementary Watershed (REWs) and Hydrologic Response Units (HRUs). In this paper, a new discretization approach for landforms that have similar hydrologic properties is developed and discussed here for the Integrated Hydrologic Model (IHM), a combining simulation of surface and groundwater processes, accounting for the interaction between the systems. The approach used in the IHM is to disaggregate basin parameters into discrete landforms that have similar hydrologic properties. These landforms may be impervious areas, related areas, areas with high or low clay or organic fractions, areas with significantly different depths-to-water-table, and areas with different types of land cover or different land uses. Incorporating discrete landforms within basins allows significant distributed parameter analysis, but requires an efficient computational structure. The IHM integration represents a new approach interpreting fluxes across the model interface and storages near the interface for transfer to the appropriate model component, accounting for the disparate discretization while rigidly maintaining mass conservation. The discretization approaches employed in IHM will provide some ideas and insights which are helpful to those researchers who have been working on the integrated models for surface-groundwater interaction.

Keywords: discretization; distributed hydrological model; Integrated Hydrologic Model (IHM); interaction

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1 Introduction

Distributed hydrologic models have been developing rapidly since the first blue-print of a physically-based distributed model released by Freeze and Harlan (1969). Compared to lumped models, it has much advantage concerning the representation of spatial variability. Generally, it is assumed that properties within a grid or a subarea are homogeneous. However, different grids or sub areas are allowed to be heterogeneous. In some models some distribution of properties is allowed over the smallest discretization element (Refsgaard and Storm, 1995; Ross *et al*., 2004). For this reason, distributed parameter models can represent a watershed more realistically than lumped parameter models.

Surface water processes are typically bounded by irregularly shaped drainage basins, while groundwater is controlled by uncertain distributed aquifer properties with quite different discretization that present unique challenges for representing the dynamic interchange between surface and subsurface storages and fluxes. Large regional areas inherently include large spatial variability. However, discretization areas with strong inhomogeneity may not reproduce observed hydrologic

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responses for day-to-day conditions or may not be related to the scale of the discretization unit. So, for the integrated models, the discretization scheme is a challenging task for hydrologic modelers.

A key question in distributed modeling is the selection of the criteria for the discretization of the watershed into grid elements. Many researchers have been working on the discretization method of integrated models for surface-groundwater interaction. There are a number of integrated (i.e., couple surface and ground water) hydrology models that have been developed in the last decades, and examples include SHE (Abbott *et al.*, 1986), MIKE-SHE (Yan and Smith, 1994; Refsgaard and Storm, 1995; DHI, 1998), MOD-HMS (HydroGeoLogic Inc., 2003; Panday and Huyakorn, 2004), SWATMOD (Sophocleous *et al.*, 1999), tRIBS (Vivoni *et al.*, 2003), FIPR Hydrologic Model (FHM) (Ross *et al.*, 1997) and Integrated Hydrologic Model (IHM) (Ross *et al.*, 2004). These models provide very different approaches in discretizing spatial variability, and in these models, the choice of an appropriate spatial scale for the modeling units is a crucial issue (Zhang and Ross, 2010). It is really in need to explore the mechanism using unique discretization approaches for better understanding the process of surface water-groundwater interaction.

An alternate approach is to allow detain of the raw data, the GIS data of landform, soil and other properties to control the resolution of the model but are a computational efficient numerical scheme to combine similar hydrologic response. The IHM proposes one such technique. The IHM conceptualization begins by linking two public domain models: Hydrologic Simulation Program-Fortran (HSPF) (Bicknell *et al.*, 2001) for surface water uniquely interpreted for HRUs, and the finite-difference-based Modular Three-dimensional Finite-difference Ground-water Flow Model (MODFLOW) (McDonald and Harbaugh, 1988) for groundwater. The concept of aggregated, hydrologically similar HRUs are incorporated into the IHM (Ross *et al.*, 2004; 2005a) by using hydrologic and segments (HLSs) within each surface basin. The hydrologic response from a basin contributing to a stream or wetland is the aggregated individual responses from the various HLSs in that domain. All hydrologically similar HLSs in a meterologic discretization (zone) are assigned the same infiltration, surface runoff, and evapotranspiration (ET) parameters based on weighted averages for HLS computational element. However, groundwater depth-to-water-table variability and groundwater ET characteristics are retained at the HRU scale in a very unique efficient (Ross *et al.*, 2005b). In this paper, different discretization methods are compared and a detained description of the HLS discretization method employed in the integrated surface and groundwater model IHM will be introduced and examined.

2 Different Discretization Approaches Comparisons

The commonly used discretization approaches for distributed hydrological models can be broadly categorized into four types, based on the nature of the discrete components: Regular Mesh, Triangular Irregular Networks (TINs), Representative Elementary Watershed (REWs) and Hydrologic Response Units (HRUs). These discretization methods popularly used are compared in details.

Most distributed hydrological models are based on a regular mesh. A particular example is MIKE-SHE (Abbott *et al.*, 1986). This approach, referred to as a 'reductionist' approach (Gottschalk *et al.*, 2001; Dehotin and Braud, 2007) is argued that the equation becomes a parameterization of the process, since parameters can not be estimated from field measurements (Beven, 2002). It is not always rationalized for choosing the grid size taking into account the processes that are represented, but seems rather the result of commodity and data resolution (Dehotin and Braud, 2007).

Because of the inadequate treatment of heterogeneity for square elements, meshes based on Triangular Irregular Networks (TINs) (Ivanov *et al.*, 2004a; Vivoni *et al.*, 2004) have been recently developed. It offers a good compromise between efficiency and accuracy as shown by the performances of the tRIBS model, developed on this irregular geometry (Ivanov *et al.*, 2004a; 2004b).

Another example of hydrological spatial discretization is the concept of Representative Elementary Area (REA) proposed by Wood *et al.* (1988), later improved to the concept of Representative Elementary Watershed (REWs) by Reggiani *et al.* (1998; 1999; 2000) and extended by Tian *et al.* (2006). REWs form the elementary modeling units divided into several zones corresponding to the various hydrological processes. Global mass, momentum and energy balance laws are formulated at the sub-catchment scale. The corresponding equations remain unchanged whatever the scale (e.g., for REWs defined at various Strahler order). On the other hand, fluxes between REWs and their zones (saturated, non-saturated, overland, concentrated and river flow) must be defined for each scale. Sub-catchment scale variability can be parameterized in the derivation of these fluxes (Dehotin and Braud, 2007).

Other authors tried to define more 'hydrological' modeling units based on the concept of hydrologic similarity, and can be defined using, for instance, the topographic index of Beven and Kirby (1979). Within these areas, it is assumed that the catchment response is similar. The concept is used in the TOPMODEL (Beven and Kirby, 1979). In order to represent land-use heterogeneity, the concept of Hydrological Response Units (HRUs) (Flűgel, 1997) is used in the Soil Water Assessment Tool (SWAT) model (Neitsch *et al*., 2005). HRUs represent a sub-catchment scale discretization composed of a unique combination of land cover, soil and land management. Portions of the landscape, which exhibit similarity in hydrologic response to forcing functions (e.g., rainfall) or stresses, are collectively referred to as hydrologic response units (HRU). Whether using physically-based models or statistically-based models, it is important to properly identify the HRUs within the domain of interest. Land cover only (topography combined with soils) and topography, soils, and land cover together can be used as the basis of an HRU. Anthropogenic influences such as imperviousness and irrigation fluxes also influence the basis for an HRU.

Sub-discrtizing the model domain with HRUs has merit as a specific land cover existing in specific areas because of the soils, surface slope, depth-to-water-table, and topography-related soil moisture conditions. Differences in soil type are often coincident with differences in land cover and topography, and it is difficult to discern the separate effects of each landscape characteristic on downstream hydrologic response (Kouwen *et al*., 1993). Famiglitti and Wood (1994; 1995) concluded that spatial variability of soil moisture is the dominant control on surface runoff, ET and thus, recharge response, and particular land covers are associated with the prevailing soil moisture condition of an area. Further, the spatial distribution of soil moisture is directly related to the combined effects of topography, soils and depth-to-water-table.

Other concepts include the Grouped Response Unit (GRU) (Kouwen *et al*., 1993), and the Aggregated Simulation Area (ASA) (Kite, 1997). GRU is a special term introduced by Kouwen in order to describe watershed subdivision in the WATFLOOD hydrological model, while the term ASA is used by Kite to describe the watershed subdivision in the semi-distributed land use-based runoff processes (SLURP) hydrological model (Susilo, 2002). The group response unit approach is based on calculating the response for each of the land cover classes within the element and then weighting the response by land cover area fractions within the grid cell. In SLURP, the watershed is divided into modeling units called ASA. An ASA is a group of smaller areas that have known properties.

From the comparison between various discretization methods above, it indicates that each type of hydrological modeling unit devised has advantages and disadvantages. Generally, the subdivision of the watershed depends on the watershed characteristics, data availability, computing power, and the expertise of the modeler (Susilo, 2002).

3 Methodology

The discretization approaches used in IHM will be introduced and examined from four major parts; they are 1) land segment surface hydrology, 2) temporal discretization, 3) spatial discretization, and 4) adjustments for discretization.

3.1 Land segment surface hydrology

For the IHM conceptualization, it is first assumed that surface hydrology processes extending to the saturated zone (water table) of the groundwater system can be simulated by HSPF or a modified HSPF allowing some process improvements. Irregularly-shaped watershed sub-basins are further sub-discretized into multiple land segments using the highest resolution landuse topography and soils GIS databases, as shown in Fig. 1, including pervious and impervious land parcels (at the smallest delineation). The land parcels vary in size and shape relating land use, soil type, surface slope, and other surface and subsurface characteristics. IHM allows for multiple land segment types, at the user discretion, based on land use, soils, slope and other considerations. As landuse and soils databases can be quite detained, broad reclassification are useful (e.g., multiple grassland types and similar soil series are combined into a general classification) to discretize land-based hydrologic processes within each sub-basin.

Each land segment type in a sub-basin is then comprised of many non-contiguous land parcels that form one pervious simulation unit (PERLND) which includes connected or non-connected impervious areas. 'Effective' impervious areas of land segments within the sub-basin are aggregated into one or more impervious land (IMPLND) operations. Surface hydrologic response from each sub-basin is an aggregated response of the contributing PERLND and IMPLND simulation units. The example sub-basin with land segments shown in Fig. 1 includes the categories open water and wetlands which are handled as reaches (RCHRES) in IHM as explained in the section on surface-water bodies. Land segment discretization and a distinctive accounting for imperviousness within each sub-basin provide a more discrete and hydrologically representative simulation unit. This improves simulated responses compared to lumping all land uses and imperviousness into one simulation unit that represents the whole sub-basin. Through this form of discretization, IHM provides a 'semi-distributed' representation which is discussed further later.

The discretization of sub-basins into multiple land segments is implemented in IHM to: 1) increase description of hydrologic-process variability over the model domain, 2) increase predictive capability by implementing more physically-based parameter values, and 3) establish a calibration process that allows model parameters to be derived from land use categories and soil types with characteristics that are acceptable across the entire model domain (i.e., values for land use-based hydrologic parameters for grass areas or values for soils-based hydrologic parameters for a soil type are the same throughout the model domain). The mathematical details that implement the concepts of multiple land segments within sub-basins and imperviousness are described later in the integration mechanics section.

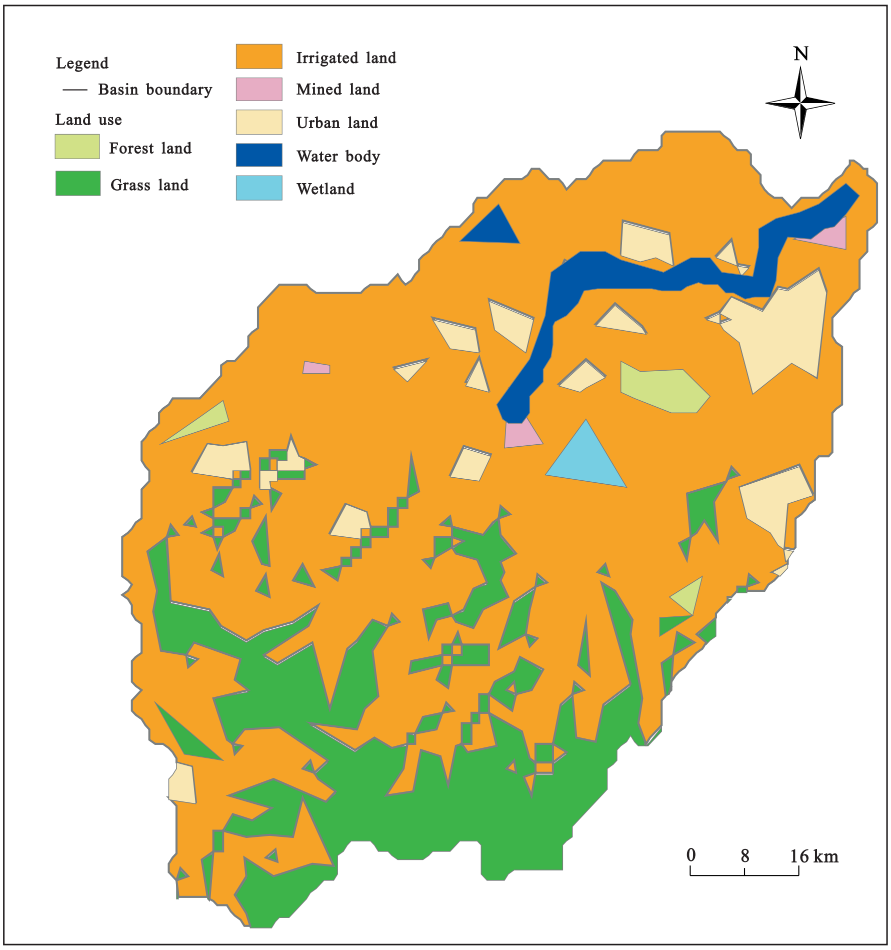

Fig. 1 Individual land segments within a sub-basin

3.2 Temporal discretization

The Temporal discretization also varies between HSPF and MODFLOW appropriate to the different time scales of surface and groundwater processes. The integration time step of IHM, the time interval over which time-averaged 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 (especially Hortonian runoff) simulations are typically performed on hourly or less (15 minutes or less is preferred) increments. In contrast, groundwater response time scales are much longer, facilitating time steps of days to weeks. Also, surface water features, including lakes, wetlands and streams, have a different characteristic timescale compared to rainfall/runoff processes. Therefore, time step length is allowed in IHM to calculated receiving water response using HSPF reaches (RCHRESs) for the land segment computations (PERLNDs and IMPLNDs). 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 in IHM.

Surface and soil hydrologic processes in the IHM are further discretized using the HLS discretization. Even within the smallest discretization available (e.g., HRUs or HLSs), field-scale variability exists. Therefore, the IHM conceptualization uses parameter distribution concepts for some variability rather than being constricted to a pure homogeneity assumption for the HLS. Furthermore, for larger regional applications, sufficient data do not exist nor are they practical to solve Richard's equation for each unique soil moisture distribution. Therefore, a simpler 'relative moisture condition' based treatment of the vadose zone is employed (Zhang and Ross, 2007). In this manner, runoff and recharge are distributed over irregular hydrographic discretization for surface water and regular (grid cell) discretization for below water table ground water flow computations. More detail about the discretization of IHM can be found in Ross *et al*. (2005b).

3.3 Spatial discretization

Land segments and surface water bodies are distinctly discretized for the HSPF and MODFLOW components of IHM. A HSPF land segment (index j) is comprised of multiple hydrologic response units (HRUs) which exhibit similarity in hydrologic response over time for an applied stress. 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 dependence on land use characteristics. Unless there exists detailed mapping of impervious areas, only an area weighted percent imperviousness by land segment can be determined. Aggregation of imperviousness from all land segments within a sub-basin into one IMPLND in HSPF is the simplest way to handle the issue. However, the model is set up to accommodate a separate impervious element for each appropriate land use category.

In this example, HRUs have been aggregated into five pervious land segments, an impervious IMPLND (not shown), and water bodies (open water and wetlands), represented by reach discretization. In this example, aggregation of HRUs is based on general categories of land use where the five pervious land segments include urban, irrigated, grass/pasture (non-irrigated), forested, and mined/disturbed, and the wetland and open water categories are represented by reach discretization. In IHM, a land segment of a particular type is unique between sub-basins.

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 forms individual land fragments as shown in Fig. 2. 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 henceforth as land fragments (index ij) within each cell as shown in Fig. 3. Within a cell, the number of unique land seg-

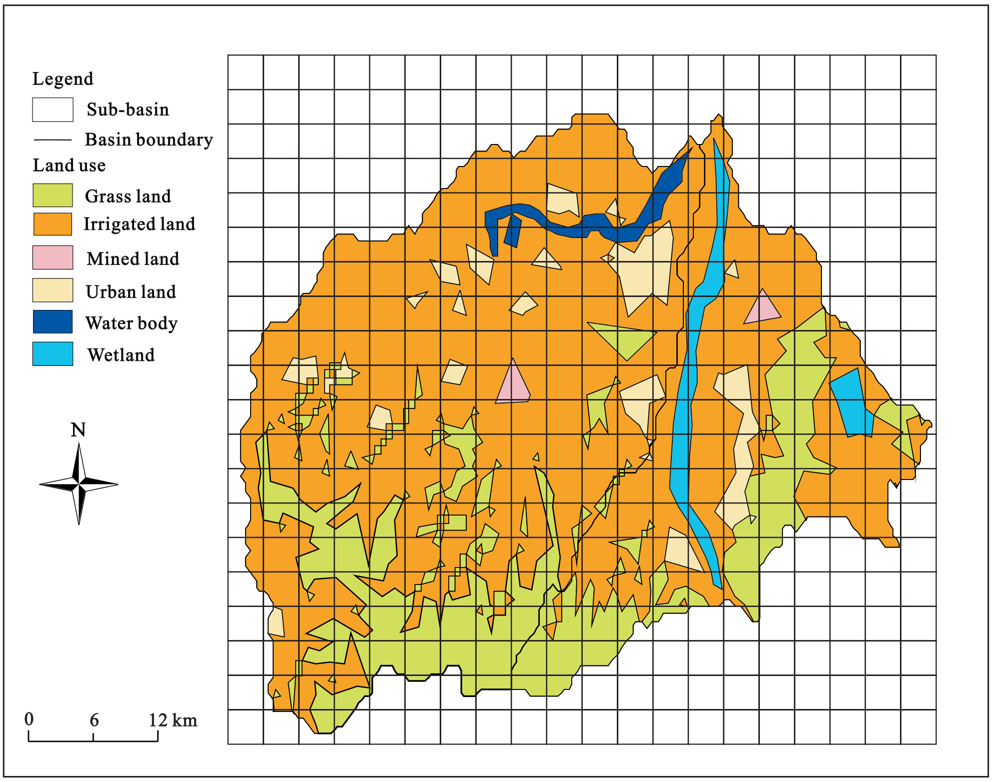

Fig. 2 Example of land fragments within grid cells

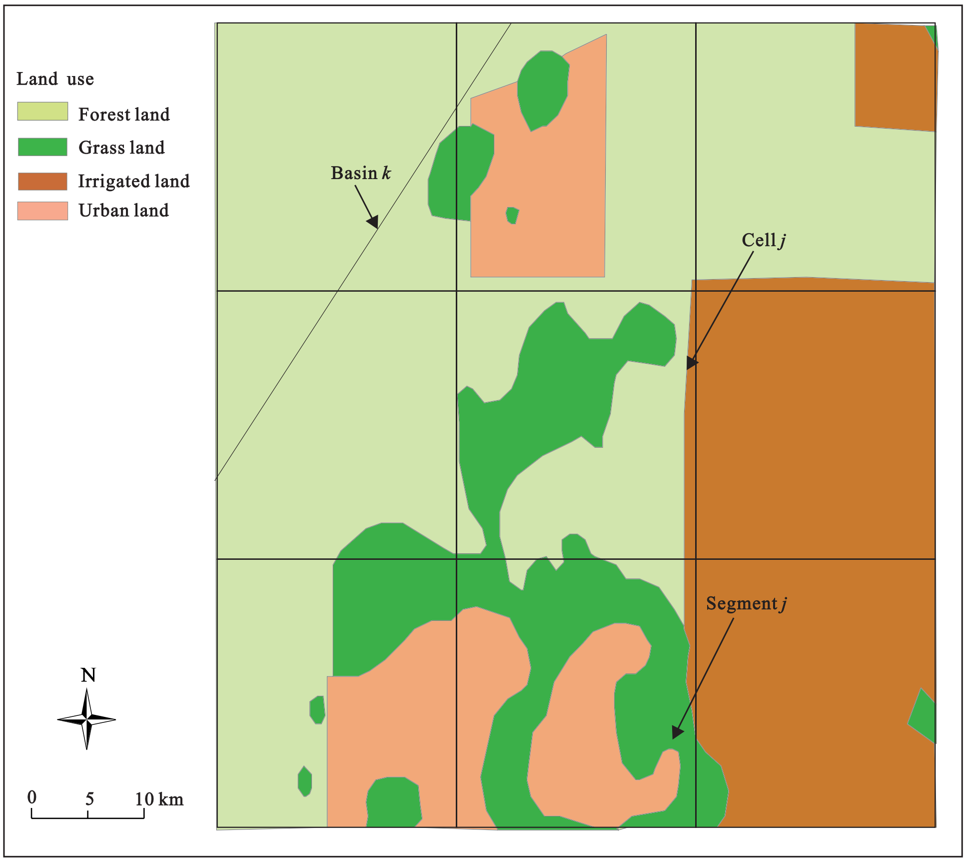

Fig. 3 Example of sub-basins, land segments, land fragments and grid cells

ments, including those that lie in different sub-basins, is equal to the number of aggregated land fragments. Each HSPF land segment is associated with one or more MODFLOW cells.

In IHM, the information associated with aggregated land fragments within each MODFLOW cell is used throughout the integrated simulation. By using land fragments to dynamically modify model variables for HSPF and MODFLOW, IHM provides 'semi-distributed' discretization of the model domain (Fig. 2). IHM is not fully distributed because land-segment hydrology is discretized over a larger area than a single finite-difference cell or finite-element. However, intra-cell variability in hydrologic behavior (e.g., recharge and runoff) is facilitated by this approach. The advantage is computational efficiency provided by performing only one set of computations for all hydrologically similar fragments distributed over the sub-basin domain.

Surface water bodies, including streams, lakes, and wetlands, are distinctly discretized in HSPF and MODFLOW for integrated modeling with IHM. An HSPF reach (index l) is comprised of multiple segments of streams and individual lakes and wetlands. The corollary to HRUs for surface water bodies is a segment of a stream or an individual lake or wetland. Model objectives, limitations on runtime, or other considerations constrain the number of HSPF reaches which form the basis for RCHRES simulation units in HSPF. The individual lakes, wetlands, and stream segments are aggregated in a consistent manner to stay within the defined limit for HSPF reaches for the model application. An example of HSPF reaches is shown in Fig. 4. In this example, there are three general types of HSPF reaches, including conditionally-connected (unconnected), connected and routing. Each of the three types of HSPF reaches can be presented within each sub-basin, as shown in this example.

For MODFLOW, the individual lakes, wetlands and stream segments are intersected with the grid. The intersection can create multiple distinct parts of one lake or wetland (index m) that fall into multiple cells of MODFLOW. The distinct parts of each water body are maintained in MODFLOW as River (RIV) package reaches and are assigned to an HSPF reach indexed by l. The many-to-one association of index m to l facilitates transfer of water depths from HSPF to MODFLOW and gain or loss of water to/from groundwater (flux) from MODFLOW to HSPF. Examples of association between HSPF reaches and MODFLOW reaches are shown in Fig. 5 and Fig. 6 which are representation of a process within a model.

3.4 Adjustments for discretization

To conserve mass when transferred through the inter

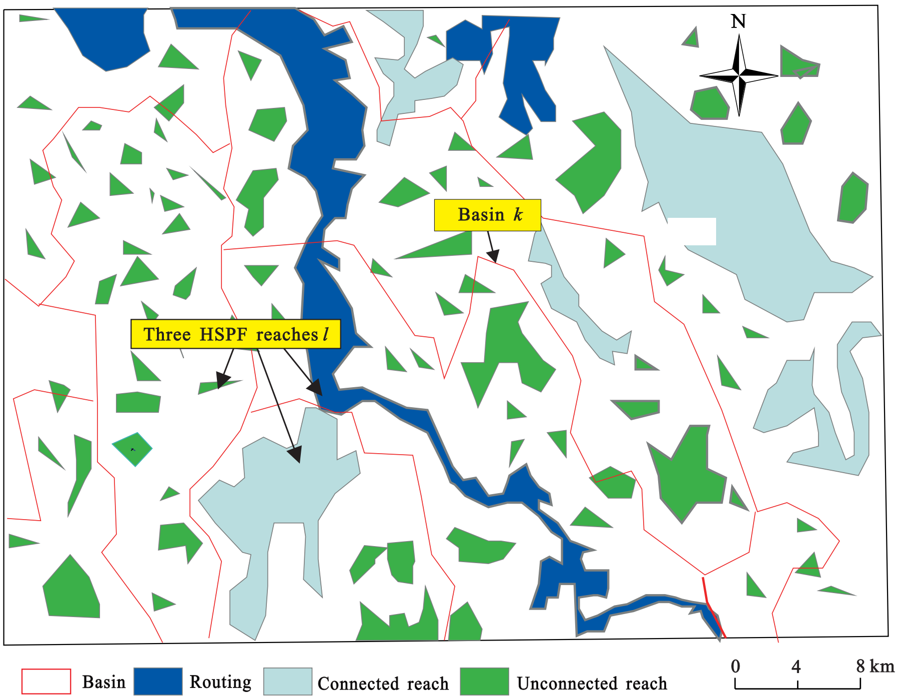

Fig. 4 Example of Hydrologic Simulation Program-Fortran (HSPF) reaches in a sub-basin

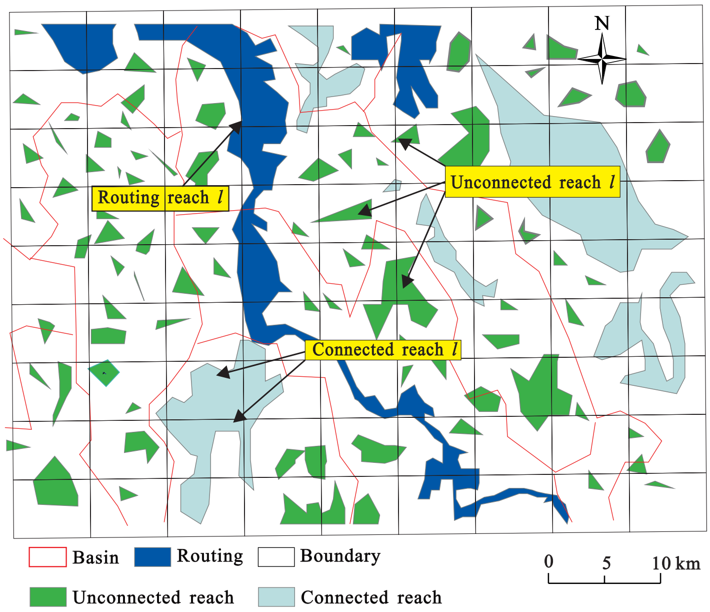

Fig. 5 Sample of association of Hydrologic Simulation Program-Fortran (HSPF) reaches to basins and cells

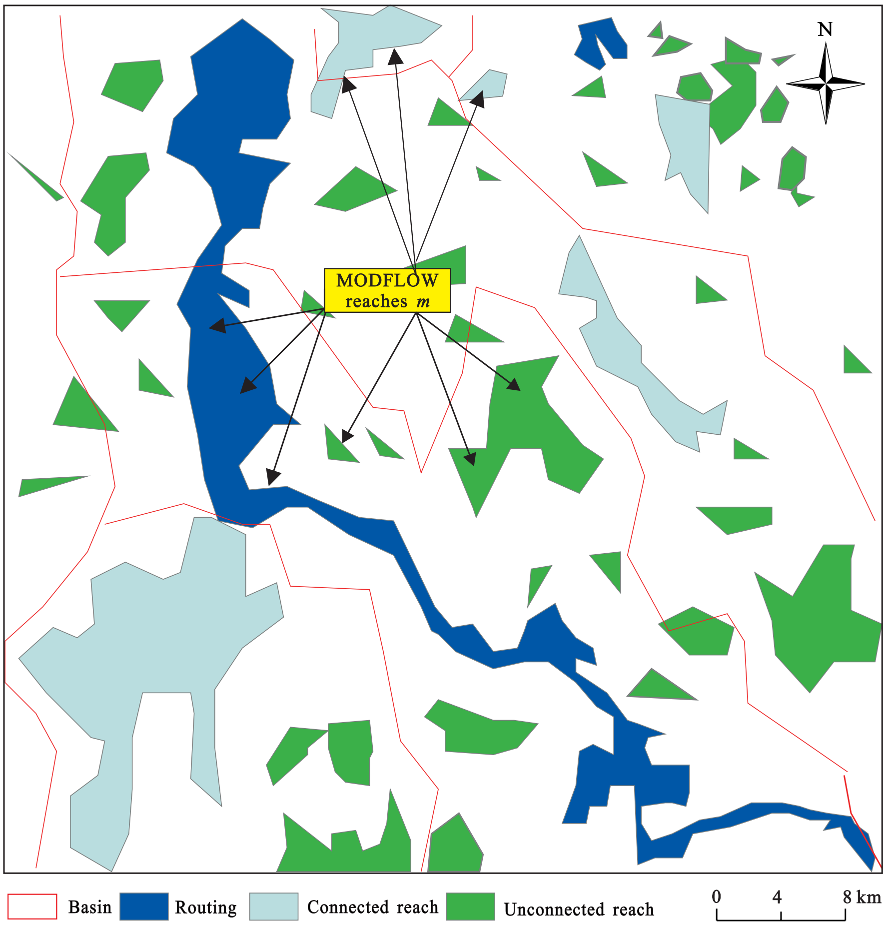

Fig. 6 Sample of MODFLOW reaches within grid cells

boundary condition (IBC), adjustments are required to account for differences in discretization, and the presence of imperviousness and water bodies.

3.4.1 Actual and equilibrium vadose zone storage

After every integration time step there is an ending value for the relative soil moisture condition, $R_{\mathrm{LZRAT}j}^{\ t-}$ (LZRAT is lower zone ratio), from HSPF for each land segment and an ending value for the groundwater head at each cell from MODFLOW. From Fig. 7, variables with index $t - \Delta t_I$ refer to the preceding integration time step and variables with index t refer to the present integration time step. Variables with t^H time indices correspond to the period right after HSPF and prior to MODFLOW. At this time index, moisture conditions, groundwater recharge and potential ET flux to groundwater have been found from HSPF and are prepared for input to MODFLOW. Time index t corresponds to the end of the integration cycle after MODFLOW and before HSPF (for the next integration cycle). At this time index, water table depths, baseflow, and ground-water ET has been found from MODFLOW and vadose storage is updated for HSPF as a result of vertical movement of the water table.

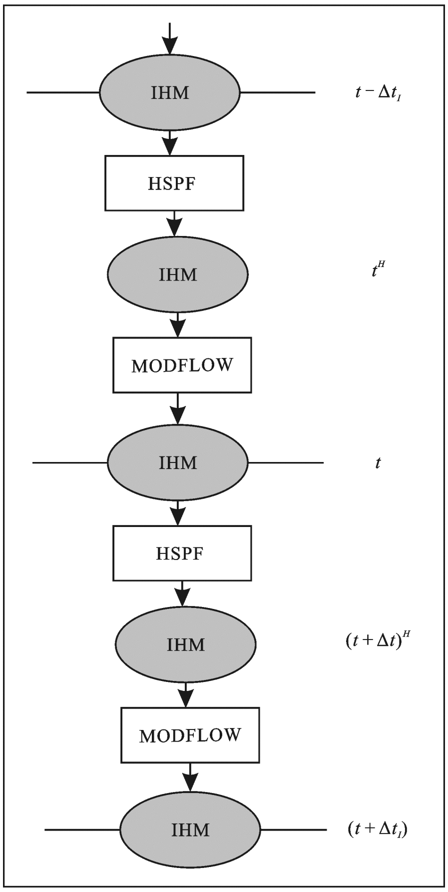

Fig. 7 Sequence of operations for Integrated Hydrologic Model (IHM)

To restart HSPF following MODFLOW water table changes, updated values for lower zone storage, $D_{\mathrm{LZS}_j}^{t+}$ and $D_{\mathrm{LZSN}_j}^{t+}$, for each land segment must be determined. First, the updated equilibrium vadose zone storage, $D_{\mathrm{LZSN}_{ij}}^{t+}$, for each land fragment is calculated using the soil zone thicknesses and soil moisture contents for equilibrium and wilting point (Ross *et al.*, 2004), and the equation is as following.

$$D_{\mathrm{LZSN}ij}^{\ t+} = \left(\theta_{\mathrm{FC}_i} - \theta_{\mathrm{WP}_i}\right)\left[b_1 + \frac{b_2}{2\xi_{\mathrm{ICZ}_i}}\left(b_2'' - b_2'\right)\right] \tag{1}$$

where θ_{WP_i} is wilting point soil moisture content of cell i, b_1 is thickness of the upper gravity zone of the soil moisture model for the current integration time step; b_2 is thickness of the intermediate capillary zone of the soil moisture model for the current integration time step; b'_2 is thickness of the soil between the bottom of the root zone and the top of the capillary fringe; b''_2 is thickness of the soil between land surface and the top of the capillary fringe; ξ_{ICZ} is intermediate capillary rise thickness (upper part of capillary zone above capillary fringe); θ_{FC_i} is specific retention or field capacity (equilibrium) moisture content of the upper gravity zone (depth to water table, d_{WT} > thickness of capillary zone, ξ_{CZ}). Next, the updated actual vadose zone storage, $D_{\mathrm{LZS}_{ij}}^{t+}$, of each land fragment is calculated using the product of the known relative moisture condition for the land segment, $R_{\mathrm{LZRAT}_j}^{t-}$, and the updated equilibrium vadose zone storage, $D_{\mathrm{LZSN}_{ij}}^{t+}$, of the land fragment as:

$$D_{\mathrm{LZS}_{ij}}^{t+} = R_{\mathrm{LZRAT}_j}^{t-} D_{\mathrm{LZSN}_{ij}}^{t+} \tag{2}$$

Then, the updated actual vadose zone storage for the land segment j, $D_{\mathrm{LZS}_j}^{t+}$ is calculated by summing the land fragment values,

$$D_{\mathrm{LZS}_j}^{t+} = \left[\sum_{i=1}^{o} D_{\mathrm{LZS}_{ij}}\right]^{t+} \tag{3}$$

The updated equilibrium vadose zone storage for the land segment *j*, $D^{t+}_{\mathrm{LZSN}_j}$ is

$$D^{t+}_{\mathrm{LZSN}_j} = R^{t-}_{\mathrm{LZRAT}_j} D^{t+}_{\mathrm{LZS}_j} \tag{4}$$

For the next integration time step, $D^{t+}_{\mathrm{LZSN}_j}$ is used as the initial value and $D^{t+}_{\mathrm{LZSN}_j}$ is used over the entire period encompassed by the integration time step. This procedure is the most mass conserving and ensures that each land segment in HSPF stops and starts at the break between integration time steps with the same relative moisture condition, therefore,

$$R^{t+}_{\mathrm{LZRAT}_j} = R^{t-}_{\mathrm{LZRAT}_j} \tag{5}$$

3.4.2 *Variable specific yield*

For each MODFLOW cell, *i*, at time indices t^H (refer to Fig. 7) an area-weighted average specific yield $SY_i^{t^H}$ is found incorporating pervious, impervious, wetland and water feature areas,

$$SY_i^{t^H} = \frac{\left(\sum_{j=1}^{n} SY_{ij}^{t^H} A_{ij} + SY_{o_i}\left(A_i - \sum_{j=1}^{n} A_{ij}\right)\right)}{A_i} \tag{6}$$

where A_i is area of grid cell *i*; A_{ij} is area of land fragment *j* of cell *i*; $SY_{ij}^{t^H}$ is variable specific yield of land fragment *j* of cell *i* for the water-table aquifer for all conditions; SY_{o_i} is specific yield of cell *i* for the water-table aquifer for deep water table ($d_{\mathrm{WT}} > \xi_{\mathrm{CZ}}$) and equilibrium soil moisture content.

3.4.3 *Depth-to-water table*

From the depth-to-water table information from each cell, average d_{WT} (d_{WT_j}) is found on an area-weighted-average basis for each land segment, *j*, through association to all of the land fragments that comprise the land segment. The average d_{WT} is not used for integrated calculations but is archived and provided as post- simulation information.

$$d_{\mathrm{WT}_j} = \frac{\sum_{i=1}^{o} d_{\mathrm{WT}_i} A_{ij}}{A_j} \tag{7}$$

where A_j is area of land segment *j*; d_{WT_j} is average d_{WT} of cell *i*.

3.4.4 *Vadose zone plant coefficient*

Considering discretization for ET, the preliminary estimate for fraction of groundwater potential ET for land fragment *j* of cell *i* ($F^{t+}_{\mathrm{GWET}_{ij}}$) is

$$F^{t+}_{\mathrm{GWET}_{ij}} = \begin{cases} 1 & \text{for} \quad d^{t-}_{\mathrm{WT}_i} < \xi_{\mathrm{CF}_i} \\ \dfrac{(\xi_{X_{ij}} - d^{t-}_{\mathrm{WT}_i})}{(\xi_{X_{ij}} - \xi_{\mathrm{CF}_i})} & \text{for} \quad \xi_{\mathrm{CF}_i} \le d^{t-}_{\mathrm{WT}_i} \le \xi_{X_{ij}} \\ 0 & \text{for} \quad d^{t-}_{\mathrm{WT}_i} > \xi_{X_{ij}} \end{cases} \tag{8}$$

where ξ_{CF_i} is soil-based capillary fringe (near saturation region) thickness of cell *i*; and $\xi_{X_{ij}}$ is the extinction depth of the land fragment *j* of cell *i*, which is determined from

$$\xi_{X_{ij}} = \xi_{\mathrm{RZ}_{ij}} + \xi_{\mathrm{CZ}_i} \tag{9}$$

where $\xi_{\mathrm{RZ}_{ij}}$ is depth of root zone of the land fragment *j* of cell *i*.

For the land segment *j*, the converse fraction for the land segment *j* ($F^{t+}_{\mathrm{SWET}_j}$) is used subsequently for the lower zone ET coefficient and is calculated as

$$F^{t+}_{\mathrm{SWET}_j} = \sum_{i=1}^{o} \frac{(1 - F^{t+}_{\mathrm{GWET}_{ij}})}{A'_j} A'_{ij} \tag{10}$$

where *o* is the number of cells contained within the land segment *j*. Then for each land segment, *j*, the lower zone ET coefficient ($K^{t+}_{\mathrm{LZETP}_j}$) is

$$K^{t+}_{\mathrm{LZETP}_j} = (P_{\mathrm{PC}}(t) F^{t+}_{\mathrm{SWET}_j})_j \tag{11}$$

where P_{PC} is time varying plant ET coefficient. The details about this module can be found in Ross *et al.* (2005b) which is focused on the ET conceptualization.

3.4.5 *Groundwater potential evapotranspiration rate*

For each grid cell, some groundwater ET will commence when the water table reaches the deepest extinction depth of all land fragments within the cell. Therefore, the extinction depth of cell *i* (ξ_{X_i}) is

$$\xi_{X_i} = \underset{j=1}{\overset{n}{\mathrm{MAX}}}(\xi_{\mathrm{RZ}_{ij}})_i + \xi_{\mathrm{CZ}_i} \tag{12}$$

The weighted groundwater potential ET ($PET_{\mathrm{GW}_i}^{t^H+\Delta t_l}$) used in MODFLOW is found from the product of the fragment modified plant coefficient, $K_{E_{ij}}$, and the remaining potential ET, PET'_j, as

$$PET_{\mathrm{GW}_i}^{t^H+\Delta t_I} = \frac{\sum_{j=1}^{n} K_{E_{ij}}^{t} PET_j'^{t^H+\Delta t_I} \delta_{ij} A_{ij}}{A_i} \tag{13}$$

where δ_{ij} is the Kroniker delta, which indicates the presence or absence of contact between the capillary zone and the lowest extent of the root mass on a land fragment basis. For each land fragment j of cell i, Kroniker delta is calculated as

$$\delta_{ij} = \begin{cases} 1 \ \ \text{for} \ \ \xi_{X_{ij}} > d_{\mathrm{WT}_i}^{t-} \\ 0 \ \ \text{for} \ \ \xi_{X_{ij}} \le d_{\mathrm{WT}_i}^{t-} \end{cases} \tag{14}$$

The details about these this module can be found in Ross *et al*. (2005b) which is focused on the ET conceptualization.

4 Results and Discussion

4.1 Misrepresented overland flow

When calculating overland flow from cell based topography, artificially tortuous paths are created because the short diagonal flow paths are resolved into vector components that are then passed to adjacent cells beyond which they remain in resolved vector components. In a grid-based overland flow model, the flow or movement of water occurs across the faces of the cell may be described using kinematic, diffusion, or fully dynamic wave equations. These equations are in fact good representations of the physical flow properties but, unfortunately, at a much small scale than is resolved with the grids (refer to the length scale of overland sheet flow previously discussed). While topographic slope and aspect describe the direction of sheet flow and the shallow concentrated flow is quite different and can not be resolved with most topographic data. Thus, if the flow was not appreciably channelized (e.g., sheet flow) and the grids were generally aligned with the flow, the governing equations for kinematic, diffusion, or dynamic wave propagation would be valid. However, because it becomes channelized into shallow concentrated flow, randomly oriented and collected into small stream flow within a length scale of ~10^2 m, the equations no longer can be used with the resultant grid pathway. Thus while the governing equations are valid for the intended flow regime, there is a particular scale dimension over which they must apply. Shallow concentrated flow in natural systems exhibits extremely irregular, tortuous behavior. It is doubtful that any topographic datasets would be sufficiently detailed to even identify let alone characterize the geometry and orientation of these flow features (Ross *et al*., 2005b).

Overland flow that follows the resultant misrepresented, tortuous path means that the model will be calibrated with considerably longer hydraulic lengths. This requires the model to be calibrated with smaller resistance, slope and infiltration parameters. Thereafter, these calibration parameters are no longer physical but scale-dependent model parameters. Furthermore, the over estimation of hydraulic lengths, given the same head gradient, means that the slope in the grid based representation is considerably less than it should be (Ross *et al*., 2005b).

4.2 Basin characteristics

The major characteristics of the river basin used in IHM include basin area and basin delineation. Firstly, for basin area, grid based models do not usually follow basin boundaries. Basins are traditionally defined using topography and are highly irregular. However, in many instances and especially in shallow slope environments typical of the coastal plain (e.g., Florida), basins become difficult to define solely from topography (Ross *et al*., 2005b). To define drainage basins in these regions one must consider hydrography (drainage features), land use, roads, and often small culverts to properly determine basin boundaries. Typically, this requires aerials and site visits to discover and verify drainage features. This is critical physical information which often does not fit well with a regular grid representation and certainly would rarely coincide with gridded topographically defined catchment description. For the resultant gridded topographic domain the basin divides are lost due to apparent topographic gradients form grid node to grid node. When basin areas are determined from these gridded domains, errors will be significant. The resultant error in basin area is commonly compensated for with model parameter adjustments, thereby losing predictive capability.

For basin delineation, grid based discretization of surface water catchments are dependant on good topography to define the cell to cell slopes and ultimately the connection to the outfall. Topography is known to be poor around densely vegetated areas like rivers and creeks and wetlands. For shallow water table saturation excess dominated runoff, the areas of most importance in the model would be those where the topography is the poorest. Many case studies indicated that better high resolution DEM will get more satisfied delineation results, which can provide more accurate information for spatial discretization.

4.3 Hydrography discretization

The wetland/water features include head dependent groundwater fluxes associated with groundwater heads down to the scale of individual fragments and the grid-cell discretization for all reaches, static and dynamic. The HSPF reaches receive rainfall, the sum of baseflow contribution (positive and negative), potential or reference (wetland specific) ET time series, all contributing upstream inflows, diversions and all contributing land segment runoff. Reemphasizing, only the dynamic MODFLOW reaches use updated stages to calculate baseflow.

Management and analysis of the large volume of data which support 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 spatial ET and recharge variation. Hydrography characteristics must be summarized for the appropriate discretization and located.

4.4 Scale and discretization

There are difficulties associated with grid-based discretization when the discretization is coarser than the hydraulic scale of surface water processes: infiltration, runoff and recharge. Many integrated hydrologic models use rectangular grid blocks to simulate overland flow and other surface processes because of the computational simplicity of having one discretization framework for both surface and subsurface processes. However, the scale of hydraulic behavior and data availability may vary appreciably for these two domains (above and below the land surface). Often for manageability in runtime and data definition a compromise discretization size must be utilized, especially for sizable model domains. This dimension may be on the order of 10^2 m to 10^3 m, for example, for regional model domains. As mentioned by Downer and Ogden (2004), appropriate vertical discretization of Richards equation is very important for two-dimensional watershed-scale. Several known shortcomings of finite and typical discretization at this length scale of surface water properties have been summarized, such as inappropriately long hydraulic lengths, and poor basin descriptions.

Defining the model computation elements and model parameters based on land use allows the parameters to be redefined when the land use condition changes. The land use based model can better represent the physical properties of the basin. Grid based models are not directly tied to the land use conditions unless the dimensions are very small. Therefore, the parameters are difficult to modify directly and, then, poorly predict changing land use conditions.

The need to simultaneously simulate the surface and ground water components of a watershed through numerical modeling adds an additional layer of complexity to the discretization problem. As mentioned by Nemeth and Solo-Babriele (2003), differences in the governing physical formulations (e.g., Darcy′s law for ground water, and Saint Venant equations for surface water), response times (significantly faster for surface water), and the time scales of interest (significantly longer for ground water) complicate the process. Integrated surface and groundwater modeling has attracted significant interest in the research community. The issues of spatial discretization figure prominently in these integrated frameworks, as the types and scales for such discretization might be different of surface versus groundwater simulations (Ross *et al.*, 2005b).

5 Conclusions

In order to appropriately simulate the hydrologic processes that influence ET, runoff, base flow, and surface storage attenuation, it is desirable to explicitly utilize the land use information in the conceptualization and discretization of hydrologic models as well as the assignment of the model parameters. Integrated surface water/groundwater hydrologic modeling adds complexities because the land use data and their unique hydrologic properties must be conceptualized and discreitzed into both the surface water and groundwater domains.

Using GIS, basins can be subdivided by land use categories into computational elements called hydrologic response units or HRU′s. Utilizing HRU′s in model discretization allows the discrete representation of the various hydrologic responses for each land form. This approach lumps areas of similar hydrologic response while avoiding the lumping of contrasting parameters. As opposed to grid-based models, which may inadvertently introduce arbitrary boundaries, land use discretization maintains physical basin and landform characteristics. In order to properly capture the full storage capacity found within a basin, all lakes and wetlands can be conceptualized and simulated as hydrography elements. The aerial extent of the hydrography can be obtained from detained land use mapping. Model parameters for the reaches can be defined with land use and soils designations to correctly represent the storage and attenuation characteristics of the hydrography included in the model. Assigning model parameters with the original land use data assures consistent parameterization throughout the model domain.

The IHM has been formulated using small hydrologically similar computational elements, which provides for computational efficiency sufficient to handle large regional applications and adequate distribution to keep all parameter assignments to physical homogeneous landforms. Consistency in fluxes and storages between the model components has been maintained. 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. The model is being tested through calibration, verification and validation exercise on regional and detailed field scale applications and simple analytical comparison.

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