UNDERSTANDING FEN HYDROLOGY – A HIERARCHICAL, MULTI-SCALE GROUNDWATER MODELING APPROACH

By

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ABSTRACT

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The hydrologic system that sustains groundwater-fed fens is not very well understood. Fens are among the most bio-diverse wetlands and generally occur along the peripheries of regional groundwater mounds, which are characterized by geo-morphologic variability at multiple spatial scales (from 10s of meters to kilometers). Traditional approaches for understanding fen hydrology have simplified the hydrologic system that supports the fens, such as using one scale of model to represent multi-scale variability in topography and geology. I argue that fens are a product of complexity in topography and geology, and therefore, simplified models cannot be used to completely characterize such systems. In this research I use hierarchical, multi-scale groundwater modeling at two fen sites in southern Michigan to understand the hydrologic processes and mechanisms that sustain these unique ecosystems. The methodology adopted in this research takes advantage of the detailed and extensive hydrologic data that is made available by the GIS and IT revolution in recent decades.

The general approach used was to build a hierarchy of nested steady-state models to capture the groundwater flow system at spatial scales ranging from the regional watershed to the fen site. A Transition Probability-based approach was used to create 100 realizations of a fully 3-dimensional geologic model to represent the complex geologic variability. The groundwater models were calibrated to stream base-flows and to hydraulic heads at numerous wells from the statewide database. Three-dimensional particle tracking was used to predict the sources of water

to the fens and the corresponding delivery mechanisms. This approach was used to model the hydrology of two fen sites - MacCready Fen, located among a cluster of fens, and Ives Road Fen, a geographically isolated fen, in southern Michigan. The area around Ives Road Fen had a unique geologic structure, consisting of a potential break in the clay layer that connected the local flow system to the regional flow system. Based on the 100 realizations of the geologic model, the predicted likelihood of occurrence of the break in the clay layer was greater than 80%, which had major implications for the fen's ability to obtain water from the regional flow system.

Results from the multi-scale simulations illustrate the complex and inter-connected nature of the hydrologic system that supports the fens. The water in the MacCready Fen traced back to a network of sources, including a wetland and a local recharge mound, and Skiff Lake, which is connected to the regional Hillsdale groundwater mound through a "cascade delivery mechanism." Ives Road Fen, in addition to getting water from a local recharge area and a small pond near the fen, also gets water from the regional mound and a till plain. Water from the regional flow system moved through a "pipeline," consisting of a confined aquifer beneath a thick clay layer, to deliver water to the fen through a break in the clay layer. A geographically-isolated fen is thus hydrologically connected to the same regional mound that provides water to fens that occur in clusters. The regional mound thus acts as a "master recharge area," since it is the ultimate source of water not only to the fens, but also for many rivers, lakes, wetlands and aquifers. The implication of these findings is that rather than protecting individual fens and their immediate surroundings, fens must be managed as part of a much larger, inter-connected groundwater system. The current approach for managing fens and other ecosystems needs to be reassessed and should move away from localized, short-term fixes to system-based, long term solutions.

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ABSTRACT

The hydrologic system that sustains groundwater-fed fens is not very well understood. Fens, which are among the most bio-diverse wetland types, generally occur along the peripheries of regional groundwater mounds. These areas are characterized by geo-morphologic variability at multiple spatial scales (from 10s of meters to kilometers). Traditional approaches for modeling such systems use simplifying assumptions that cannot completely capture the 3-dimensional, multi-scale variability of geology and topography. In this study, we use a data-enabled, hierarchical, multi-scale groundwater modeling approach to understand the hydrology of MacCready Fen in southern Michigan. We develop a hierarchy of dynamically-linked models to enable groundwater simulation at all scales of interest (site-scale to regional-scale), and use reverse particle tracking to delineate the areas that contribute groundwater to the fens. The modeling results show that the fen receives groundwater from multiple sources: an adjacent wetland, a local groundwater mound, Skiff Lake, and the regional groundwater mound. While most of these sources provide water through a "direct" connection to the fen, the regional mound provides water through an indirect, "cascading" connection, in which water from the mound

flows to an intermediate source (Skiff Lake) before reaching the fen. The regional mound is also the source of water to multiple other fens, streams and lakes in this area; it creates a large, inter-connected hydrologic system that sustains a number of fens. In order to sustainably manage such systems, fen conservation in the future must move away from localized, short-term fixes towards system-based, long-term solutions.

INTRODUCTION

Fens are Groundwater-Dependent Ecosystems (GDE) (Kløve *et al.* 2011) that support the existence of many rare plant and animal species. Fens are most commonly found in the glaciated regions of North America and Europe, which are characterized by complex hydro-geology and topography. Such environments are generally conducive to the formation of surface water bodies, as the water table is controlled by the topography (Toth 1963; Freeze and Witherspoon 1967; Haitjema and Mitchell-Bruker 2005). In addition to their biodiversity, fens also play a critical role in helping to maintain stream water quality, as they are generally located at the headwaters of major streams (Bedford and Godwin 2003). Due to the significant influence of groundwater on fens, they have been used as "whole-ecosystem gauges" of groundwater recharge under climate change in California (Drexler *et al.* 2013). Bedford and Godwin (2003) state that although few estimates exist, available estimates indicate that fens have been lost or degraded extensively due to altered hydrology and water chemistry over the last 50 years. Thus, a better understanding of the underlying hydrologic system that sustains fens is necessary.

In order to prevent the loss and fragmentation of these unique ecosystems due to climate change or anthropogenic impacts, it is important that fens be systematically managed and protected. Current efforts at managing biodiversity in fens are limited to site-based approaches like seed dispersal, as well as cattle grazing, cutting and mowing or fire (Middleton *et al.* 2006a; 2006b). Fojt and Harding (1995), who studied the effects of changing mowing regime and hydrology on fen vegetation in the United Kingdom, found that even though such localized efforts are beneficial, "changes in hydrology cannot be compensated for by increased management." Similarly, in Michigan, where fens tend to occur in geographic clusters, conservation is localized around each individual fen, even though it is recognized that fens and other GDEs are usually benefited by large, regional groundwater systems. Kløve *et al.* (2011) stress that in order to understand the vulnerability of GDEs there is a need for quantitative assessment of the interactions between groundwater and the environment. Holistic management of fens would necessitate an understanding of the groundwater system that supports fens and the myriad species they support. A detailed review of fens, their characteristics and the different approaches used to understand their hydrology is presented next.

Fens and their characteristics

Fens are considered to be special wetlands due to the disproportionately high densities of biodiversity that they support. Bedford and Godwin (2003) state that fens are among the most bio-diverse of all wetland types in the United States due to their high species density, richness, and regional diversity. The number of uncommon, rare, threatened and endangered species that fens support is also noteworthy. In several states, fens harbor 7 - 17% of the rare flora in those states, but occupy only 0.01 - 0.07% of the states' area (Bedford and Godwin 2003). Michigan fens harbor the federally-listed Mitchell's satyr butterfly, Hines emerald dragonfly and the Eastern massasauga rattlesnake in addition to several other rare amphibians, reptiles and insects.

The reason for the fens' disproportionate biodiversity has been attributed to their water chemistry (Almendinger and Leate 1998; Amon *et al.* 2002; Bedford and Godwin 2003; Drexler *et al.* 1999a). This water chemistry is attributed to the relatively constant supply of alkaline, nutrient-poor groundwater to the fens (Bedford and Godwin 2003; Kost and Hyde 2009; Schot *et al.* 2004). Carpenter (1995) found that groundwater accounts for 43 – 58% of the total water budget in a calcareous fen in Wisconsin. Drexler *et al.* (1999a) used a chemical mass balance approach and found that 84 – 88% of the inflows into a small fen in New York came from groundwater inflow. Roulet (1990) studied the hydrology of a spring-fed wetland in Canada and found that the groundwater input to the wetland was an order of magnitude larger than precipitation. Gilvear *et al.* (1993) found that the groundwater inflow accounted for 89% of all water inputs to Weston Fen (United Kingdom). Amon *et al.* (2002) and Roulet (1990) also observed that the water table in fens is continuously at or near the land surface, but not inundated for any significant length of time. In fact, Amon *et al.* (2002) argue that in order to maintain saturated conditions at the fens, the size of its recharge zone "must be large enough to accommodate any losses." Conversely, Beford and Godwin (2003) state that if a fen has local rather than regional water sources, its "water table may drop during extended periods of drought." Upward hydraulic head gradients have also been observed in many fens (Almendinger and Leate 1998; Carpenter 1995).

Several authors state that the spatial distribution of fens as well as the development of specific types of fens is a function of climate and hydrogeologic settings (Bedford 1996, 1999; Winter 1992; Winter *et al.* 1998). Bedford and Godwin (2003) further state that constant groundwater discharge that can maintain saturated conditions is determined by the climate of the region (that balances precipitation and evapo-transpiration), and the topographic and geologic features of the landscape that control the movement and chemistry of groundwater. They found that fens are generally located at the headwaters of streams and lakes, and therefore, have a major effect on stream and lake water chemistry. Also, fens provided buffering of surface water temperatures by supplying cooler water in the summer and warmer water in the winter. Winter (1999) studied the relationship between surface water bodies and groundwater flow systems, and observed that the fluxes of water and chemicals from and to groundwater depends on the position of surface water bodies with respect to the different scales of groundwater flow, and also on local geologic controls and the magnitude of evapo-transpiration, which controls the seepage distribution (gaining, losing or flow-through). Winter *et al.* (2003) observed that a fen in Minnesota that was surrounded by springs with relatively small surface watersheds had stable flows almost independent of climate variability, which indicated that their source of water was a much larger and more stable groundwater system. Developing an understanding of the interactions between climate, geology, and hydrology that create the conditions that allow fens to flourish is a complex task. Several approaches have been used to understand the hydrologic system that supports these rare ecosystems, the findings from which are discussed next.

Analytical understanding

Theoretically, it has been well established that discharge areas have sources of water at the local, intermediate or regional scales (Toth 1963). Empirically too, there is considerable evidence for such multi-scale behavior (Toth 1962; Meyboom 1967; Ophori and Toth 1989). Toth (1963) made the first, and probably most significant, attempt at a multi-scale approach to understanding groundwater flow systems. Toth's seminal work attempted to understand groundwater flow systems due to complex multi-scale topography using a simple, idealized, and mathematical approach. In this study, Toth classified groundwater flow systems as belonging to one of three regimes, namely local, intermediate, or regional. The formation of these flow systems depended on three factors: i) the thickness of the permeable layer of sediments, ii) the general slope of the watershed and iii) the local relief. The existence of local systems is dependent mostly on the extent of local relief. The more well-defined the local relief, the more pronounced are local systems. A direct consequence of the local systems is the presence of "alternating recharge and discharge areas" across a valley, and that places located close to each other may have unrelated origins of water. This also has an impact on water quality, as mineralization of groundwater is directly related to groundwater residence times. Although Toth's work was from a broad hydrogeological perspective and not specifically directed to wetland hydrology, it provides a template for understanding the processes that deliver water to fens/wetlands. More importantly, it stresses the important role of the aquifer geometry and topographic relief in creating local, intermediate and regional flow systems.

A discharge area can receive water from local, intermediate and regional sources depending on its location in the basin and its hydrologic characteristics (Winter *et al.* 2003). Winter (1988) stated that the general topographic and geologic conditions that are favorable to the formation of wetlands (discharge areas) include discontinuities in the slope of the land surface and the pinching out of permeable strata. In general, groundwater recharge happens at the higher elevations of a watershed and discharges at lower elevations. On this basis, Winter created a generalized landscape and its possible variations that can result in the formation of wetlands. Both Winter and Toth stressed the important role of the geometry of the landscape and stratigraphy in creating local and regional systems of flow. Even though their analytical approaches are conceptual and general enough to apply to any site, understanding the flow systems for real sites using their approaches is often very difficult.

Empirical understanding

Meyboom (1967) analyzed head data along a cross-section in a so-called "knob-and-kettle" landscape in Canada, and was able to distinguish between local and intermediate flow systems as predicted by Toth's model. Winter (1976) developed numerical vertical profile models for hypothetical settings that use one or multiple lakes to show detailed patterns of groundwater flow around lakes in various hydrogeologic settings. Van Buuren (1991) proposed a hydrological approach for landscape planning to protect threatened ecosystems, in which local and regional systems of flow are to be revived by appropriate management strategies. Shedlock *et al.* (1993) studied the interactions between groundwater and wetlands on the southern shore of Lake Michigan, and identified regional, intermediate and local flow systems. Jansen *et al.* (2000) studied the hydrology of *Cirsio-Molinietum* fen meadows in The Netherlands from Toth's (1963) perspective of local, intermediate and regional flow systems. They reviewed a number of previous studies that used a combination of hydrological modeling, geochemical research and hydrologic system analysis to arrive at an understanding of fen hydrology. On this basis, they came up with 6 distinct local and regional groundwater systems that support the fens. They provide schematic cross-sectional views that depict the processes that deliver ground/surface water to the fens. Winter *et al.* (2003) presented a number of case studies that demonstrated that groundwater-sheds in various types of terrain did not coincide with the surface watersheds. Moreover, most small watersheds had local, intermediate and regional sources of water.

A number of data-based approaches have also used a combination of direct hydraulic head measurements, indirect chemistry or temperature data, and hydrologic intuition to infer groundwater flow directions. Siegel and Glaser (1987) used groundwater levels and chemistry data to understand the hydrogeology of a bog-fen complex in the Lost River Peatland in

Northern Minnesota. Stuyfzand (1993) studied the hydrology and hydrochemistry of the coastal dune areas in the Western Netherlands and stressed that hydraulic head measurements are not always sufficient to reconstruct flow patterns given the accuracy of measurements and the small vertical head gradients. In such cases, temperature or chemistry data may be used to indirectly infer the flow directions. Kehew *et al.* (1998) delineated the recharge/discharge areas for a flow-through wetland in southwestern Michigan using the chemical and isotopic composition of groundwater around the wetlands. Drexler *et al.* (1999b) used hydraulic head measurements from a detailed network of piezometer clusters in a small fen in New York to reveal the existence of very fine-scale groundwater flows (within a few meters). They observed areas of recharge, discharge and lateral flow within the small wetland itself, which also showed both spatial and temporal variability.

Jansen *et al.* (2001) used calcium concentration measurements to infer the seasonal variability of groundwater flow directions. Their research stressed that the local topographic relief is essential for the creation of local systems of flow. Grootjans *et al.* (2005, 2006) also used temperature data to infer local groundwater flow to calcareous spring mires in Slovakia. Acreman and Miller (2004, 2006) classified wetlands based on landscape location and on “water transfer mechanisms,” and also created conceptual vertical profile models in order to assess the impacts of anthropogenic hydrological changes on wetlands. They also stressed that the importance of sources of water to wetlands should not be evaluated on the basis of volumetric contributions, i.e. even small quantities of water can be critical during droughts or for determining water quality.

Winter *et al.* (2001) conducted extensive field studies for wetlands in four different hydrogeologic and climatic settings and found that each wetland had considerably different sources of water (local, intermediate or regional). The fen in New Hampshire obtained most of its water from a lake up-gradient of it, while another in Minnesota was supplied largely by intermediate and regional groundwater discharge that recharges far away from the fen. A prairie-pothole wetland in North Dakota obtained most of its water from precipitation and lost most of it to evapo-transpiration, and a wetland in the sand-hills of Nebraska received water from both the regional and local systems of flow. Given the complexities of each fen site, the authors point out the challenges that must be overcome to manage and protect wetlands. Although this research used only data and hydrologic intuition to deduce the flow systems, it is important to point out that the amount of temporal data required for this analysis was huge, ranging from 5 to 17 years.

Abbas (2011) used the Michigan statewide database (GWIM 2006) to design a data-driven approach for predicting local, sub-regional and regional sources of water to a cluster of fen-sites in southern Michigan. This approach used historic static water level data to interpolate the horizontal flow directions at the regional scale. For more detailed vertical dynamics, Abbas used vertical profile models for 19 fen sites that clearly indicated the possible water delivery mechanisms to the fens. One of the major findings from this research was that most fens are located close to regional groundwater mounds, which act as headwaters to major streams in Michigan. The regional mounds are the eventual source of water to the fens, although the water is delivered to the fens through a number of complex delivery mechanisms from local, intermediate or regional sources.

Although several studies have stressed the need for a thorough understanding of the local and regional systems of flow that support the existence of fens (Almendinger and Leete 1998; Bedford 1999; Siegel 1988; van der Kamp and Hayashi 2009), most data-based approaches, with the exception of Winter et al. (2001) and Abbas (2011), have studied flow at one scale due to the lack of multi-scale data.

Process-based models

Most process-based studies have delineated either local or regional sources of water to wetlands. These models could not resolve the detailed multi-scale topography, stream networks, wetlands, and lakes that are crucial towards understanding the multi-scale nature of flow. Wassen *et al.* (1990) used regional head data to develop a vertical profile model using FLOWNET to delineate local, sub-regional and regional flow systems in a fen ecosystem in The Netherlands. This approach demonstrated the multi-scale nature of flow systems that support fens. Buxton *et al.* (1991) and Modica *et al.* (1998) used a groundwater flow model and particle tracking approach to analyze flow patterns, groundwater residence times and recharge areas for aquifers and gaining streams. Schot and Molenaar (1992) used a process-based approach to study the impacts of human activities on regional flow systems and groundwater composition.

Hunt *et al.* (1996) estimated groundwater inflows in wetlands in southwestern Wisconsin using 4 different approaches, which showed the existence of a local flow system (local recharge and discharge areas) in a regional discharge area. Tiedeman *et al.* (1997) and Koreny *et al.* (1999) used 3-Dimensional MODFLOW models and a particle tracking approach to model and delineate the local and regional flow systems for Mirror Lake, New Hampshire and an artificial wetland in Ohio, respectively. Batelaan *et al.* (2003) applied an integrated vegetation mapping and groundwater modeling approach to identify discharge areas, and applied particle tracking to delineate regional groundwater systems and corresponding recharge areas. They also studied the anthropogenic impacts on flow systems due to land-use changes by modeling pre-development, present, and post-development scenarios. Dekker *et al.* (2005) used a HYDRUS2D saturatedunsaturated groundwater flow model at the local scale to evaluate management scenarios for restoration of acidified floating fens in The Netherlands. Cobb and Bradbury (2008) used a 2-D GFLOW groundwater model to delineate the regional scale source waters for 11 springs and wetlands in Wisconsin that provide a habitat for the endangered Hine's emerald dragonfly.

Need for Multi-scale approach

Both the empirical and process-based approaches have failings in attempting to capture the multi-scale dynamics that control wetland hydrology. The most obvious impediment is the lack of data to resolve the variability of topography, surface water bodies, and stratigraphy, which create the multi-scale flow systems that allow fens to flourish. Thus, there is a need for a truly multi-scale approach for understanding wetland hydrology.

Gilvear *et al.* (1993) created a 3-D, steady state MODFLOW model to quantify the water balance terms and hydrochemistry for a rich calcareous fen, Badley Moor Fen, in the United Kingdom. The model predicted that significant upwelling of carbonate-rich groundwater from a Chalk aquifer sustains the fen. They used a refined, local model to resolve vertical dynamics with prescribed-head boundary conditions from a coarser regional model. Gilvear *et al.* (1994) developed 3-dimensional models and 2-dimensional vertical cross-section models for both local and regional scales for three fens in East Anglia, UK to assess the usefulness of a classification scheme for fens proposed by Lloyd *et al.* (1993). Although the approach used by Gilvear (1993, 1994) employed a regional model and a refined local model, their method could not capture the multi-scale nature of the topography, geology and hydrologic framework (rivers and lakes) that drives fen hydrology.

OBJECTIVES

It is evident from the studies cited previously that fens are unique ecosystems created by the confluence of multiple factors: climate, topography, geology and hydrology. Since most fens are found in the regional headwater areas for streams, it is obvious that these regional recharge areas play an important role in supporting the fens. However, in preserving these ecosystems it is necessary to move away from the traditional approach to conservation, i.e., localized protection that focuses on the short-term, towards a new paradigm of system-based conservation that looks not merely at the local and short-term scales, but also at the larger and longer scales of interest (Nadeau and Rains, 2007). For instance, although there is recognition of the impact of local and regional groundwater flow systems on fens, quantifying these hydrologic processes and mechanisms that allow the fens to flourish is very complex. Therefore, it is necessary to set up a quantitative framework that can identify the hydrologic processes that drive fen hydrology. Such a framework would make it possible to study the response of fens to perturbations, to study the impact of scenarios such as climate change or land-use change on the fens' survival, and to assess and evaluate various options for sustainable management of these ecosystems.

To address these overall objectives, this research uses a process-based, multi-scale groundwater modeling approach to understand fen hydrology. The specific objectives of this research are:

- to investigate the multi-scale hydrogeologic system that supports the existence of fens,
- to identify and delineate the sources of water to fens and the corresponding water delivery mechanisms and,

- to assess the implications of the findings from this research on sustainable management of fens.

The next section of this paper describes the multi-scale approach adopted in this research, which is followed by an illustrative example of this approach. The results from this example are presented and discussed next, following which, the significant implications and conclusions from this study are outlined.

METHODS

In order to capture the multi-scale dynamics that deliver water to fens, it is necessary to resolve the multi-scale topography and geology in adequate detail. The general approach adopted in this study is to model as large an area as necessary to capture the regional-scale dynamics, and to progressively refine the model in smaller areas of interest, culminating in a site-scale model to resolve local dynamics. Thus, all scales of variability, from regional to intermediate to local to site-scale are resolved.

Hierarchical Multi-scale Modeling

A "hierarchical patch dynamics modeling" approach developed by Li and his co-workers (Afshari *et al.* 2008; Li *et al.* 2003, 2006, 2006, 2009) that enables multi-scale modeling in a highly flexible and efficient manner was used in this research. In this approach, a parent model with coarse resolution was created at the regional scale and local "patches" and "patches within patches" were introduced wherever higher resolution was needed. Thus, a series of nested parent and child models were created. The child models were linked to their parent models by a 2-way hydraulic head coupling mechanism, such that child models derived their boundary conditions from the parent model, and the parent models were updated with local information from the child models to reflect details at the local level.

Governing Equations and Algorithm

For a generic model, $M^{p,l}$, which refers to model patch p in level l, the governing equations can be given as:

$$S_s^l \frac{\partial H^l}{\partial t} = \nabla.\left(\underline{\underline{K}}^l.\nabla H^l\right) + q^l$$

Down-scaling BC
$$H^l\Big|_{\Gamma_1} = f\left(H^{l-1}\Big|_{\Gamma_1}\right)$$

(1-1)

Up-scaling BC
$$H^l\Big|_{\Omega_1} = f\left(H^{l+1}\Big|_{\Omega_1}\right)$$

IC
$$H^l(\vec{x},0) = H^{l-1}(\vec{x},0)$$

where S_s is the specific storage coefficient, H is the hydraulic head, t is time, ∇ is the gradient operator, $\underline{\underline{K}}$ is the saturated hydraulic conductivity tensor, q represents source (positive) or sink (negative) terms including pumping/injecting wells, streams, lakes, drains etc; Γ_1 is the computational domain boundary between $M^{p,l}$ and its parent model, Ω_1 is the computational domain of the child model, f is a generic function, and $\vec{x}$ is the spatial vector. The superscript l refers to the model level for the current patch, with parent model at level l-1 and child model(s) at level l+1.

The naming convention used here is described as:

- ***Main Model:*** The top-most level ($l = 0$) model, referred to as regional model.
- ***Parent model***: A model at any level ($l = 0, 1, \ldots L\text{-}1$) that has at least one child model.
- ***Child model:*** A model at any level ($l = 1, 2 \ldots L$), which has a finer grid than its parent model. Also referred to as patch model, and can have only one parent model. Orphan models (child models without a parent model) are not allowed as boundary conditions cannot be imposed on such models.

In general, boundary conditions (BCs) and initial conditions (ICs) are only provided for the main model (i.e., the largest scale model). In order to obtain solutions for models at other levels, their BCs and ICs are imposed from their respective parent models as explained below:

(1) With the given BCs and ICs, main model can be solved numerically and its head, H^0, will be obtained throughout the whole computational domain.

(2) Head along the interfaces of main model and its child models (patches) can be interpolated from H^0. ICs for child models can be obtained by interpolating heads inside their domains from H^0.

(3) The procedure of solving for the heads of a model at level l by obtaining BCs and ICs from its parent model at level (l-1) is repeated until $l = L$. This procedure is called down-scaling.

(4) After the heads, H^L, in the last model level have been calculated, they are used as the base heads to update the heads along the child-parent interfaces. This will result in a change in the BCs of the parent models (upper level models) along the interfaces of parent-child models, which will be calculated from their child model's head, H^l, and thus, H^{l-1} will be

updated. This procedure is repeated until main model ($l = 0$) is reached. This procedure is called up-scaling.

(5) Steps (1) to (4) are repeated until the maximum head difference between consecutive iterations is lower than a given convergence criterion (typically at least 0.001 m). When the system converges, the whole modeling system is stopped.

Data for Multi-scale modeling

The prime reason for the feasibility of multi-scale modeling is the high-resolution data made available by the GIS and IT revolution in recent decades. As pointed out by both Toth (1963) and Winter (1988), topography and aquifer geometry are critical to the formation of local and regional flow systems. Therefore, any multi-scale model that attempts to delineate these flow systems must accurately resolve these features. In a multi-scale model, each progressive scale should add details that the previous scale cannot resolve. Figure 1-1 provides a few examples of data that are available, which can be used for multi-scale modeling.

Topography

As illustrated by Toth (1963), topographic variability at multiple scales is the prime reason for the formation of multi-scale flow systems. Large scale variability, such as a regional topographic slope, results in the formation of regional flow patterns. At smaller scales, variability in the form of smaller "hills and valleys" can create intermediate and local flow systems. Capturing this level of detail is impossible without high-resolution data. The availability of 10 m DEM data (NED USGS 2006), which captures the regional scale of variability, as well as detailed local features, allows understanding the effect of multi-scale topography on multi-scale flow systems. The traditional approach to modeling such systems is to create a single high-resolution model that resolves all details. In contrast, the hierarchical approach uses a coarse grid in the regional model to capture regional trends, and local patches of fine grids, which can capture local features. Although the data are of uniform density, the regional-scale model will only capture the large-scale trend in the topography, while more intricate topographic features are “revealed” at finer model scales.

Hydrology

Surface water data (lakes and streams) is available from the National Hydrographic Database (NHD USGS 2010). This database allows modeling large lakes and streams at the regional scale, and also the small lakes and streams at the site-scale. While the larger streams are the regional discharge area and provide the regional context to the overall system, local streams and lakes can create smaller flow systems. By incorporating these data into the modeling framework, we can accurately resolve the multi-scale hydrologic features.

Geology

The Michigan Statewide Groundwater Database (GWIM 2006) provides the lithologic data that make it possible to map the multi-scale geologic variability. At the regional scale, this data allows delineating large-scale geologic formations, and at the local scale, small clay lenses and embedded aquifer materials can be delineated using this database. These large-scale and small-scale features can interact and create complex flow patterns, which need to be resolved. In order to model the large-scale geology, the traditional approach of using geologic layers to represent different aquifer units is feasible. However, geologic layers cannot capture variability at finer vertical and horizontal scales. In order to resolve this kind of variability, a fully 3-dimensional, geologic model with high vertical resolution can be used. One drawback of this approach is that the amount of borehole data needed for accurate representation of the geology is significant.

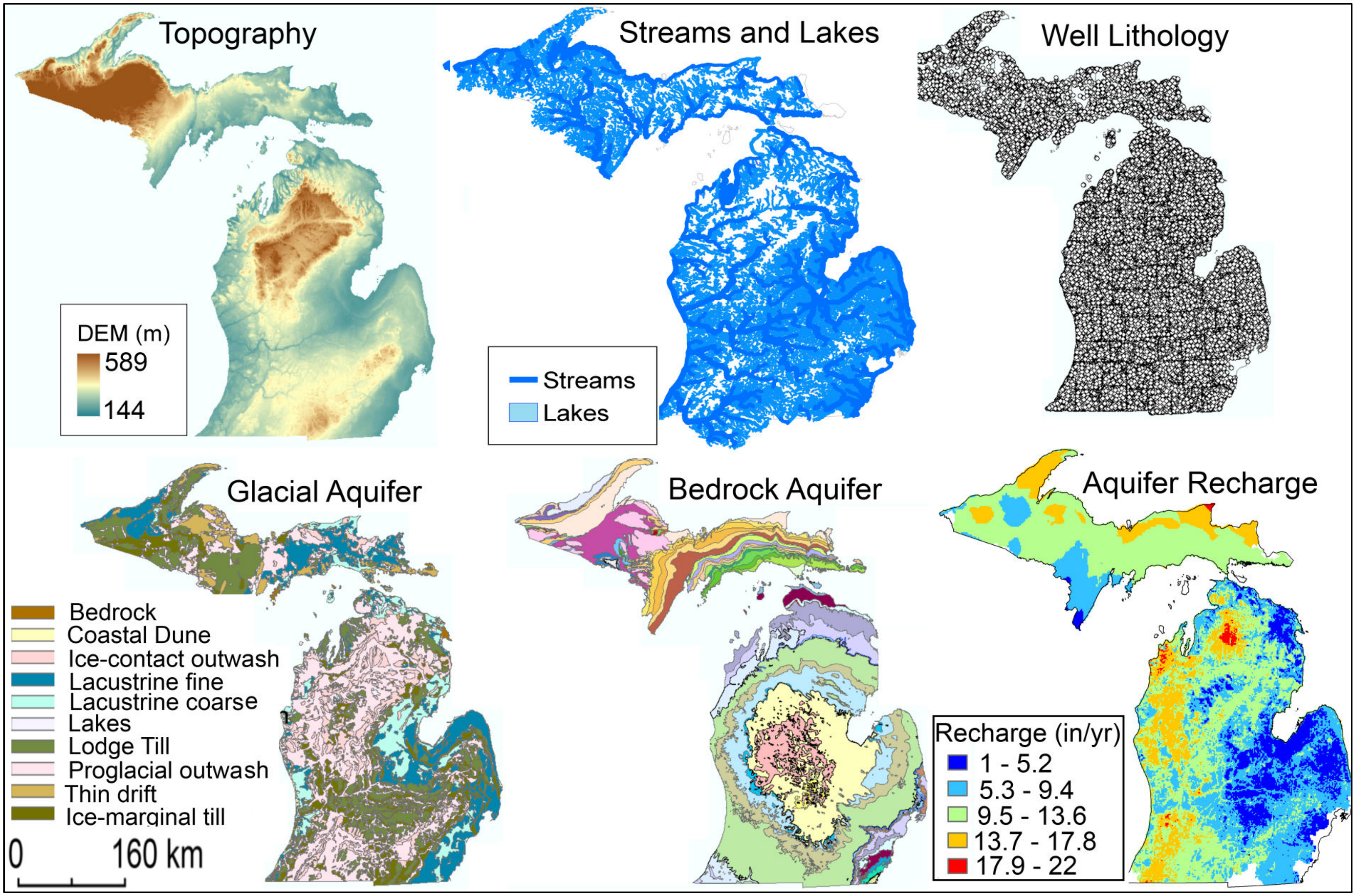

Figure 1-1 – Statewide data for the hierarchical modeling system. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this dissertation.

ILLUSTRATIVE APPLICATION

A watershed-scale groundwater model at the intersection of the Grand River, Kalamazoo, St. Joseph, and Raisin River watersheds indicates that multiple fens are located around the edge of the regional discharge area, i.e., the Hillsdale groundwater mound (Figure 1-2). This model was not calibrated or validated, but rather was used to illustrate the correlation between regional headwater areas and fen occurrences.

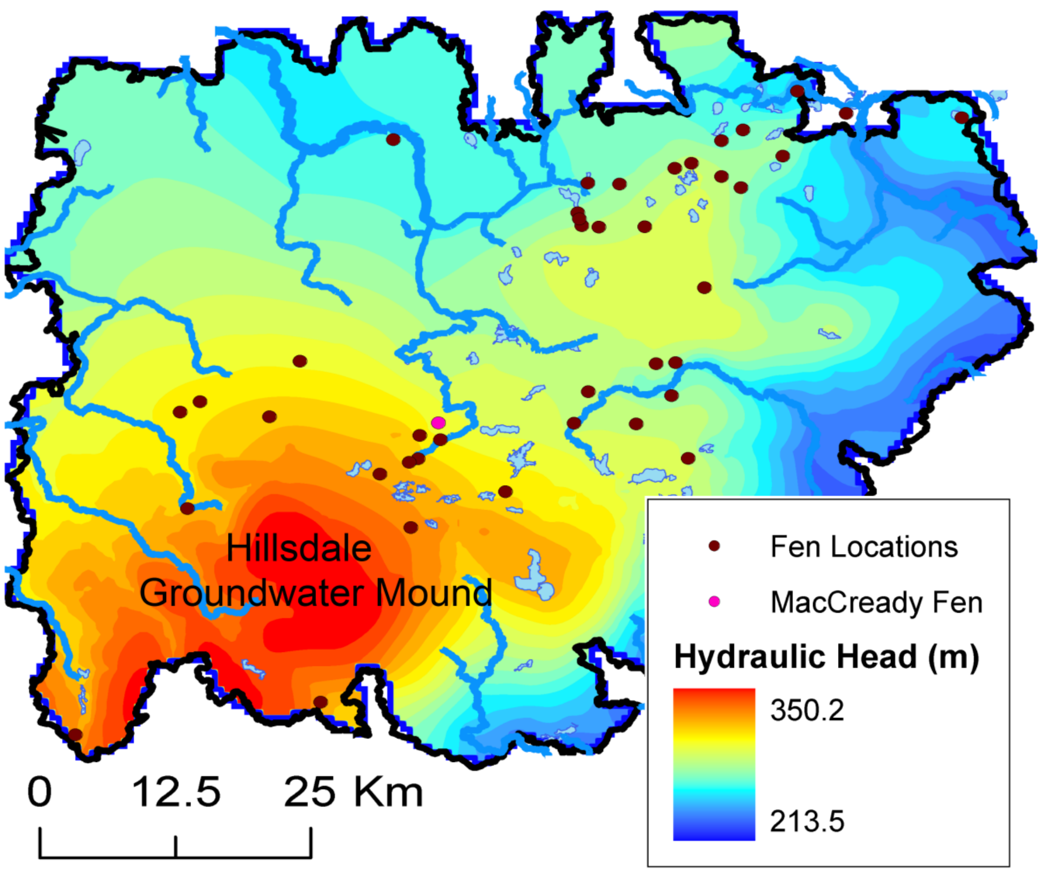

Figure 1-2 – Watershed-scale model showing the occurrence of fens around regional mounds.

Among the cluster of fens located around this regional groundwater mound is MacCready Fen, in an area that serves as the headwaters for Grand River. The fen itself is located adjacent to several small lakes and streams as seen in Figure 1-3. The hierarchical multi-scale modeling approach discussed earlier is applied to model the hydrology of this fen in southern Michigan.

This fen was selected for this study to represent the cluster of fens in this area. The multi-scale topography, hydrology and geology for this area are discussed next, on the basis of which, the conceptual model for the fen's hydrology is developed.

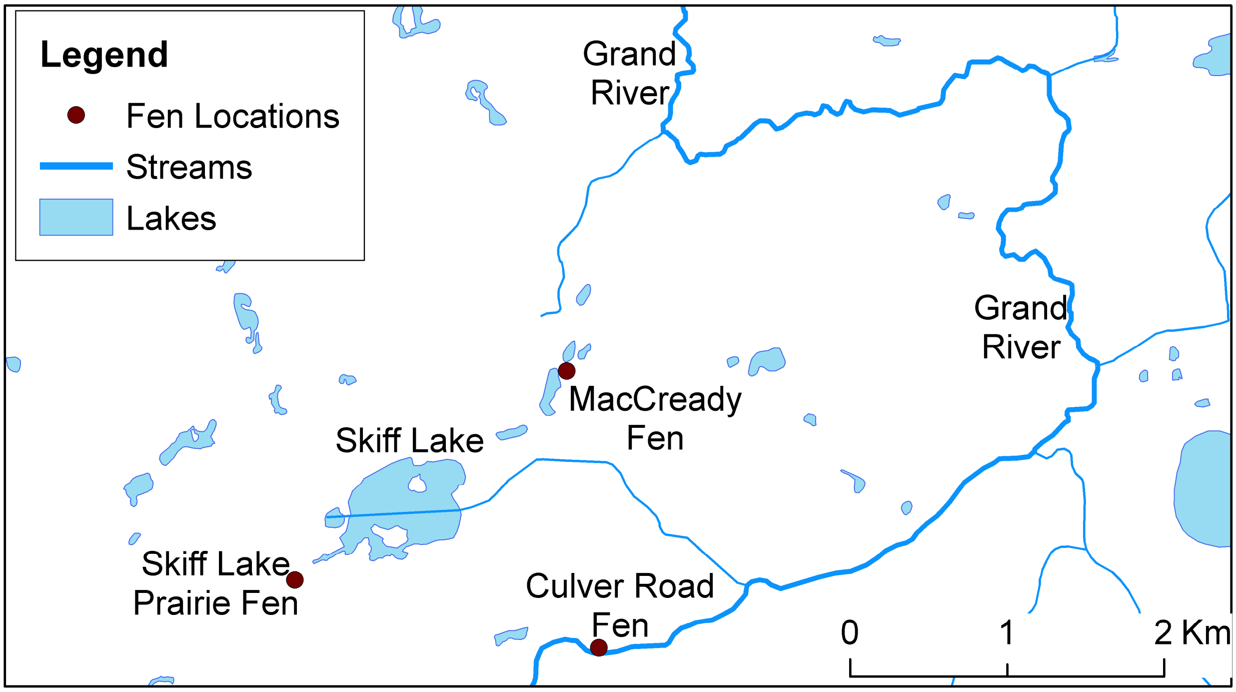

Figure 1-3 – Plan view of MacCready Fen in southern Michigan.

Multi-scale Topography and Hydrology

MacCready Fen is located next to three small lakes and is bordered to its west by an esker, which is a "long, narrow ridge of sand and gravel" (Apple & Reeves 2007). The presence of the esker is possibly beneficial to the fen as it prevents surface runoff from inundating the fen. On the western side of the esker lies a small wetland at a slightly higher elevation than the fen, which indicates that water in the wetland may flow to the fen under the esker. This wetland is drained by a 1st order stream, which flows north to the Grand River, which is about 1 kilometer north of the fen. A multi-scale representation of the topography and hydrology in this area is presented in Figures 1-4 and 1-5 respectively. For better understanding, a cross-section view is also provided in Figure 1-6. From the cross-section view it is clear that the regional-scale model is able to resolve only the large-scale trend in the topography. Especially in the area around the fen, the regional model is unable to resolve the finer details. Moving from the regional scale to the local- and site-scale levels “reveal” more topographic details. At these scales, the resolution is fine enough to accurately characterize the topography around the fen, most importantly the esker.

Since Grand River is the regional discharge zone near the fen, it implies that the regional direction of groundwater flow must be toward the river. As the river flows in general from south to north, and since the fen is located to the west of the river, the fen’s water source(s) cannot be to the east of the river. The regional topographic high is located in Hillsdale County, which is almost 15 kilometers south of the fen. The groundwater table in this area is highest and is the regional recharge zone for this area. Given the regional topographic slope, the groundwater flow directions must be towards the northeast. However, it is difficult to identify actual sources of water since the topography is undulating and highly variable, which creates complex 3-dimensional flow patterns. From the topography around the fen, it is clear that the area toward the north and east of the fen appear to be relatively flat, while the topography to the west and southwest slopes towards the fen. Indeed, a local topographic mound is found to the west of MacCready Fen. Conceptually, it is clear that the fen’s sources of water must be located to the south or southwest of the fen.

Given the highly variable and undulating nature of the topography in the areas up-gradient of the fen, it is difficult to conceptually predict the exact sources of water to the fen. Skiff Lake, which is a fairly large lake located to the southwest of the fen, is very likely to be a source of water to the fen. Also, as previously mentioned, the wetland near MacCready Fen on the other side of the esker is also likely to be a source of water. Due to the local topographic mound near the fen, and due to the presence of the esker, any rainfall event in this area is likely to cause ponding of water in the wetland area. Even though a 1^{st} order stream drains this wetland, it is likely that some of the wetland's water is converted to groundwater by infiltration from the wetland, which then reaches the fen by flowing under the esker. The conversion of surface water into groundwater will likely result in altered water chemistry (acidic to basic or neutral), which is beneficial to the fen in general. Although the quantity of groundwater that the wetland provides to MacCready Fen may be small or even inconsequential, this may be critical during times of drought. Moreover, the esker prevents inundation of the fen due to rainfall runoff, which makes the presence of the esker in this area critical to the fen's survival.

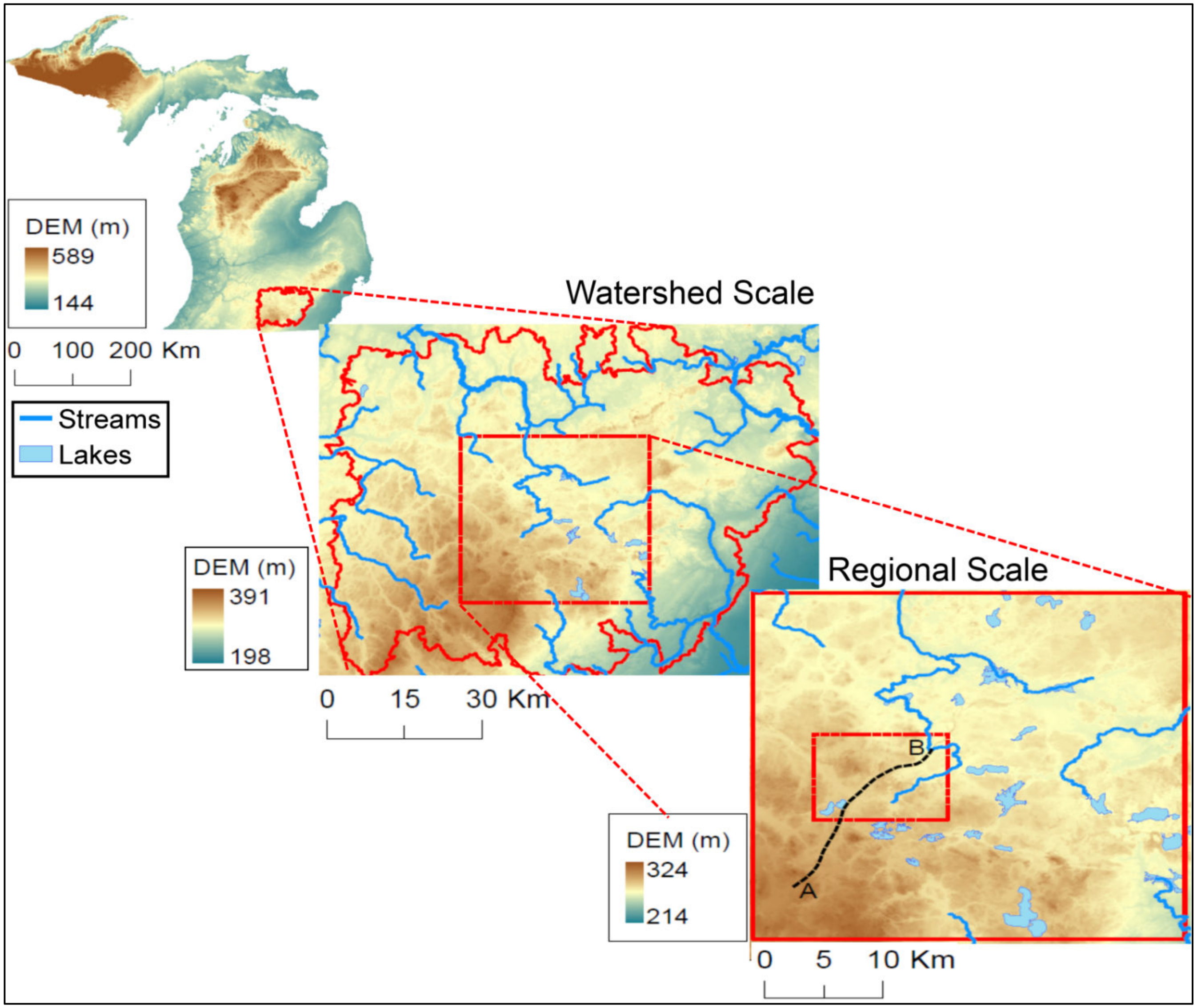

Figure 1-4 – Multi-scale representation of Topography and Hydrology for MacCready Fen (NED USGS 2006, NHD USGS 2010).

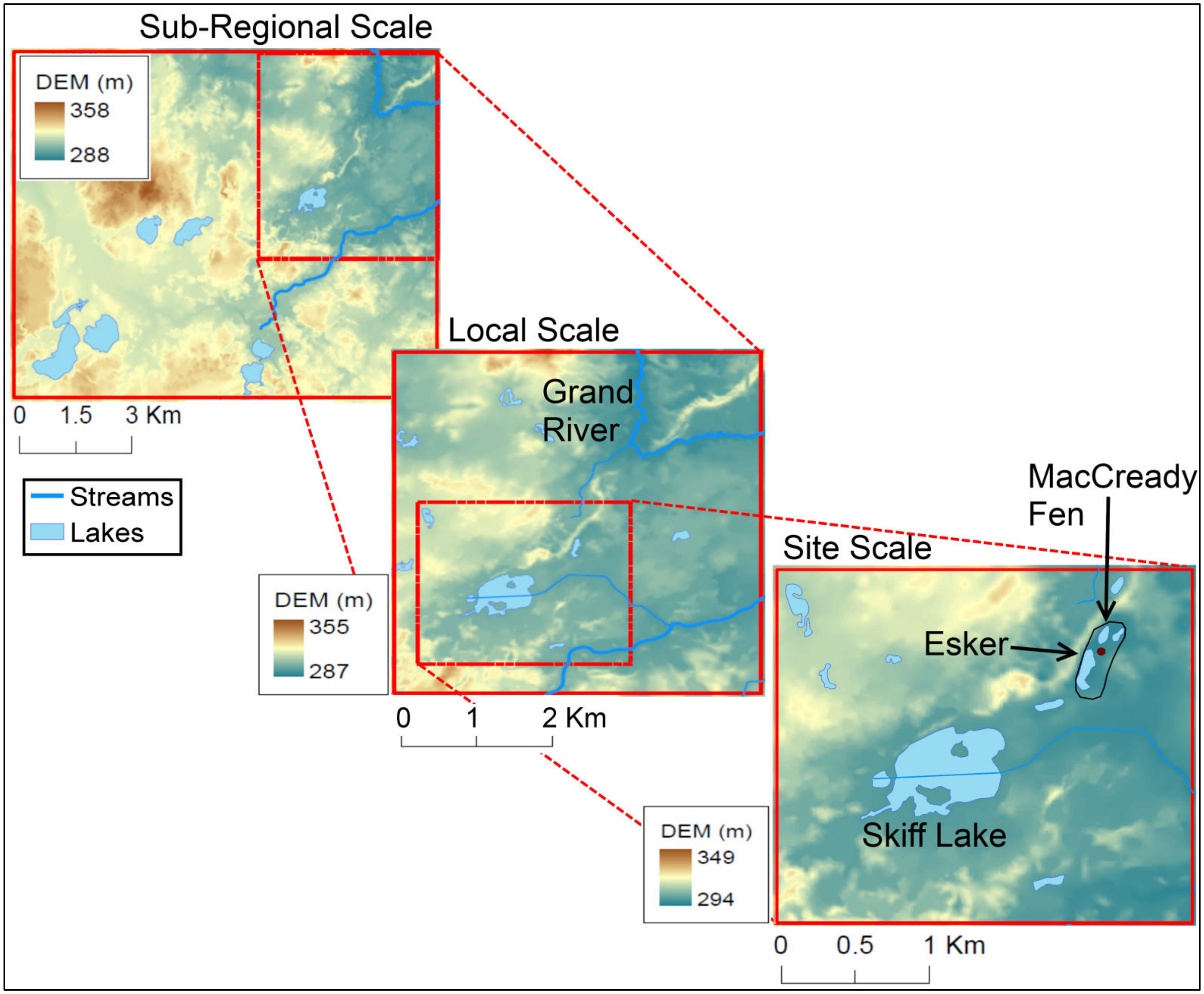

Figure 1-5 – Multi-scale representation of Topography and Hydrology for MacCready Fen (NED USGS 2006, NHD USGS 2010).

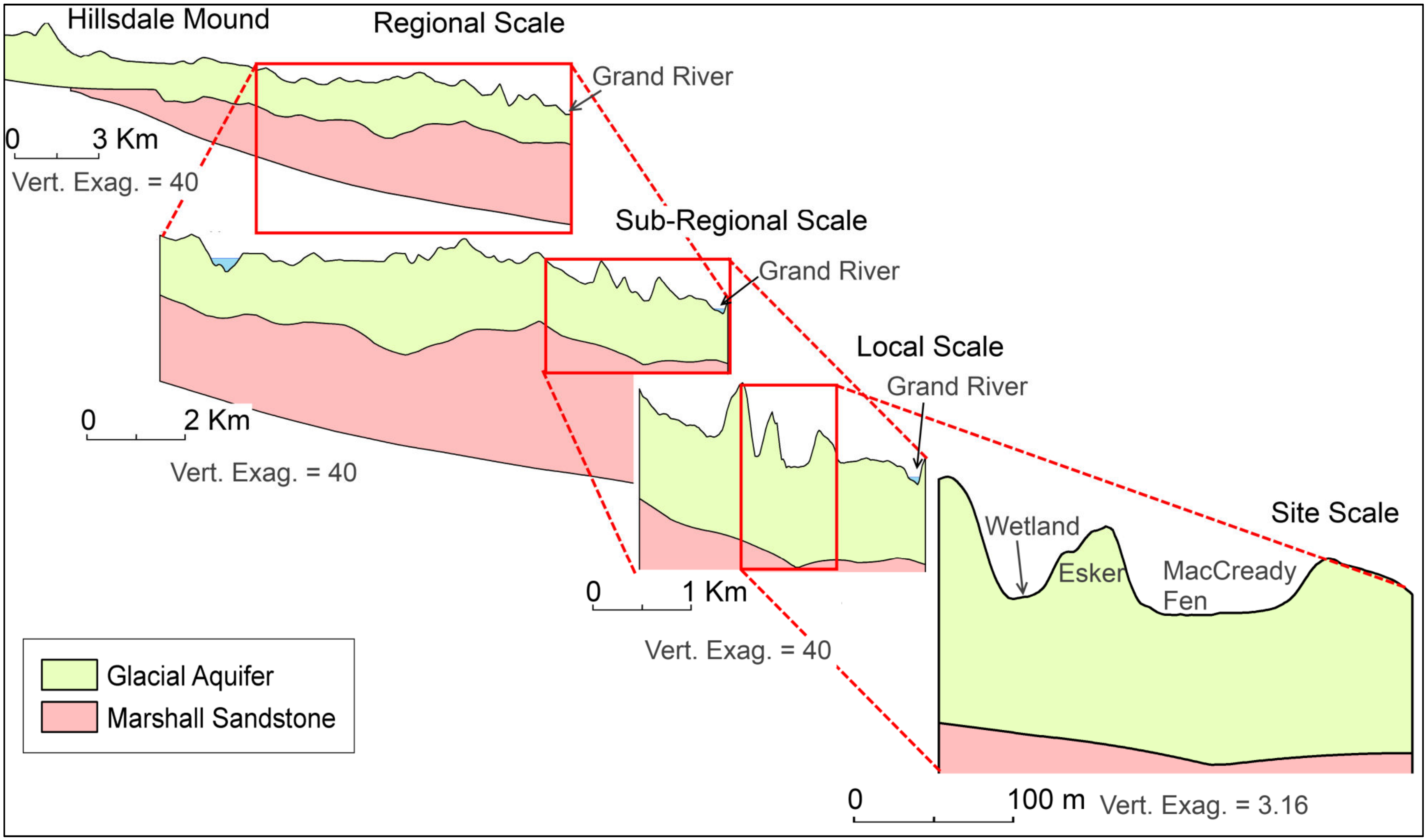

Figure 1-6 – Multi-scale cross-section views of topography and large-scale geology along section AB (Figure 1-4).

Geology

The glacial geology in Jackson County near the fen consists predominantly of glacial outwash (coarse-grained sand and gravel), which is very permeable (Apple & Reeves 2007). Locally, the thickness of the glacial sediments is generally 30 meters or less. The glacial land-system map from the statewide database (GWIM 2006) indicates the presence of a few isolated fine-grained sediments in this area (Figure 1-7). Boreholes in the neighborhood of MacCready Fen indicate the presence of shallow clay lenses, which may have some impact on the groundwater flow patterns in this area.

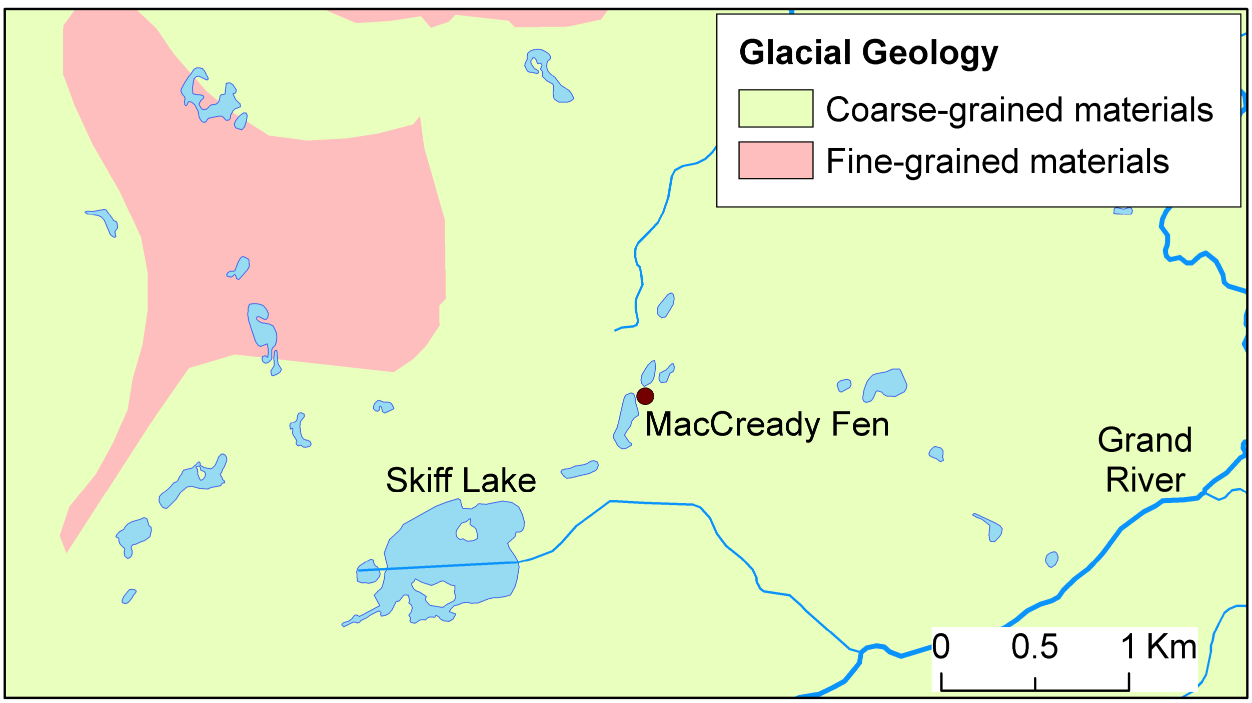

Figure 1-7 – Local glacial geology near the fen.

In terms of the regional glacial geology, the coarse-grained outwash materials, which are predominant in the fens' immediate surroundings, are replaced by fine-grained materials around the Hillsdale mound (Figure 1-8). In general, wherever streams are found, the fine-grained materials are replaced by coarser outwash material. The general thickness of the glacial aquifer reduces towards the south and can be as thin as 3 meters or less in some parts of the Hillsdale mound.

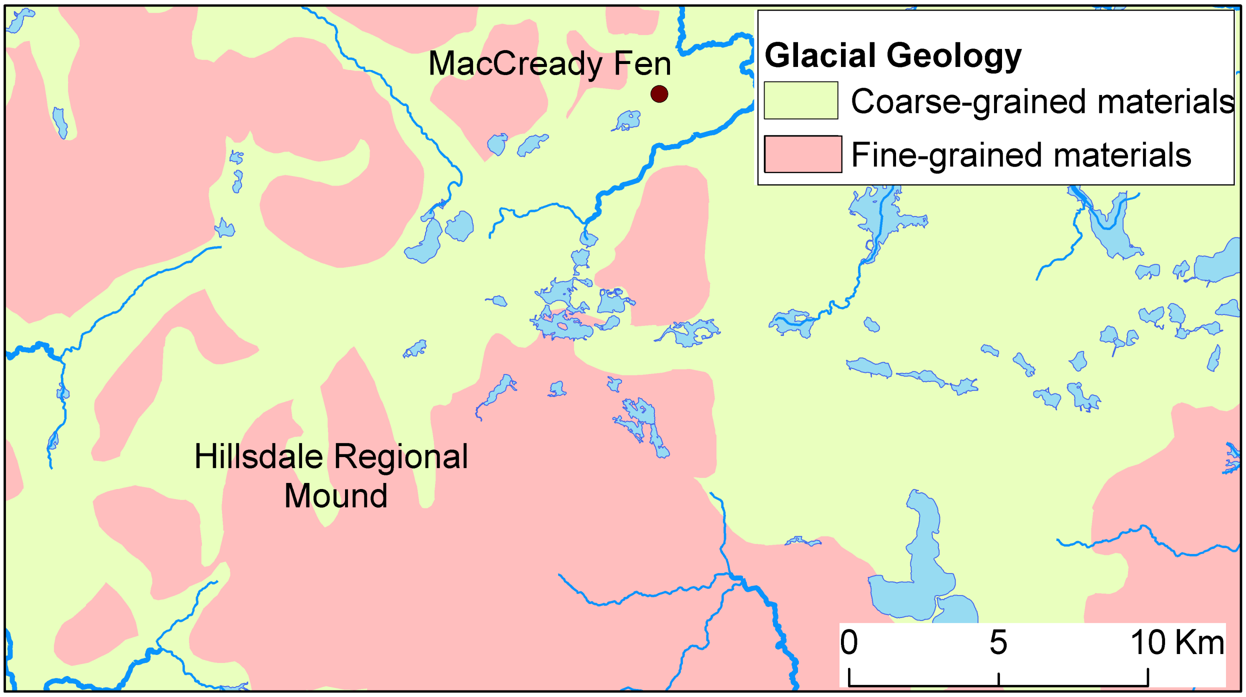

Figure 1-8 – Regional glacial geology.

The deeper bedrock that underlies the glacial deposits is the Marshall Sandstone formation (Figure 1-9). In the area near the fens, the sandstone formation is about 60 meters thick and is a fairly productive aquifer. Beneath this sandstone, is the Coldwater Shale formation (a confining unit), which can be assumed to be a no-flow boundary. The Marshall Sandstone aquifer slopes upwards to the south and pinches out completely about 10 kilometers to the southeast of MacCready Fen. In this area, the Coldwater Shale replaces the sandstone as the bedrock unit. Winter (1988) indicated that the pinching out of permeable rocks can create conditions favorable for the formation of wetlands, which is indeed seen in this case.

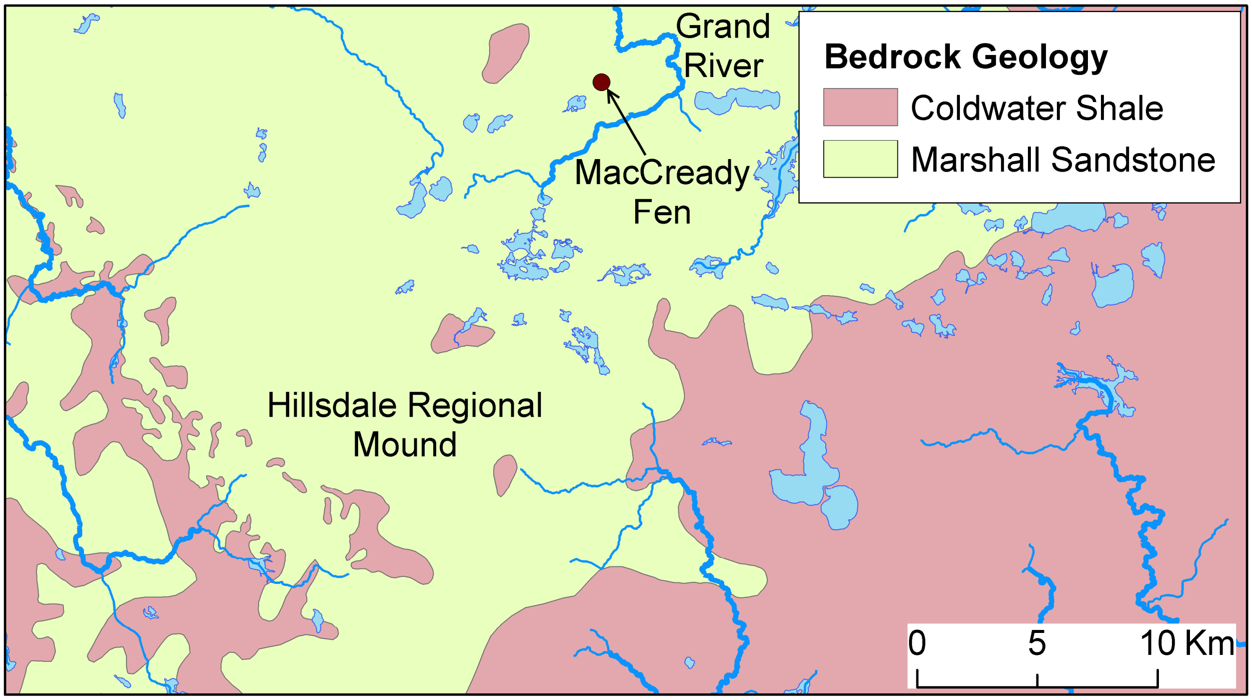

Figure 1-9 – Regional bedrock geology.

<u>Modeling complex geology - Transition Probability Approach</u>

In order to better represent the complex geology in this area, a Transition Probability approach was used to create a geologic model. Multi-scale lithologic data from the statewide groundwater database (GWIM 2006) was used for this (Figure 1-10). The complex geologic environment was simulated using T-PROGS (Transition Probability Geo-Statistical Software) (Carle 1999). The first step in this approach is classifying the different geologic materials using lithologic information from borehole data. For example, 'Sand' or 'Gravel' in a well borehole was classified as good aquifer material, which is symbolized as 'AQ.' Similarly, 'Clay' or 'Silt' was classified as a confining material ('CM'). Other materials that were neither 'AQ' nor 'CM', such as 'Silt_and_Sand' or 'Clay_and_Gravel' were classified as 'PCM' (partially confining material). Bedrock material such as 'Sandstone' or 'Limestone' was classified as one category, 'R'. In principle, the borehole data may be classified into any number of such materials. For the sake of simplicity, 4 materials, ‘R’, ‘AQ’, ‘PCM’ and ‘CM,’ were used to model the whole range of variability of glacial deposits and bedrock geology..

Using this classification scheme for the borehole data, the geologic model was created as described in Carle (1999). The geologic models were created at two resolutions: a regional model to resolve large-scale features, and a site scale model to resolve smaller scale variability. At the regional scale, the geologic model was constructed using more than 8500 boreholes. At the site scale, the model was constructed using data from 201 boreholes in the area around the fen. In order to model the esker accurately, a few synthetic boreholes were added along the esker, which were assigned a lithology similar to that normally found in eskers, i.e. sand and gravel. The geologic model was calibrated by visually assessing how well the model could represent the large-scale geology while simultaneously honoring the data at the borehole. The calibration was performed by manually adjusting the values of the anisotropy ratio, i.e. the ratio of the horizontal extent of an aquifer material to its vertical extent. The vertical extent of each aquifer material was reflected in its average vertical thickness, which was inferred directly from the data. For instance, if the data showed that the average thickness of a piece of clay was 5 meters, and if the anisotropy ratio was set to 10, then the horizontal extent of the clay would be 50 meters. Details of both geologic models are provided in Table 1-1. Since each realization of the geologic model represents only one likely geologic scenario, 100 realizations of the geologic model were simulated. The eventual geologic model was created by choosing the most likely possibility of the 100 realizations. For example, if in a particular grid cell of the geologic model, the distribution of ‘R’, ‘AQ’, ‘PCM’ and ‘CM’ was 40, 25, 20 and 15 realizations respectively, then that grid cell would be assigned ‘R’ as the aquifer material. Both regional and local geologic models were created in this manner.

A 3-D view of both geologic models is presented in Figure 1-11. Cross-section views from the regional and local model are presented in Figure 1-12, which show that the fen is in a 'sand-and-gravel' type aquifer ('AQ') along with a few scattered shallow clay lenses. This type of variability can cause localized preferential flow paths, which may have a significant impact on groundwater flow paths to the fen. The regional model is consistent with the geology seen in Figure 1-8, with fine-grained materials close to the Hillsdale Mound, and predominantly coarser materials near the Grand River.

Table 1-1 – Details of the local and regional geologic models.

Parameters		Local Model	Regional Model
NX, NY, NZ		155, 123, 94	134, 136, 75
DX, DY, DZ (m)		50.3, 50, 1.5	299.4, 298.4, 3.0
Average vertical thickness (m)	'R'	71.4	50.7
	'AQ'	8.2	8.7
	'PCM'	6.1	6.6
	'CM'	6.2	7.6
Ratio of horizontal extent to vertical thickness	'R'	0.9	2.8
	'AQ'	10	10
	'PCM'	10	10
	'CM'	10	10

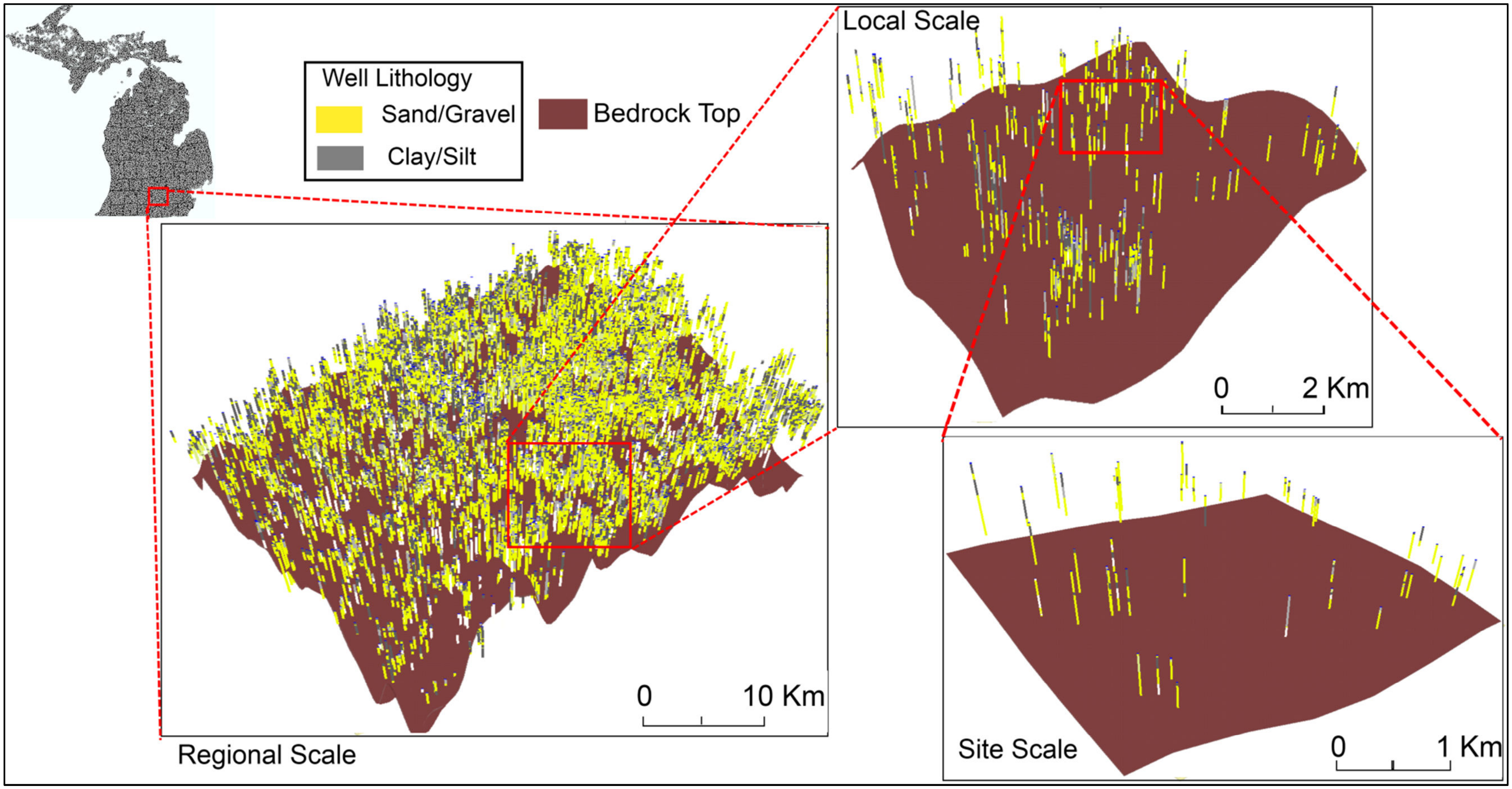

Figure 1-10 – Multi-scale Well Lithologic Data from the Michigan Statewide Groundwater Database (GWIM 2006).

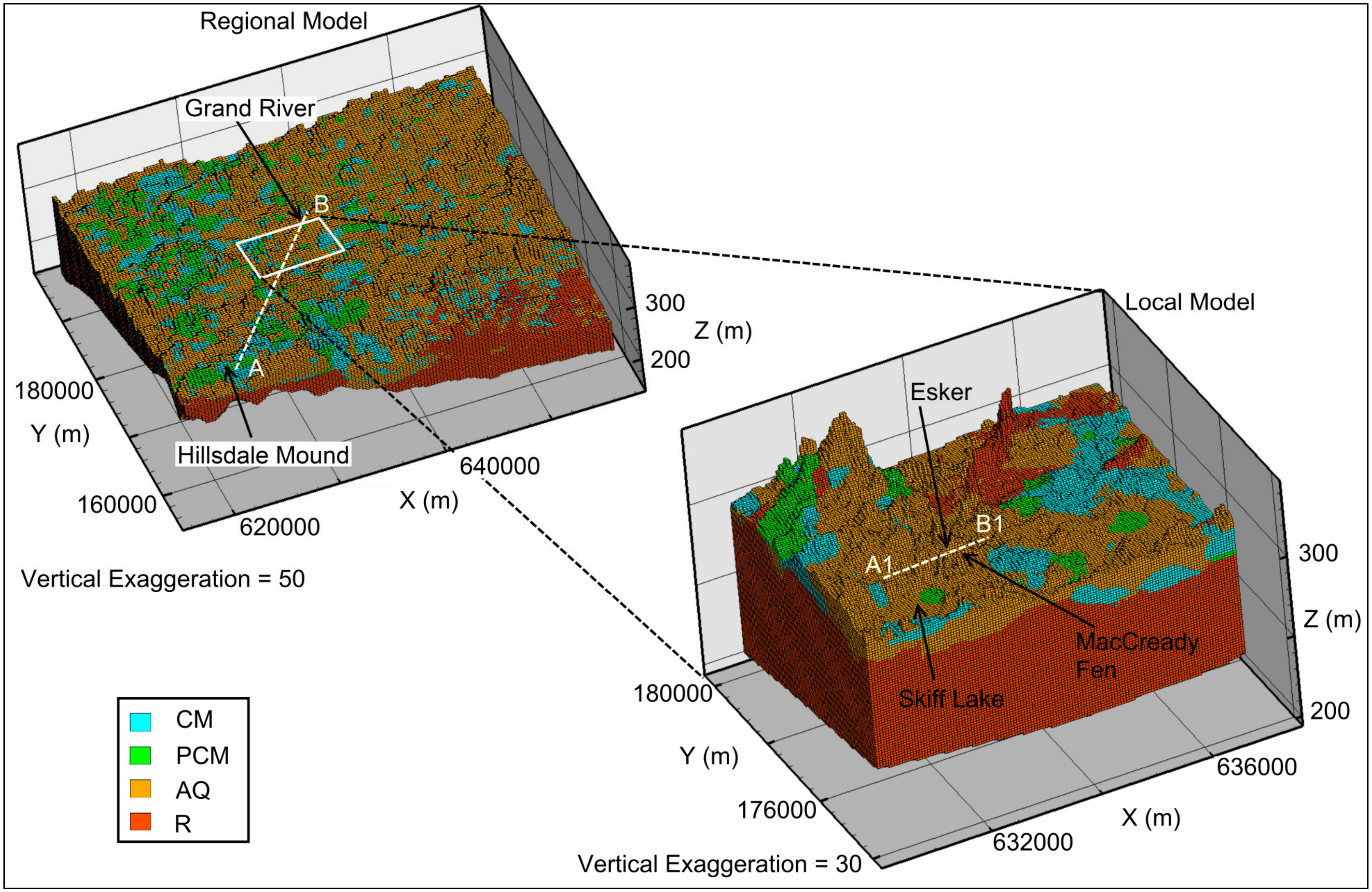

Figure 1-11 – Multi-scale Geologic model from Lithologic data using TPROGS (Carle 1999).

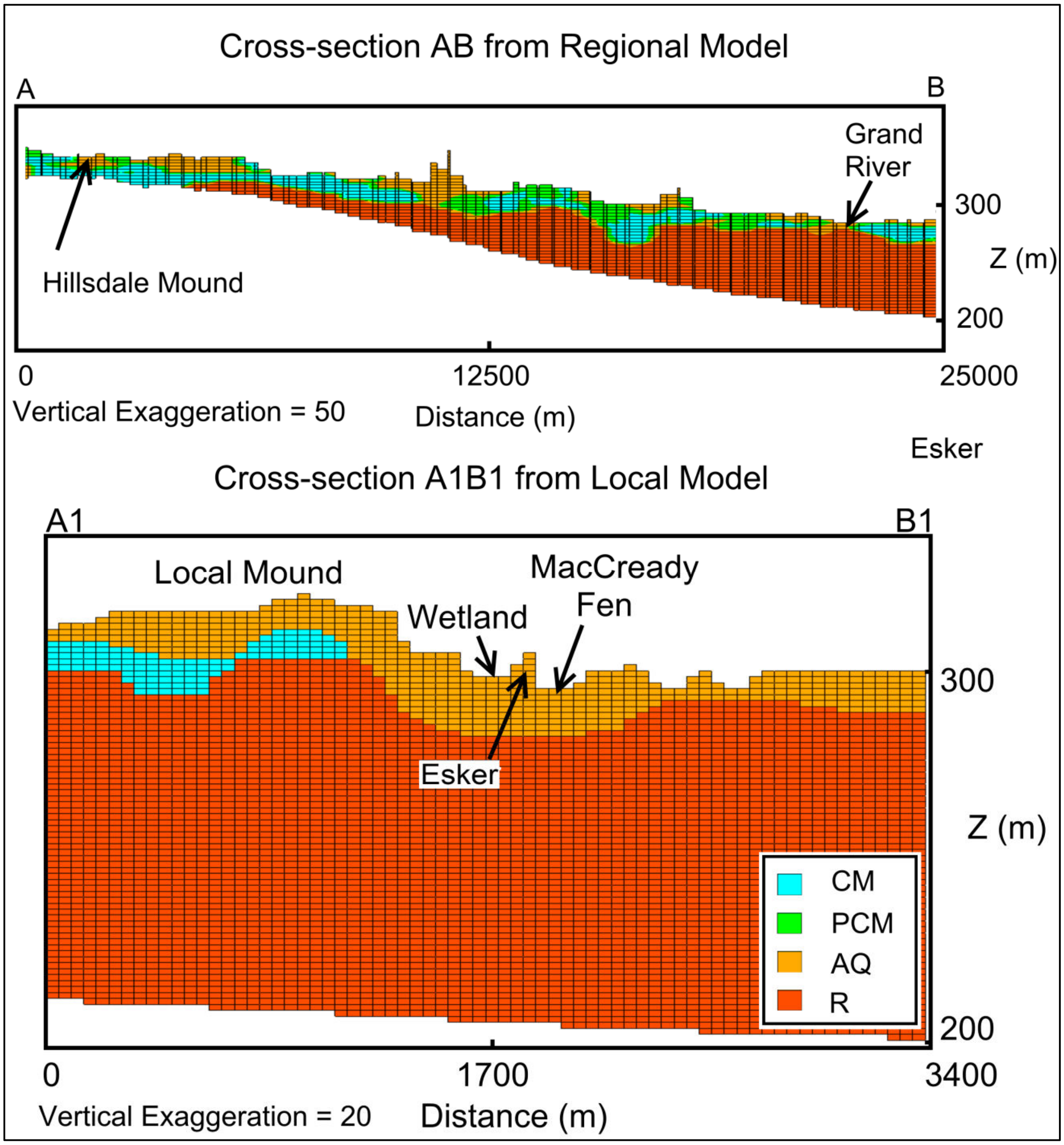

Figure 1-12 – Cross-section views from geologic models (AB and A1B1 from Figure 1-11).

Conceptual Model

Based on the understanding of the multi-scale hydro-geology and topography, it is clear that the source(s) of water to the fens are located to the west and southwest of the fens. The regional flow system in this area consists of water from the Hillsdale groundwater mound flowing to the regional discharge area, i.e. Grand River. Since the fens are located close to the regional discharge area, it is likely that they benefit from up-welling from this regional flow system. The regional conceptual model for this system can be represented as shown in Figure 1-13. At the local scale, the conceptual model can be deduced from the local topography and geology (Figure 1-14). In the case of MacCready Fen, the adjacent esker acts as a barrier and ensures that the surface watershed of the fen is relatively small, which prevents excessive inundation from surface runoff. The wetland on the other side of the esker is a possible source of water to the fen. The local topographic high, which may create a local groundwater recharge area, is another potential source of water to MacCready Fen. Although this conceptual understanding provides some indications of possible sources of water to the fen, quantifying this conceptualization and for simulating the multi-scale flow dynamics, it is clear that a multi-scale modeling approach that can incorporate both regional and local topographic, hydrologic and geologic features is needed.

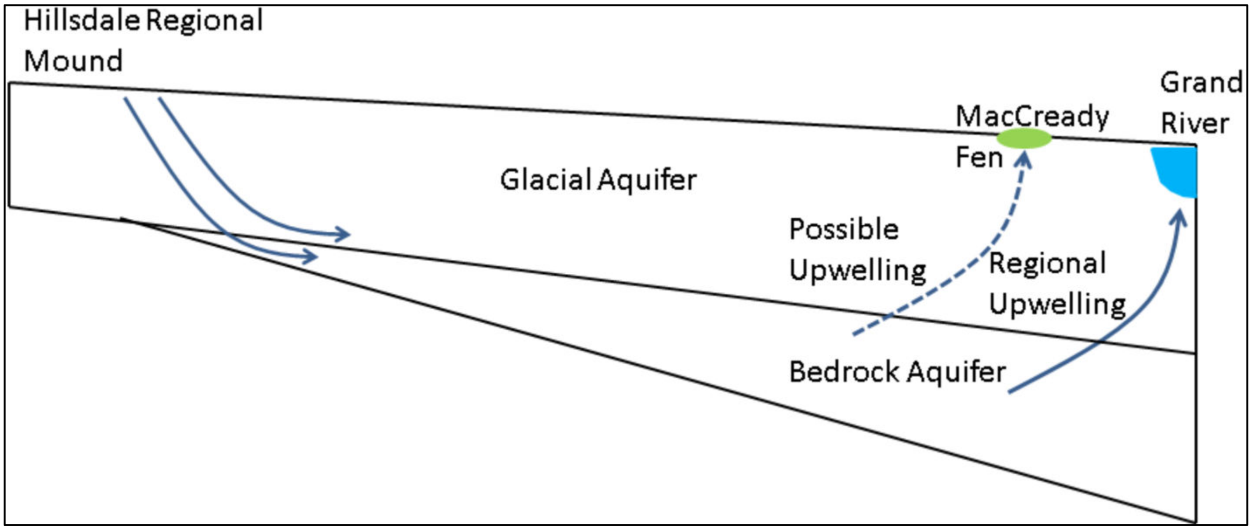

Figure 1-13 – Regional conceptual model for MacCready Fen.

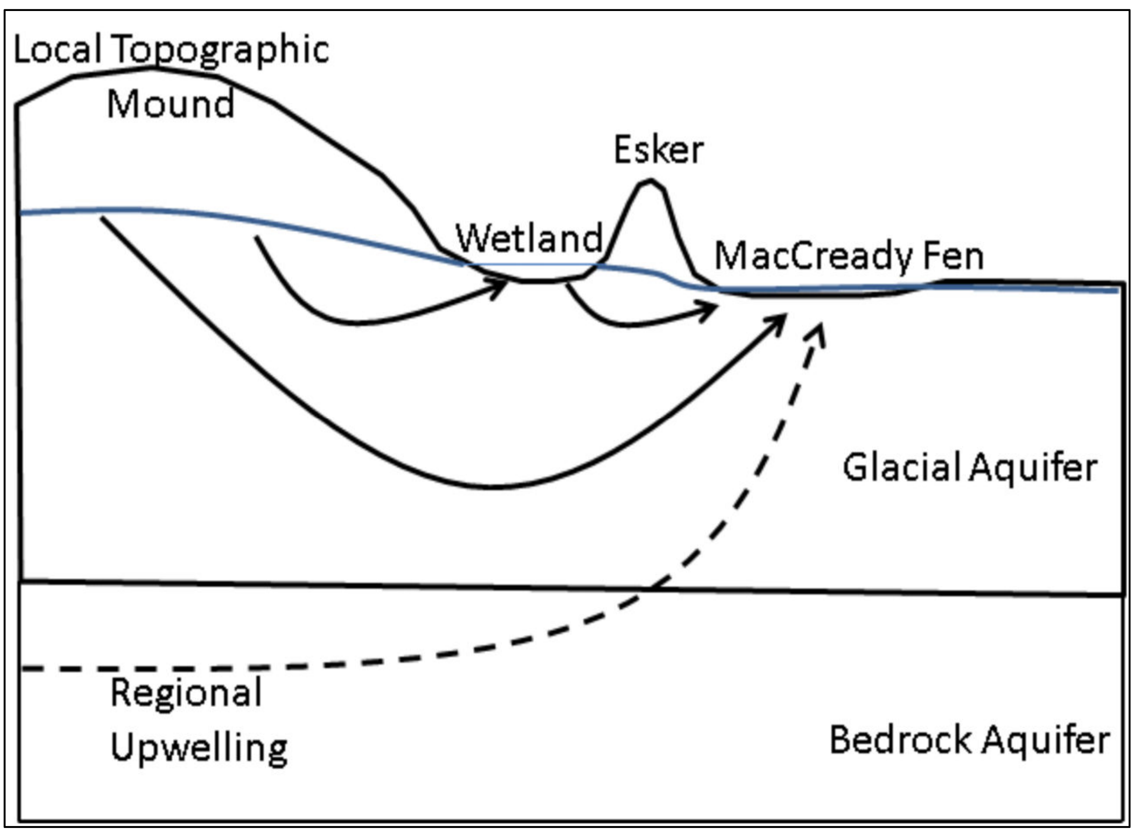

Figure 1-14 – Local conceptual model for MacCready Fen.

Model Development

In order to represent the local and regional processes necessary to understand fen hydrology, we use the data-enabled, multi-scale modeling framework to develop a hierarchy of groundwater flow models. The first step in this process is to design a model grid that can capture the multi-scale details adequately. The regional parent model is formulated with a coarse resolution in order to be able to resolve the large scale features, such as the regional recharge and discharge zones. Within the parent model, sub-models or child models are added wherever necessary at the desired resolution. The process is repeated recursively until the area of interest is adequately resolved. In this case, the finest model must model the topography accurately such that the fen, the esker (approximately 100 meters wide) and the adjoining wetlands are resolved adequately. The vertical resolution in the models is also increased going from the regional to the site scale, such that the site model is able to resolve geologic features such as localized clay lenses. Details of model discretization are provided in Table 1-2.

Table 1-2 – Details of discretization of the hierarchical modeling system.

Model	NX	NY	NZ	DX (m)	DY (m)
Watershed Scale (M^{01})	161	133	1	599.9	597.8
Regional Scale (M^{11})	123	124	4	299.2	300.1
Intermediate Scale (M^{21})	115	93	8	99.4	99.7
Local Scale (M^{31})	146	165	8	33.2	33.2
Site Scale (M^{41})	170	158	16	16.5	16.5

The multi-scale models were conceptualized using one geologic layer to represent both the glacial and bedrock aquifers. The bottom of the model was set to the top of the Coldwater Shale formation (interpolated from the statewide database). The geologic layer in the model was divided into a number of computational layers, ranging from 1 layer at the watershed scale to 16 computational layers at the site scale. Recharge rates for the model were assigned from the statewide database (GWIM 2006). Streams and lakes were modeled as two-way head-dependent cells, while the land surface elevation was modeled as one-way drains with drain elevation set to land surface elevation. Streams and lakes were assigned leakances depending on their size as given in Tables1- 3 and 1-4 respectively.

Table 1-3 – Stream leakances and water depth based on stream order.

Stream Order	Leakance (m/day)	Water depth (m)
1	1	0.3
2	2	0.5
3	5	1
4	10	1.3
5	20	1.6
6	50	2

Table 1-4 – Lake leakance and water depth based on lake size.

Lake area less than (acres)	Leakance (1/day)	Water depth (m)
1	0.005	0.3
10	0.01	0.5
100	0.05	1
1000	0.1	1.3
10^4	1	1.6
10^5	5	2
10^6	10	3
10^7	20	4
10^8	50	5
10^9	100	6

The models were run to steady state to represent long-term average conditions in the glacial and bedrock aquifers. A steady state model was considered sufficient to replicate the regional flow system, but its applicability at the site scale had to be assessed. Many previous studies have noted that fens are characterized by saturated conditions throughout the year without being inundated for any significant length of time, i.e. a steady water table. Thus, a steady state model at the site scale was deemed to be sufficient to simulate the fen's water table.

In order to make full use of the geologic model, the groundwater model's vertical discretization had to be as fine as possible. The 4 aquifer materials, 'R', 'AQ', 'PCM' and 'CM', in the geologic model were represented in the groundwater model by converting them into an effective hydraulic conductivity value for each grid cell. Each aquifer material was assigned a typical hydraulic conductivity value, which was used to calculate the hydraulic conductivity in each groundwater model grid cell. For example, if one groundwater model cell contained two geologic model cells with typical values K_1 and K_2, the hydraulic conductivity of the groundwater cell was calculated as the average of K_1 and K_2. Typically, clay or silt ('CM') have a much smaller hydraulic conductivity than sand or gravel ('AQ'), and therefore, arithmetic averaging of their hydraulic conductivities tends to be biased towards 'AQ.' Therefore, it was important to have as many vertical grid cells in the groundwater model as possible, such that no vertical averaging of the hydraulic conductivity was necessary. The typical hydraulic conductivity values were used as calibration parameters in the groundwater model.

Vertical Discretization Scheme

The vertical discretization scheme used in this approach to incorporate the geologic model into the groundwater model is different from the traditional finite-difference based approach. For instance, if the model has 10 layers, the entire aquifer thickness is divided into 10 layers of equal thickness. This can cause the layers to closely mimic the topography, and can therefore result in so-called "dry cells" in the groundwater model. To get around this problem, we use an iterative water table-based discretization scheme. The model is first discretized and solved using only 1 computational layer, which provides the preliminary water table. The saturated thickness of the aquifer is computed using this water table, which is then used to divide the saturated thickness into the desired number of vertical layers (Figure 1-15). This ensures that the vertical discretization is smooth, which mimics the water table. This process can be done iteratively by gradually increasing the number of layers until the desired discretization is reached. For instance, if 9 vertical layers are needed, one can go from 1 to 3 to 6 and then to the eventual 9 layers. This kind of discretization is usually needed for finer-scale models where sudden changes in topography can be expected. Note that this discretization only applies to unconfined aquifers where the aquifer's saturated thickness depends on the position of the water table.

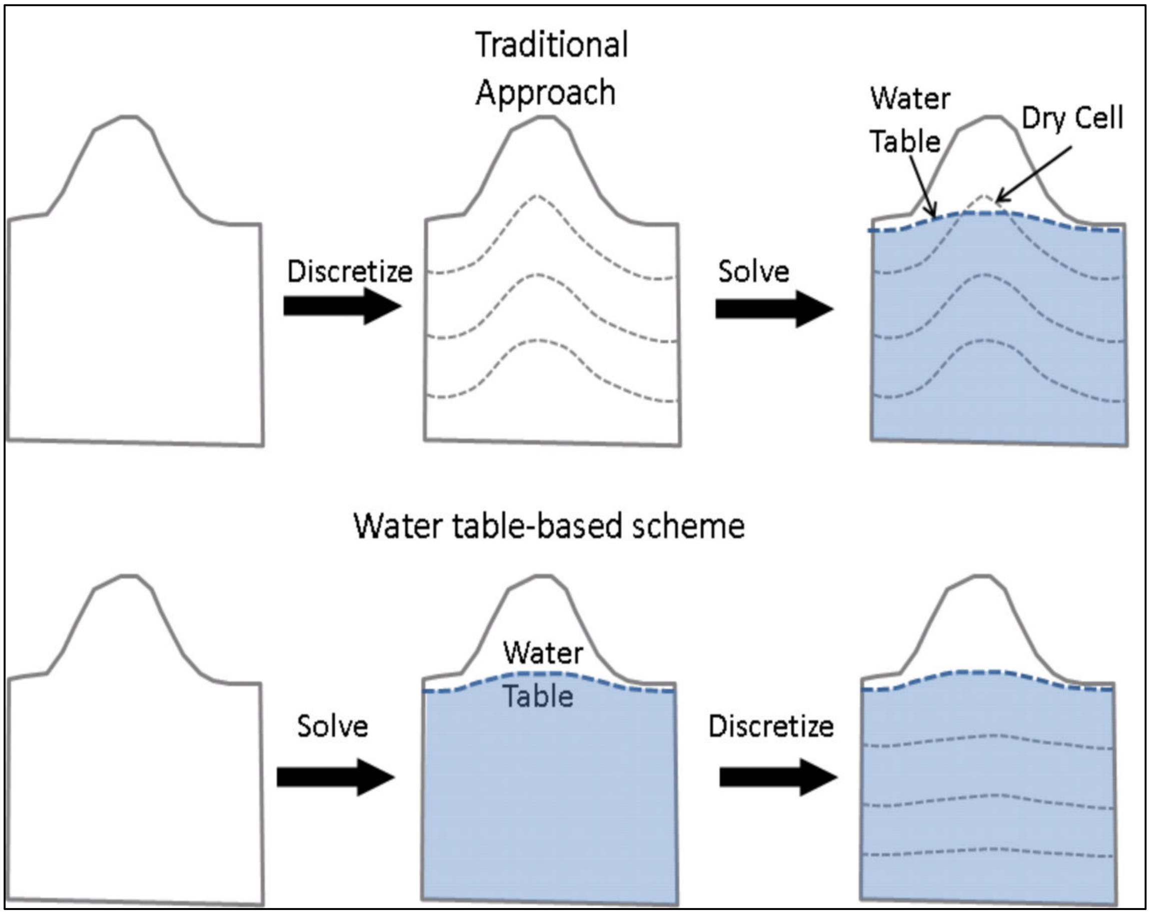

Figure 1-15 – Illustration of water table-based vertical discretization scheme.

Model Calibration and Particle Tracking

The models were calibrated using static water levels at water wells from the statewide database and base-flow estimates at USGS stream-flow gaging stations. The calibration parameters for the model were: a) multiplication factor for recharge rate to the glacial aquifer, b) multiplication factor for river and stream leakances, c) multiplication factor for drain leakance, and d) typical hydraulic conductivity (*K*) values for the 4 aquifer materials as described previously. The first three parameters were used to calibrate the model to the observed base-flow at the USGS stream-flow gauging station on the Grand River (USGS Site – 04109000). The typical *K* values were manually adjusted to minimize the error between observed and simulated hydraulic head values. The final calibrated model parameters are presented in Table 1-5. Once the model was calibrated, 3-dimensional reverse particle tracking was performed to identify the sources of water to the fen.

Table 1-5 – Calibrated model parameters.

Parameter	Value
Multiplication factor for Recharge	1
Multiplication factor for river and stream leakances	10
Multiplication factor for drain leakance	0.001
Hydraulic conductivity ‘R’ (ft/day)	150
Hydraulic conductivity ‘AQ’ (ft/day)	100
Hydraulic conductivity ‘PCM’ (ft/day)	1
Hydraulic conductivity ‘CM’ (ft/day)	0.1

RESULTS AND DISCUSSION

The results from the hierarchical modeling system are presented and discussed next. Figures 1-16 and 1-17 show the predicted hydraulic heads in the first model layer from the hierarchical models for MacCready Fen.

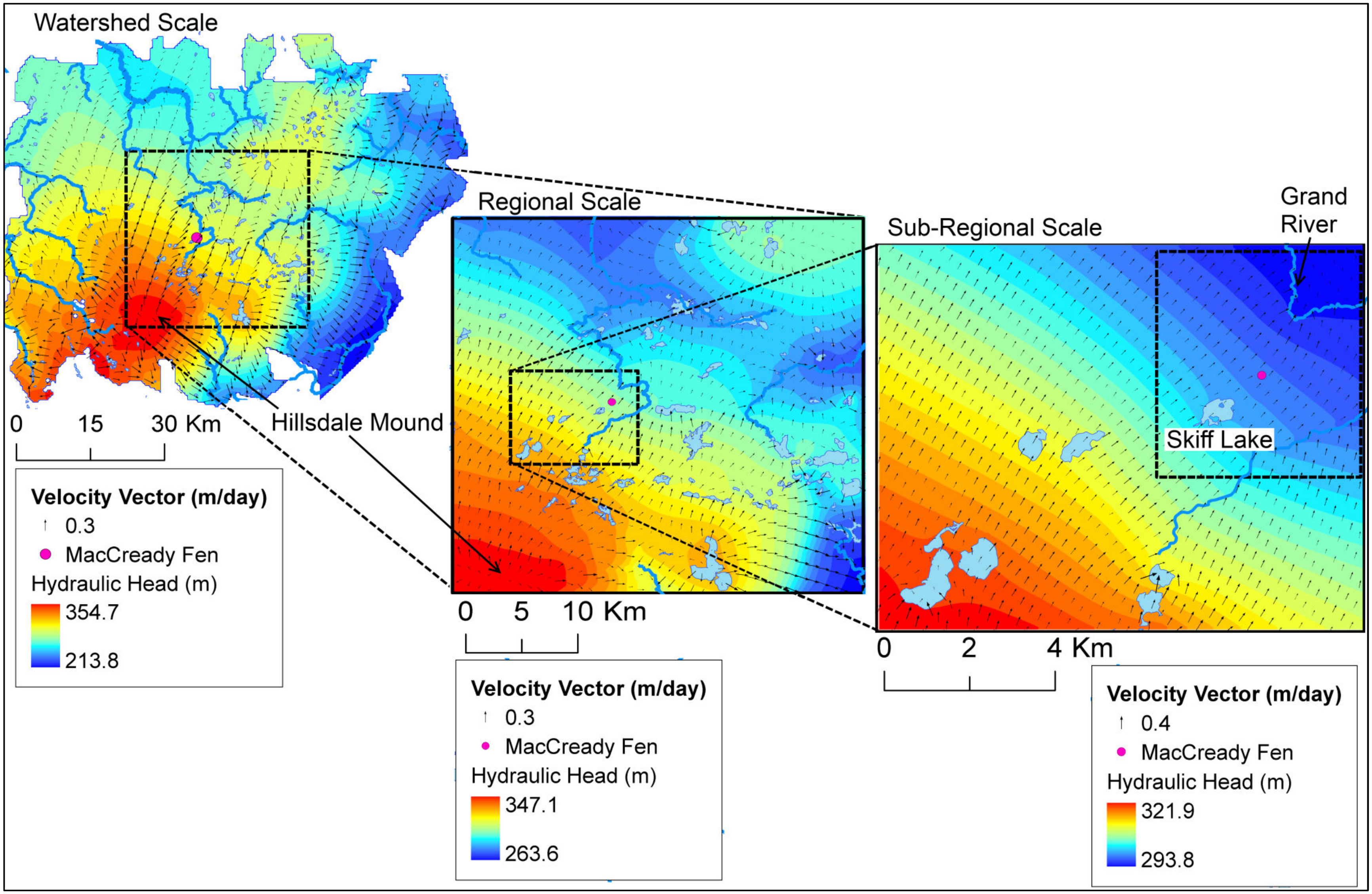

Figure 1-16 – Groundwater head contours from the hierarchical modeling system.

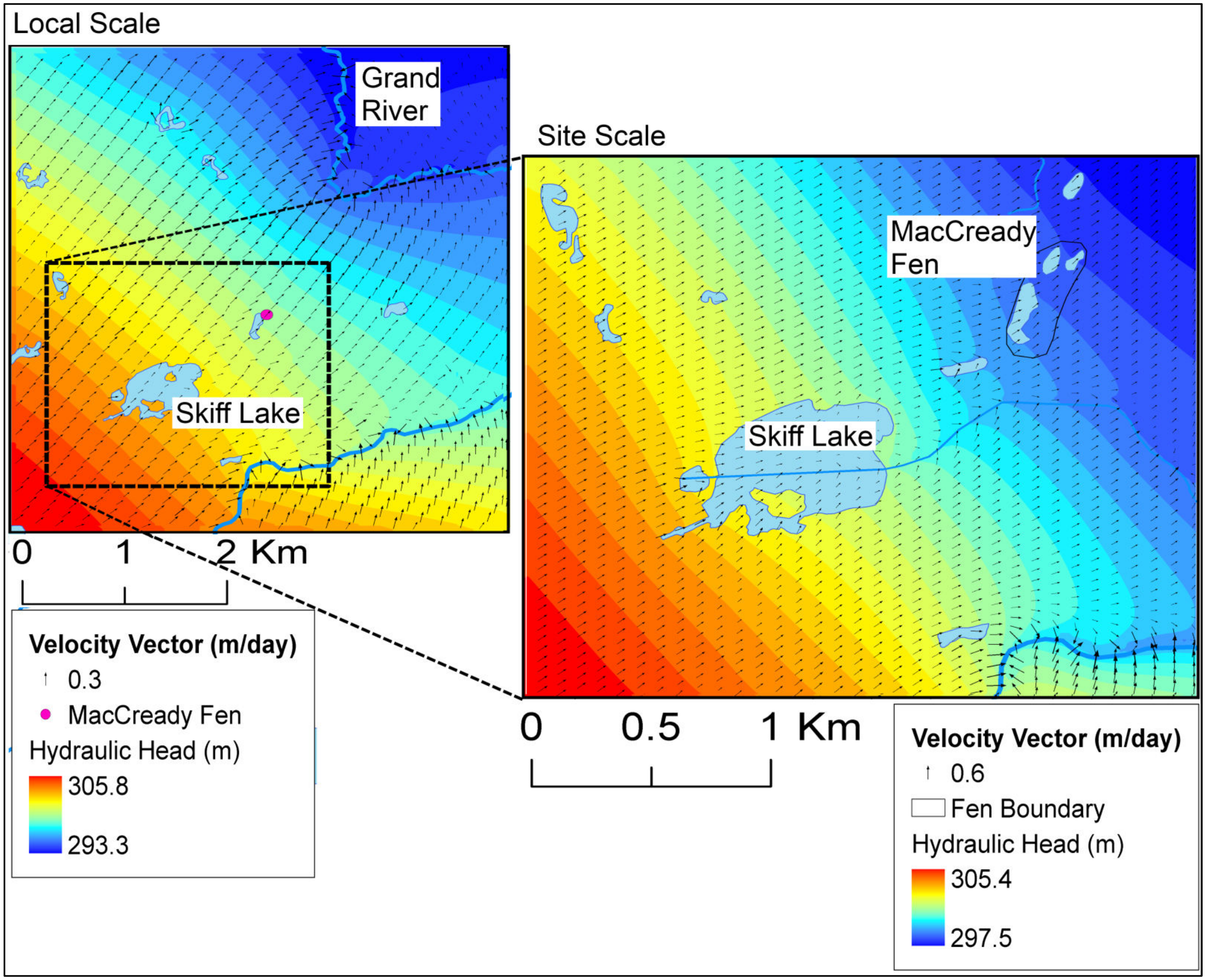

Figure 1-17 - Groundwater head contours from the hierarchical modeling system.

Hierarchical calibration

The base-flow prediction from the model was 233015 m^3/day, which was in agreement with the observed base-flow for the Grand River at Jackson (USGS Site 04109000) of 225000 m^3/day. Figure 1-18 shows the comparison of observed water levels with the simulated model heads in the hierarchical model. At the regional scale, there were 4317 data points for comparison with the model, which decreased to 310 at the sub-regional scale, and further down to 87 at the local scale. At the site-scale, there were too few data points available for meaningful comparison with the model. From the calibration plots we see that the hierarchical model is able to reasonably simulate the observed hydraulic heads at the regional scale. At the local scale, the model's performance is relatively poor compared to the regional scale. The reasons for the poor performance at the local scale can be attributed to a combination of the following two factors: a) poor data quality due to measurement error, temporal bias or geo-spatial inaccuracy and b) inability of the model to resolve local geologic features due to lack of data. In either case, with additional localized data collection, these can be overcome. In this study, though, no additional data were collected. Thus, one of the major drawbacks of this study is that the data quality is not sufficient to perform model calibration at the local scale. However, the model's ability to capture regional hydrologic processes is not hampered by this drawback. More importantly, the groundwater flow directions and flow paths, which are of primary interest in this study, are influenced more by the topographic and stratigraphic structure than by the aquifer's hydraulic properties.

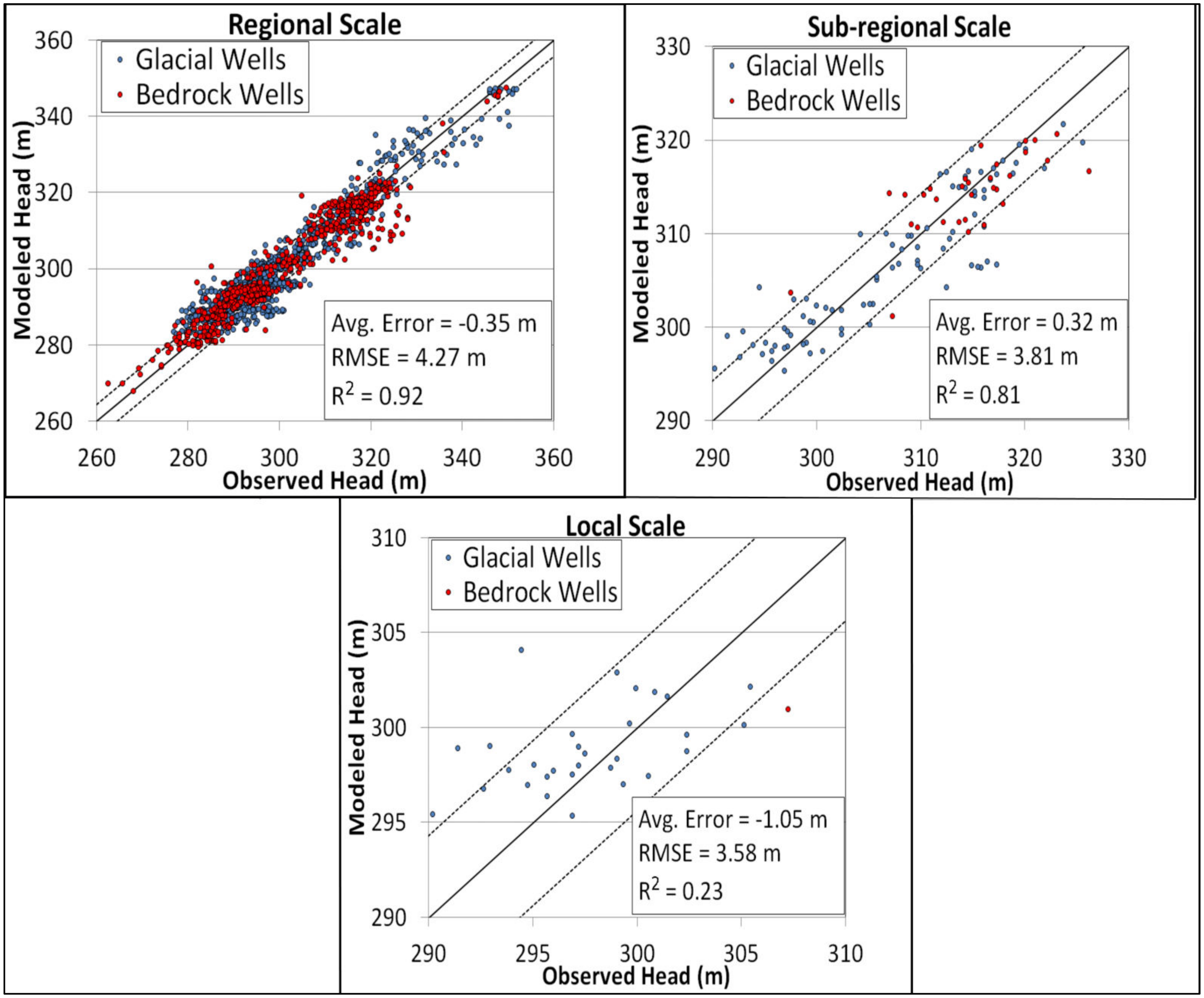

Figure 1-18 – Hierarchical calibration charts for hydraulic heads in the glacial and bedrock aquifers.

Sources of water and delivery mechanisms

The results from reverse particle tracking show that MacCready Fen gets its water from multiple sources that trace their origins all the way back to the Hillsdale groundwater mound. Figure 1-19 presents the results from the multi-scale particle tracking approach used to delineate the sources of water to the fens.

The nearest direct source of water to MacCready Fen is the wetland that lies on the other side of the esker, although it is likely a minor source in terms of water quantity. The wetland, in turn, gets its water from local runoff and from adjacent groundwater upland areas. Other minor sources to the fen include local groundwater recharge areas to the southwest of the fen. The major source of water to the fen is Skiff Lake, which is located about 600 meters to the south-southwest of the fen. Skiff Lake, in turn, gets its water from local runoff and from groundwater inflows. The groundwater influx to Skiff Lake does not originate from one source, but is rather dispersed along a "band" of groundwater recharge area that traces all the way back to the Hillsdale regional groundwater mound as shown in Figure 1-19. The fen is thus connected to the regional groundwater mound through an intermediate source, Skiff Lake. The delivery mechanisms that provide water to the fen can therefore be characterized into "direct" and "cascading" connections. A direct connection is one in which water flows directly from the source to the fen, for instance, water from the local groundwater recharge area flows directly to the fen. A cascading connection is one in which water flows from a source to an intermediate source, and then to the fen. The connection between the regional mound and the fen can be called a cascading connection, with Skiff Lake acting as the intermediate source. Although the existence of these connections can be established by the particle tracking approach, quantifying the amount of water contributed by each source is much harder. In order to provide some preliminary understanding of the quantum of flux from the different sources, a mass balance analysis for the fen and Skiff Lake is performed next.

<u>Comments on particle tracking approach</u>

The reverse particle tracking approach used the results from the groundwater model to track particles backwards from the fen to their eventual sources. The groundwater model used the 3-dimensional geology created from the most likely of 100 realizations of the Transition Probability approach as previously described. It is apparent that if particle tracking was done using a groundwater model created from any 1 of those 100 realizations, the predicted particle paths would have been different. A more robust approach, but much more time-intensive, would be to create particle paths for each of those 100 realizations, using which a probabilistic envelope of particle paths could be created. This approach would predict the plausibility of a particular particle path, and would be very valuable, especially for analyzing different management options and for performing what-if analyses. However, the approach used in this study represented the most likely geologic scenario.

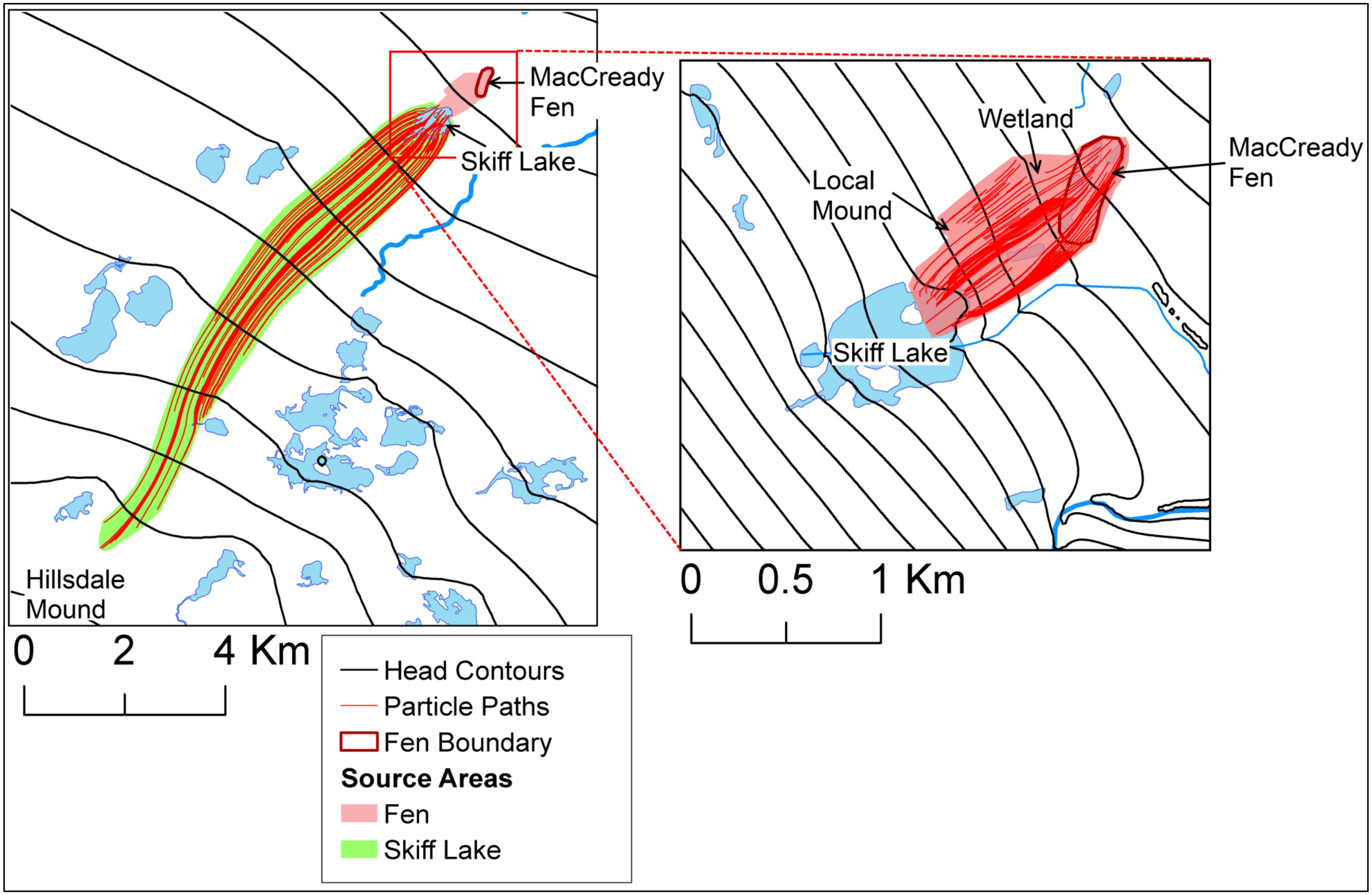

Figure 1-19 – Particle tracking results depicting sources of water to MacCready Fen

Mass Balance for MacCready Fen

Mass balance analysis for MacCready Fen was performed using Equation 1-2.

$$P + RO + GW_{IN} - E - ET - GW_{OUT} - SW_{OUT} = 0 \qquad (1\text{-}2)$$

where P is precipitation, RO is runoff, GW_{IN} is the groundwater inflow, E is the evaporation from an open water surface, ET is the evapo-transpiration from vegetation, GW_{OUT} is the groundwater outflow and SW_{OUT} is the surface outflow. In the case of MacCready Fen, all terms in this mass balance equation other than GW_{OUT} are included, since the fen is a discharge area.

The precipitation rate to the fen was obtained from National Weather Service (NWS) data as 876 mm/year. The evaporation rate from an open water surface was obtained from Farnsworth et al. (1982) as 686 mm/year, and the potential evapotranspiration (*PET*) for the fen was obtained using Thornthwaite and Mather (1957) as 762 mm/year. The area covered by the fen was approximately 94,031 m^2, out of which lakes accounted for approximately 31,524 m^2. From the local topography around the fen, its runoff catchment area was estimated to be between 1.5 - 2 times the fen's area. In order to get a minimum and maximum runoff estimate into the fen, a uniform runoff coefficient was assigned to the catchment, ranging between 0.3 and 0.7. The surface outflow at the fen's outlet was measured on December 4th, 2009 as 13.1 L/s (1132 m^3/day), which was assumed to be representative of long-term steady state conditions. The mass balance terms as calculated for the fen are given in Table1- 6.

Table 1-6 – Mass balance terms for MacCready Fen.

Source/Sink	Flux (m^3/day)
Precipitation	225
Runoff	101 – 316
Evaporation	59
Evapo-transpiration	130
Surface outflow	1132

From the mass balance terms, the groundwater influx to the fen can be estimated to be in the range 781 – 995 m^3/day. In the model, the fen was simulated as a drain with drain elevation set to 0.6 meters below the land surface, and a drain leakance that was calibrated to the estimated groundwater influx to the fen. The calibrated leakance of the fen was 0.005 /day with the simulated groundwater flux of 969 m^3/day, which was within the range of estimated values.

Mass Balance for Skiff Lake

A similar mass balance analysis for Skiff Lake was performed using Equation 1-2. In the case of Skiff Lake, evapo-transpiration was not included in the mass balance. The precipitation to the fen was set to 880 mm/year from National Weather Service (NWS) data. The evaporation rate from an open water surface was obtained from Farnsworth et al. (1982) as 673 mm/year. The area of the lake was 339,775 m^2, and its catchment area was about 2 - 3 times the lake's area, with runoff coefficient ranging between 0.3 and 0.7. The surface outflow at the lake's outlet was measured on December 4th, 2009 as 48.8 L/s (4216 m^3/day), which was assumed to be representative of long-term steady state conditions. The mass balance terms as calculated for Skiff Lake are given in Table 1-7.

Table 1-7 – Mass Balance terms for Skiff Lake

Source/Sink	Flux (m^3/day)
Precipitation	819
Runoff	491 – 1720
Evaporation	627
Surface outflow	4216

In this case, there are 2 unknowns from Equation 1-2, namely the groundwater inflow and outflow. Using the remaining terms of the mass balance equation, the net groundwater flow to Skiff Lake (i.e. the difference between inflow and outflow) was estimated to be in the range 2303 – 3532 m^3/day. In the model, Skiff Lake was calibrated using the lake's leakance to the estimated groundwater flux. The calibrated leakance of the lake was 0.05 /day and the simulated groundwater inflow to and outflow from the lake were 3798 and 694 m^3/day, resulting in a net groundwater flux to Skiff Lake of 3104 m^3/day, which was within the range of estimated values.

By combining the results from the mass balance analysis and the particle tracking, it can be seen that a significant portion of the water in the fen comes from Skiff Lake, because the density of particle paths between Skiff Lake and the fen is the highest. However, it is obvious that there is bound to be significant uncertainty in apportioning the fen's influx to the different sources, which can better constrained by further data collection. Additional data that needs to be collected for better understanding of the system and to improve model calibration is discussed later.

Comments on mass balance analysis

The significant assumption in the mass balance analysis was that the stream-flow data collected at the fen and on Skiff Lake on December 4^{th}, 2009 was representative of long-term conditions. Given that the measurement was made in the winter, evaporation and evapo-transpiration would be negligibly low. From NWS precipitation data, the total rainfall in this area between December 1^{st} and December 4^{th}, 2009 was less than 1.5 inches, which would contribute very little in terms of precipitation or runoff to the overall mass balance. Thus, the stream-flow at the fen or lake's outlet would be balanced by the net groundwater flux to the fen or lake respectively. Although this does not create any additional uncertainty in terms of the predicted sources of water or their delivery pathways, it increases the upper bound of the estimated groundwater flux to the fen from 995 to 1132 m^3/day, and for Skiff Lake from 3532 to 4216 m^3/day. Obviously, as previously indicated, additional data would further constrain the mass balance analysis. For instance, a time-series of stream-flows at the fen and lake outlets would shed considerable light on the hydrologic connection between the lake and the fen. Also needed is data for the summer months, which would indicate how the fen survives during "low" flow.

System connectivity

From the particle tracking results it is clear that the fen gets its water from a network of sources. Figure 1-20 provides a schematic representation of the connectivity between the fen and the multiple water sources tracing all the way back to the Hillsdale mound. From this detailed multi-scale study, we see that the system that provides water to the fen is much larger and more inter-connected than expected. It is clear that the fens are benefitting from this complex network of sources of water and delivery mechanisms. It is important to note that MacCready Fen is one among a cluster of fens around the regional mound, as already seen in Figure 1-2. It is likely that other fens in the neighborhood must have similar complex network of sources and corresponding delivery mechanisms, all of which may be traced back to the regional mound. The regional groundwater mound is thus, the eventual source of water to all the fens in this area, and also numerous other lakes, streams, other wetlands and aquifers. Thus, the regional mound acts as a "master recharge area," providing water not just for one habitat or one species, but multiple ecosystems and species, and also major aquifers that supply human needs.

Establishing this system connectivity for even one fen is a challenging task, and needs multi-scale simulation and analysis as demonstrated here. The broad implication of these findings is that regional headwaters are extremely critical for the well-being of the larger hydrologic system. Managing such systems needs not just a qualitative understanding of the system and its connectivity, but also a quantitative framework to assess the effects of perturbations on the system and to evaluate various management options.

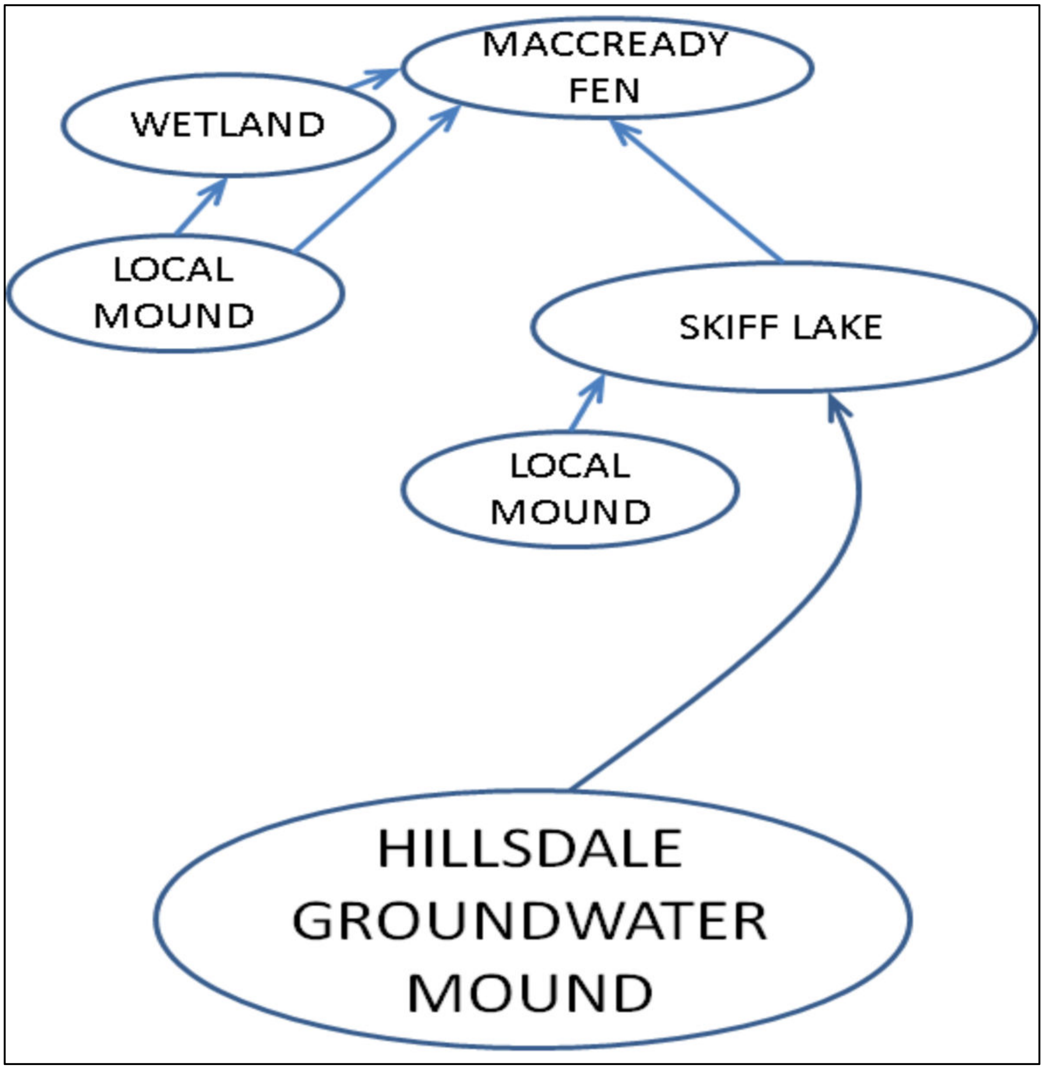

Figure 1-20 – Schematic representation of connectivity between the fen and its water sources.

Implications for management

Based on the sources of water to the fen and the delivery mechanisms, it is clear that that the system that supports the fen is larger, more complex, and more interconnected than might be expected. This has serious implications on sustainable management of the fen in the future, especially considering the possible effects of climate change and increasing human population. Climate change is expected to bring increased temperatures, which is likely to result in early springs, milder winters and greater precipitation. This may result in higher evapotranspiration rates, which can potentially lower the water table in the fens. The existence of fens is predicated upon maintaining permanently saturated conditions, thus lowered water tables could be very harmful. Higher rainfall rates would result in greater surface runoff resulting in inundation of fens, which would change the water chemistry (surface runoff is acidic) and thus affect the fens. Surface runoff is also more prone to contamination, which can threaten fen survival. Similarly, increasing human population will result in land-use changes, increased groundwater withdrawal, denser road networks (and associated road-salt), and increased demand for agricultural land, all of which pose serious threats to fens and the species they support.

Given the interconnected nature of this hydrologic system, and since the eventual source of water to multiple fens, lakes, streams, wetlands and aquifers is the regional groundwater mound, it is critical to preserve this master recharge area. In complex systems such as this, it is essential to understand the connectivity between the various system components, so that the entire system can be protected effectively. Such systems may be best protected by protecting the "critical" node of the system, i.e. the node that has the greatest impact on the overall system. For instance, although the regional groundwater mound may not provide water directly to any particular fen, it sustains the hydraulic gradient that drives the entire system. Thus, while protecting Skiff Lake would protect MacCready Fen, which is nearby, protecting the master recharge area (critical node) would be more efficient, since its impact would be felt over the entire system. Since fens occur at the critical interface between groundwater and surface water, and due to their sensitivity to changes in water level and water chemistry, they can be used as a barometer for the health of the overall system (Drexler *et al.* 2013). For instance, if regional groundwater recharge rates are lowered in the future, the fens will be among the first to disappear from the landscape due to correspondingly lowered water tables. In order to manage and protect these ecosystems in the future, a quantitative approach, such as the one demonstrated in this study, can be used to predict the effects of hydrologic perturbation on the fens. To offset the potentially harmful effects of these perturbations, various management options can be designed and evaluated using this quantitative framework, which can be used to select the most appropriate strategy for protecting the overall hydrologic system.

FUTURE WORK

The hierarchical multi-scale modeling methodology used in this study represents the first step in an effort to use a system-based approach towards understanding fen hydrology. Future work should focus on: 1) Probabilistic mapping of the fen's sources of water, 2) Quantifying the fen's water balance and apportioning the flow into the fens from different sources, and 3) Evaluating the impact of perturbations such as climate change on the fen.

Probabilistic mapping of sources of water

As discussed previously, the particle tracking approach used to identify the sources of water to the fen had some disadvantages, which could be overcome by using a more robust, albeit laborious approach. This would involve using each of the 100 realizations from the Transition Probability-based geologic model to create 100 groundwater models, all of which would be identical in all respects except the underlying geologic structure. By performing reverse particle tracking on each of these 100 models, a probabilistic envelope of possible water sources to the fen could be obtained. The greater the probability of a particular particle path, the higher the chance that water could come to the fen from that path. Such a probabilistic approach would be very valuable for decision-making while evaluating different management options. For instance, if two potential sources of water to the fen provide similar quantities of water, the more probable source would be more worthwhile to conserve.

There is another aspect to the connection between a fen and its source of water. In general, a deep, regional connection to the fen is more resilient to hydrologic disturbances than a shallow, local connection. The resilience of a connection is also determined by other geologic factors, such as the presence of a clay layer, which can protect against contamination. Thus, it is important to assess the connection between a fen and its water source based on its resilience. For instance, a connection that is deep or that is protected by a clay layer would need less protection from hydrologic perturbations, such as high-capacity pumping wells or potential sources of contamination.

Quantifying the fen's water balance

The models developed in this research almost entirely used information from statewide databases, but used very limited site-specific data for calibration. Although these models are quite robust in terms of predicting groundwater flow directions, there is considerable uncertainty in determining the actual flow rates into the fen from its different sources. Quantifying these flows is critical if these models are to be used as decision-making tools in the protection and preservation of such ecosystems. For this purpose, additional site-specific data would be needed:

1. Flow characteristics at the fen - A time-series of data such as the flow rate, pH, and temperature at these points would shed light on the magnitude of the various components of the water budget of the fen. Similar analysis at nearby surface water bodies (streams, lakes and wetlands), would indicate the connections that exist between them and the fen.

2. Water levels at the fen – The most distinguishing feature of fens is said to be that their water level remains rather steady throughout the year, which can be ascertained by collecting a time-series of water levels at the fen. This data would also be very helpful while calibrating a transient model for this system.
3. Groundwater elevations – Installing a network of nested piezometers near the fen and up-gradient of the fen would measure the groundwater elevations at various depths (shallow to deep). This would help understand flow-convergence and up-welling towards the fen, and could also be used to improve model calibration.
4. Groundwater chemistry – From the above-mentioned piezometers, water chemistry data can be collected, which, when used in conjunction with the fen's water chemistry data, would help quantify the relative contribution of local and regional flow systems to the fen.

Sustainable management of fens

The need for the quantitative framework demonstrated in this research is that it allows decision-making on the management of fens based on a scientific basis. For instance, the likely impacts of climate change, such as increased precipitation, higher temperatures, milder winters, and early springs, all of which can have a drastic impact on the fens and their hydrology. One of the likely impacts of climate change is much higher evapo-transpiration rates, which would lower the water tables that will cause the fens to shrink, fragment or even disappear. Similarly, increasing human demand for agricultural land to feed a growing population, which will be accompanied by an increase in urbanization, may have undesirable impacts on fens and affect their survival. The approach illustrated in this research can be used to model the effects of climate change, and to plan and evaluate appropriate conservation strategies for sustainably managing the fens into the future.

CONCLUSIONS

This research demonstrated a hierarchical, multi-scale groundwater modeling approach to understand the hydrologic processes that supports the survival of groundwater-dependent ecosystems such as fens. In particular, MacCready Fen in Southern Michigan was chosen for detailed multi-scale modeling in order to predict its sources of water and the corresponding delivery mechanisms. The results from this research showed that the fens obtain water from a combination of multiple sources, including a nearby wetland, a local groundwater recharge area, a nearby lake, and finally the regional groundwater mound (Hillsdale County). The major source of water to the fen was Skiff Lake, located about 600 meters away from the fen. The regional mound does not deliver water directly to the fen, but routes it through Skiff Lake, thus creating a "cascading" connection. In contrast, water from the local groundwater recharge area is delivered through a "direct" connection to the fen. These two mechanisms, the direct and cascading connections are the predominant delivery pathways for water from the sources to reach the fen. It is also important to note that MacCready Fen is one among a cluster of fens located around the regional mound, all of which may likely be connected to the regional mound through a similar network of sources. Thus, the groundwater system that supports MacCready Fen and other fens in the neighborhood is much larger, more complex and inter-connected than might be expected. The regional groundwater mound provides water to not just one fen, but for multiple fens, streams, lakes, wetlands and aquifers. This "master recharge area" is the most critical node in this inter-connected groundwater system, which needs to be protected to protect the entire ecosystem. Since fens are extremely fragile habitats that are among the first to disappear due to hydrologic disturbances, they can be used as barometers for the health of the whole ecosystem. This quantitative approach demonstrated in this research can be used for sustainable management of these fens in the future.

ACKNOWLEDGEMENTS

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Chapter 2 UNDERSTANDING THE HYDROLOGY OF A GEOGRAPHICALLY-ISOLATED FEN - IVES ROAD FEN IN SOUTHERN MICHIGAN

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ABSTRACT

Geographically-isolated fens, such as Ives Road Fen in southern Michigan, are outliers on the landscape that are located far away from other fens. The hydrogeologic processes that allow these seemingly isolated fens to survive are not very well understood. In this paper, we apply a data-enabled, hierarchical modeling approach to simulate the groundwater flow systems at all scales of interest (local- to regional-scale). We use a Transition Probability approach to accurately characterize the complex 3-dimensional geologic variability in the area of interest. We applied a three-dimensional reverse particle tracking approach to understand the flow systems and to delineate groundwater contribution areas to the fen. The modeling results show that the fen receives most of its water from a local recharge area, and a small pond located to the west of the fen. Regional sources of water to the fen include recharge from a till plain and the regional groundwater mound. The local sources to the fen deliver water through a "direct" connection to the fen. The regional mound delivers water through a "pipeline" consisting of a confined aquifer lying beneath an extensive clay layer. Water in this pipeline reaches the fen by upwelling

through a break in the clay layer. The regional mound that provides water to this isolated fen also provides water to other fen clusters. The major implication of these findings is that fen conservation requires a system-based approach to understand the inter-connected nature these ecosystems, rather than focusing on individual fens and their immediate surroundings.

INTRODUCTION

Wetlands are a product of climatic, hydrologic, geologic, and anthropogenic factors and are found in a variety of landscapes. They are most often seen in areas with shallow water or on floodplains of rivers, streams, lakes and estuaries. Wetlands are also seen in poorly drained depressions and are generally referred to as "isolated" wetlands (Tiner 2003). In the context of wetlands there has been considerable study of the factors that determine their isolation. Tiner (2003) states that "isolated wetlands" may be defined from a geographic, hydrologic or ecologic perspective. While geographic isolation is easiest to determine, hydrologic or ecologic isolation are much harder to define and need detailed studies. Tiner (2003) also points out that from the ecological standpoint, "there is no such thing as an isolated wetland," because "everything is connected to everything else." The generally accepted definition of a geographically isolated wetland (Leibowitz 2003; Leibowitz and Nadeau 2003) is a wetland that is "completely surrounded by upland" (Tiner 2003). The basis for this definition is that such wetlands do not have an obvious surface-water connection to nearby waters. This approach ignores the fact that these wetlands may be hydrologically connected through groundwater connections or by intermittent surface water connections during precipitation events. Winter and LaBaugh (2003) argued that the position of a wetland in a landscape determines its isolation from the regional groundwater flow system. They also pointed out that the hydraulic conductivity of the geologic materials dictates the degree of connection between surface water bodies, i.e. depending on whether it takes weeks or decades for water from a wetland to reach a nearby stream, the concept of isolation would change.

The only mechanisms by which isolated wetlands can lose water are through evapotranspiration or by loss to the groundwater system (Leibowitz 2003). The extent of operation of these two mechanisms depends on the hydrogeologic and climatic settings of the region. Depending on which of these mechanisms dominate, the effect of these wetlands is to attenuate flood peaks, reduce total runoff volume, slow delivery and desynchronize runoff (Leibowitz 2003). In terms of their role in the habitat too, isolated wetlands are known to support a high degree of biodiversity (Leibowitz and Nadeau 2003). Although it is not clear if the functioning of isolated wetlands is directly related to their isolation *per se*, it has been postulated that they are not truly isolated, but rather occupy an intermediate position in the "isolation-connectivity continuum" (Leibowitz and Nadeau 2003).

Bedford and Godwin (2003) state that fens, which are groundwater-fed wetlands that support a disproportionately large number of plant and animal species, are by definition isolated wetlands. The unique characteristics of fens arise from the fact that they occur at the headwaters of streams and lakes, such that they are isolated from surface waters, but intimately connected to groundwater (Bedford and Godwin 2003). It has also been demonstrated that headwater streams have a "profound influence on shaping downstream water quantity and quality" (Alexander *et al.* 2007). Moreover, fens also buffer water temperatures as they provide cooler water in summer and warmer water in the winter months (Amon *et al*. 2002). Thus, the role of fens in protecting the overall ecosystem is thus truly multi-dimensional.

Fens in southern Michigan generally tend to occur in geographic clusters, as seen from Figure 2-1. It is well known that fens need the right combination of climatic, hydrogeologic and topographic conditions in order to survive (Bedford 1996, 1999; Bedford and Godwin 2003; Winter 1992; Winter *et al.* 1998). This indirectly implies that although fen occurrences are rare, given favorable conditions (climate and hydro-geology), it is likely that fens will occur in clusters. Bedford and Godwin (2003) mapped 78 fens in New York and 73 fens in Wisconsin, many of which appear to be part of clusters. In Michigan, such fen clusters are found around regional groundwater mounds that are the headwaters to many major streams. However, a few fens (such as Ives Road Fen in Figure 2-1) are geographically "isolated" from these clusters. Even though the hydrology of fens, in general, is not very well understood, it is conceivable that when fens are part of a geographic cluster they may share the same source(s) of water or obtain their water through similar delivery mechanisms. The hydrology of isolated fens, on the other hand, is even less well understood and may potentially offer valuable insights into the groundwater processes that are so vital to fens and the many species they support.

It is important to point out that Ives Road Fen does not fit Tiner's (2003) definition of an isolated wetland since it occurs on a topographic slope. Bedford and Godwin (2003) provide another context for isolation, i.e. fragmentation of fens within fen clusters due to the impact of human activities. Ives Road Fen does not satisfy this requirement either. Nor indeed is Ives Road Fen located near the regional groundwater mound or small headwater streams like other fens in this area. Instead, it is separated from the regional mound by a glacial till plain, and is located adjacent to a 3^{rd} order stream of the Raisin River. The closest fen to Ives Road Fen is located almost 19 kilometers away, while the average inter-fen distance among 150 fens in Michigan is just over 5 kilometers. Almost two-thirds of these 150 fens have at least one adjacent fen less than 5 kilometers away. Only 10% of the fens have their nearest fen more than 10 kilometers away, of which only 2 other fens have a neighbor farther away than does Ives Road Fen. Thus, while Ives Road Fen is not the only fen that is geographically isolated, it is clearly one of the most isolated. In this context, we use the term "isolated fen" to signify the geographic, and seemingly hydrologic, isolation of Ives Road Fen in the landscape.

OBJECTIVES

Using a quantitative framework to understand the complex inter-play between climate, hydrology, geology and topography that creates conditions favorable to the formation of groundwater-dependent ecosystems such as fens is a challenging task. The overall objective of this research is to use a process-based groundwater modeling approach to quantitatively understand the hydrologic system that supports the existence of a geographically-isolated fen. In particular, this study attempts to understand the hydrology of Ives Road Fen in southern Michigan. The specific objectives of this study are to:

- Delineate the source water areas for Ives Road Fen,
- Identify the corresponding water delivery mechanisms to the fen, and
- Assess the implications of the findings on management of such fens.

METHODS

In order to accomplish these overall objectives, a hierarchical, multi-scale modeling approach was used. A Transition Probability approach was used to model the complex 3-D geology. More details on these two approaches are provided in Sampath *et al.* (manuscript in preparation).

SITE DESCRIPTION AND CONCEPTUAL MODEL

Ives Road Fen is located on a narrow strip of coarse-grained outwash material adjacent to the Raisin River in Lenawee County in southern Michigan (Figure 2-1). The predominant glacial material in this area is a fine-grained glacial till that occurs on both sides of the Raisin River extending significantly towards the east and west of the river. The local and regional topography, geology and hydrology (streams and lakes) for the fen is discussed next, on the basis of which, the conceptual model for this site is developed.

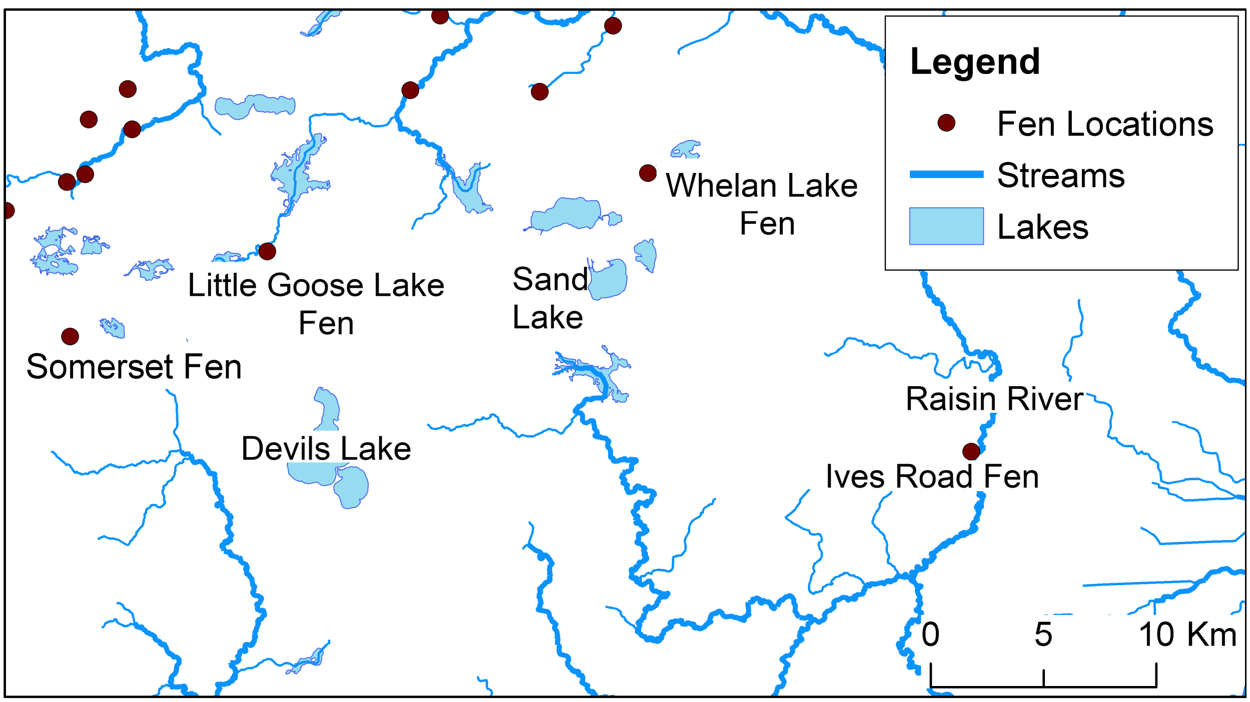

Figure 2-1 – Plan view of Ives Road Fen in southern Michigan.

Multi-scale Topography and Hydrology

Ives Road Fen is bordered to its east by the Raisin River and to the northwest by a small pond. The distance between the pond and the Raisin River is about 500 meters, but the difference in their water levels is almost 5 meters. The land surface slopes away rather steeply from the pond towards the river, and on this relatively steep slope, Ives Road Fen is located. Due to this slope, there is no ponding of water on the fen, as all surface water runs off towards the Raisin River. At the regional scale, the topography slopes gently towards Raisin River from the Hillsdale mound as seen in Figures 2-2 and 2-3. In areas where there is a general topographic slope with relatively negligible local topographic relief, such as in this case, it is common for regional groundwater flow systems to develop (Toth 1963). Apart from Raisin River, there are no other large surface water bodies near the fen. The nearest large lakes (Lake Erin, Sand Lake, and Wamplers Lake) are almost 16 kilometers away to the west of the fen at the edge of the Hillsdale groundwater mound.

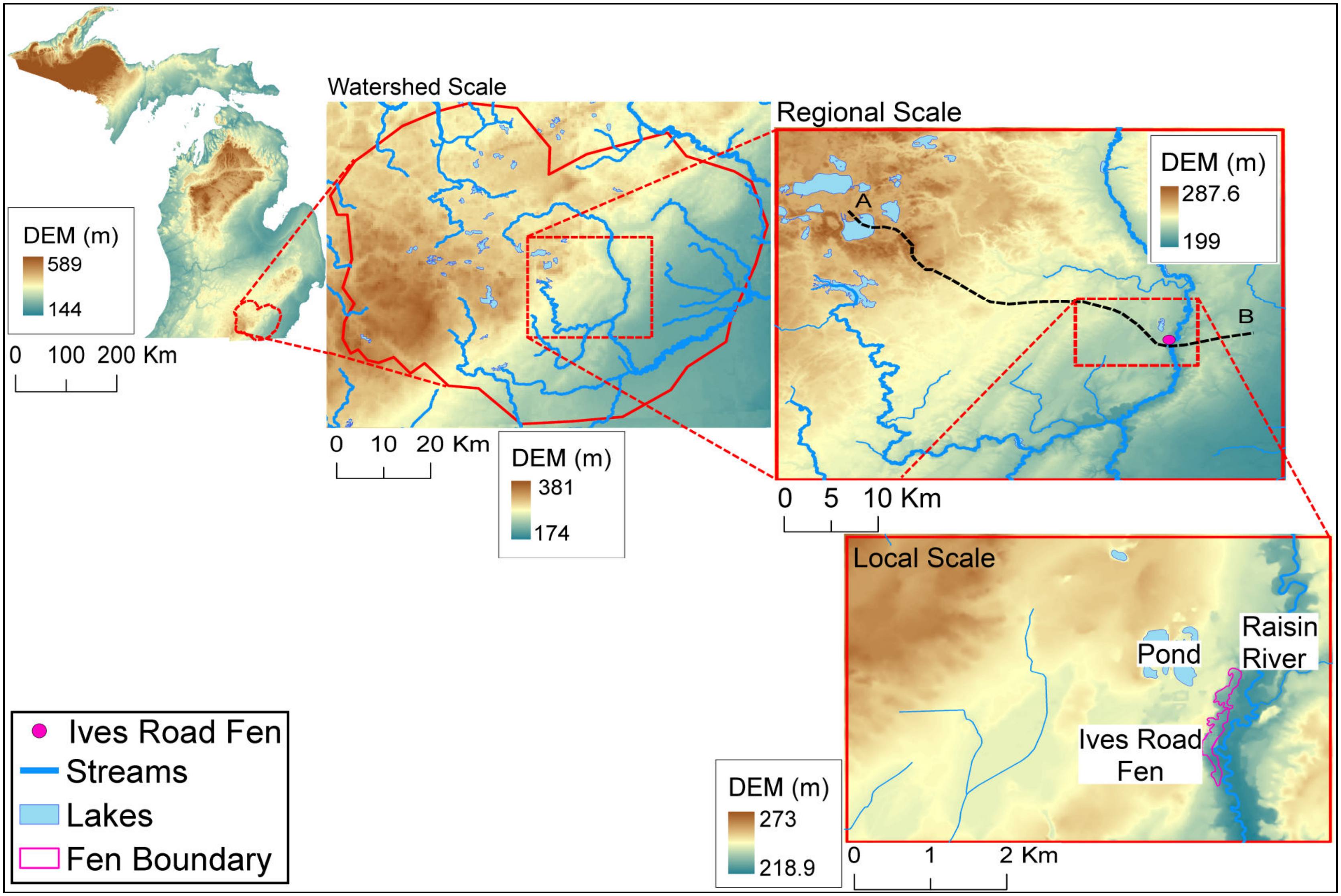

Figure 2-2 – Multi-scale representation of Topography and Hydrology for Ives Road Fen (NED USGS 2006; NHD USGS 2010).

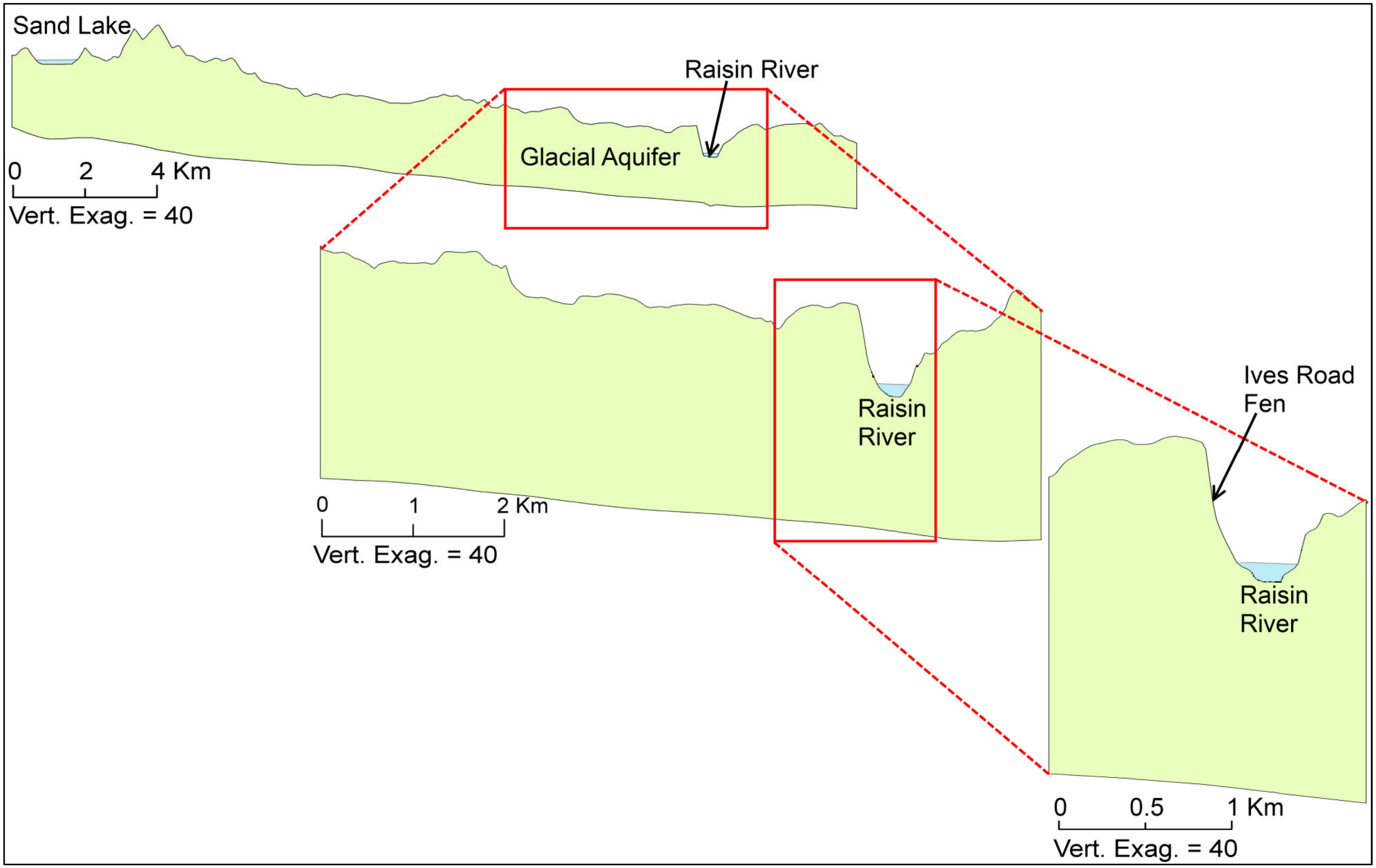

Figure 2-3 – Multi-scale cross-section views of topography along cross-section AB (Figure 2-2).

Geology

The shallow glacial geology in a narrow band along Raisin River consists of a coarse-grained deposit created by a glacial outwash channel (Figure 2-4). Under this well-sorted material, older fine-grained clay-like materials are found. Evidence for this is seen in the well logs from the statewide database (GWIM 2006). At the regional scale, the shallow outwash aquifer is bordered on its west by a series of moraines and till plains composed of medium- and fine-textured tills (Figure 2-5). There are a few large lakes at the northeastern edge of Hillsdale mound, which lie past the till plain. From the borehole data it is seen that there is a fairly thick (more than 30 meters) and extensive clay layer in the till plain, beneath which a confined aquifer is found. From the borehole data we can also infer that there may be a break in the clay layer at the intersection of the till plain and the shallow outwash aquifer. This break connects the lower confined aquifer to the shallow outwash aquifer adjacent to the Raisin River. This can create preferential flow paths, resulting in interesting flow patterns. The deeper bedrock unit in this area is the Coldwater Shale formation, which is a confining unit and can be assumed to be a no-flow boundary (Figure 2-6). Given the complex geologic environment in this area, this geology needs to be resolved with as much detail as possible in order to understand the fen's hydrology. Due to the relatively high density of borehole data, it is possible to create a complex, 3-dimensional geologic model at a fine resolution using a Transition Probability approach, which is discussed next.

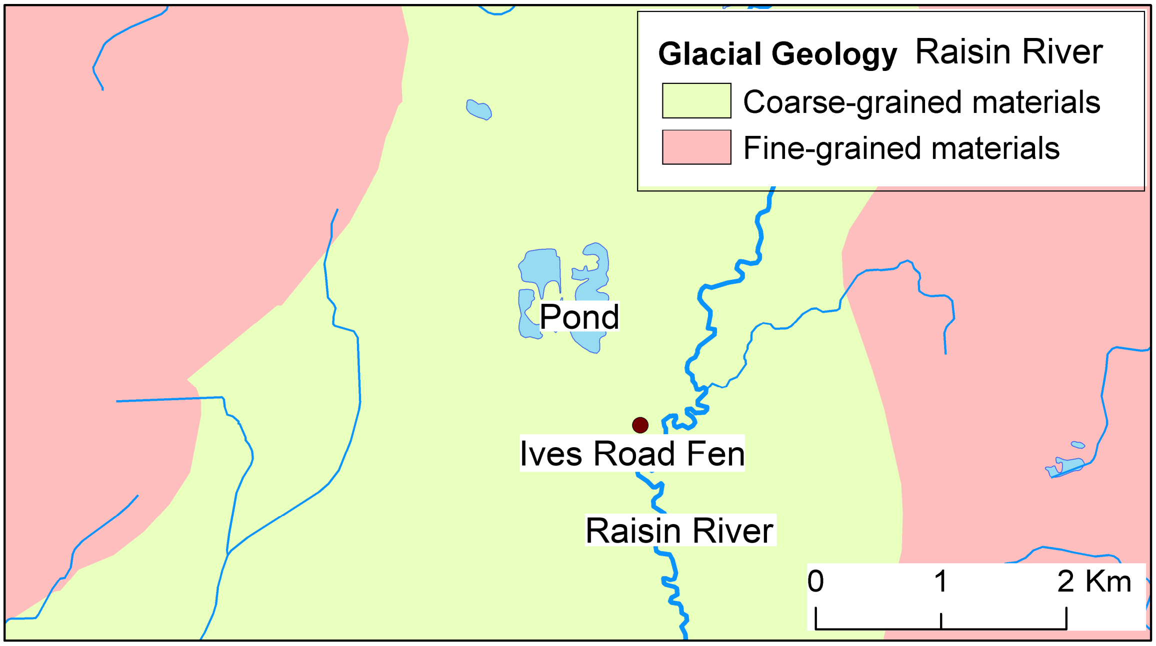

Figure 2-4 – Local glacial geology near Ives Road Fen.

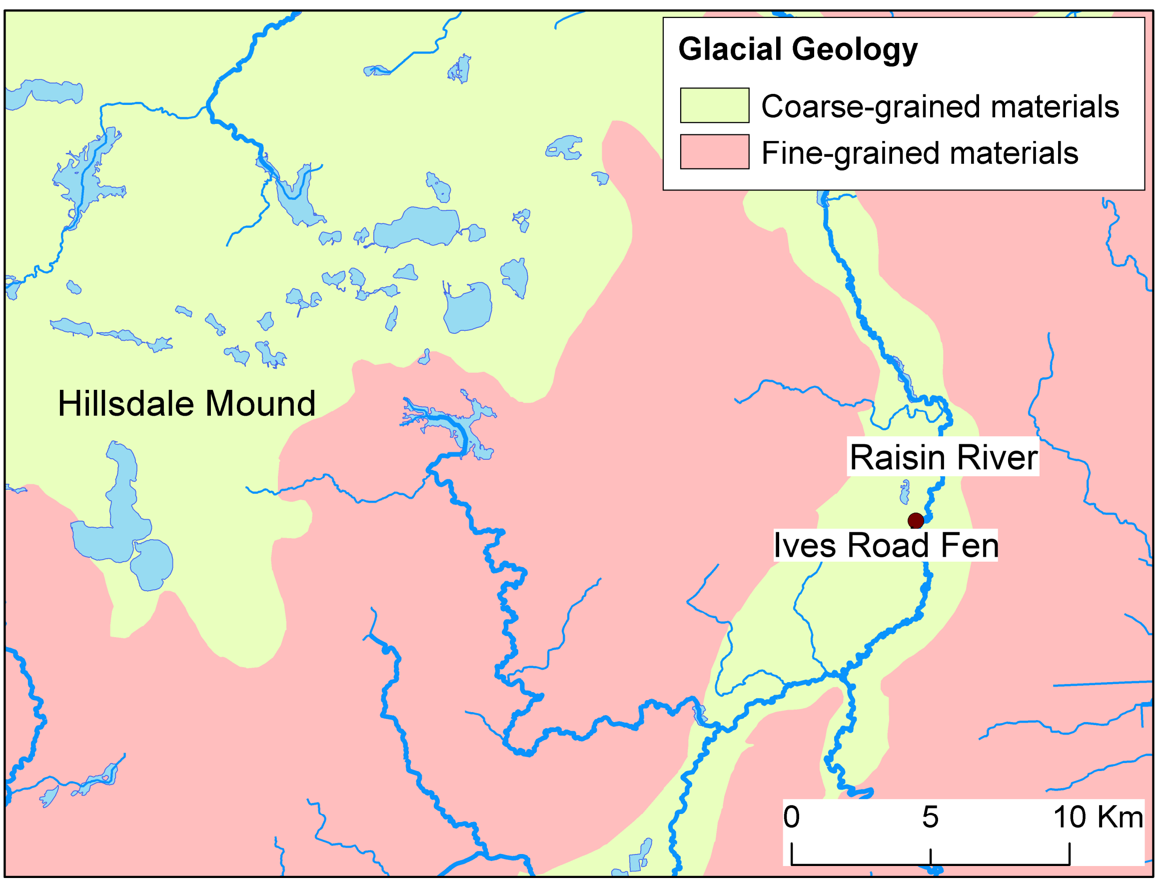

Figure 2-5 – Regional glacial geology.

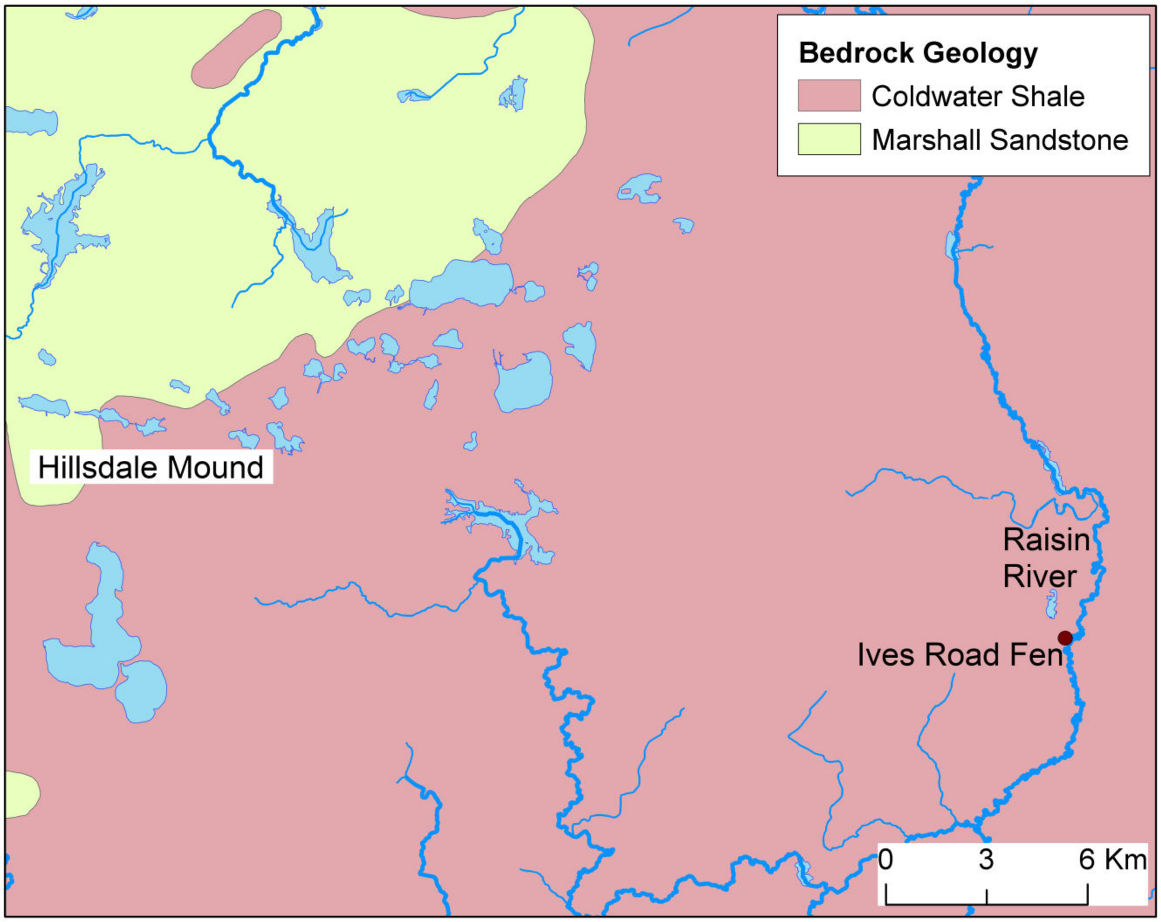

Figure 2-6 – Regional bedrock geology.

Modeling complex geology - Transition Probability Approach

In order to represent the complexity in the geologic environment near Ives Road Fen, a geologic model was created using a Transition Probability approach. Multi-scale lithologic data from the statewide groundwater database (GWIM 2006) was used for this purpose (Figure 2-7). The Transition Probability approach was simulated using T-PROGS (Transition Probability Geo-Statistical Software) (Carle 1999). The first step in this approach was to classify the different geologic materials using lithologic information from borehole data. For example, 'Sand' or 'Gravel' in a well borehole was classified as a good aquifer material ('AQ'). Similarly, 'Clay' or 'Silt' was classified as a confining material ('CM'). Other materials that were neither 'AQ' nor

‘CM’ were further sub-divided into ‘MAQ’ (marginal aquifer) or ‘PCM’ (partially confining material). In principle, the borehole data may be classified into any number of such materials. For the sake of simplicity, 4 materials, ‘AQ’, ‘MAQ’, ‘PCM’ and ‘CM,’ were used to model the entire range of variability of geologic materials.

Using the above-mentioned classification scheme for the lithologic data, the geologic model was created as described in Carle (1999). The geologic model was constructed using more than 2700 boreholes. The most prominent feature in the geology of this area was the presence of the fairly thick and extensive till plain, which was replaced by the shallow outwash deposit close to the Raisin River. The geologic model was manually calibrated by adjusting the values of the anisotropy ratio, i.e. the ratio of the horizontal extent of an aquifer material to its vertical extent. The vertical extent of each aquifer material was reflected in its average vertical thickness, which was inferred directly from the data. For instance, if the data showed that the average thickness of a piece of clay was 5 meters, and if the anisotropy ratio was set to 10, then the horizontal extent of the clay would be 50 meters. The calibration was done by visually examining the extent and continuity of the clay layer (till plain), and the shallow outwash aquifer. Details of the calibrated geologic model are provided in Table 2-1. Since each realization of the geologic model represents only one likely geologic scenario, 100 realizations of the geologic model were simulated. The eventual geologic model was created by choosing the most likely possibility of the 100 realizations. For example, if in a particular grid cell of the geologic model, the distribution of ‘AQ’, ‘MAQ’, ‘PCM’ and ‘CM’ over the 100 realizations was 15, 5, 5 and 75 realizations respectively, then that grid cell would be assigned ‘CM’ as the aquifer material. Thus, it was possible to evaluate the likelihood of the break in the clay layer discussed previously.

Table 2-1 – Details of the geologic model.

Parameters		Value
NX, NY, NZ		180, 163, 117
DX, DY, DZ (m)		160.3, 159.5, 1.5
Average vertical thickness (m)	‘AQ’	6.8
	‘MAQ’	5.6
	‘PCM’	6.7
	‘CM’	11.5
Ratio of horizontal extent to vertical thickness	‘AQ’	15
	‘MAQ’	4
	‘PCM’	4
	‘CM’	8.13

A 3-D view of the geologic model is presented in Figure 2-8. Cross-section views of the geology and a percentage likelihood map for the occurrence of ‘CM’ along this cross-section are presented in Figure 2-9. From these plots it can be seen that the till plain is fairly thick and extensive and is also the most likely geologic scenario as seen from the high percentage likelihood of occurrence of ‘CM’. The percentage likelihood of ‘CM’ in the shallow outwash aquifer is also extremely low, which is also expected (low likelihood of ‘CM’ corresponds to high likelihood of ‘AQ’ and vice versa). Note that at the intersection of the till plain and the shallow outwash, there is an area of low likelihood of ‘CM,’ (less than 20%) which indicates that the likelihood of a break in the clay layer is more than 80%. This may be critical in creating upwelling of water from the regional system towards the Raisin River, and potentially to the Ives Road Fen.

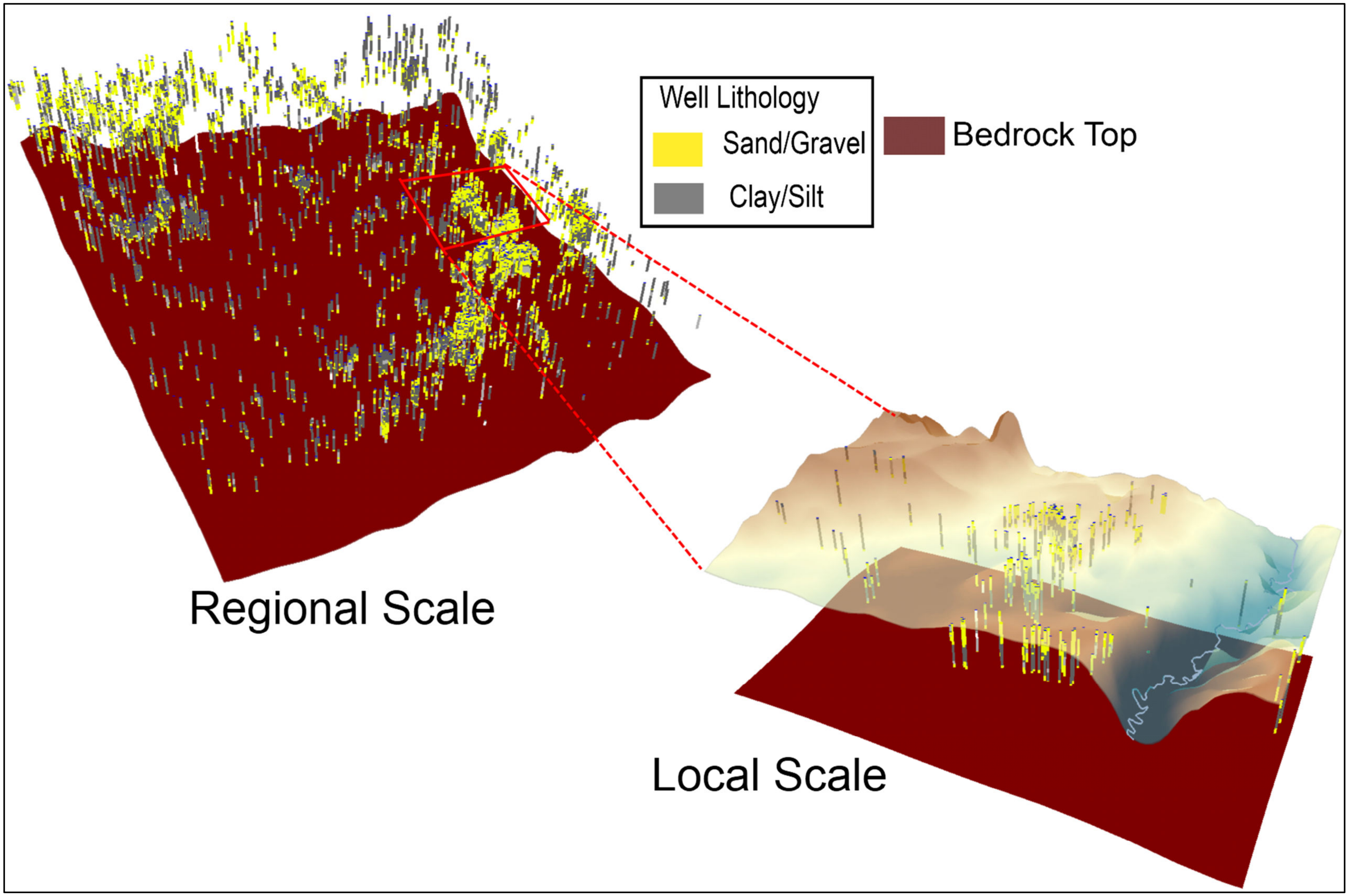

Figure 2-7 – Multi-scale Well Lithologic Data from the Michigan Statewide Groundwater Database (GWIM 2006).

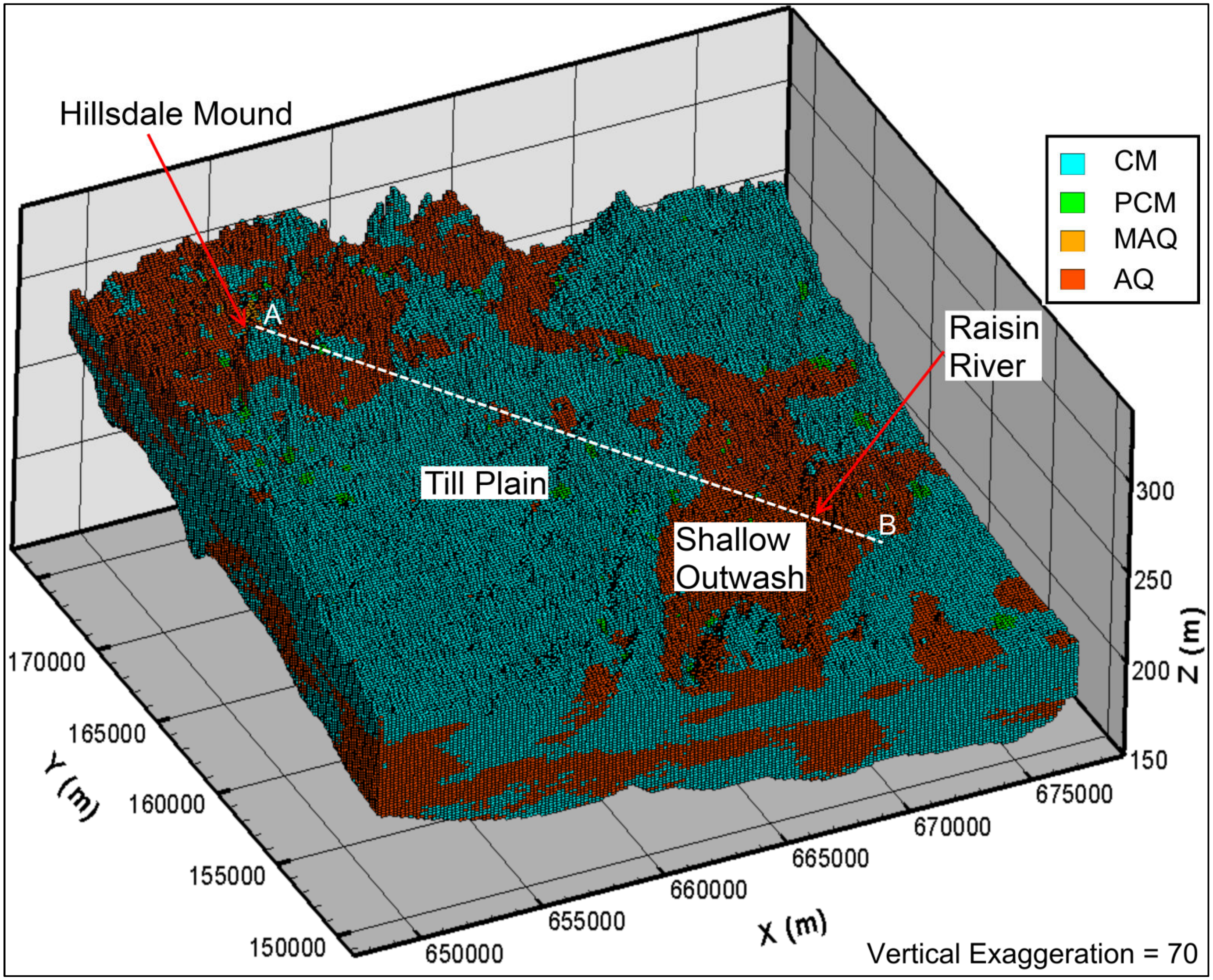

Figure 2-8 – Transition Probability-based geologic model from Lithologic data using TPROGS (Carle 1999).

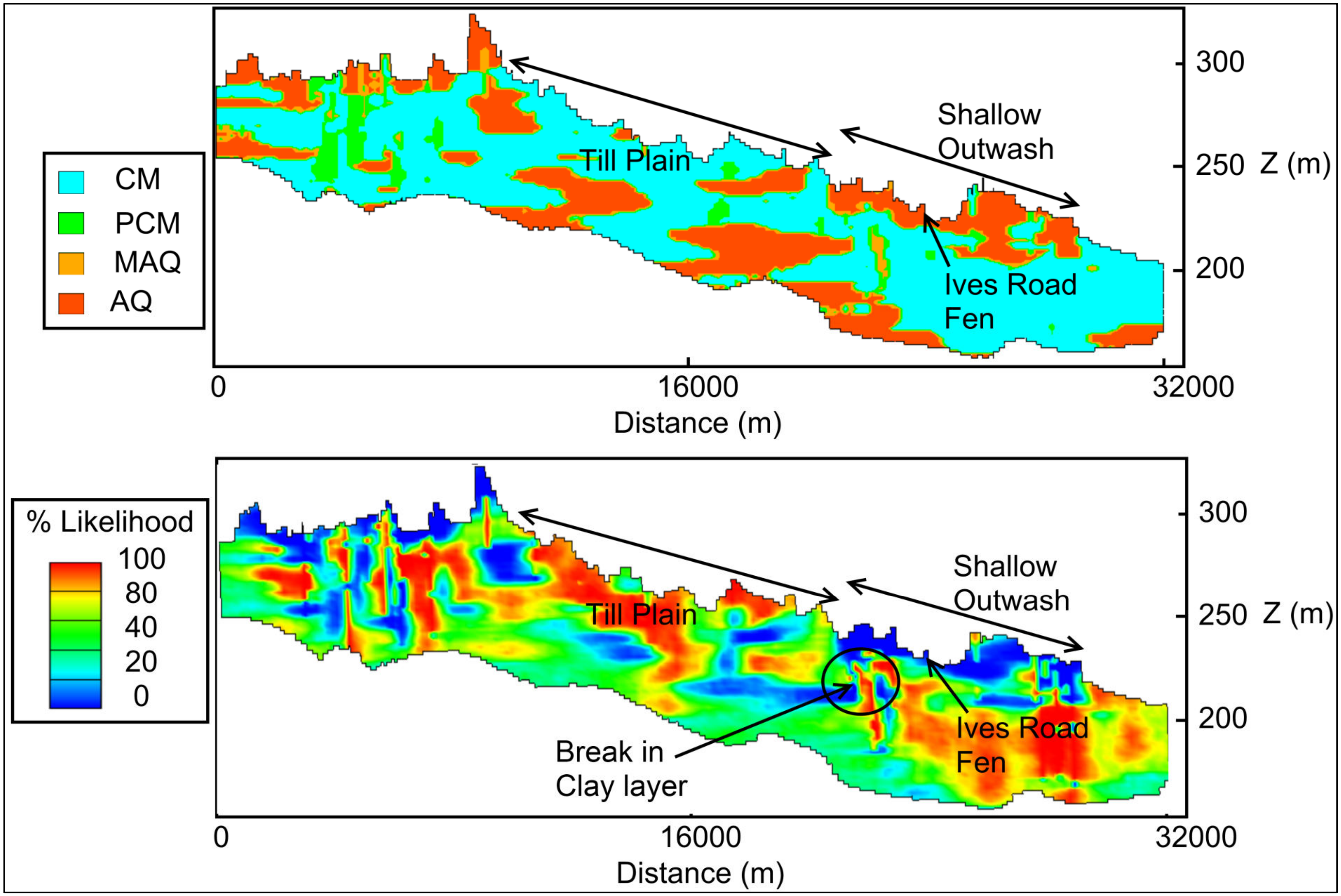

Figure 2-9 – View of cross-section AB (Figure 2-8) from the geologic model and percentage likelihood of occurrence of 'CM' (clay).

Conceptual Model

Based on the understanding of the local and regional hydrogeologic and topographic features, it is clear that the regional discharge area is Raisin River, which must receive water from Hillsdale groundwater mound, the regional recharge area. From the 3-D geologic model created from the lithologic data it is clear water from the mound reaches Raisin River through the confined aquifer beneath the clay layer. In order to conceptualize this connection, the confined aquifer can be thought of as "pipeline" protected by the clay layer. The two ends of this "pipeline" are connected to the regional mound and to Raisin River. The hydrologic connection to Raisin River is achieved by means of a break in the clay layer created by depositional processes along the river. Ives Road Fen, which is on the banks of Raisin River, benefits from this complex geologic process. Figure 2-10 presents a schematic conceptual model for this regional connection between the Hillsdale mound and Ives Road Fen. At the local scale, the fen likely receives water from the small pond to its west and the local recharge area into the shallow outwash aquifer (Figure 2-11).

Although the conceptual model of this system is clear, modeling this complex geology is very challenging. The conventional methodology of groundwater modeling is to divide the vertical extent of the model into geologic layers, such as glacial and bedrock aquifers. From the lithologic data, it is evident that this kind of systematic 3-dimensional variability in aquifer materials is hard to model using a quasi-3D approach of geologic layers. In order to account for this kind of variability, a fully 3-dimensional geologic model is needed. Obviously, such a model will need much greater vertical resolution in order to accurately characterize the variability in distribution of aquifer materials.

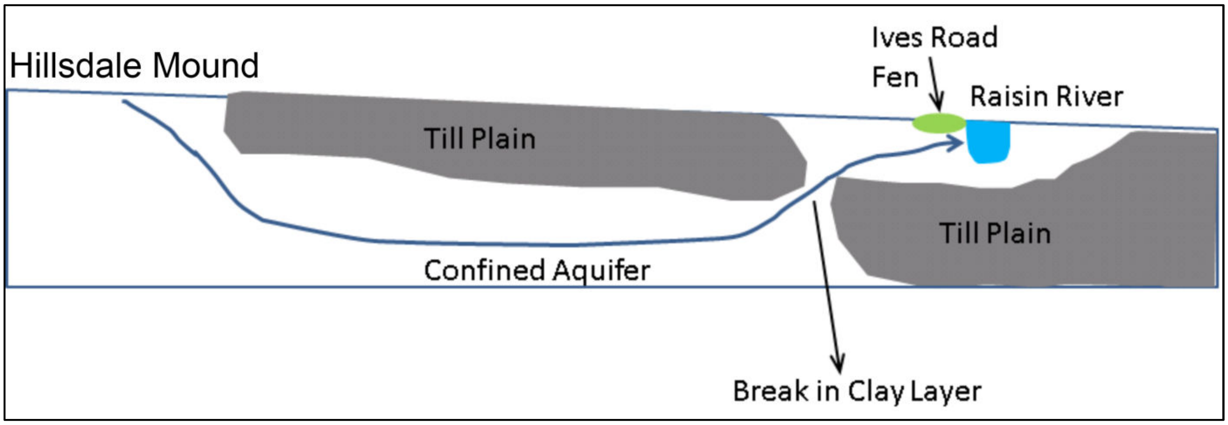

Figure 2-10 – Regional conceptual model for Ives Road Fen.

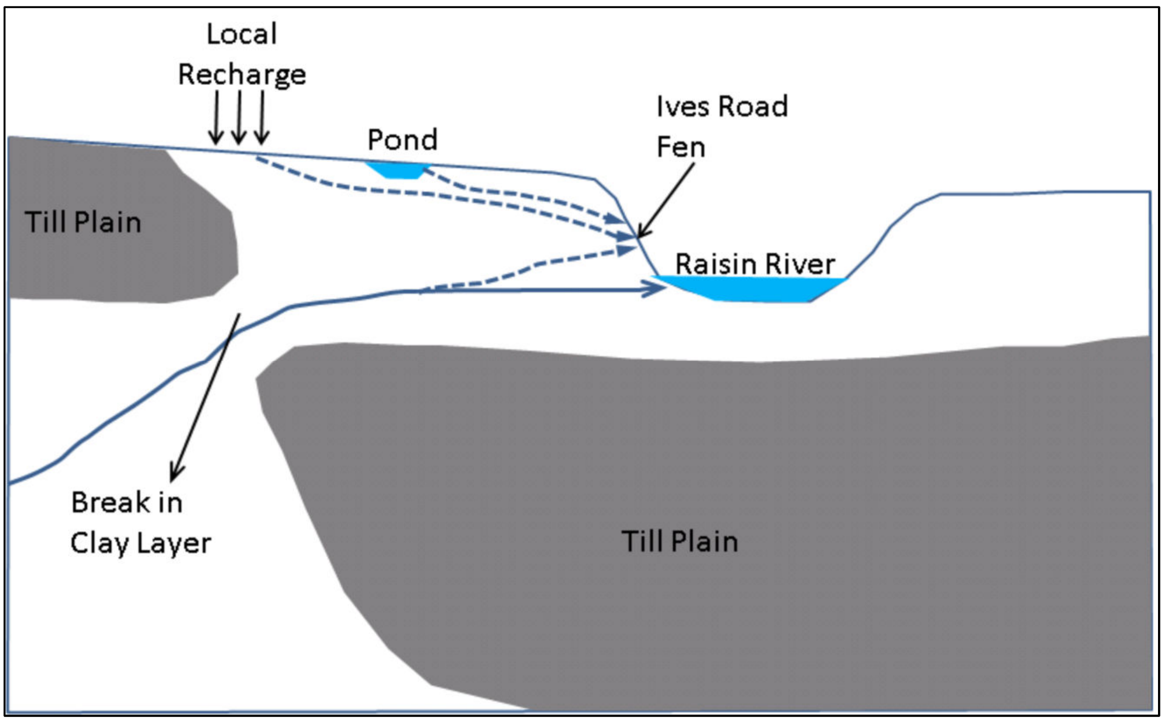

Figure 2-11 – Local conceptual model for Ives Road Fen.

MULTI-SCALE MODELING

Data for Multi-scale modeling

Topography and aquifer geometry, which form the hydrogeologic framework, are critical to the formation of local, intermediate, and regional systems of groundwater flow (Toth 1963;

Winter 1988). The ability of the multi-scale models to capture this hydrogeologic framework depends both on the data resolution and the model's resolution. The land surface elevation was modeled using 10 meter Digital Elevation Model (DEM) data (NED USGS 2006). Surface water features (lakes and streams) were incorporated from the National Hydrographic Database (NHD USGS 2010), based on the model's spatial resolution, i.e. lakes smaller than the model's grid size were not modeled at that scale. The Transition Probability approach that was used to model the aquifer geometry used borehole data from the well logs in the statewide database (GWIM 2006).

Model Development

A hierarchy of steady state groundwater flow models was developed for Ives Road Fen using the data-enabled, multi-scale modeling framework (Sampath *et al.* (manuscript in preparation)), such that the multi-scale hydrologic processes were adequately resolved. Details of the hierarchical model are provided in Table 2-2. While the applicability of a steady state model to replicate long-term average conditions at the regional scale is justified, its relevance at the local scale is questionable. However, since many studies have noted that fens are characterized by saturated conditions throughout the year without being inundated for any significant length of time (i.e. a steady water table), a steady state model at the local scale was deemed to be sufficient to simulate the fen's water table.

Table 2-2 – Details of discretization of the hierarchical modeling system.

Model	NX	NY	NZ	DX (m)	DY (m)
Watershed Scale (M^{01})	207	169	4	449.0	450.2
Regional Scale (M^{11})	175	158	16	150.9	150.7
Local Scale (M^{21})	213	152	16	30.0	30.0

The multi-scale models were conceptualized using only one geologic layer to represent both glacial and bedrock aquifers. In the areas where the Coldwater Shale formation was the bedrock unit, the glacial aquifer was considerably thick and was explicitly modeled as one geologic layer, with the shale formation at the bottom as a no-flow boundary. In the remaining model area where the Marshall Sandstone formation was the bedrock unit, the glacial aquifer and Marshall Sandstone formation were combined into one geologic layer as the glacial aquifer is quite thin in this area. Beneath the sandstone lies the Coldwater Shale, a confining unit, and was thus modeled as a no-flow boundary at the bottom. The top of the Coldwater Shale formation was used as the bottom of the geologic layer and was obtained from the statewide database (GWIM 2006). This geologic layer was vertically discretized into 16 computational layers in order to resolve the vertical variability in the geologic model created from the Transition Probability approach. The Transition Probability approach classified the lithologic data from the well logs into 4 materials, ‘AQ’, ‘MAQ’, ‘PCM’ and ‘CM’, corresponding to the range of variability from a good aquifer material to a confining material. The hydraulic conductivity for every model grid cell was calculated based on the proportion of the two materials occurring within the cell using typical hydraulic conductivity values for the two materials.

Aquifer recharge values for the model were assigned from the statewide database (GWIM 2006). The area with the extensive till plain was modeled using a lower rate of recharge, which was thought to be appropriate for an area with significant clay thickness. Streams and lakes were modeled as two-way head-dependent boundaries, while the land surface elevation was modeled as a one-way drain with drain elevation set to land surface elevation. The leakances for the streams and lakes were assigned based on their sizes, details of which are provided in Tables 2-3 and 2-4.

Table 2-3 – Stream leakances and water depth based on stream order.

Stream Order	Leakance (m/day)	Water depth (m)
1	1	0.3
2	2	0.5
3	5	1
4	10	1.3
5	20	1.6
6	50	2

Table 2-4 – Lake leakance and water depth based on lake size.

Lake area less than (acres)	Leakance (day^{-1})	Water depth (m)
1	0.005	0.3
10	0.01	0.5
100	0.05	1
1000	0.1	1.3
10^4	1	1.6
10^5	5	2
10^6	10	3
10^7	20	4
10^8	50	5
10^9	100	6

<u>Model Calibration and Particle Tracking</u>

The models were calibrated using static water levels at water wells from the statewide database and base-flow estimates at USGS stream-flow gaging stations. The calibration parameters for the model were: a) multiplication factor for the aquifer recharge rate, b) recharge in the till plain, c) multiplication factors for the lake and stream leakances and the drain leakance and d) typical hydraulic conductivity (*K*) values for 'AQ' and 'CM.'. The first three calibration parameters were mainly used to calibrate the model to the observed base-flow at the USGS stream-flow gauging station on the Raisin River (USGS Site 04176000). Since the till plain comprised of an extensive clay layer, its recharge rate was likely to be rather small, and therefore, its recharge rate was also calibrated. The hydraulic conductivity values for 'AQ' and 'CM' were calibrated to match the hydraulic heads at the wells from the statewide database. Although the geologic model classified the aquifer materials into 4 types, the groundwater model converted this geology into a binary system comprising 'AQ' and 'CM,' which represented the whole range of variability in *K* values. The typical *K* values for 'AQ' and 'CM' were manually adjusted to minimize the error between observed and simulated hydraulic head values. The final calibrated model parameters are presented in Table 2-5. The calibrated model was used to perform 3-D reverse particle tracking to identify the sources of water to the fen.

Table 2-5 – Calibrated model parameters.

Parameter	Value
Multiplication factor for Recharge	1.55
Recharge in the till plain (inches/year)	2
Multiplication factor for lake and stream leakances	10
Multiplication factor for drain leakance	0.0001
Hydraulic conductivity 'AQ' (ft/day)	100
Hydraulic conductivity 'CM' (ft/day)	1

RESULTS AND DISCUSSION

The results from the hierarchical modeling system are presented and discussed next. Figure 2-12 shows the results from the hierarchical models for Ives Road Fen.

Hierarchical calibration

The base-flow into the Raisin River predicted from the model was 530469 m^3/day, which was in agreement with the observed base-flow for the Raisin River at Adrian (USGS Site 04176000) of 538000 m^3/day (approximately 220 ft^3/second). Figure 2-13 shows the comparison of observed water levels with the predicted model heads for the regional and local models. At the regional scale, there were 720 data points to compare with the model, which decreased to 31 at the local scale. At the site scale, no meaningful comparison was possible due to lack of data. From the calibration plots we see that the hierarchical model was able to reasonably simulate the observed hydraulic heads at the regional scale. The reason for the relatively poor performance of the model at the local scale can be a combination of two factors: i) poor data quality due to measurement error, temporal bias or geo-spatial inaccuracies and ii) inability of the model to resolve local geologic features due to lack of data. Moreover, the data used for this calibration was from the statewide database, which reflects the long-term steady state conditions, since the data were collected at various points in time, indeed across decades and during various seasons. The significant advantage of using this data is that the data quantity is much larger than typically used in groundwater studies. Needless to say, model calibration with this kind of data is relatively difficult, and fitting the model through the "cloud" of data may be considered to be relatively satisfactorily. Also, since this study did not involve any additional site-specific data collection, this drawback could not be overcome.

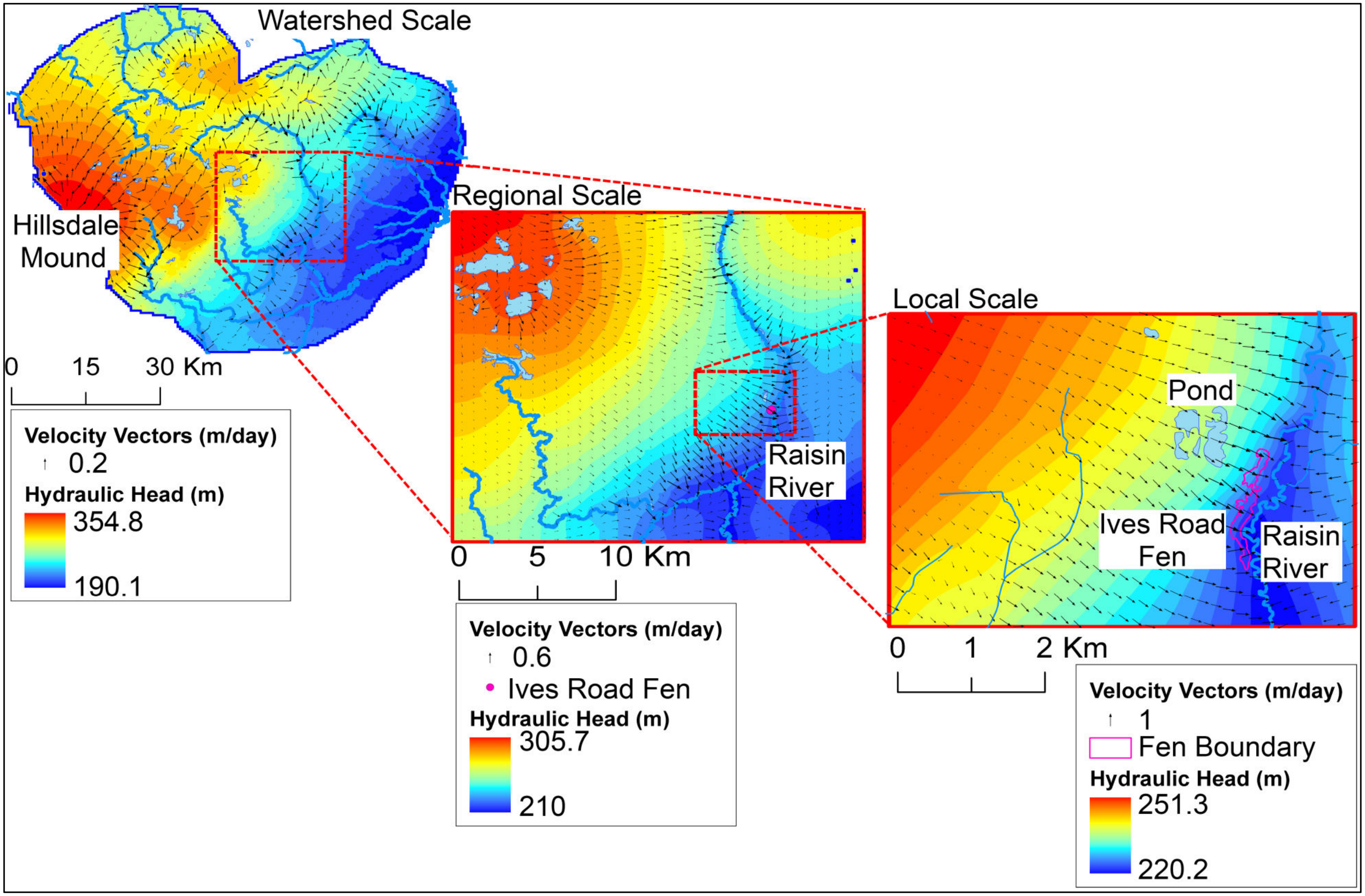

Figure 2-12 – Groundwater head contours from the hierarchical modeling system (1st model layer).

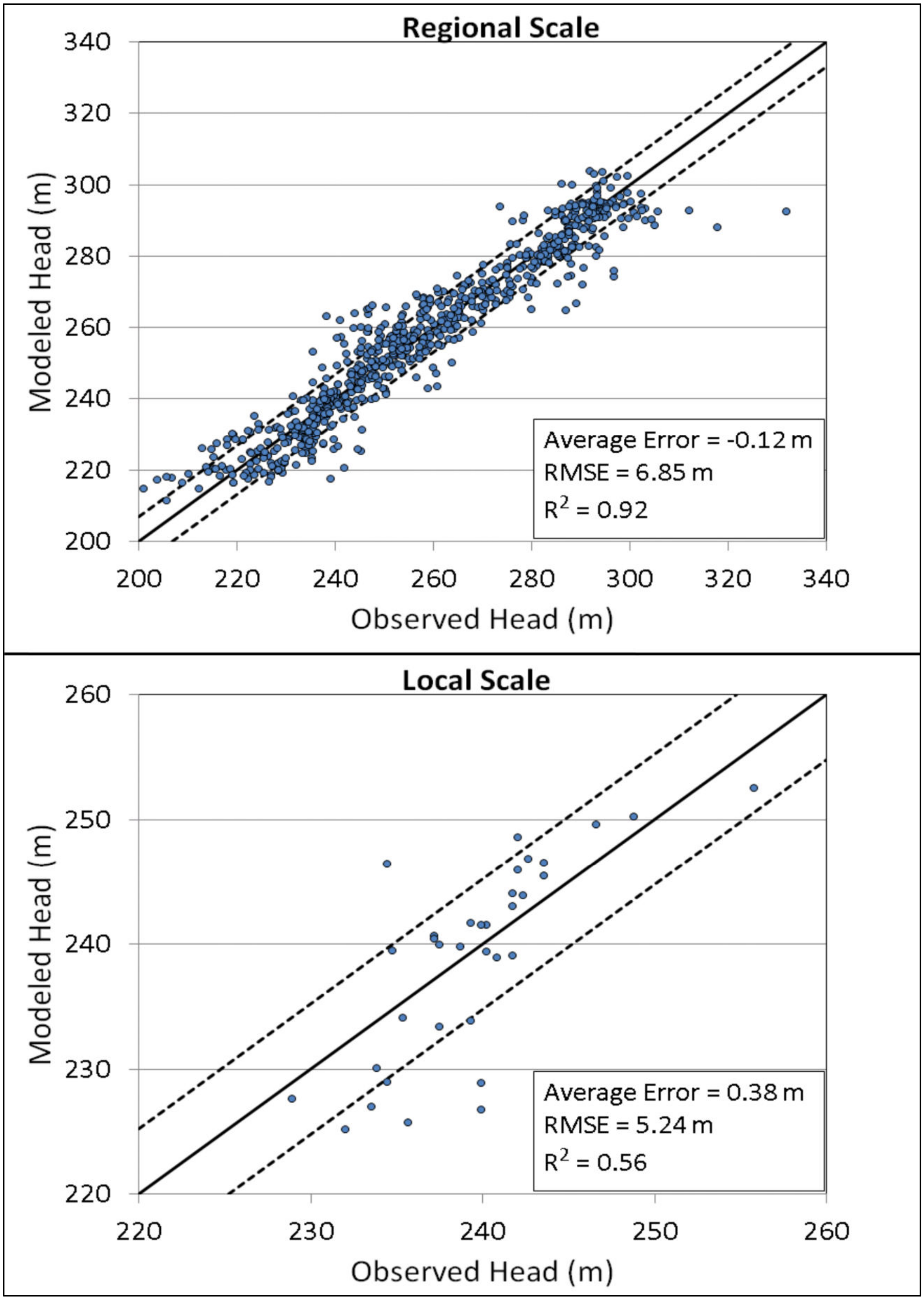

Figure 2-13 – Hierarchical calibration charts for hydraulic heads.

Sources of water and delivery mechanisms

The results from reverse particle tracking in Figure 2-14 show that Ives Road Fen is getting its water from multiple sources, including the small pond located to the west of the fen and local recharge in the shallow outwash aquifer. At the regional scale, water comes to the fen from recharge into the till plain and also from as far away as the northeastern edge of the Hillsdale groundwater mound (Sand Lake). These predicted sources of water are in agreement with the conceptual model for this site. The pond and local groundwater recharge deliver water to the fen through two distinct mechanisms, namely “direct” and “cascading” connections. Water from the local recharge area is delivered directly to the fen. On the other hand, water from the local surface- and ground-watershed is delivered to the small pond, and then flows to the fen, and can be called a cascading connection. The regional sources deliver water to the fen through a completely different mechanism, which may be called a “pipeline” connection. Recharge from the till plain and the Hillsdale mound flows through the confined aquifer beneath the protective clay layer, and emerges through a break in this clay layer into the shallow outwash aquifer. Here, it joins the local flow towards the Raisin River and provides water to the fen. Therefore, contrary to the definition of Ives Road Fen as an “isolated” fen, it is, in fact, hydrologically connected by a combination of geologic factors to the same regional mound that provides water to other fen clusters. The particle tracking approach only indicates the sources of water to the fen, but does not indicate precisely the flux that enters the fen or the relative contributions from the different sources delineated. Even though no direct data is available that can indicate the fen’s influx, a preliminary mass balance analysis is performed for the fen and the pond nearby. Following this, another mass balance analysis is performed to attempt to quantify the contribution of water from each source to the fen.

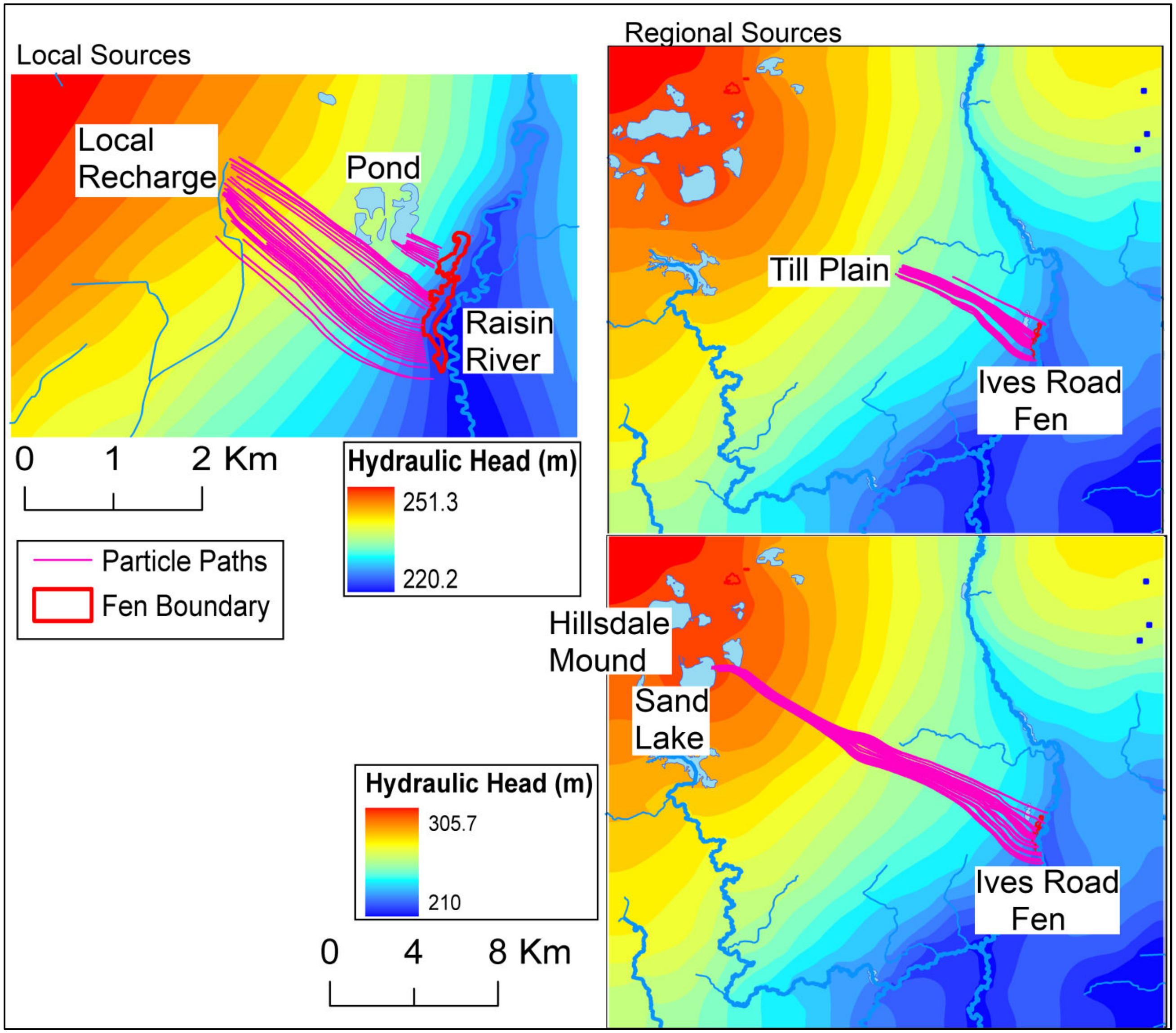

Figure 2-14 – Multi-scale particle tracking results depicting sources of water to Ives Road Fen.

Mass balance analysis for the fen

In the absence of any site-specific flux data at the fen, the mass balance analysis for Ives Road Fen is difficult to constrain. Given the size of the fen (~ 270,000 m^2), and a potential evapo-transpiration (*PET*) rate of 762 mm/year (obtained using Thornthwaite and Mather (1957)), the flux lost due to evapo-transpiration would be 564 m^3/day. From aerial photographs of the fen (available on website www.maps.google.com), it can be seen that several (at least 3 to 4) small streams and rivulets drain Ives Road Fen and empty into the Raisin River. Assuming the range of flow rates in each of these streams to be 0.1 -1 ft^3/s (cfs), the total flow rate in all streams will be in the range 0.4 – 4 cfs (1 cfs ~ 2450 m^3/day). Thus, the total inflows into the fen must be in the range 1543 – 10350 m^3/day, which is quite a large range. Given this information, the fen was modeled as a drain, whose leakance was calibrated to the estimated range of fluxes presented above. Figure 2-15 presents a comparison between the fen's leakance and the influx to the fen, which illustrates that the fen's flux increases with an increase in leakance, but begins to level off beyond a certain point. The calibrated leakance for the fen was 0.5 day^{-1}, with a calibrated influx of 3264 m^3/day.

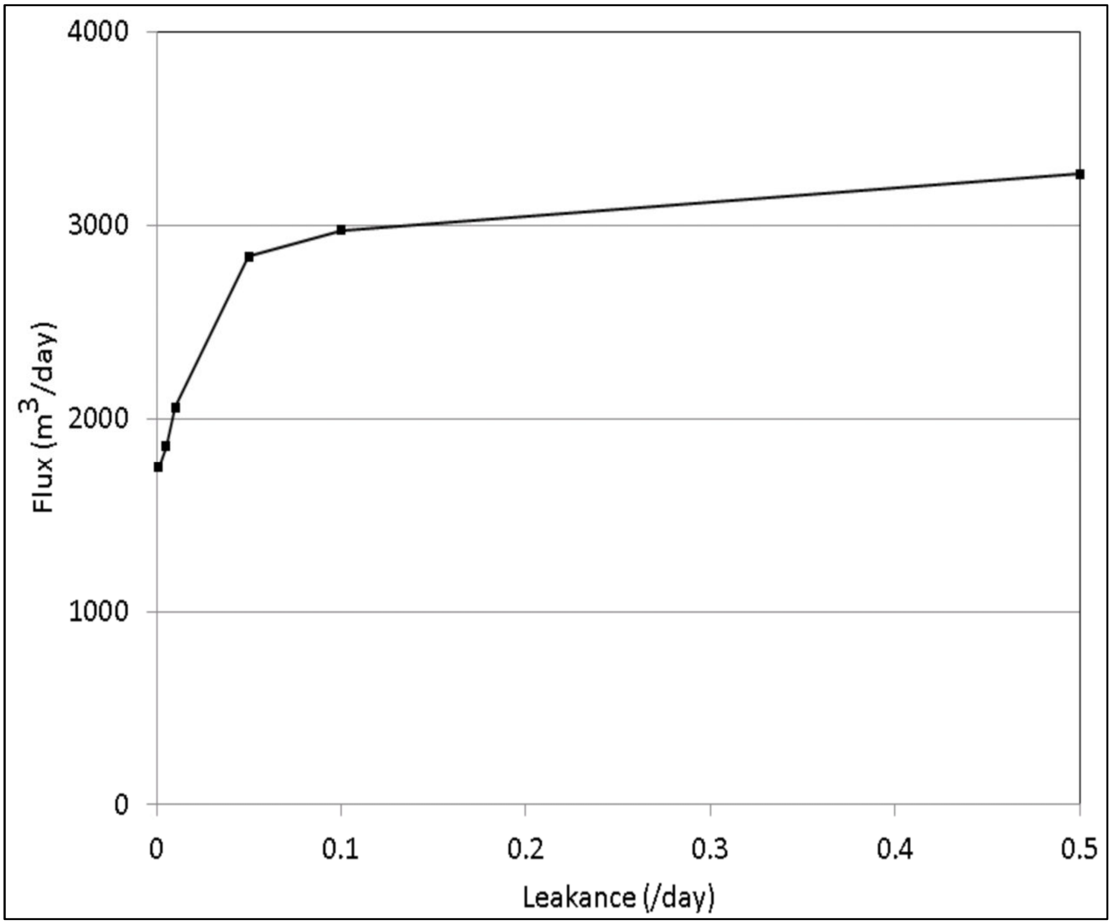

Figure 2-15 – Comparison of fen's influx with the fen's leakance.

Mass balance analysis for the pond

A similar mass balance analysis for the pond near Ives Road Fen was performed using Equation 2-1.

$$\mathrm{P} + \mathrm{RO} - \mathrm{E} + \mathrm{GW_{IN}} - \mathrm{GW_{OUT}} = 0 \qquad (2\text{-}1)$$

where P is precipitation, RO is runoff, GW_{IN} is the groundwater inflow, E is the evaporation from an open water surface, and GW_{OUT} is the groundwater outflow from the lake. The precipitation to the pond was set at 904 mm/year from National Weather Service (NWS) data. The evaporation rate from an open water surface was obtained from Fransworth et al. (1982) as 686 mm/year. The area of the lake was 310,390 m^2, and its catchment area was about 1.25 – 1.5 times the lake's area. In order to get a minimum and maximum runoff estimate into the pond, a uniform runoff coefficient was assigned to the catchment, ranging between 0.3 and 0.7. The mass balance terms as calculated for the pond are given in Table 2-6.

Table 2-6 – Mass Balance terms for the pond.

Source/Sink	Flux (m^3/day)
Precipitation	769
Runoff	288 – 807
Evaporation	583

Using the remaining terms of the mass balance equation, the net groundwater flow to the pond (i.e. the difference between inflow and outflow) was estimated to be in the range 474 – 993 m^3/day. In the model, the pond was calibrated to the estimated groundwater flux using the lake's leakance as a calibration parameter. The calibrated leakance of the lake was 0.008 day^{-1} and the simulated groundwater inflow to and outflow from the lake were 475 and 1217 m^3/day, resulting in a net groundwater flux from the pond of 742 m^3/day, which was well within the expected range of values.

Quantifying the contribution of water to the fen from different sources

The particle tracking approach was able to identify the potential sources of water, but was unable to quantify the exact proportion of water obtained from the different sources, for which a mass balance analysis was performed. Since no site-specific data was available, this analysis could not be constrained by actual flux values. Based on the particle tracking results, the major local sources were groundwater recharge from the shallow outwash area adjoining Raisin River, the pond located to the fen's west. Regionally, water from Hillsdale mound and from recharge in the till plain that upwelled through the break in the till plain were also potential sources of water to the fen. Based on this understanding of the sources of water, two mass balance polygons were created in the model. The first polygon, a schematic of which is shown in Figure 2-16, reflects the till plain, for which the mass balance can be written as shown in Equation 2-2.

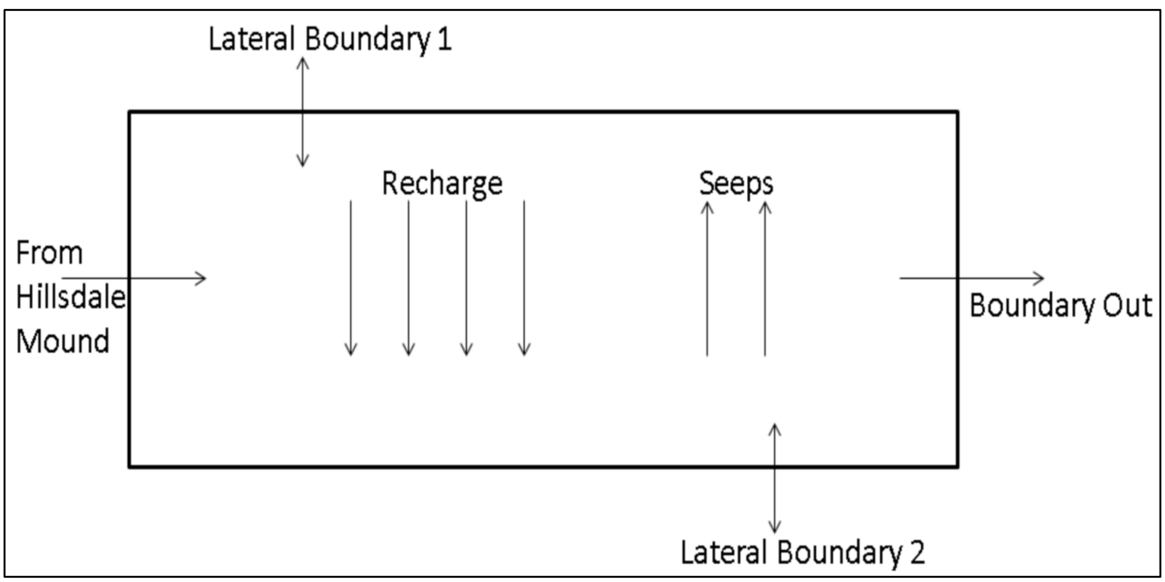

Figure 2-16 – Mass Balance polygon for the till plain.

$$Boundary\ In + Recharge - Seeps \pm Lateral\ Boundary = Boundary\ Out \quad (2\text{-}2)$$

In this equation, the source terms are '*Boundary In*' and '*Recharge*', which refer to the flux entering into the polygon from Hillsdale Mound and the groundwater recharge from the till plain respectively. The sink terms are '*Seeps*' that is the loss due to surface seepage and '*Boundary Out*', which is the flux that exits the polygon. The lateral boundary terms can be source or sink terms depending on whether they bring water into the polygon or not. The mass balance terms for this polygon are presented in Table 2-7.

Table 2-7 – Mass Balance terms for the first polygon.

Source/Sink	Flux (m^3/day)
From Hillsdale Mound (Boundary In)	1781
Groundwater Recharge	1833
Lateral Boundary 1	-749
Lateral Boundary 2	1011
Seeps	-328
Boundary Out	3549

The second polygon, shown schematically in Figure 2-17, reflects the area from the edge of the till plain to the fen boundary. The mass balance for this polygon is written as shown in Equation 2-3.

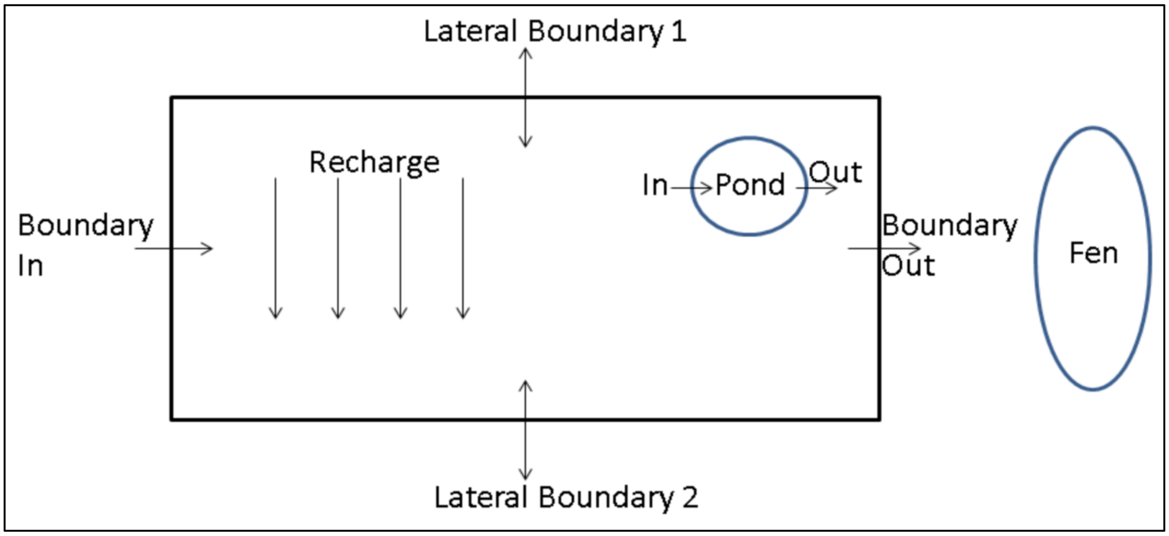

Figure 2-17 – Mass Balance for the shallow outwash aquifer.

$$Boundary\ In + Recharge \pm Lateral\ Boundary - Pond\ In + Pond\ Out = Boundary\ Out \tag{2-3}$$

In this equation, the source terms are '*Boundary In*', '*Recharge*' and '*Pond Out*', which refer to the flux entering the boundary, groundwater recharge in the glacial outwash aquifer, and the flux provided by the Pond near the fen. The sink terms are the '*Pond In*' that is the flux entering the shallow aquifer from the Pond, and '*Boundary Out*', which is the flux that exits the polygon towards the fen. The lateral boundary terms can be source or sink terms depending on whether they bring water into the polygon or not. Note that the '*Boundary In*' term from this equation is the same as the '*Boundary Out*' term from Equation 2-1. Also note that the '*Boundary Out*' reflects the flux exiting the polygon towards the fen and Raisin River. The mass balance terms for this polygon are presented in Table 2-8.

Table 2-8 – Mass Balance terms for the second polygon.

Source/Sink	Flux (m^3/day)
From Hillsdale Mound + Till Plain (Boundary In)	3549
Groundwater Recharge	5859
Lateral Boundary 1	-155
Lateral Boundary 2	43
Pond In	-475
Pond Out	1217
Boundary Out	10038

Although the mass balance equation is straightforward, it is difficult to distinguish exactly how much of the '*Boundary Out*' term comes from the different sources. For example, in the first polygon, some of the flux from Hillsdale Mound may be lost to surface seepage, and some more might exit through one of the lateral boundaries. This problem is present for the other polygon too, where, for example, some of the flux from local recharge may be lost to the Pond, and some more might exit through one of the lateral boundaries. In order to account for this, the '*Boundary Out*' term in Equations 2-2 and 2-3 were sub-divided such that a range of values that reflected the minimum and maximum possible contribution from the different sources were obtained as given in Table 2-9.

Table 2-9 – Contribution of water from different sources.

Source	Flux (m^3/day)	Percentage
Hillsdale Mound	579 - 1803	6% – 18 %
Recharge from Till Plain	1454 – 2879	14% - 29%

Local Recharge	5229 – 5902	52% - 59%
Pond	1217	12%

Note that the apportioning of the fluxes done above was for the flux leaving the polygon, which was 10,038 m^3/day, which is much larger than the flux entering the fen (3264 m^3/day). A portion of the flux leaving the polygon enters the fen, and the rest goes past the fen and enters the Raisin River as base-flow. Despite that, it is likely that the fen is receiving water from the different sources in the same proportion as calculated above. Even otherwise, it should be noted that groundwater with greater residence time tends to be more mineralized, which fens tend to favor. Therefore, water from far away (Hillsdale mound and the till plain), which mixes with local recharge after up-welling through the break in the clay layer, may cause a change in water chemistry (neutral or basic pH). Thus, the relatively smaller sources (in terms of water quantity) may be extremely important in terms of their water quality implications. To summarize, the fen's largest source of water is from local recharge into the shallow glacial outwash aquifer. However, a significant portion of the water comes from far away, i.e. the Hillsdale mound and from the till plain. In spite of the presence of fairly continuous and thick clay in the till plain, it is the second largest source of water to the fen. Even though there is considerable uncertainty in actual flux entering the fen, the proportion of water from the different sources predicted from this analysis can be useful in understanding the system. Needless to say, additional data collection will be very helpful for better understanding of this complex system, which is discussed later.

Implications for management

Given the characteristics of the hydrologic system that supports Ives Road Fen, and the relative strengths of the different sources of water to the fen, managing the fen is quite challenging. Obviously, local recharge is the most important source of water to the fen, and thus, this area must be kept relatively free from hydrologic disturbances. Changing the land-use patterns in this area can cause reduction of groundwater recharge to the aquifer, which may significantly impact the inflow to the fen. Also, since the shallow aquifer consists of outwash materials with high hydraulic conductivity and effective porosity, any contamination that enters the groundwater is likely to travel relatively quickly to the fen. Thus, both groundwater quantity and quality in this area must be carefully managed. The small pond near the fen is a relatively minor source in terms of water quantity, but it may be important during times of drought. The regional sources from the till plain and the Hillsdale mound are relatively robust, as they are protected by the extensive and thick clay layer. As long as the regional hydraulic gradient is maintained, these sources will continue to provide water to the fen. However, for these sources, it is not just the source of water that needs to be protected, but also the confined aquifer that transmits water from the source to the fen that needs protection. If the confined aquifer is used extensively for water supply purposes, due to increased demand, it may reduce the hydraulic gradient required for water to "up-well" through the break in the clay layer. Therefore, water withdrawals from this aquifer need to be regulated and monitored so that the hydraulic gradient needed for the fen can be maintained. In terms of shallow groundwater contamination from leaking septic tanks or underground storage tanks, the clay layer provides considerable protection. By virtue of its position near Raisin River, Ives Road Fen may face threats from inundation due to flooding in the river. Flooding of the river can be due to a combination of factors, such as increased precipitation due to climate change or changing land-use patterns in the river's surface watershed. Regardless of the cause of flooding, its effects on the fen can be very damaging. An increase in surface water not only changes the water chemistry of the fen but also increases the likelihood of contamination.

FUTURE WORK

The approach demonstrated in this study was the first step in moving towards a holistic, system-based approach to understand fen hydrology. Evidently, the most obvious disadvantage of the study was the lack of site-specific data that could help characterize the fen's water balance more accurately. The most important task in improving the understanding created by this study must be to quantify the fen's mass balance and to determine the contribution of water from the different sources to the fen. The other uncertainty in the analysis presented in this research was the assumption that there was a break in the clay layer. While this did seem very likely from the geologic model and also from the particle tracking results, independently validating this break in the clay layer would help remove considerable uncertainties. Other tasks include a probabilistic mapping of the fen's sources of water, and also evaluating the impact of climate change and other anthropogenic influences, such as land-use change, on the fen.

Quantifying the fen's water balance

As already mentioned, there is considerable uncertainty in determining the fen's water balance, and in accurately determining the flux from the different sources to the fen. Quantitative approaches, such as the one demonstrated in this research, are useful as decision-making tools, since they allow testing various management options. Thus, quantifying the fen's water balance flows is critical, for which additional site-specific data collection is necessary. Measuring a time-series of flow characteristics at the fen, such as the flow rate, pH, and temperature would help in determining the relative contribution of surface and groundwater to the fen. In the case of Ives

Road Fen, a similar analysis at the pond located to the west of the fen would indicate the connectivity between the fen and the pond. Similarly, measuring the fen's water level would indicate if the fen's water level is indeed "steady" throughout the year. Collecting groundwater elevations and chemistry data (pH, temperature) at multiple piezometers at various depths around and up-gradient of the fen would help indicate the relative strengths of local and regional flow systems that provide water to the fen. For instance, groundwater from a deep, regional flow system is likely to be more basic compared to shallow, local systems.

Validating the break in the clay layer

The break in the clay layer was indicated from the 100 realizations of the geologic model as very likely. The particle tracking results from the groundwater model also indicate that there is a break in the clay layer. However, the groundwater model samples the geologic model at a lower resolution, which can cause some artifacts; therefore, the break needs to be independently validated. A direct method to detect the break in the clay layer is by drilling boreholes in this area to verify the lithology, which is probably akin to finding the proverbial needle in a hay-stack. An indirect method to detect a break in the clay layer would be using head gradients and/or water chemistry. If a break exists, the head gradient between the shallow and the deeper confined aquifer would be smaller than if there was no break in the confining unit. Similarly, water chemistry in the shallow aquifer would be more similar to the confined aquifer if there was a break than otherwise.

Probabilistic mapping of sources of water

A probabilistic map of the sources of water to the fen could be obtained by performing particle tracking on a groundwater model created using each of the 100 realizations of the geologic model. Although this approach is obviously laborious and quite time-intensive, it is a robust approach and would provide a probabilistic envelope of possible water sources to the fen. As a decision-making tool, this approach would allow the evaluation of different management options. For instance, valuable conservation resources are better spent on a more probable source of water to the fen than an unlikely or less likely source. Water sources can also be mapped on the basis of their inherent resilience due to geologic factors. In general, a deep, regional connection to the fen is more resilient to hydrologic disturbances than a shallow, local connection. Thus, it is important to assess the connection between a fen and its water source based on its resilience. For instance, a connection that is deep or one that is protected by a clay layer would need less protection from hydrologic perturbations, such as high-capacity pumping wells or potential sources of contamination.

Sustainable management of fens

The current approach for fen conservation focuses on localized management, rather than a system-based understanding of the underlying hydrologic system. This study illustrated that a quantitative, system-based approach is well-suited for sustainably managing fens, especially considering the potential challenges in the future as we deal with the undesirable consequences of climate chance. An increase in precipitation and temperature, along with higher temperatures, milder winters and earlier springs, may have undesirable consequences on fen hydrology. For example, higher evapo-transpiration rates may cause lowering of water tables, which will cause the fens to shrink, fragment or even disappear. Anthropogenic influences, such as increased urbanization and greater demand for agricultural land, may also have a drastic impact on fens and affect their survival. The approach illustrated in this research can be used to model the effects of these perturbations, and to assess and evaluate appropriate conservation strategies for the sustainable management of fens in the future.

CONCLUSIONS

This research demonstrated a hierarchical, multi-scale groundwater modeling approach to understand the hydrologic processes that supports the survival of fens, which are groundwater-dependent ecosystems. In particular, Ives Road Fen in southern Michigan was chosen for detailed multi-scale modeling in order to predict the sources of water and the corresponding delivery mechanisms. The complex geology of the model area for this research necessitated the use of a fully 3-dimensional transition probability approach to model the variability in aquifer materials. The results from the hierarchical simulations showed that Ives Road Fen obtains water from multiple sources, including a local recharge area, a small pond nearby, and groundwater recharge from the regional groundwater mound and a till plain. Local recharge delivers water through a “direct” connection and also through a “cascading” connection, in which water flows from local recharge to the small pond and then into the fen. Water from the regional sources is delivered to the fen through a unique “pipeline” connection. This pipeline consists of a confined aquifer lying below an extensive clay layer. A break in the clay layer connects this confined aquifer to a shallow outwash aquifer, from where water flow to the fen. In terms of water quantity, the local recharge area is the most significant source, while the regional sources are the next largest source. Although water from the pond is minor in terms of water quantity, it may play an important role in delivering critical low-flow during droughts. Ives Road Fen, although seemingly isolated from other fens, is, in fact, hydrologically connected to the same regional groundwater mound that provides water to other fen clusters.

Additional data collection at the fen site and around it is needed for further improving the understanding gained from this study. Most importantly, the break in the clay layer predicted from the geologic model, which is critical in this analysis, needs to be independently validated.

In terms of management, it is clear that the local recharge area is vital to the fen's survival, and needs to be protected, both for groundwater quantity and quality. Given that a considerable portion of the water comes from regional sources, the confined aquifer also needs to be protected from large-scale water withdrawals. At the regional level, it is clear that the regional mound is a source of water to not just one fen, but to multiple fens, lakes, rivers, wetlands and aquifers. Thus, the regional mound is the critical node in this system, which, if protected, will have desirable outcomes for the entire ecosystem. Given the fragility of these habitats, fens should be used as barometers for the health of the overall system. Quantitative approaches, such as the one demonstrated in this research, must be used to help understand these complex ecosystems and to sustainably manage and preserve them.

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Chapter 3 SUMMARY OF ORIGINAL CONTRIBUTIONS

Using a multi-scale groundwater modeling framework I have developed a hierarchy of groundwater models to understand the complex hydrologic system that supports groundwater-fed fens. In particular, I have used this modeling framework in order to rigorously:

1. Delineate the groundwater contribution areas to two fens in southern Michigan,
2. Identify unique water delivery mechanisms to the fens
    a. Direct connections – where water flows directly from the source of water to the fen,
    b. Cascading connections – where water flows from a source to one or more intermediate sources before reaching the fen, and
    c. Pipeline connections – where a geographically-isolated fen is connected to the source of water through a “pipeline” consisting of a confined aquifer lying below a clay layer.
3. Infer the hydrologic inter-connectivity between various fens, rivers, lakes and wetlands.

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