

PRAIRIE FEN HYDROLOGY

By

Hassan Abbas

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ABSTRACT

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Prairie fens provide habitat to more than 50 rare species, including the federally endangered Mitchell's satyr butterfly. Substantial resources have been invested in their protection; however, these conservation efforts have proceeded without an understanding of the underlying groundwater flow regime that is critical to these fens. Regional scale hydrological investigations could cost hundreds of thousands of dollars for an individual fen, and therefore, are rarely undertaken in a management context – confining the conservation efforts to the local fen community and adjacent lands. Without delineation of groundwater sources, the conservation community has had limited ability to protect the fen groundwater quantity and quality.

In this research we explored the use of a data driven modeling approach for groundwater modeling and to improve our ability to understand fen hydrology at different spatial scales. The approach used in this study directly analyzes, filters, and processes water well records and surface water elevations to estimate groundwater flow. We developed a steady state mean flow model for the southern Michigan basin, regional scale models for 9 fen clusters/sites, and site-specific vertical profile models for 19 fens. Vertical profile models facilitated understanding groundwater delivery mechanisms from regional recharge mounds to individual fens. Our major findings are: 1) occurrences of fens exhibit a clear systematic pattern on the regional scale; 2) most prairie fens are located around or at the foot of several large groundwater “mounds” at the intersection of major watersheds. These mounds are critical, regional source water areas for

aquifer systems, fens, and other groundwater-dependent ecosystems (GDE); 3) these critical regional mounds play a disproportionately large role controlling the sustainability of groundwater resources and GDE; 4) Groundwater flow patterns in the regional source water areas are complex and most fens are recharged from multiple sources; 5) Prairie fens located seemingly far apart in different watersheds, counties, or states may share the same regional source water; and, 6) Prairie fens exhibit four distinct types of groundwater connections, which are: i) *shallow connections* – groundwater recharge from local hills and surface water in lakes/wetlands at higher elevations adjacent to a fen seeping into the fen through shallow, and relatively short, groundwater flow paths; ii) *deep connections* – source waters recharge at distant locations coming in contact with deeper glacial/bedrock formations before upwelling into the fen; iii) *confined connections* – a distant source water recharge area becomes connected to a fen through older outwash beds confined under recent till plains; and, iv) *cascading connections* – groundwater sources directly linked to fens being dependent on other surface/sub-surface source waters.

These findings have significant practical implications and support the need to reconsider the current priorities and restoration strategies. In particular: 1) our improved ability to use GIS data creates new possibilities with basin-wide implications for the holistic management of fen ecosystems; 2) fen management must move beyond water's edge to account for the impact of regional flow systems; 3) because of the connectivity of the basin's groundwater systems, a few “smart” actions in key locations could yield high ecological returns; 4) when we protect prairie fens and their upstream sources, we are also protecting other ecosystems downstream; and, 5) occurrence of fens in the regional aquifer recharge areas at the intersections of watershed boundaries implies that coordination across the river basins as well as the political divides and between water resources and ecological communities would be imperative for protection of fens.

To my parents

And my brothers Mohsin (1961-1995) and Hussain (1965-2010)

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MOTIVATION

Prairie fens are geologically rare and ecologically unique groundwater dependent terrestrial ecosystems in Michigan providing habitat to more than 50 rare Midwest plant and animal species, including the federally endangered Mitchell's satyr butterfly and the Eastern Massasauga rattlesnake, which is a candidate for federal listing. Due to their regional significance as globally rare ecosystems and as hotspots for rare species, substantial resources have been invested in the protection and management of prairie fens. However, these conservation efforts have proceeded without an understanding of the underlying groundwater flow regime and associated groundwater contributing areas that are critical in maintaining these fens. Detailed field evaluations of ground-watersheds generally cost hundreds of thousands of dollars for an individual fen, and are therefore rarely undertaken in a management context. As a result, land protection and conservation efforts have focused on only the local fen community and the immediately adjacent lands. Without a delineation of ground-watersheds that supply a given fen, the conservation community has had very limited ability to protect the fen groundwater quantity and quality. A "Great Lake Expert's Roundtable Report" (GLPF 1998) stressed that current conservation efforts [for most ecosystems] in the basin are too disjointed and focused too much on local, visible symptoms and we must think in terms of protecting the underlying processes, the functionalities, and the biological engine to enable sustainable restoration.

This research aims at improving our understanding of subsurface hydrology at these unique groundwater dependent ecosystems, particularly in terms of system connectivity, source water delineation and delivery mechanisms of groundwater to the fens.

A prairie fen is a type of peat land through which a continuous supply of cold groundwater, rich in calcium and magnesium carbonates, prevails throughout the year (Kost and Hyde 2009) and sustains the ecological functions of the ecosystem.

Prairie fens in Michigan provide habitat to Federally Listed Mitchell's satyr (MS) butterfly (*neonympha mitchellii mitchellii*) – one of the rarest in North America (Barton and Bach 2005). Historically, the butterfly had existed at thirty plus locations across Michigan, Ohio, Indiana, New Jersey and Maryland (Barton and Bach 2005; Hyde et al. 2001), but as per summer of 2010 survey conducted by Michigan Natural Feature Inventory (MNFI) the butterfly's occurrence was only reported at sixteen sites in Michigan (MNFI 2010) and just one in Indiana (Kost and Hyde 2009). The specific conditions required for the viability of MS populations remain uncertain, but the maintenance of quality and quantity of the groundwater feeding the fen is considered vital to a viable satyr population (USFWS 1998). There are 150 known prairie fen sites in Michigan as shown in Figure 1.1.

Besides providing critical habitat to rare species, fens also provide critical ecological services to the environment and their protection is considered vital (USFWS 1998). Many of the region's rivers and lakes have their headwaters emanating from the pristine waters of these fens, supporting countless fish and aquatic species. They provide critically important ecological services by delivering clean waters to streams and lakes (Bedford and Godwin 2003; Kost and Hyde 2009).

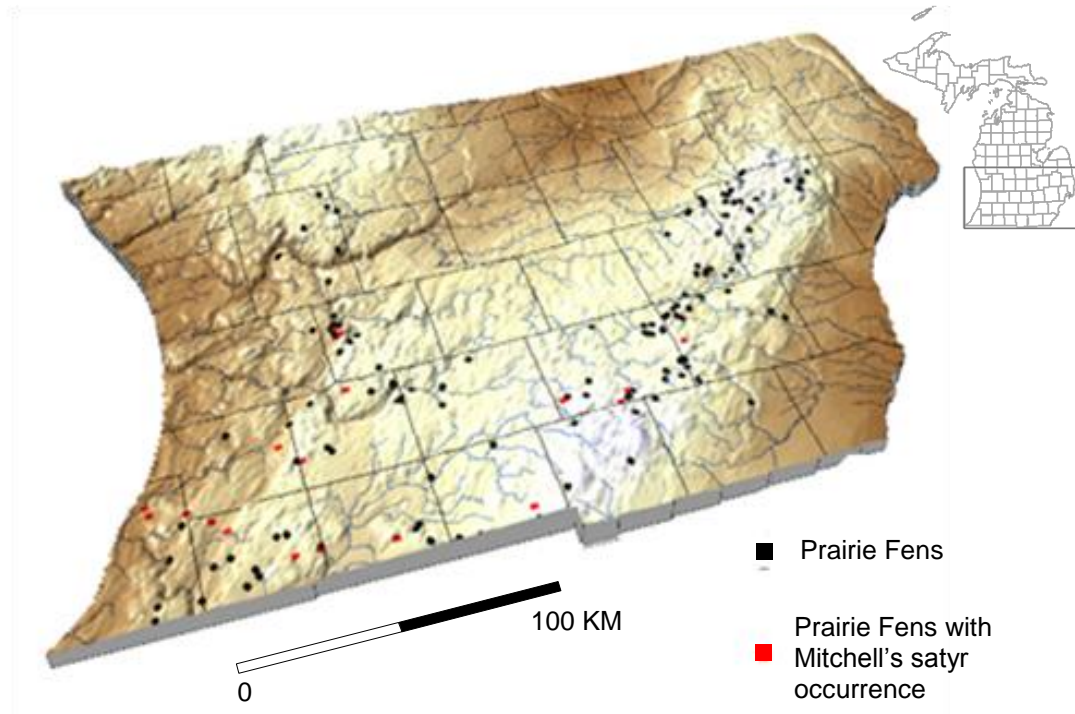


Figure 1.1 Southern half of Michigan's Lower Peninsula showing locations of prairie fens and Mitchell's satyr occurrence. The map was created by using DEM data (NED USGS 2006), NHD data (NHD USGS 2010) and fen locations data (including occurrence of Mitchell's satyr) from Michigan Natural Features Inventory. Shaded relief represents surface topography. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this dissertation.

Deficient information on groundwater conditions across fens may be preventing resource managers from insights that would facilitate protection of fens and their rare species. As a result of the current lack of understanding of the multiple scale groundwater context for most fens, critical information is often missing for making decisions on where and how to most effectively invest limited conservation resources for protection, management, and permitting.

SCIENTIFIC CHALLENGES

The fens generally occur in complex hydrogeological settings and while investigating the hydrology at any particular site, one of the major scientific challenges faced by the fen conservation community is the lack of knowledge about the source water areas of groundwater feeding into the fens. Prairie fens generally occur in hummocky topographies of glacial moraines, within an extensive network of small streams, lakes, and other wetlands, making the subsurface hydrology very complex. Shallow groundwater recharges under “knobs” and discharges in the “kettles”, and when superimposed by the regional topography it gives rise to deeper regional groundwater flow systems (Meyboom 1967). The delivery mechanisms of groundwater to the fens in complex hydrological settings of prairie fens are not well understood for most sites.

Figure 1.2 shows conceptualization of multi-scale subsurface flow regime beneath a hummocky landscape with a number wetlands, lakes and small streams. Large number of surface water features and shallower water tables in the vicinity of fens may suggest that water tables are topographically controlled and may be dependent on the complex topography in the region (Haitjema and Mitchell-Bruker 2005). The figure illustrates that some groundwater discharge zones depend on local flow systems only (marked A) while some others may be dependent on both the local and the regional flow systems (marked B). While the recharge zone for a shallow system may be from a few hundreds of meters to a couple of kilometers from its discharge zone (marked F), the source water area for regional groundwater discharge could be tens of kilometers away (marked E). Discharge zones are generally more visible in the landscape. Every discharge zone can be associated to one or more source water areas such as a recharge area in the landscape, a surface water body etc. However, finding and establishing connections between

discharge zones and corresponding source area is challenging, especially when the groundwater systems supporting the fens are multi-scale and complex as described above. It requires knowledge/data on subsurface hydrology and geology.

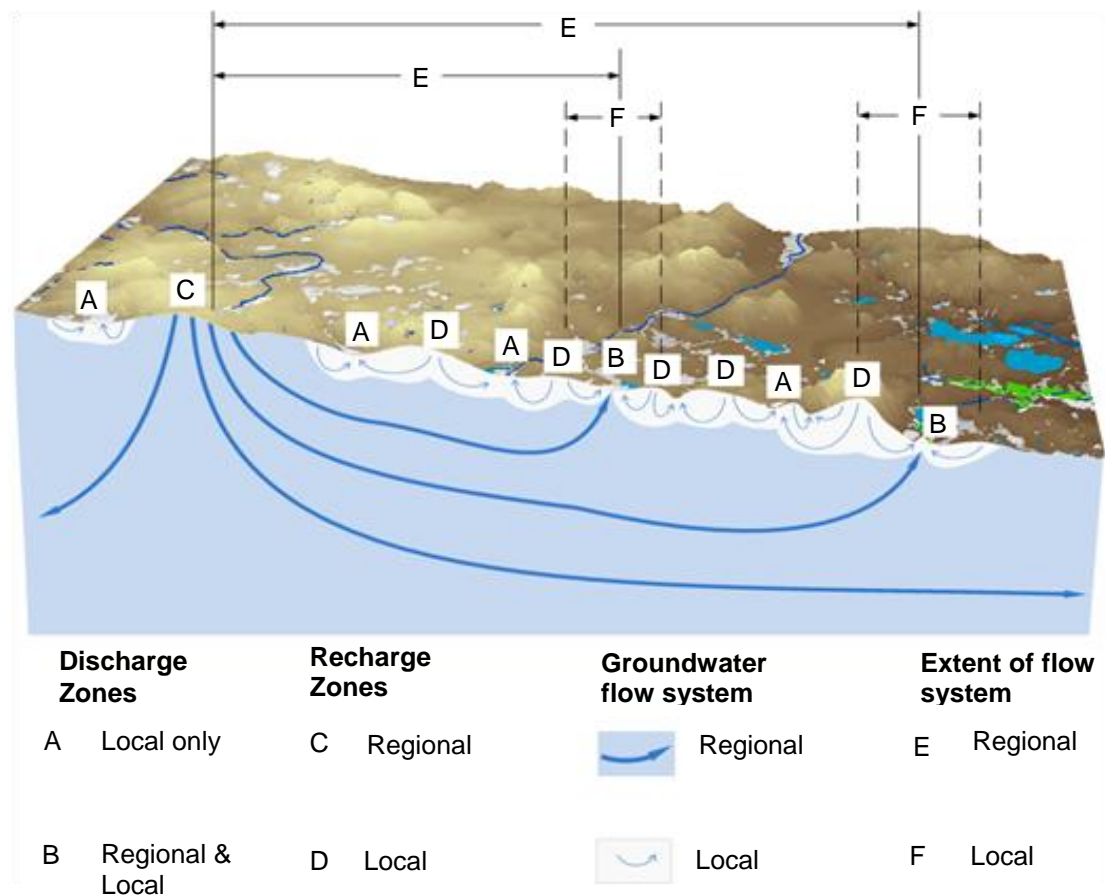


Figure 1.2 Conceptualization of multiples scales of groundwater flow systems [Modified from Meyboom (1967)]

Fens occur in groundwater discharge zones within the local hydrological settings and are mostly recognized by the type of vegetation/species. Quality and quantity of water are critical factors determining the type of species and the socio economic values provided by the fens (SNH 2010). In order to synergistically, holistically and effectively protect, restore and manage fen ecosystems, the efforts need to be coordinated at the scales compatible with the scale of

hydrological regime in which the fen occurs. Such coordination may be greatly helped if ecologists, hydrologists and managers involved in the process know the science behind the following questions:

- How do basin wide groundwater systems and hydrogeology correlate to the occurrence of prairie fens within the landscape?
- Where are the local/regional source-water areas for fens which must be protected/managed to ensure that fens keep receiving the influx of required quality and quantity of groundwater?
- What are the natural delivery mechanisms of groundwater from source areas to the fens sites in different hydrogeological settings which must not be disrupted within a region to ensure uninterrupted supply of groundwater to the fens?

REVIEW OF PRIOR WORK

Historical Perspective

Geologists and natural scientists have been wondering over the quality, quantity and sources of water to the wetlands since the early 19th century. Dau (1823) observed some wetlands (bogs) were fed ‘from mainly rain and dew of heaven’ and ‘not fed by earth’. Dependence of vegetation on quantity of water flowing through the wetlands was observed by C.A. Weber in 1902 (Couwenberg et al. 2002). Du Rietz (1949; 1954) differentiated bogs and fens on chemistry of their water and observed dependence of vegetation on pH. Gorham (1957) discussed major contributing factors responsible for the occurrence of fens which include climate, geology, topography and biology. He suggested that geological factors may dominate the other factors and discussed the importance of extreme fluctuations of water. He pointed that

climate sets the broad limits within which peat formation [including fens] takes place and it may be considered first, but also pointed out that while climate sets the broad limits, the local moisture conditions and salts leached to the surface are controlled by relief. Less porous till of the hills and plateaus favors fens influenced by mineral soil water. The rainwater and its composition after percolation through mineral soils materials become different, as it picks up calcium and magnesium bicarbonates, becoming less acidic favoring the formation of fens. Such early works led to the classification of fens as rare ecological systems, their dependence on groundwater hydrology, and their relationship with the local and regional landscapes.

The current literature primarily discriminates prairie fens from other wetlands for their dependence on stable and calcareous groundwater contributions, necessary to maintain saturated substrate conditions throughout the year (Bedford and Godwin 2003; Spieles et al. 1999). Hydrology has been recognized as one the most important factors for fen development and its biological functions (Bowles et al. 2005; Dekker et al. 2005; Harvey et al. 2007a; Harvey et al. 2007b; SNH 2010).

Need for Multi-scale Thinking

In particular, many researchers pointed out that hydrology is a process and fens are only a small part of larger groundwater systems. Batelaan (2003) stressed that knowledge of groundwater flow at both local and regional scales is a pre-requisite for sustainable land and water management. By combining the synergy of hydrologic modeling and vegetation mapping, he stressed the need for protection of ecologically valuable areas and land-use that would support integrated water management. Wassen et al. (1990) stressed that hydrological research that integrates the results of regional and local studies is essential if the ecology of fen ecosystems is to be understood. Grootjans et al. (2006) discussed that small groundwater-fed systems are very

vulnerable to hydrological changes and climate change due to the lowering of groundwater tables in the vicinity, and stressed the need to study the hydrological systems that stabilize the site conditions.

Siegel and others (Siegel 1988; Variano et al. 2009) discussed how local flow systems controlled by the smaller scale features may be modified by flow systems at larger scales. Variano et al. (2009) showed through kilometer-scale tracer studies in Everglades how basin-scale forcing from water management structures/operation can override the effects of local landscape features in guiding the flow. Siegel suggested that evaluation of recharge-discharge function for wetlands is one of the most difficult things because of the interactions of multiple groundwater flow systems. Many authors have emphasized the need for a broader approach at catchment/landscape scale to understand upland-wetland linkages and the hydrological systems (Bedford 1999; Grootjans et al. 2006; Price et al. 2005). Wassen et al. (1990) suggested that extensive fen systems sustained by large hydrological systems are less vulnerable to local drainage, but large scale interference with the regional hydrology eventually has split up the large fen systems into many small fens, each with a small local hydrological system. More recent publications also maintain the view that most small fens are the remnants of once more extensive systems (SNH 2010).

Gorham (1957) suggested topography or relief dictates the flow of nutrients leached from the soil and argued that while geological factors may almost entirely suppress other factors, climate sets the broad limits within which the formation of fens may occur. Winter (1998) argued that wetlands that receive discharge from regional groundwater flow systems will continue to receive that discharge even if the wetland depression in the upland is drained. He also suggested

that modification of groundwater discharge areas generally have less significant impact on wetlands than modification of recharge areas.

Some authors have strongly argued for shifting the focus from merely number of hectares lost or degraded to the alteration in environmental and hydrological variables at regional scale that cause ecosystems to form and be maintained through time (Almendinger and Leete 1998a; Bedford 1999; GLPF 1998). Almendinger and Leete (1998a) separated the fen hydrogeology at local and regional scales. They included factors such as climate, geologic deposits, regional landforms, groundwater movement from areas of recharge to fen location, deep vertical groundwater gradients, and groundwater age as the regional factors. They concluded that rate vegetation in fens rely on the integrity of regional groundwater flow system up-gradient from the fens. Bedford (1999) stressed the hydrogeological understanding of wetland-landscape linkages and argued that restorations should begin with a cumulative impact analysis for the entire region in which restoration is proposed.

Many large scale studies had been conducted over vast regional areas to establish the connections between the occurrence of fens and regional systems. Amon et al. (2002) studied more than 70 fens sites covering 11 states in the Midwestern United States, and 13 in other regions including Alaska, Canada and Ireland. This study described how different fens were sustained by forces of climate, landscape, and geology, which permit groundwater to seep continuously into the root zone at a focused location. This study also presented hypothetical flow mechanisms of groundwater interactions in the immediate vicinity of fens. Halsey et al. (1997) presented a comprehensive study for the fens in the Canadian province of Manitoba. This study correlated climate, topography, soil texture and bedrock geology to the occurrence of fen over contiguous regional scale of the province and emphasized the importance of integrity of the

overall system to maintain the health of all fens. Meyboom (1967) discussed occurrence of fens in hummocky topography of glacial moraines, conceptualizing, in a qualitative way, the dependence of fens on multiple scales of shallow/deep groundwater systems, and concluded that groundwater discharge areas in the landscape where fens occur, would have their sources linked to one scale of flow system or the other. Bedford (1999) suggested the likelihood that a wetland receives ground water from more than one flow systems can be deduced from its topographic position in the watershed. Such large scale studies, involving large number of fen sites, however, has not been investigated the sub-surface flow regime at regional scales (perhaps because of data limitations) and its connections with the occurrence of fen sites.

Many authors, nevertheless, have hypothesized and/or investigated connections of fen sites with the regional groundwater systems which may be crucial to the existence of particular fen sites. Winter (1998) suggested that the seriousness of the impact on an ecosystem is commonly related to scale. He argued that it may be appropriate to assume that regional groundwater flow systems are recharged in uplands and discharged in lowlands, however, a similar assumption commonly does not apply on a local scale, because of the spatial and temporal dynamics of groundwater recharge. Siegel and Glaser (1987) in their study on Lost River peat land in northern Minnesota identified a beach ridge 10km from the study site as the “probable” recharge zone for the groundwater seeping in peat land and regarded it as *regional* connection. Most of their work was based on observed groundwater levels and chemistry in the observation wells within the peat lands. They also concluded that small changes in volume of groundwater discharge in peat land may significantly affect the vegetation. Almendinger and Leete (1998b) reported ‘local and regional’ hydrology of six fen sites in Minnesota. The *local* scale hydrology at these fens was taken as the peat land-forms and the substrate within a few

hundreds of meters of the sites, while the *regional* hydrology for these sites was investigated between 2~6 km. Connections of source water areas to the fen sites were identified but these connections were based only on general landforms and geology in the area rather than detailed hydrological data from the source water areas. Stein et al. (2004) conducted a regional study for subsurface hydrology of 20 slope wetlands concentrated in the central portion of the San Juan Creek Watershed, within an area of approximately 12 x 5 km. “Shallow” and “deep” systems were investigated at 1m and 15m depths respectively. Vertical flow dynamics discussed for various fen sites were investigated based on site geology. Groundwater flow along the vertical profiles was illustrated using hydrologic intuition and not the actual data. Inferences were drawn for the “probable recharge mechanisms” at regional scale based on groundwater monitoring only within the local sites. Recharge zones within the watershed (approximately 30 x 35 km) extending beyond the study area were assumed as the ‘probable’ source water areas for the wetlands. The study concluded that occurrence of wetland was dictated by local and regional geologic settings and sustained by both local and regional groundwater sources.

Need for a Quantitative Framework

Managing the flow regime as single system at large scales is gaining popularity as a preferred approach in many parts of the world, across the political divides and trans-boundary basins (EU 2000; IJC 2009; NSW CMA 2004; SOGW 2009); however, there are significant challenges in the implementation of this concept.

Groundwater models had been used as tool to systematically investigate fen hydrology at many studies and to guide data collection for further monitoring. However, most existing models lack sufficient resolution, are limited to one particular scale or a narrow range of scales, and/or

are often prohibitively expensive to apply in a system-oriented management setting that requires modeling integrated processes and large numbers of fen sites (Price et al. 2005)

Batelaan et al. (2003) combined vegetation mapping and groundwater modeling to identify discharge areas and delineate corresponding recharge areas respectively. Their models were based on particle tracking in MODFLOW. The models were built on regional scale and primarily delineated horizontal flow dynamics between expected source water areas and the groundwater discharge zones. Bradbury and Cobb (2008) delineated groundwater contribution areas of 11 springs in Wisconsin using reverse particle tracking in horizontal groundwater models using MODFLOW. The scale of these models ranged from less than a mile to a couple of miles. Gilvear et al. (1993) modeled regional and local flow dynamics for Bradley Moore fen in UK. Their regional model, 17 x 8 km, was used to determine boundary conditions for the local scale model. Vertical flow dynamics were conceptualized in the local model. Using MODFLOW they built a 3-layer model to resolve vertical flow at local scale and used chemistry data from piezometers to interpret results for more detailed vertical dynamics and to relate discharge zones to corresponding recharge zones.

Grapes et al.(2006) used a simple one layer regional-scale model using MODFLOW for Lambourn Valley, UK. They inferred local scale dynamics through site specific data. Combining results from regional model and local data they demonstrate the use of the results of catchment - scale ground water modeling to determine the hydrodynamics of 'local' floodplain wetlands. Their results demonstrate the importance of taking catchment-scale water flow into account when managing isolated wetlands in a permeable catchment.

Acreman (2004) and Acreman and Miller (2006) suggested that one of the first steps in understanding wetland hydrology should involve identifying which water transfer mechanisms

are operating at the wetland and which of these are the most important in maintaining the present ecology. They also emphasized the need to understand groundwater interactions in a third dimension, i.e., looking at vertical cross sections. Various studies have described how water may be delivered from the source water area to a fen/wetland employing the vertical visualization (Acreman 2004; Acreman and Miller 2006; Dall'O' et al. 2001; Gilvear et al. 1993; Toth 1972; Winter 1998), but most of these studies have either employed hypothetical models and/or have used hydrogeologic theories/intuition to define these mechanisms. Some authors have employed use of vertical profile models to delineate vertical flow paths in more details. Most of these studies have involved regional scales, and consequently have not studied more than a couple of sites, perhaps because of data limitations. Such studies are therefore mostly site-specific. It may be difficult to draw generalized conclusions from these.

Bleuten et al. (2006) used MODPATH to model vertical profile dynamics of groundwater for Ob River Terrace Fen in Russia. Vertical flow dynamics in this model were calculated by using groundwater heads from piezometers along a 13 km long profile as upper boundary condition and calculating flow lines in vertical profile. Horizontal flow pattern was not modeled but assumed parallel to the profile based on general groundwater flow gradients in the region. van Belle et al. (2006) used FLOWNET to build two vertical profile models in Het Hol, The Netherlands, using hydraulic head data along two transects as the top boundary condition. The profiles were approximately 10 km each. The flow pattern delineated by the model was used to infer discharge areas along the profiles. The groundwater system at the regional scale was not modeled in the horizontal plain to determine if the profiles also aligned with the horizontal flow paths. Loon et al. (2009) studied a large regional area along River Vecht, The Netherlands, to investigate historical changes in groundwater regime and to delineate current source water areas

for fens in the region. They modeled vertical flow paths along two pre-determined profiles to conclude that fens were being fed from the regional sources.

Wessen et al. (1990) investigated groundwater connections between the regional groundwater flow system at an individual fen site in central Netherlands. They concluded that nested groundwater flow systems existed within the fens and that regional and sub-regional groundwater flow systems strongly influenced the local hydrology of the fens. This study is an exception from most others in that groundwater data was used at both local and regional scales. Vertical groundwater flow was also modeled in this study for a transect along regional groundwater flow path using FLOWNET. However, this study was undertaken in a highly modified landscape where surface water levels in polders were extensively available for the artificially controlled regional hydrology. The techniques presented in this study are useful, but its results may not be generalized for the fens occurring in more natural settings.

Challenges Facing Multiple Scale Thinking on Flow Regime Integrity

The following bullets provide a summary of specific data-related modeling challenges:

- The river basins are large and require large volumes of hydrological, geological, land-use, soils, topography data to effectively characterize their flow regimes.
- Collecting data is expensive and time consuming.
- It is difficult to organize a coordinated data collection program at large scales, especially when a basin is divided in multiple administrative jurisdictions.
- Since data requirements are diverse between various agencies, it is difficult to collect, utilize and share data in a synergistic way.

- Many historical records exist in hard prints and extremely tedious to use. These records may be lying in bits and pieces with different agencies and difficult to gather.
- Data converted to or collected in electronic format by different agencies can have format compatibility issues, requiring tedious preprocessing before they can be used.
- Strict and standard QA/QC procedures had mostly been absent at the time many historical records were collected.
- Desired density and uniform coverage to characterize a basin scale system may not be available in the existing data sets.

These issues make it difficult to access data even when it is available, requiring tedious pre-processing before it could be effectively utilized.

Currently the subsurface hydrology for most of the 150 known prairie fen sites in Michigan is not well understood. Some of these sites make candidates for potential reintroduction sites for MS populations but the source water areas are not clearly known for any of these sites. While identification of regional sources of groundwater would be pivotal for prairie fens management, the understanding of local scale dynamics and delivery mechanisms of groundwater to at the individual fens sites are also crucial for their effective management.

AIM AND OBJECTIVES

Recent advances in GIS, GPS, and Remote Sensing have, however, opened new possibilities. Michigan Public Act 148 (2003) required the Department of Environmental Quality (DEQ) to create a “groundwater inventory and map”. Water well drillers’ well records database, called Wellogic, and the Groundwater Inventory and Map Project database, called GWIM, turned out as the outcomes of the Public Act. These geo-referenced databases, besides other data,

also contain information on hydrological and other properties of the natural systems necessary to construct conceptual groundwater models almost anywhere in the state. When systematically utilized, this vast data source can significantly enhance our ability to characterize and model Michigan's groundwater systems

The aim of this research is to enhance our understanding of prairie fen hydrology that may be useful for conservation, protection and management of prairie fens.

The specific objectives of the research are:

- to determine groundwater flow regime at the statewide scale around the 150 known prairie fens sites in southern Michigan and to correlate the occurrence of prairie fens with the basin-wide hydrological landscape;
- to identify source water areas for selected fen sites at local, sub-regional and regional scales in varying hydrogeological settings;
- to investigate delivery mechanisms of groundwater from the source areas to the selected fen sites; and,
- assess implications of hydrologic understanding on fens protection, conservation and management.

OVERVIEW

Data-driven groundwater modeling approach adopted in this research directly analyzes, filters, and processes water well records for static water elevations and hydraulic conductivity to estimate groundwater velocity field. Hydraulic head is mapped using static water levels data. Hydraulic conductivity estimates are derived from lithologic information. Groundwater velocity is computed based on preprocessed hydraulic head and conductivity using Darcy's equation (2.1):

$$\mathbf{V} = \frac{1}{\eta} K \nabla h \quad 2.1$$

Where \mathbf{V} = velocity of groundwater flow

η = effective porosity

K = hydraulic conductivity

h = hydraulic head

∇h = divergence of h or the hydraulic gradient

The approach capitalizes on recent national movement in geospatial data integration and Michigan's statewide groundwater database (e.g. State of Michigan (2006),(2009), MNFI (2010), GWIM (2006)). The approach also takes advantage of the fact that prairie fens occur in topographically complex areas characterized by the presence of large numbers of scattered lakes,

wetlands, ponds, swamps, creeks, and drains that can be used approximately as “natural piezometers” for shallow groundwater systems.

One of the most significant advantages of a data driven modeling approach lies in that the data is available everywhere across the state in sufficient density to model groundwater systems around most fen sites. The disadvantage, however, is that data interpretation alone may not always allow transient simulations and estimating of water budgets. And since the models are not process based, they may be directly employed for scenario testing.

Three types of groundwater models were built:

- Statewide scale model – covering the entire southern Michigan basin;
- Regional scale models – around the selected fen sites/clusters extending from 10 to 40 km;
- Vertical profile models – across the selected profiles within the regional models with profile lengths varying between 10 to 30 km

In this study we preferred data-driven groundwater modeling approach over the traditional groundwater modeling approach which may allow us to build a full 3D numerical model to resolve all the complexities in the system. However, if any such model is built, it would be data hungry with a very complex structure. Moreover, this model would have to resolve flow dynamics at multiple scales which would make the model even more complex.

STATEWIDE MODEL

At the statewide scale, the subsurface groundwater flow regime was delineated by interpolating static groundwater level data acquired from water well records to identify

groundwater sources of regional significance. The 150 prairie fen sites across the state were superimposed over the delineated pattern of groundwater to correlate their occurrence with the pattern of subsurface flow regime. Furthermore, the occurrence of fens and subsurface flow regime were also compared with the glacial landforms, surface hydrology and topographic data. Inferences on the occurrence of fens were drawn based on these comparisons.

REGIONAL MODELS

Areas for regional scale modeling were selected around the groundwater sources of regional significance identified at the statewide scale. The subsurface groundwater heads were delineated for shallow, drift and bedrock aquifers. Specifically:

- elevations from all surface water bodies and wetlands are used to delineate local, shallow groundwater head patterns around fens;
- water well records and sampled surface water elevations from major streams and lakes are used to delineate regional head in the glacial aquifer; and,
- records from water wells are used to delineate regional groundwater head in the bedrock aquifer.

Finally, groundwater profile models were built for selected sites to investigate vertical dynamics of subsurface flow in shallow and deep groundwater systems.

Data-Driven Characterization of Groundwater Heads in Shallow System

Data-driven characterization of shallow groundwater heads involves the estimation of shallow groundwater table h and its gradient ∇h in equation 2.1, using the data from the

statewide databases. However, enough directly measured data for shallow groundwater heads were not available from the statewide databases because:

- there were very few existing water wells records located within or near most fen locations as they are generally protected and situated away from population centers;
- even the few wells closer to the sites in the database did not adequately represent shallow groundwater system as the wells are generally screened in the deeper aquifers and do not represent the shallow system; and,
- even when shallow monitoring piezometers at specific sites do exist they are generally too few and too sparse to characterize the larger shallow system at regional scale.

Following assumptions were made with regards to heads in shallow groundwater systems in order to manipulate surface water data to delineate shallow groundwater heads:

- All streams are connected to the shallow system.
- All lakes are connected to the shallow system.
- All wetlands are connected to the shallow system.
- Shallow groundwater head, even in the wetlands which are apparently dry, would be very close to (or almost at) the ground surface.

Some wetlands may be perched and may not be connected to the shallow system altogether. The available database on wetlands did not have this information so these could not be automatically filtered out. The aim of using wetlands as part of shallow systems was only to generate lots of ‘approximate’ data. However, the uncertainty introduced by not being able to filter out perched wetlands was mitigated by the following:

- Since most fens happen to occur in coarser outwash materials, the wetlands in the vicinity are less likely to be perched due to less pervious layer within such materials
- Lithology data from well logs were used ascertain clay layers in the strata. Where continuous clay layers were found, they were incorporated in the profile models. Wetlands occurring on top of such layers were hence isolated from the system

Shallow water level in surface water features such as lakes, wetlands and streams, was treated as intersection of shallow groundwater surface with the surface topography. Scatter points were generated in the surface water features and their elevations were estimated using 30m/10m DEM raster data (NED USGS 2006). The density of points generated in surface water features across the model domain was greatly helped by the presence of relatively large number of wetlands, streams and lakes within the vicinity of the fen sites as shown in Figure 2.1 .

Water levels at the scatter points were interpolated using kriging and variogram modeling as shown in Figure 2.2. Gaussian models were fit to the variogram data by adjusting nugget, range and variance. Nugget of at least 2m was used in all variogram models to cater for ‘noise’ in the data. The data generated for shallow groundwater was inherently noisy because of:

- inaccuracy in DEM (most locations with 10m DEM were actually using 30m DEM interpolated at 10m);
- some wetlands not being wet at the surface;
- perched wetlands not connected with the aquifer; and,
- fluctuations in stage in lakes and streams.

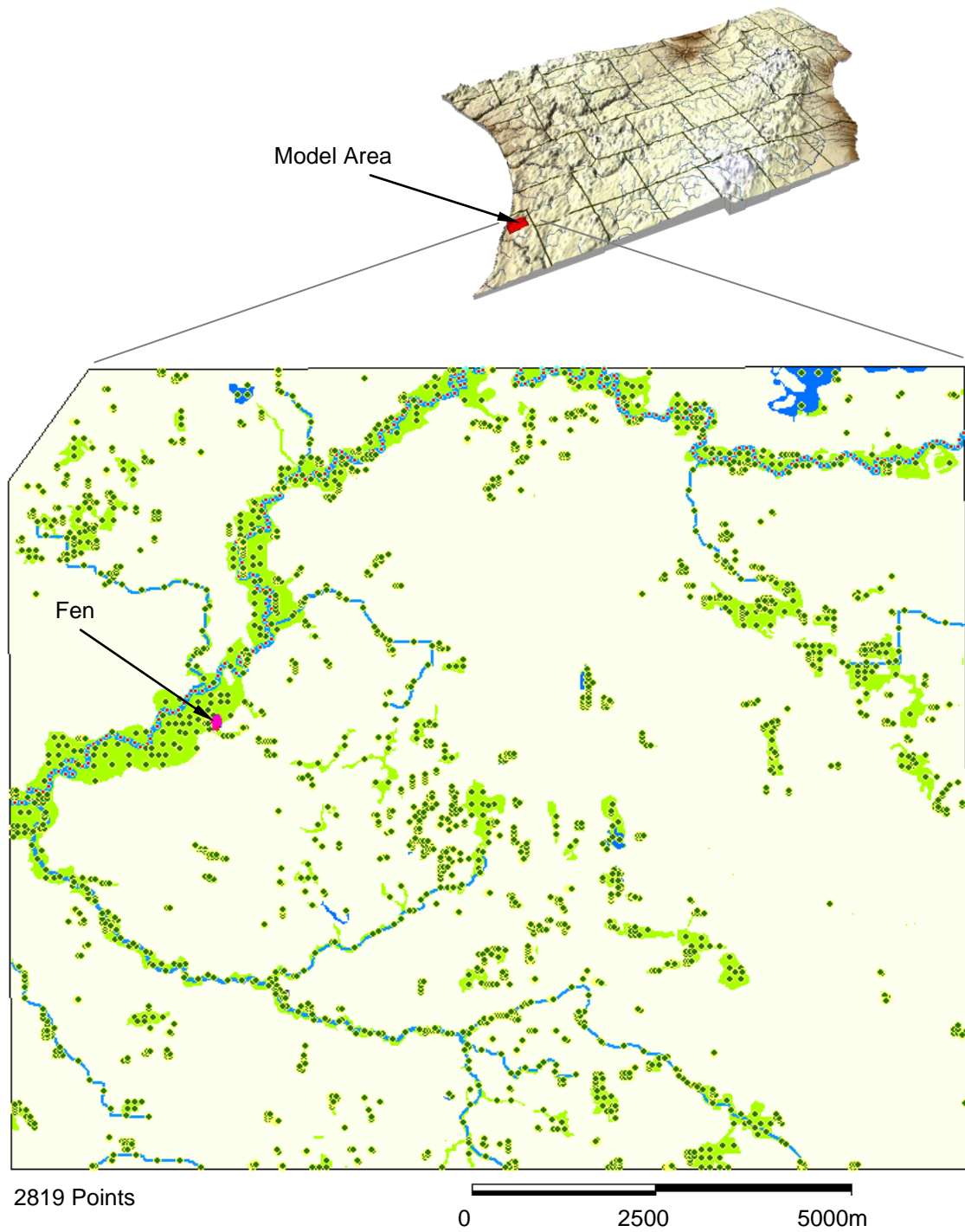


Figure 2.1 Scatter points generated in surface water features (lakes, streams and wetlands) to characterize shallow groundwater head using 30m/10m DEM around a fen site.

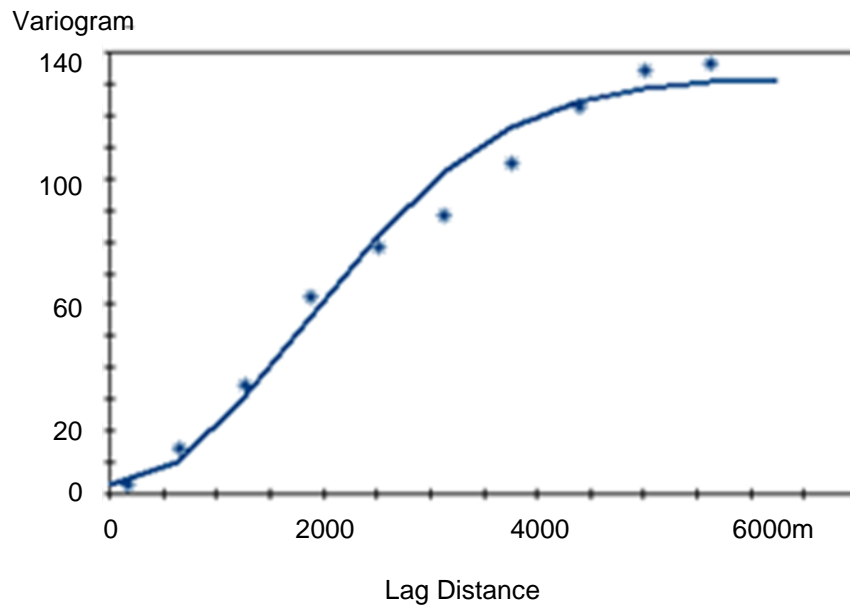


Figure 2.2 Gaussian model fit to the variogram

Between 0 and 5 passes of smoothing, as explained on page 58, were applied to the interpolated surface. A comparison of kriging surface without smoothing and 3 and 5 passes of smoothing respectively are shown in Figure 2.3. It may be noted that up to five passes of smoothing only removes ‘kinks’ from the initial contours without significantly altering the interpolated surface. The final shallow groundwater surface used in a model using 3 passes of smoothing after kriging interpolation is shown in Figure 2.4.

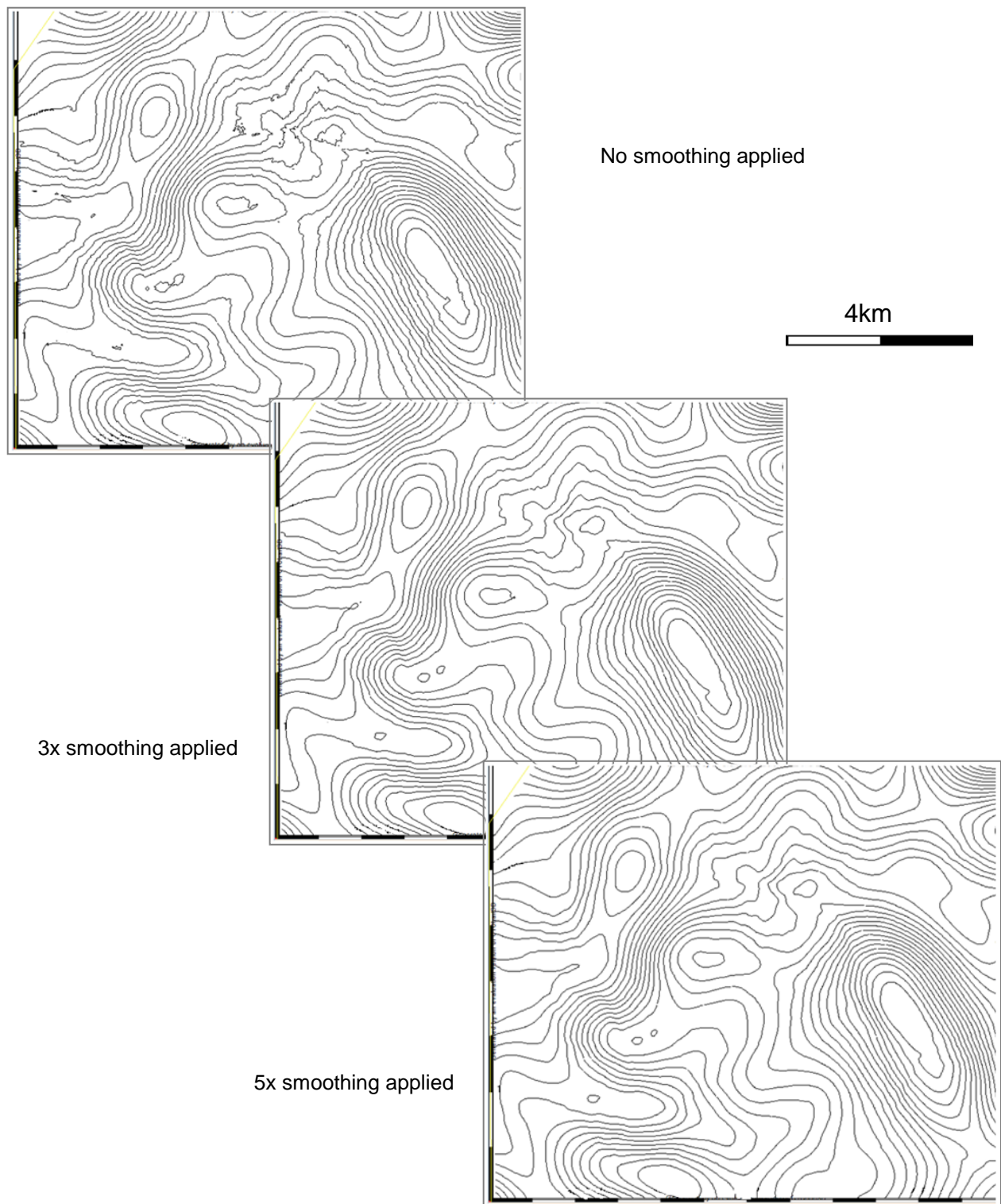


Figure 2.3 Contours at 2.12m interval represent shallow groundwater surface without smoothing (top) and with 3 and 5 passes (mid and bottom) respectively

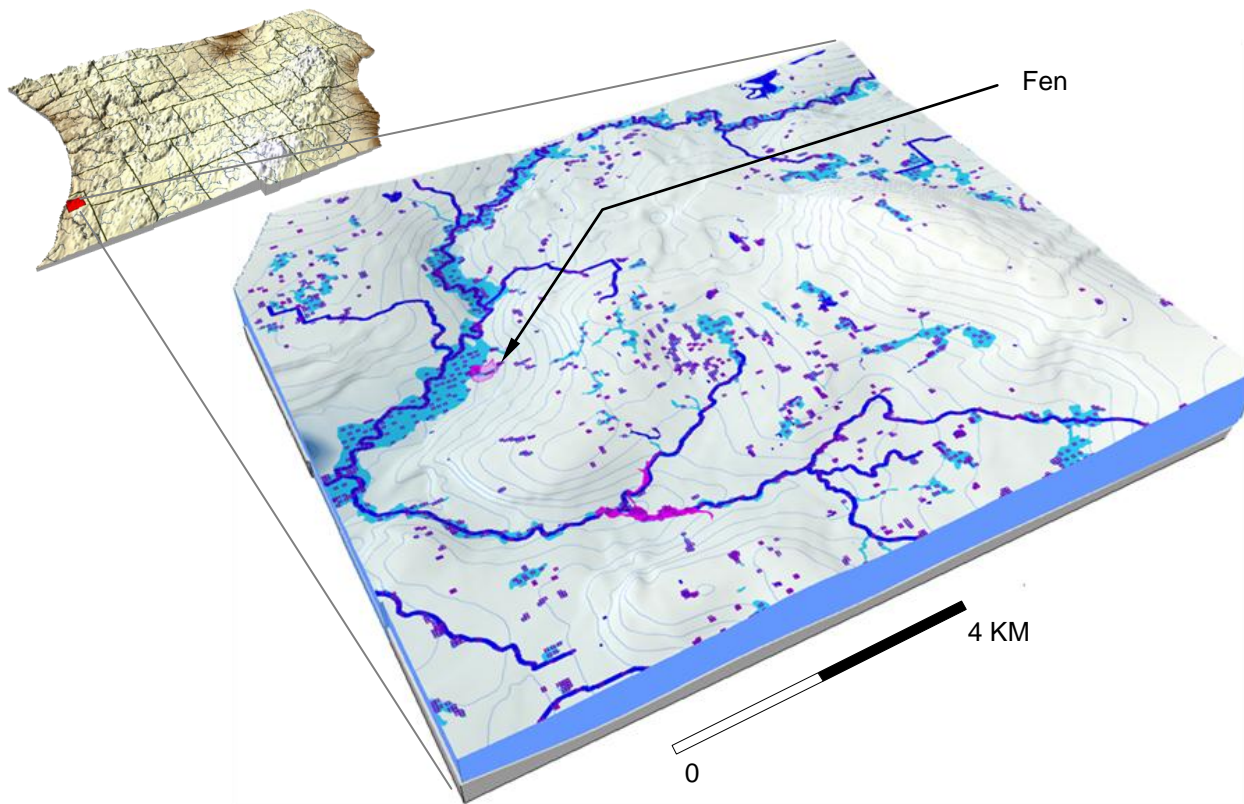


Figure 2.4 The relief and contours around fen sites represent the shallow groundwater surface interpolated from the data generated in surface water features (lakes, streams and wetlands). Contours at 2.12m interval show shallow water table varying in elevation from 176.636m to 239.196m. Contour interval is 3m.

Data-driven Characterization of Groundwater Heads in Glacial Drift

Data-driven characterization of groundwater heads in glacial drift implies the estimation deeper groundwater heads h and its gradient ∇h in equation 2.1, using the data from the

statewide water well records, based on the following assumptions for deeper groundwater systems:

- SWL data (Wellogic) from the water wells screened in the glacial drift represent groundwater head h in deep glacial aquifer;
- all third and higher order streams (NHD) are connected to deep groundwater flow systems within glacial drift; and,
- all large inland lakes greater than 100,000 square meters (NHD) are connected to deep groundwater flow systems within glacial drift.

Figure 2.5 illustrates an example of regional flow pattern derived for an area 12 km by 10 km around a fen site.

Comparison of shallow groundwater heads of Figure 2.4 with the regional ones of Figure 2.5 is shown in Figure 2.6. The differences in shallow and deep systems can be seen here. This was an expected outcome based on the multi-scale conceptualization presented in Figure 1.2.

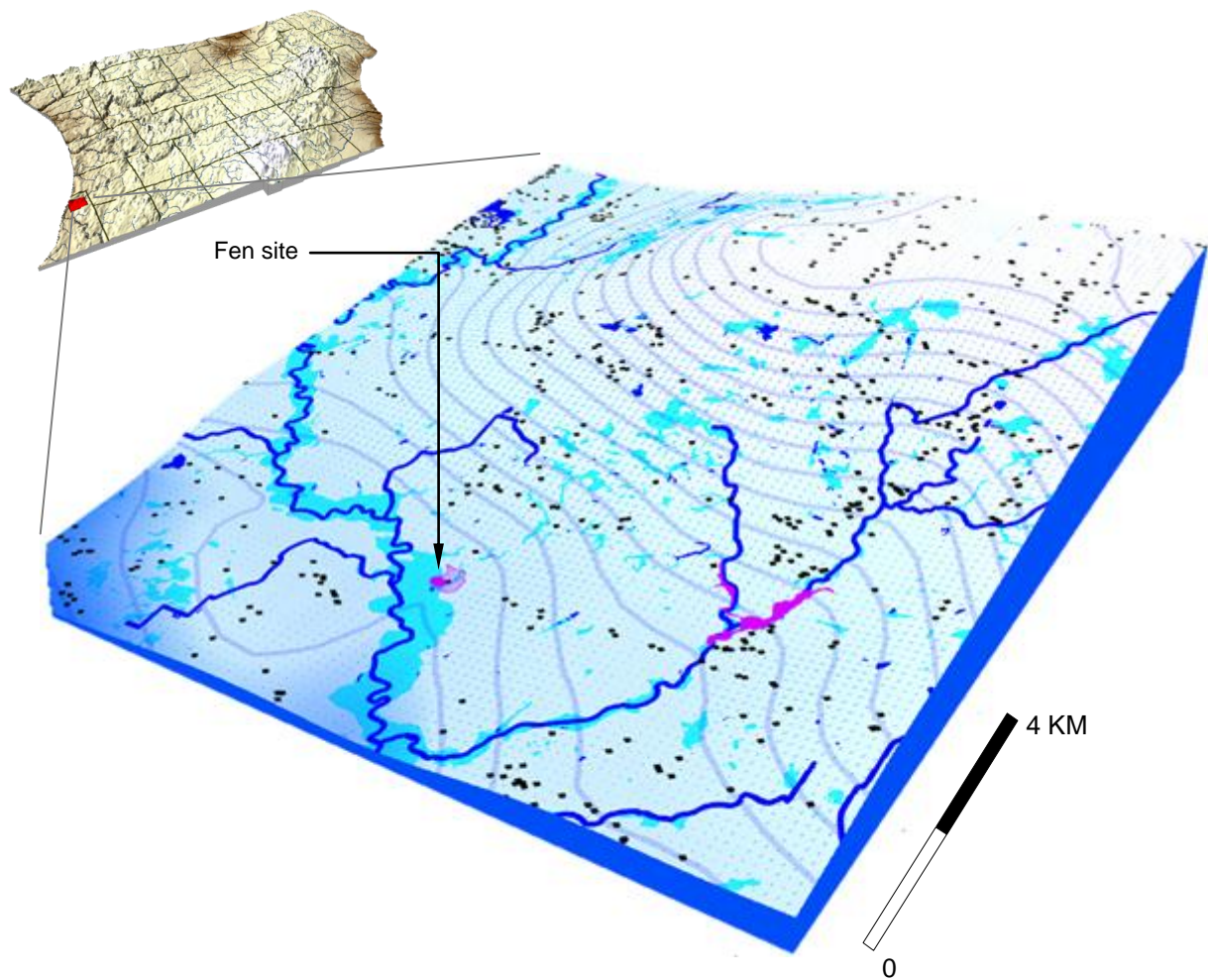


Figure 2.5 Shaded relief and contours around fen sites represent the regional groundwater surface interpolated from the water wells data. Black dots mark the data points. Contours show regional groundwater heads varying in elevation from 177.5936m to 218.419m. Contour interval is 2m.

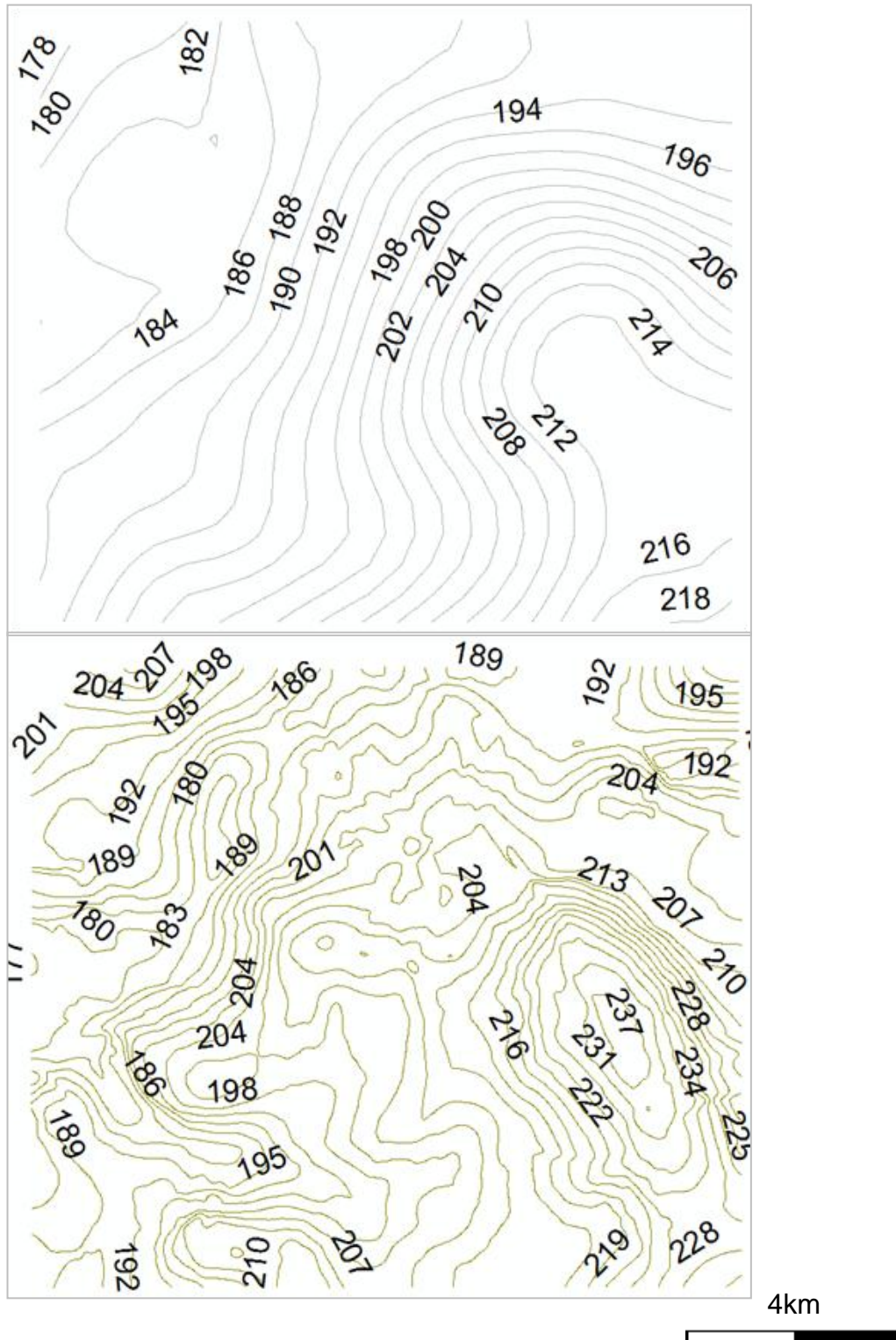


Figure 2.6 Groundwater head contour maps for deep system (top) and shallow system (bottom)

Data-driven Characterization of Groundwater Heads in Bedrock

Data-driven characterization of groundwater heads in bedrock involves the estimation groundwater heads h and its gradient ∇h for the bedrock aquifer in equation 2.1, using the data from the statewide water well records, based on the following assumptions:

- SWL data (Wellogic) from the water wells drilled in the bedrock represent groundwater head h in bedrock aquifer; and,
- where bedrock are very close to the surface, the groundwater flow systems in the bedrock are connected to large surface water features, i.e., third and higher order streams and lakes greater than 100,000 square meters.

Water level data for bedrock wells in Wellogic was interpolated to determine h for each cell in the model. In case of shallow bedrock areas, large surface water features were also taken into account.

Estimating Hydraulic Conductivity

Lithology information for the glacial drift was available in the wells data. Average horizontal hydraulic conductivity of the glacial drift, K_h , at each well location was estimated by taking the arithmetic mean of the conductivities of all lithology layers in the sequence (GWIM 2006) using equation 2.2.

$$K_h = \frac{1}{B} \sum_{i=1}^n K_i B_i \quad 2.2$$

Where B = Total depth of the drilled well

$i = i^{\text{th}}$ number of lithology record

n = total number of lithology records in the sequence

K_i = assumed horizontal hydraulic conductivity of the i^{th} lithology record

B_i = thickness of the i^{th} lithology record

K_i estimate was based on the type of material recorded in the driller's log and the type of glacial landform within which the well was drilled (GWIM 2006). Water well records that had usable lithology data were extracted from the Wellogic database. The glacial land system associated with each well location was determined using GIS overlay techniques. For each well, a hydraulic conductivity value was assigned to each lithology layer based on the type of material reported by the driller, glacial land system, and range of conductivity values of the given material in literature (GWIM 2006). Values of B and B_i were available within the well record. Using these values equation 2.2 was solved for each well location and hence an estimate for K_h was obtained at each data point. Lithology based K_h values for glacial drift were further processed at statewide scale to create statewide raster at 540m resolution raster for drift K_h using kriging interpolation (Oztan 2010). Glacial landform polygons were not enforced as boundaries while interpolating for K_h across the state.

Similar to raster maps for the conductivity of glacial drift, statewide raster maps for the transmissivity T of bedrock formations were produced at 500m resolution using the specific capacity test data from bedrock wells across the state (Oztan 2010). The specific capacity data were interpolated within the bedrock formation polygons to estimated T for the respective bedrock formation. K_h for model areas was estimated using equation 2.3.

$$K_h = \frac{T}{B} \quad 2.3$$

Where B = Assumed thickness of bedrock in the model

In order to determine horizontal hydraulic conductivity K_h for the drift aquifers within a selected model area, the values of K_h were read from the 540m conductivity raster map and interpolated for each cell in the model. In order to determine horizontal hydraulic conductivity K_h for the bedrock aquifers, the values of T were read from the existing 500m conductivity raster map, interpolated for each cell in the model and converted to K_h using equation 2.3.

Estimating Porosity

No data is available for the aquifer's effective porosity η in the databases, however, there had been studies in southern Michigan reporting value of η for the glacial drift to vary between 0.15 and 0.30 in southern Michigan (Lowry and Anderson 2006). Estimated net porosity η_{net} of sandstone bedrock in southern Michigan was reported as 0.115 in other geological works (Barnes et al. 2009). The upper Marshall formation [where most of the water wells are drilled] is a medium to coarse grained porous sandstone (Stearns 1993). Based on these studies, value of $\eta=0.1$ was assumed for both glacial drift and bedrock formations in 2.1.

Tracking Source Water in Horizontal Plane

Regional capture zones were delineated for selected fen sites using the reverse particle tracking on the static water level surface generated for the regional system. Instead of running the simulations for specified time periods, the reverse tracking was allowed to run until the flow paths hit one or more regional sources. An example of regional capture zone for a fen site is shown in Figure 2.7, showing the flow paths traced back to a sub-regional groundwater mound..

It does not necessarily mean that all flow paths within the capture zone are draining into the fen site. Some flow paths within this zone may up-well into the fen and some may up-well into the wetlands and lakes within the capture zone while still some other paths may completely bypass fen underneath the fen surface and end up in a regional sink. The groundwater flow system is truly 3D in areas where fens occur and is not fully captured in this 2D representation of capture zone. Profile models across the capture zones, as explained in succeeding sections, will be used to improve upon our understanding of vertical capture zones. The conceptual flow regime model presented in Figure 1.2 may also be kept in mind.

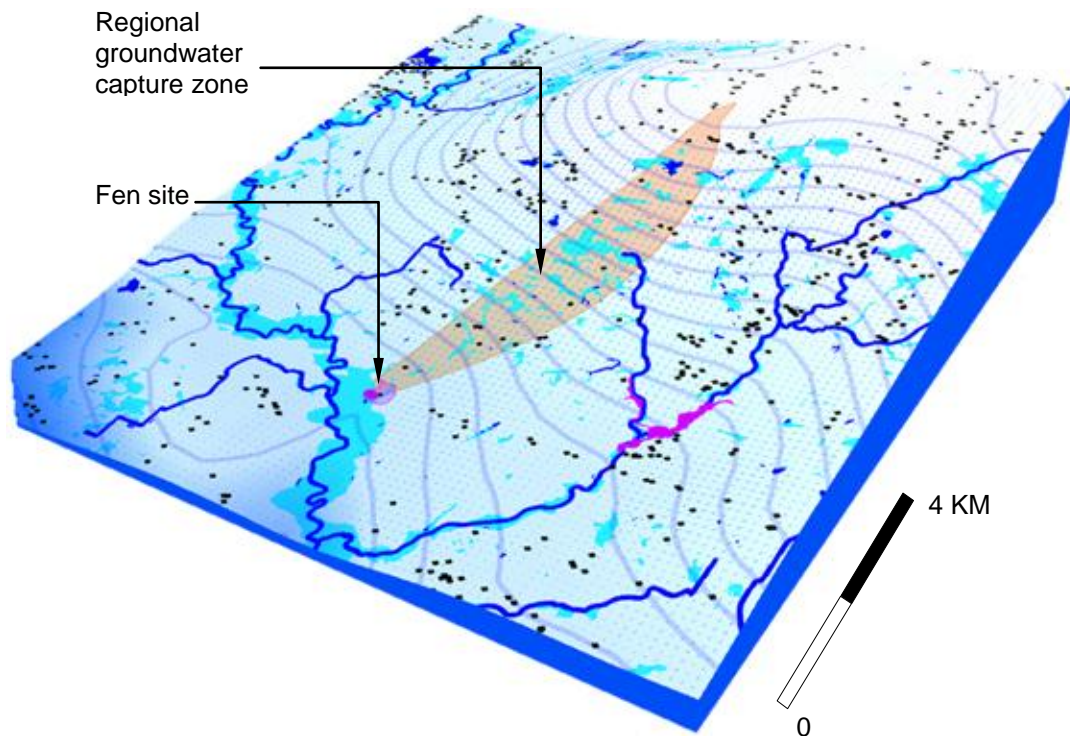


Figure 2.7 Groundwater capture zone delineation for a fen site based on reverse particle tracking. The relief and contours represent regional groundwater surface. Contours show regional groundwater heads varying in elevation from 177.5936m to 218.419m. Contour interval is 2m.

VERTICAL PROFILE MODELS FOR GROUNDWATER SYSTEMS

Groundwater capture zones delineated using the horizontal flow system as shown in Figure 2.7 only show the possible flow paths that may lead to the fen site in plan view. As illustrated in Figure 2.5 and Figure 2.4, groundwater flow gradients for regional and shallow groundwater systems may be different from each other. In a full 3D sense, many of these flow paths may bypass the fen by flowing underneath the fen or up-well in other water bodies within the captures zone before they can reach the fen. To fully resolve 3D complexities of the system we require full 3D models, but full 3D models are data hungry and expensive. Using a 2D vertical profile model through the captures can give some insights into the vertical dynamics of the flow system without having to build a 3D model. 2D profile models presented in this study, should, in no way be taken as a substitute to full 3D models, because of their inherent limitation as discussed ahead. The model may only be used for gaining insights rather than making predictions and must be interpreted with their limitations in view. The conceptualization of 2D multi-scale flow regime is already presented in Figure 1.2. The profile models were built to qualitatively gain insights into the shallow and deep groundwater flow systems and the likely delivery mechanisms of groundwater to the fen locations. Similar insights had been provided by others using mostly hypothetical approaches (Acreman 2004; Amon et al. 2002). The profile models in this employ the estimated groundwater table as a forcing function on the top model boundary and use process based simulations to track the vertical flow paths. The profile models were used primarily to gain insights on 3D flow dynamics and not for making predictions.

Modeling Assumptions

The profile models were built to resolve the vertical dynamics of groundwater flow with the following assumptions:

- Water table, taken as prescribed head, drives the flow in the system.
- No flow takes place across the profile section's longitudinal boundaries.

Water table from the shallow system was enforced as top boundary condition and the models were solved for h in the profile. Estimation of other boundary conditions and parameters are explained in succeeding paragraphs.

The profile sections for models were selected along the regional flow paths from the deeper systems. However, shallow groundwater flow direction may not always be parallel to the deeper one. The latter of the above assumptions is, therefore, more valid for the deeper parts of the profile and less so closer to the surface. This limitation must be kept in view while interpreting the profile models.

Boundary Conditions for Profile Models

A profile was selected through the regional capture zone delineated for a prairie fen site as shown in Figure 2.8. In most profile models built in the study, both ends of the profile were kept at a location coinciding with a groundwater divide to obtain a fully contained system with relatively more robust vertical boundaries. Where this was not possible, remote conditions (usually constant head) were assumed along the vertical boundaries.

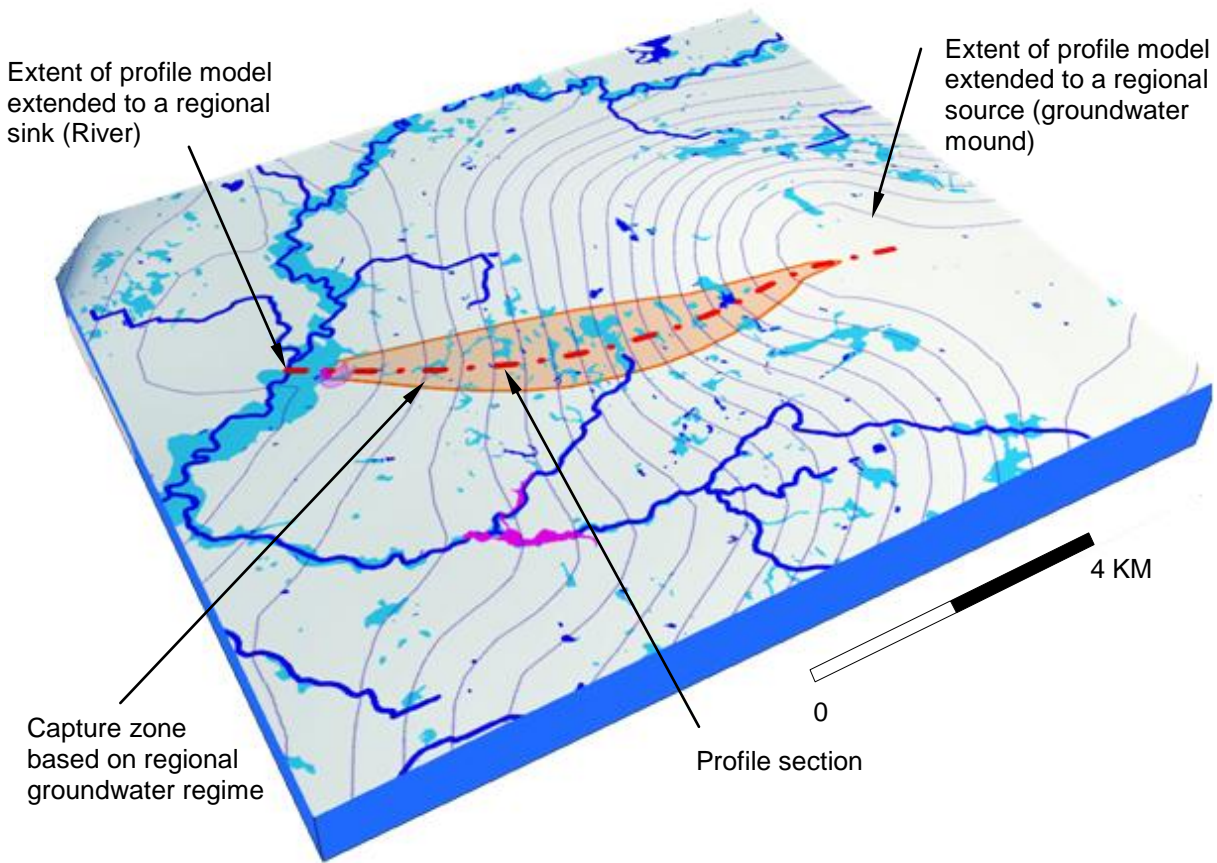


Figure 2.8 A profile sections is selected between a regional source and a regional sink, intersecting the fen site and its regional groundwater capture zone. Relief and contours in the figure represent shallow groundwater surface or the water table. Contours show regional groundwater heads varying in elevation from 177.5936m to 218.419m. Contour interval is 2m.

Top boundary of the model was defined by shallow water table taken as prescribed head. The depth of the profile models extended down to impervious bedrock formation (mostly shale) to achieve relatively more robust no-flow boundary at the base of the profile. Figure 2.9 shows the typical boundary conditions used for most profile models.

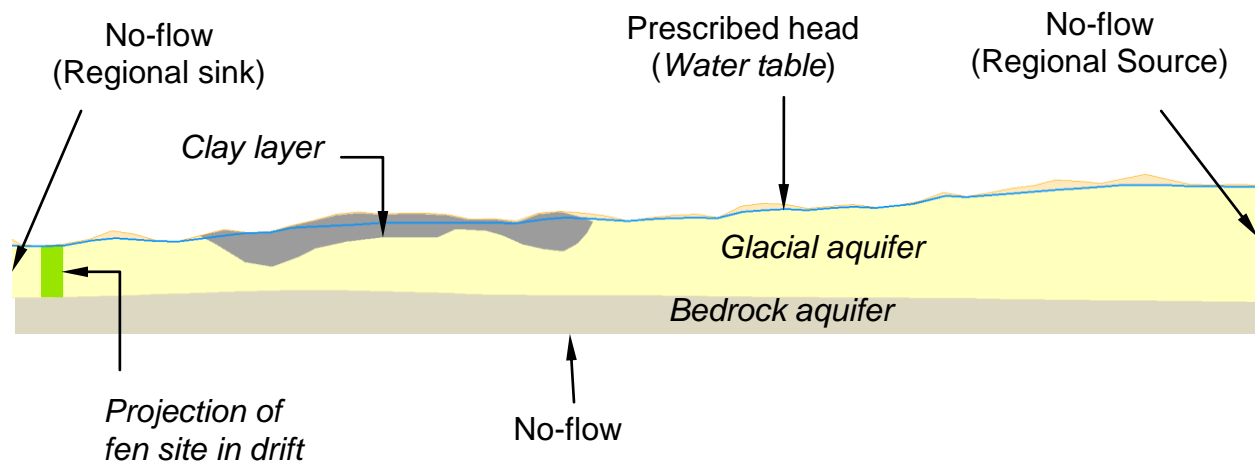


Figure 2.9 Typical boundary conditions for the profile models

Top elevation, or the topographic surface, was estimated along the profile using 30m/10m DEM raster along the profile. However, this DEM was only used for display purposes and not as a modeling parameter. An example is shown in Figure 2.10. Bottom of glacial drift, or the top of bedrock, was estimated using 500m raster for bedrock elevation along the profile. An example is shown in Figure 2.10

In most cases, only one bedrock layer was encountered under the glacial drift. An arbitrary minimum thickness of 100ft (30m) was assumed for these bedrocks. In cases more than one bedrock layers were encountered within 100ft below the drift, the actual thickness of the upper layer from 500m raster was used.

Hydraulic Conductivity

For all profile models presented in this study, mean hydraulic conductivity for the glacial drift was taken as 50ft/day and for Marshall Sandstone 250ft/day. Clay lenses within the drift and

Coldwater Shale in the bedrocks were treated as less transmissive formation with very low conductivities of 0.001ft/day and 0.0001ft/day respectively. These values were not based on data but used primarily to represent order of magnitude contrast in different materials. The contrast does not affect the qualitative assessment of vertical flow. Profile models were not used in any kind of quantitative assessment in this study. Sensitivity analysis for variability in hydraulic conductivity was also performed and explained in the next section.

Vertical Anisotropy

No data was available on the vertical anisotropy for the glacial drift or the bedrocks in the study area. Vertical anisotropy is one of the least known parameters in groundwater flow (Winter 1978). Gillhan and Farvolden (1974) tested this ratio and found it particularly sensitive in areas of recharge and discharge. Freeze (1969) concluded that K_H/K_V values greater than 100 are not uncommon. Vecchioli and others (1974) found $K_H/K_V = 500$ in a drift section of Long Island, New York. Bennett and Giusti (1971) showed that the ratio had to be close to 1000 for their simulations to match data in the coastal plains of Puerto Rico. Siegel and Glaser (2006) reviewed the values for K_H being 1-2 orders of magnitude greater than K_V . Vertical profile models were found very sensitive to the anisotropy ratio. After testing many different values for anisotropy ratios, we concluded that $K_H/K_V = 1000$ for glacial drift and $K_H/K_V = 500$ for transmissive bedrocks matched well with the data for most situations. Final profile models presented in this research are based on these values. Sensitivity analysis for Anisotropy was also performed and explained in the next section.

Estimating Water Table along the Profile

Groundwater level along the profile was taken from the shallow groundwater surface generated for the shallow system. An example is shown in Figure 2.10

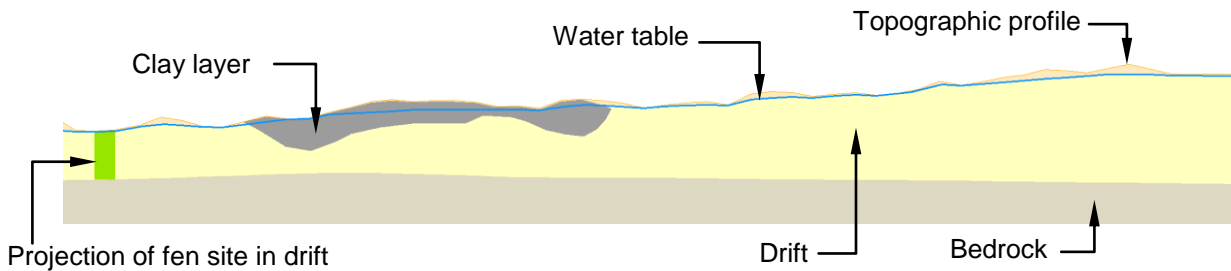


Figure 2.10 Boundaries, zones, and water table estimated for a profile model.

Estimating Discontinuities within the Glacial Drift

Clay lenses or continuous clay layers within the glacial drift were estimated from the lithology logs in the water wells data. The available water wells along the selected profiles were extracted and plotted as shown in Figure 2.11. Sensitivity analysis for discontinuities was also performed and explained in the next section.

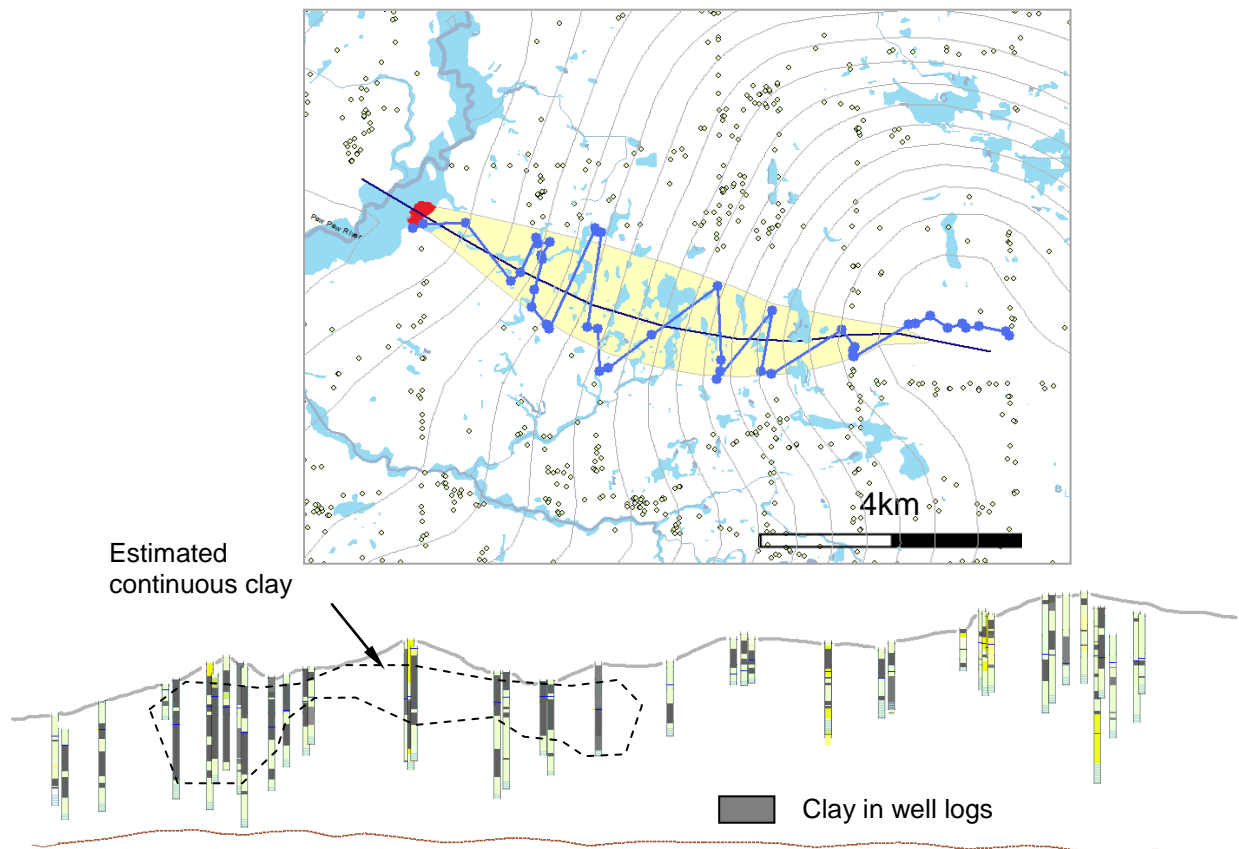


Figure 2.11 Water well logs around the profile (above) projected in vertical plane (bottom) to show clay occurrences

Clay layers recorded in the well logs were shown with darker color which gave an idea of occurrence of clay within the drift. Clay lenses or continuous confining clay units were identified based on subjective judgment from these logs.

Tracking Source Water in Vertical Plane

Profile models based on above mentioned parameters were built for the selected sites to understand how deeper and shallower groundwater systems deliver water to the sites. Forward and reverse particle tracking techniques were used to trace flow paths from local and regional systems and to find where the water was coming from to the fen sites. An illustration of profile model with flow paths is shown in Figure 2.12.

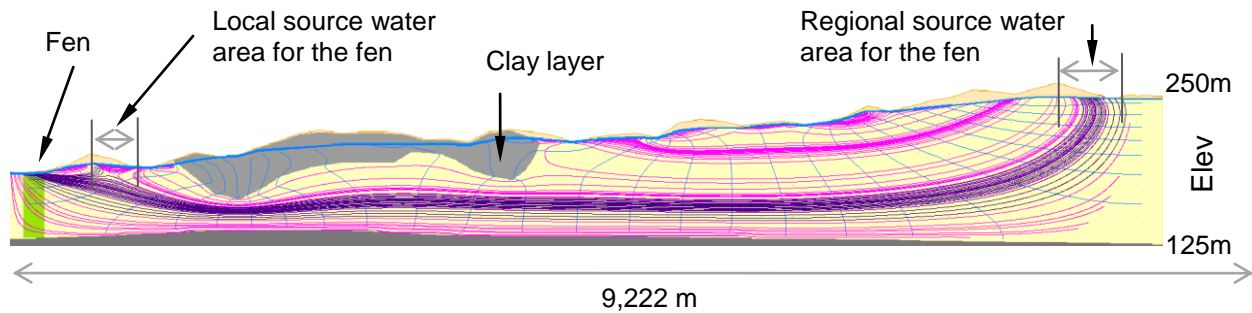


Figure 2.12 Profile model showing the groundwater flow paths (pink lines) leading to the fen site (purple lines). Light blue lines show groundwater head contours at 1.84m interval. Vertical exaggeration in this figure and all other models presented in this study is 10x, unless noted otherwise.

SENSITIVITY ANALYSIS

Hydraulic Conductivity

A number of models were analyzed using variable K field and constant K field. It was observed that the qualitative delineation of flow paths did not significantly alter when complex variable K fields were used. For final presentation in this study, uniform K fields were used in all models. One of the sensitivity results is shown in Figure 2.13 to as illustration.

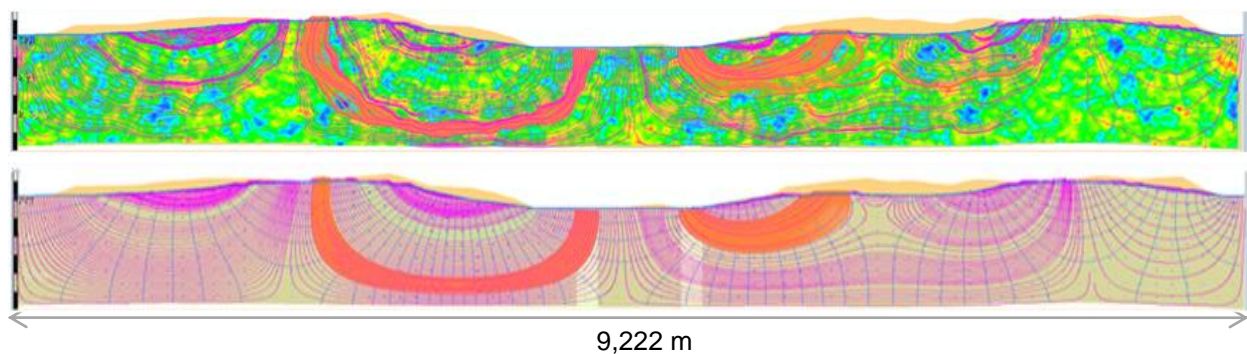


Figure 2.13 Variable (top) versus uniform K (bottom) field in glacial drift profile. Orange flow paths are fen capture zones.

Vertical Anisotropy

Different values of K_H/K_V were analyzed for profile models and the results were compared qualitatively to match with the regional flow patterns. Higher values of K_H/K_V produced too many closed systems along the profile where the regional flow systems from data interpolation had suggested continuous flow gradients. By reducing the K_H/K_V ratio, the flow patterns in profile models conformed to regional patterns in horizontal flow models. The illustration in Figure 2.14 shows K_H/K_V varying from 1/10 through 1/500 for a glacial outwash aquifer. Final anisotropy ratio for glacial outwash for all models presented in this study is 1/500.

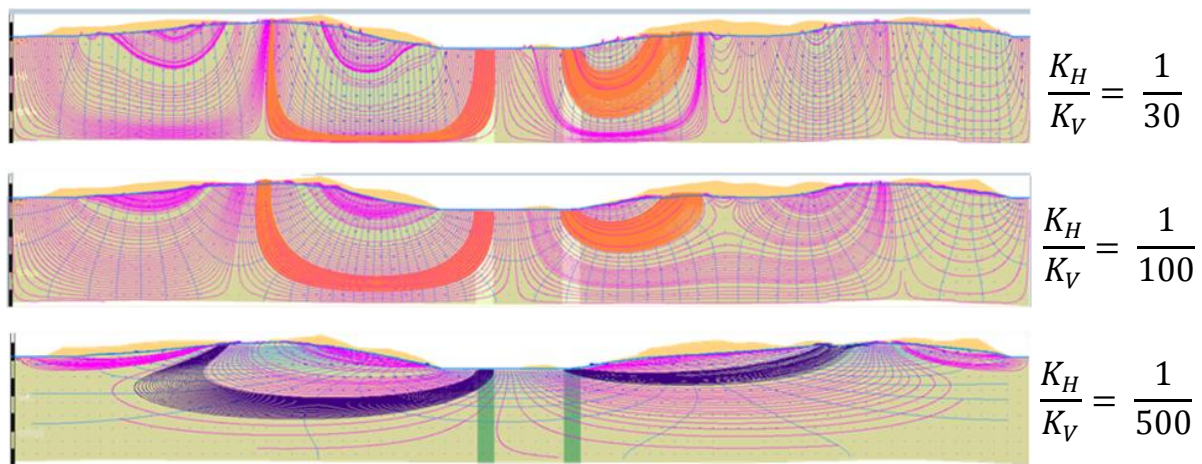


Figure 2.14 Sensitivity to vertical anisotropy. Orange and purple flow paths represent capture zone for the fen sites

Discontinuities in Drift

Well logs were analyzed for each site to identify less pervious materials in the lithology. Some sites showed very clear patterns of continuous clay layers where as in most sites the pattern revealed by well logs was random. In order to assess the impact of scattered discontinuities within the drift layer several profile models with scattered discontinuities were

compared with models without scattered discontinuities. The comparison revealed that in most cases, scattered discontinuities did not significantly alter the flow pattern. Consequently, all models presented in this study are without scattered discontinuities. However, where continuous discontinuities were ascertained from well logs, these were duly incorporated in the profile models. Figure 2.15 and Figure 2.16 show the well logs in profile and scattered discontinuities inferred from these logs. The figures also show the comparison of vertical profile models with and without discontinuities. In some cases, as in Figure 2.15, the discontinuities qualitatively impacted the flow paths leading to the fens, but in most cases, as in Figure 2.16, that was not the case.

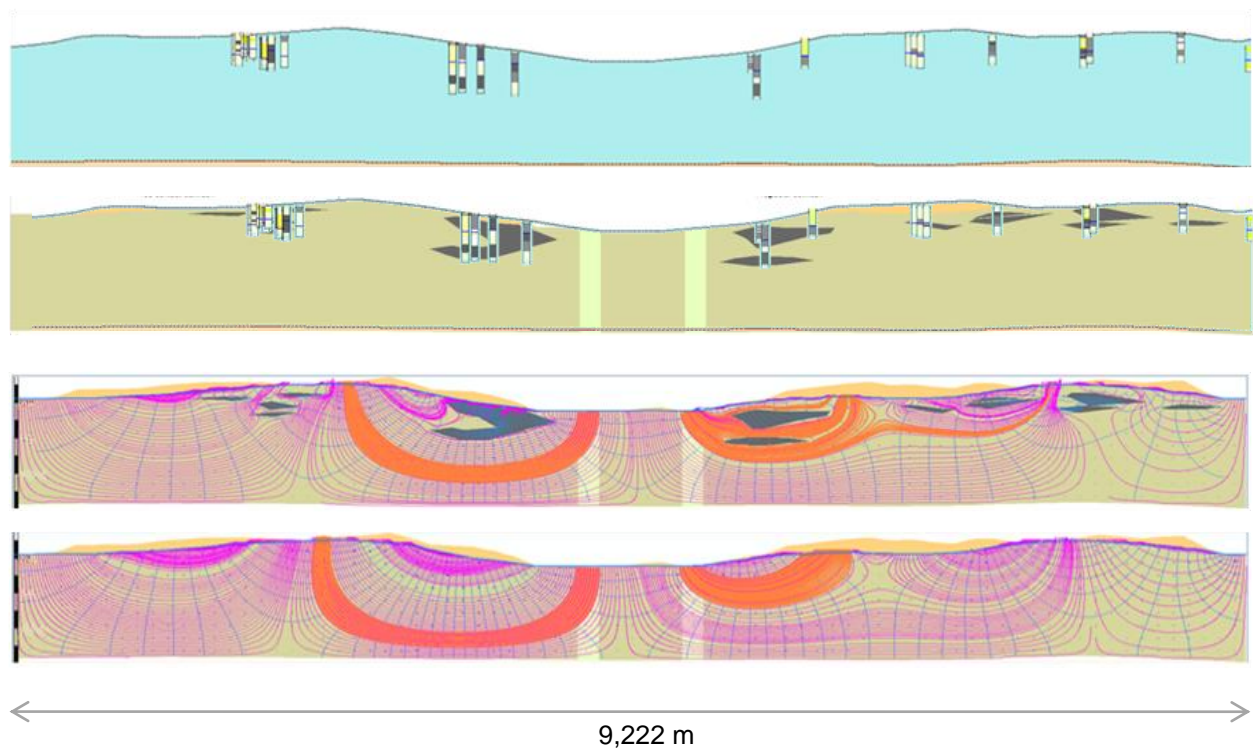


Figure 2.15 Effect of scattered discontinuities at Paw Paw Prairie Fen site. Orange flow paths indication fen capture zones.

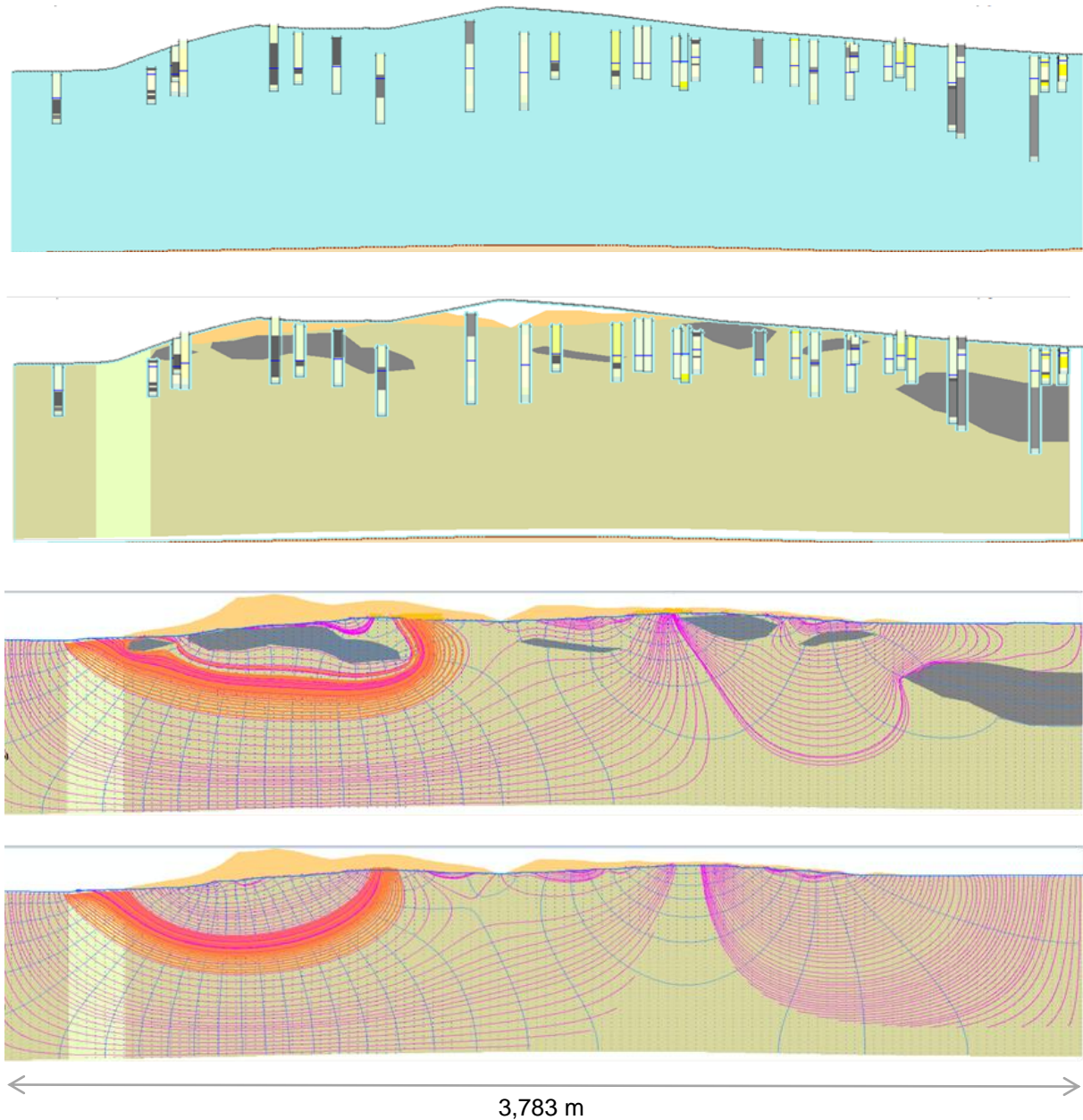


Figure 2.16 Effect of scattered discontinuities at Paw Paw Lake Fen site. Orange flow paths indication fen capture zones.

The impact of discontinuities in a vertical profile may become exaggerated because flow lines may go around the discontinuity in the transverse direction which is not captured by the profile model. Consequently, impact of small discontinuities was not taken in consideration for

all the models presented in this study because qualitative assessment of flow paths presented by these models was not being significantly impacted even if this additional complexity was added to the models.

COMPARING WITH TRADITIONAL APPROACH

In the traditional groundwater modeling approach, the models are built and calibrated to establish the current or existing conditions. This is a challenging task because most natural systems are very complex, and multiple scales in fen hydrology adds yet another layer of complexity to the system. Modeling the whole system requires knowledge about every component, parameter and boundary conditions in the system. The resulting models, therefore, are complicated and data intensive. Not only the data is expensive to collect, it is seldom the case, even in ‘data-rich’ situations, that modelers would have complete data for all the parameters in the system. The unknown parameters in the model, therefore, have to be estimated using inverse modeling techniques or intelligent guessing. Adhering to the principals of parsimony while building the traditional models can reduce the data requirements and uncertainty associated with parameters uncertainty, but adds to the uncertainty associated with the structural uncertainty is illustrated by Silberstein (2006), where structural uncertainty is reduced by increasing complexity but parameter estimation uncertainty is increased.

Advocates of simpler models suggest that simplicity is important to the development of useful models (Hill 2006). However, models should be able to capture essential complexities of the natural system, and, in case of fen hydrology, the systems are very complicated and multi-scale and cannot be adequately resolved by simpler models. Gómez-Hernández (2006) has summarized the typical difficulties one faces when using complex models:

- Data requirements are extensive for making and calibrating the model. Data quality is also an issue.
- Extensive knowledge on aquifer properties is seldom available.
- It is very difficult to match all aquifer boundaries with geological boundaries where conditions are known. Either the boundaries have to be approximated or extended over a larger area. Approximate boundaries increase uncertainty and far away boundaries increase model area, and hence increase number of parameters and data requirements.
- The more complex a model, the more parameters it has. Unknown parameters are established through inverse modeling which makes the calibrated models non-unique and difficult to constrain.
- Prediction uncertainties add from data deficiencies (and errors), non-unique calibration and complex boundary conditions.

The modeling results are always approximate within the bounds of some uncertainty. The common sources of uncertainty in traditional models are discussed below:

Aquifer Boundaries:

The areas of interest to be modeled rarely conform to natural boundaries of an aquifer system. If the model is truncated at arbitrary boundaries it introduces errors at the boundaries, if the model domain is extended to natural boundaries, it increases the model area, thereby increasing the data requirements and adding more components in the model. This is a dilemma faced by modelers whenever they have to model an existing groundwater system.

Aquifer Stresses:

Background Pumping: Complete knowledge about the location and pumping rates water wells in an area is seldom known. Their pumping rates are highly variable in time and may have an impact on small changes at local scales.

Stage in Surface Water Bodies: Stage in surface water bodies keeps fluctuating. It would seldom be the case that (fluctuating) stage data on all rivers/lakes is available in a regional setting. Even if stages are measured, the measured levels only represent a time stamp of stage and could be misleading for the average conditions.

Recharge: Recharge is highly variable over space and time. Even for the most precise estimates of recharge simplifying assumptions are made. It is extremely difficult and expensive to make accurate estimates of recharge over space and time. In most cases, uniform recharge rates are applied to large zones in the groundwater models.

Aquifer Properties:

Aquifer properties such as hydraulic conductivity can vary several orders of magnitude within a small scale. Storage coefficient similarly can vary significantly within the spatial scales of the modeling domain. The knowledge about distribution (zones) of geologic materials, responsible for the variability, is seldom known accurately. Lack of knowledge about these zones can affect the model structure and required complexity.

Initial Conditions:

It is seldom the case in groundwater modeling that initial conditions are completely known. Even for a moderately complex system, modeling the absolute initial conditions is data

intensive and requires simplifying assumptions. The uncertainty, non-uniqueness and errors associated with modeling the initial conditions are consequently projected to the predictions made for the stress scenarios for which the model is used.

ADOPTING DATA DRIVEN MODELING APPROACH

Using lots of low quality/noisy data would yield only approximate results. However, prior studies have shown that if data from Michigan's groundwater databases is processed correctly, it can closely match the traditional modeling results (Simard 2007). But since predictions from the traditional models are also approximate, we may not lose much by building the 'approximate' data models.

The relationship between data, (i.e., recorded measurements of nature) and process based traditional models is very complicated. The dilemma of uncertainty in deterministic models, due to theoretical reasons and structural simplifications, is that the models require calibration against data, while the data by itself neither exactly follows the theory nor perfectly aligned with the model structure. But in the presence of abundant data, we can even skip the process of calibration (Cunge 2003).

Hydrological science had long been divided with two approaches used independently by the modelers [theory based] and the experimentalists [data based]. Often, the two groups had little to do with each other (Silberstein 2006). In the current environment of large GIS data bases and high speed computing, we need models which combine data analysis, visualization and processing with the theory based simulations. Data-driven approximations can be useful in problems related to hydrology especially where the relation between dependent and independent variables are poorly understood (Garcia and Shigidi 2006).

Data driven modeling approach adopted in this study gives us the following advantages:

- Multiples scales of hydrology can be investigated since the data is available at multiple scales.
- Almost any part of the state can be modeled since data is available everywhere.
- Relatively simpler models, compared to the traditional models, afford the opportunity to concentrate more on understanding the natural processes underlying the fen hydrology rather than the issues related to numerical modeling of complex systems.

For this study the Michigan's groundwater was conceptualized as two or three layered aquifers system as shown in Figure 2.17. The top layer being the shallow glacial drift aquifer, fully connected with all surface water features; the middle layer being deeper glacial drift aquifer connected to large lakes and streams; and, the bottom layer being the bedrock aquifer.

As mentioned earlier, we employed data driven modeling approach to compute h and K in 2.1. The equation can be also be used to simulate the above mentioned conceptual model using process based traditional approach in which h is obtained by solving the equation for groundwater flow while K is calibrated through inverse modeling by matching h with the observed data. Based on estimated h and calibrated K , velocity field is calculated in the equation. Calibrating a model would require information on sources and sinks, complex processes, geological boundaries and other parameters such as leakance. Recharge is generally estimated through inverse modeling. Most traditional models lack enough data on these variables and are non-unique even after calibration. Conceptual layers can be added to resolve vertical dynamics of subsurface flow. Once calibrated, the models can be run for different scenarios as well as for transient simulations. Water budgets and fluxes can also be estimated. However, data

requirements for calibrating the models, especially across multiple scales, may be expensive and time consuming.

In the data driven modeling approach adopted in this study, 2.1 was characterized based on data for both h , and lithology based estimates of K , to estimate the velocity field V . Groundwater heads for shallow drift, deeper drift and bedrock aquifers were all obtained from separate data sets. These data, as opposed to traditional data, are often noisy but abundant and available from open sources. Moreover, the data are available virtually ‘everywhere’ in the state – giving the flexibility to zoom into any fen location for modeling. Interpolated heads were used as ‘prescribed heads’ in the models. Recharge estimates were not required. Models were not calibrated as they were already based on data.

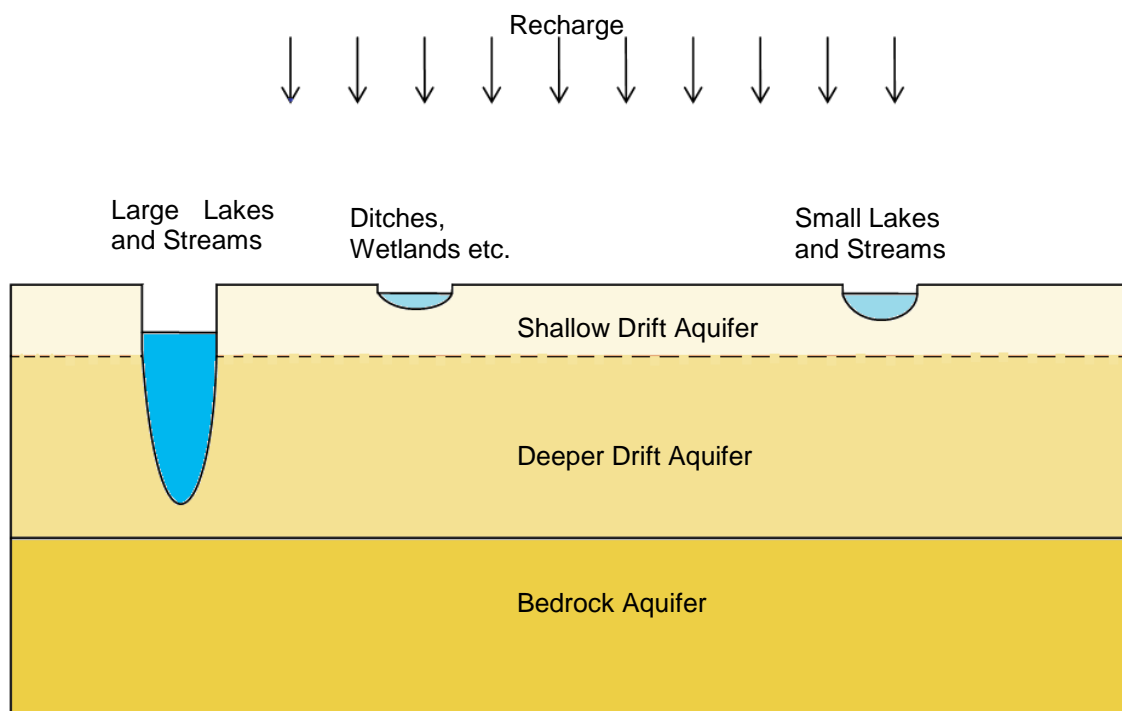


Figure 2.17 Conceptual aquifer systems in Michigan

An advantage of data modeling approach over the traditional one is that it allows modeling almost any fen in the state without having to visit the site for data collection – saving time and money, as the approach employs publically accessible GIS data, available all over the state – making possible multi-scale modeling of a large number of fen sites within a single study.

The disadvantage of data models as compared to the traditional models, however, is that they cannot be used for transient simulations and estimating water budgets. And since the models are not process based, they cannot be employed for scenario testing. The models only give the existing or long-term average picture of hydrogeologic conditions prevailing around a fen site. Such picture may be useful for identifying areas of critical hydrological processes and likely source water areas to help guide planning for detailed hydrological studies at a particular site.

DATA USED

Michigan's Statewide GIS databases were used for all data requirements in this research. These databases were compiled by Michigan Department of Environmental Quality (DEQ) under Michigan State Public Act 148 which required the department to create a groundwater inventory and map. The act also required the inventory and map to be accessible by public (GWIM 2006; PA 148 2003). This study capitalized on these publically available databases to investigate groundwater sources for prairies fens in Michigan.

Following statewide GIS data layers were used in this study to characterize groundwater flow regimes at different scales of investigation:

- Water Well Drillers Data – Wellogic (GWIM 2006), was used:
 - to characterize deeper and regional groundwater flow dynamics;
 - to estimate aquifer properties based on lithology information; and,

- to refine conceptual models.
- National Hydrography Dataset NHD layer (NHD USGS 2010) was used to delineate streams network in the models.
- Inland lakes layer was used to delineate lakes in the models (GWIM 2006).
- National Wetlands Inventory NWI data (GWIM 2006) was used to delineate wetlands in the models.
- Glacial Land Forms data (GWIM 2006) was used to refine conceptual models and was correlated with the occurrence of fens and hydrologic regimes.
- Digital Elevation Model DEM (NED USGS 2006) for topographic surface at 30m/10m resolution was used:
 - to estimate mean surface water elevation in lakes, streams and wetlands;
 - to delineate aquifer top in the model areas; and,
 - to estimate local surface water sheds around the fens.
- A combination of DEM, NHD, Inland Lakes and Wetland layers were also used to generate static water level data for shallow/local groundwater systems.
- Statewide pre-processed raster (Oztan 2010) for bedrock elevation (500m resolution) was used to delineate bedrock top in the models and to estimate thickness of glacial deposits above the bedrock.
- Bedrock geology data (GWIM 2006) was also used for bedrock aquifer properties.
- Statewide pre-processed raster (Oztan 2010) for horizontal hydraulic conductivity, K_h , (540m resolution) was used to delineate the K_h field for glacial and bedrock aquifers.

PRE-PROCESSING OF DATA

Although the data on static water levels (SWL) and aquifer properties was available in high density from the Wellogic, it could not be directly used without preprocessing because of inconsistencies and noise. Moreover, SWL data for shallow groundwater systems was not available directly from any database. Different data layers (DEM, NHD and NWI etc.) had to be manipulated to characterize shallow systems.

Noise, Outliers and Bad Data

Wellogic data was used in determining static water level SWL (for statewide and regional scale data driven groundwater models). However, using SWL from Wellogic had its own challenges because this data is very noisy, though available in high density throughout the study area (Figure 2.18).

Geostatistical algorithms for data analysis were chosen and coded by Dr. Huasheng Liao for the groundwater modeling software used in this study (Liao 2010, personal communication). Using these codes, water wells data was preprocessed at the statewide scale. The preprocessed data for SWL and hydraulic conductivity was used in this study for the selected model areas at different scales. A very brief overview of data preprocessing is as follows.

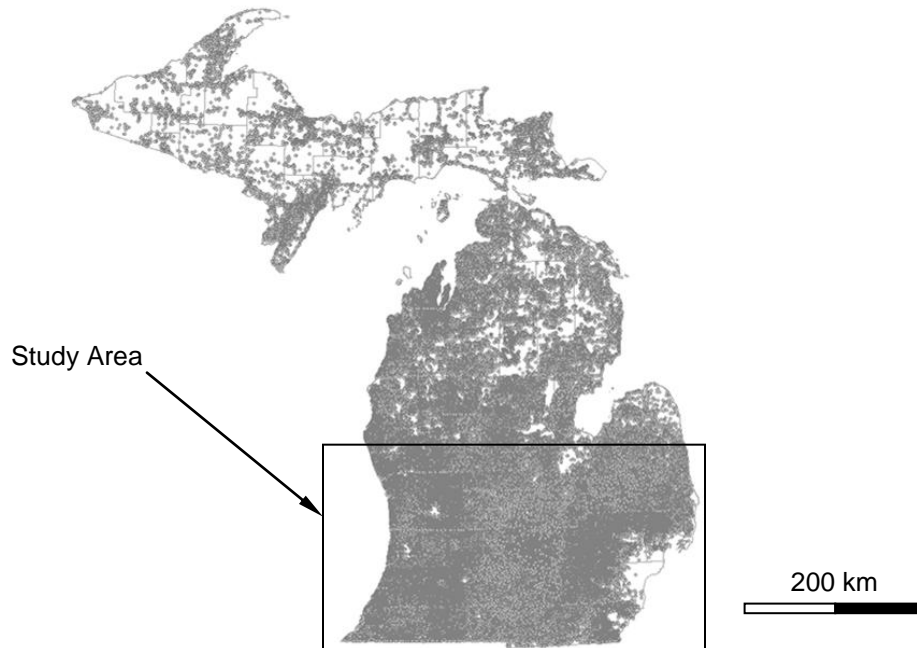


Figure 2.18 Water Well Drillers records in the Wellogic Database have a good coverage throughout the state, especially in the southern half of Lower Peninsula.

Depth to water level was recorded at the time a well was drilled and reported by the driller. This information was used to determine SWL elevation by subtracting the depth to water table from the 10m DEM. The evaluated SWL elevation for a selected band across the state is shown in Figure 2.19. One can observe the density of coverage at this scale, but also obvious from the plot is the variability and noise inherent in this data.

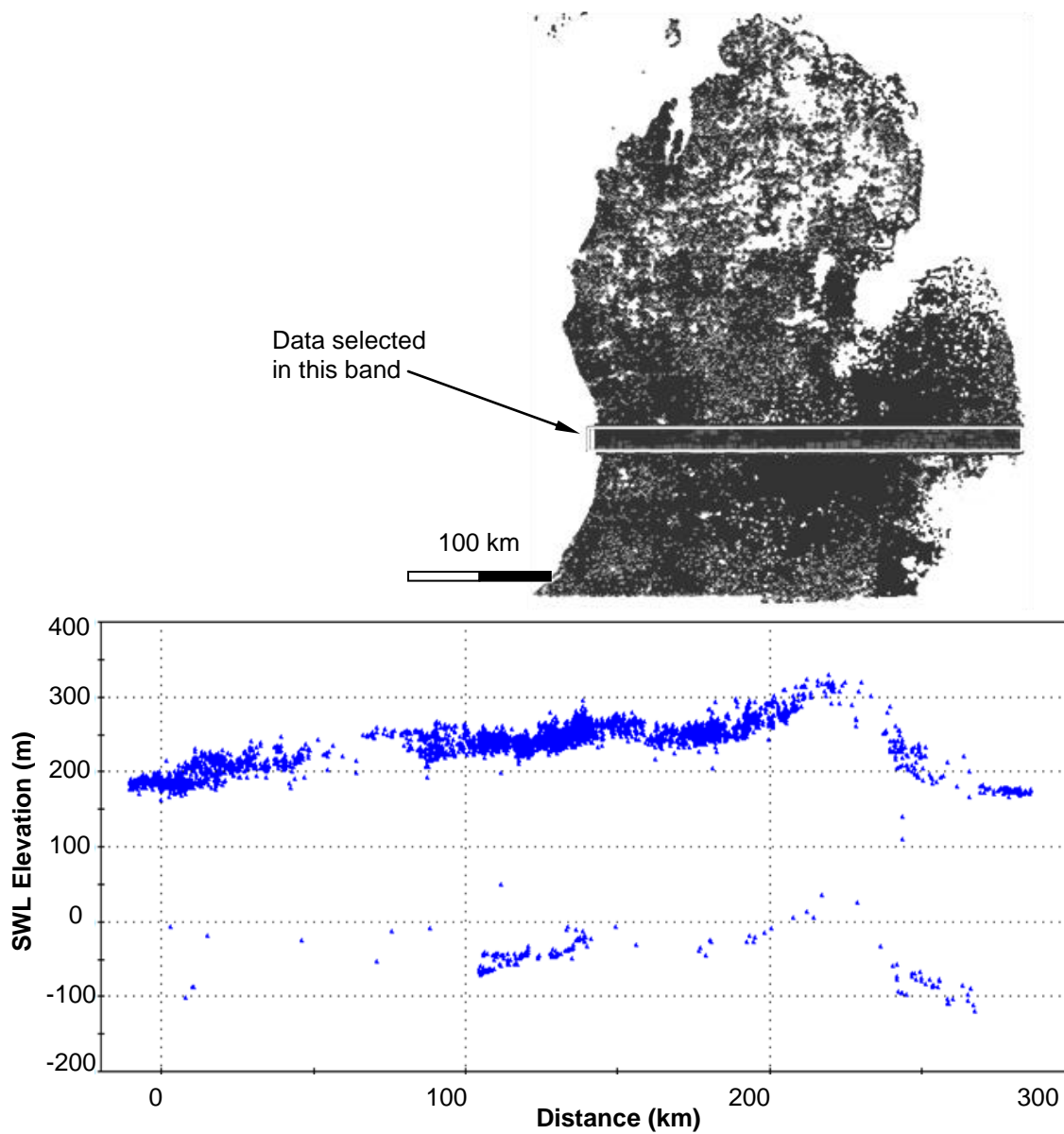


Figure 2.19 A slice of wells selected across the state and the plot of their static water level elevations.

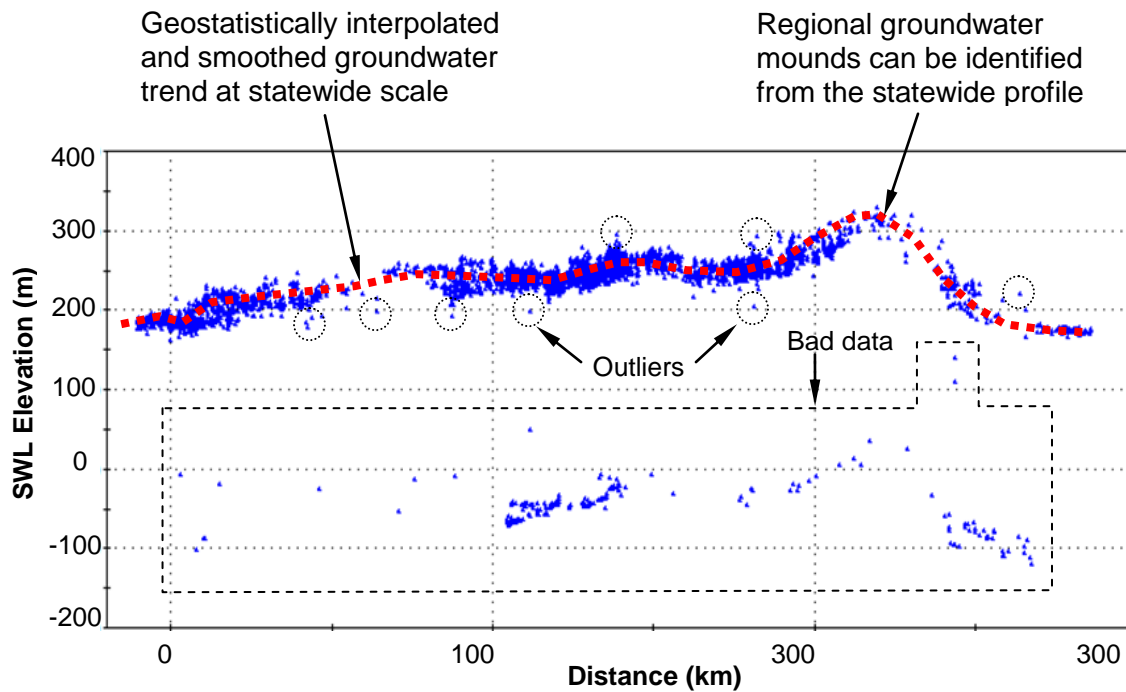


Figure 2.20 Bad data and outliers were identified and removed. Rest of the data was used to evaluate SWL trends through interpolation and smoothing.

Bad data and outliers are shown in Figure 2.20. These were identified and excluded in the preprocessing stage. The process of identification and removal of outliers and bad data has been automated in the tools developed for data processing (these tools include MIGWWP and IGW Liao 2011, personal communications). The rest of the data was used in the models. However, even after removal of bad data and outliers, the data was still very noisy. Some of major sources of noise in Wellogic data can be explained by the following (the noise was handled by using smoothing functions as explained on page 58):

- The data covers a range from mid-sixties to date. Water levels recorded at the time of well drilling. This introduces seasonal and temporal variability in well records.
- No QA/QC guidelines were required when data were recorded by the drillers.

- Well locations are based on address matching rather than actual well coordinates.
- Lots of bad data.

Including Surface Water Features

Surface water features such as streams, lakes and wetlands have their influence on the subsurface hydrology. To incorporate their influence on groundwater levels, additional SWL data, in the form of scatter points, were generated for surface water bodies as narrated earlier.

Scatter points were generated inside the lakes and wetland polygons and along the lengths of streams. Since these surface water features were assumed to be the intersections of groundwater table with the topography, surface elevations from 10m DEM were assigned to these points. An example of generated scatter points is shown Figure 2.1.

The density of points generated within lake or wetland polygons and along the length of streams was based on the size of the feature. Bigger water bodies had higher density as they would have bigger influence on groundwater as shown in Figure 2.21.

Different criteria were adopted to assign SWL values to the scatter points. First, the DEM value from the 10m raster was measured at each scatter point generated in a polygon or along a stream. For scatter points along the streams, the measured value was assigned as SWL at that point.

For lakes and wetlands, different sampling schemes were available as shown in Average of all measured values of DEM was chosen for wetland polygons as DEM elevations may vary within the wetland polygons because all wetlands (and/or some parts within a wetland) may not be wet and may have undulating relief. Lake elevations may not fluctuate as much, but to keep

the estimates closer to the mean lake levels, same scheme was used for lake polygons. Figure 2.21 shows the sampling settings used for all models in the study.

Surface Water Data Sampling Settings

Streams

Order	Sampling Interval
<input checked="" type="checkbox"/> 1st	300. m
<input checked="" type="checkbox"/> 2nd	200. m
<input checked="" type="checkbox"/> 3rd	100. m
<input checked="" type="checkbox"/> 4th	75. m
<input type="checkbox"/> 5th	500. m
<input type="checkbox"/> 6th	500. m

Head Sampling Method

Lakes

☐ 10m DEM
☐ Min of 10m DEM
☒ Average of 10m DEM
☐ Polygon attribute

Wetlands

☐ 10 m DEM
☐ Min of 10m DEM
☒ Average of 10m DEM
☐ Polygon attribute

Great Lakes

☐ 10 m DEM
☐ Min of 10m DEM
☐ Average of 10m DEM
☒ Polygon attribute

Polygons

	AreaFrom	AreaTo	X-Interval	Y-Interval	Boundary
<input checked="" type="checkbox"/>	80. acre	2.47105 acre	220. m	220. m	1000. m
<input checked="" type="checkbox"/>	40. acre	80. acre	180. m	180. m	1000. m
<input checked="" type="checkbox"/>	25. acre	40. acre	150. m	150. m	1000. m
<input checked="" type="checkbox"/>	10. acre	25. acre	120. m	120. m	800. m
<input checked="" type="checkbox"/>	5. acre	10. acre	90. m	90. m	600. m
<input checked="" type="checkbox"/>	3. acre	5. acre	50. m	50. m	500. m
<input checked="" type="checkbox"/>	1. acre	3. acre	40. m	40. m	400. m
<input checked="" type="checkbox"/>	0.5 acre	1. acre	30. m	30. m	300. m
<input checked="" type="checkbox"/>	0.2 acre	0.5 acre	20. m	20. m	200. m
<input checked="" type="checkbox"/>	0.1 acre	0.2 acre	10. m	10. m	100. m

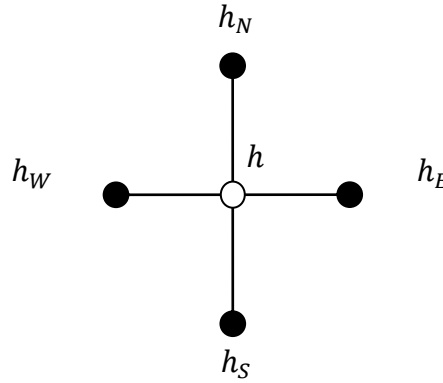
WetLand Type Filter

- ☒ Permanently Flooded
- ☒ Semipermanently Flooded
- ☒ Saturated
- ☒ Saturated/Semipermanently Flooded

Figure 2.21 Surface water data sampling settings.

Interpolation and Smoothing

SWL data acquired from water-well logs and generated along the surface water features was imported in the models as scatter points and interpolated for each grid cell in the model using inverse distance method for regional scale models (which were based on data from water wells) and kriging for the local scale models (which were based on data generated from surface water features). Since interpolation was based on noisy data as explained earlier, smoothing was applied to interpolated results for more intuitive estimation of SWL. Moving window smoothing technique using four nearest neighbors was used as explained below:



$$\bar{h} = \frac{h_N + h_E + h_W + h_S}{4} \quad 2.4$$

$$h^1 = \alpha \cdot h + (1 - \alpha) \cdot \bar{h} \quad 2.5$$

Where h is the interpolated SWL representing the hydraulic head in a grid cell

h_N , h_E , h_W , and h_S are the hydraulic heads in the neighboring cells.

h^1 is the smoothed head after first pass of the moving window

α is the weighting factor (taken as 0.5)

The general equation for several passes of moving window can be written as:

$$h^{k+1} = \alpha \cdot h^k + (1 - \alpha) \cdot \bar{h}^k \quad 2.6$$

For the deep aquifer systems, between 10 and 20 passes of smoothing were applied, more passes applied to larger systems. For the statewide model, covering the entire southern Michigan, 50 passes of smoothing were applied.

Figure 2.22 shows different levels of smoothing for a regional model. The contour interval in all cases is 2m. Final surface for this particular site was based on 10 passes of smoothing. Without smoothing the pattern looks noisy with many closed contours, while 20x smoothed surface seems too smooth. The selection of final surface is based on the subjective judgment which may differ from person to person. The judgment is based on examining the contours such that they make sense when correlated to surface hydrology and topographic features. For example, it is expected to have bends in contours along the large streams, ring contours around lakes and topographic heights etc. Similarly, it is not expected to have a line of ring contours along a river. Smoothing helped reduce noise and gain hydrologically more consistent groundwater heads. For example, in Figure 2.22, either 5x or 10x smoothed surface may be chosen. Choosing any of these surfaces will not significantly alter the quality of insights gained from the models. The number of smoothing passes used for each model is mentioned so that the model could be reproduced by others.

Generating Statewide Raster Maps for Static Water Level

Preprocessed data, along with additionally generated data was interpolated (using various geostatistical techniques such as inverse distance and kriging) and smoothed to generate statewide raster maps for static water level (SWL) at 540m resolution. These preprocessed and pre-calculated raster maps were used to estimate SWL in the selected model areas.

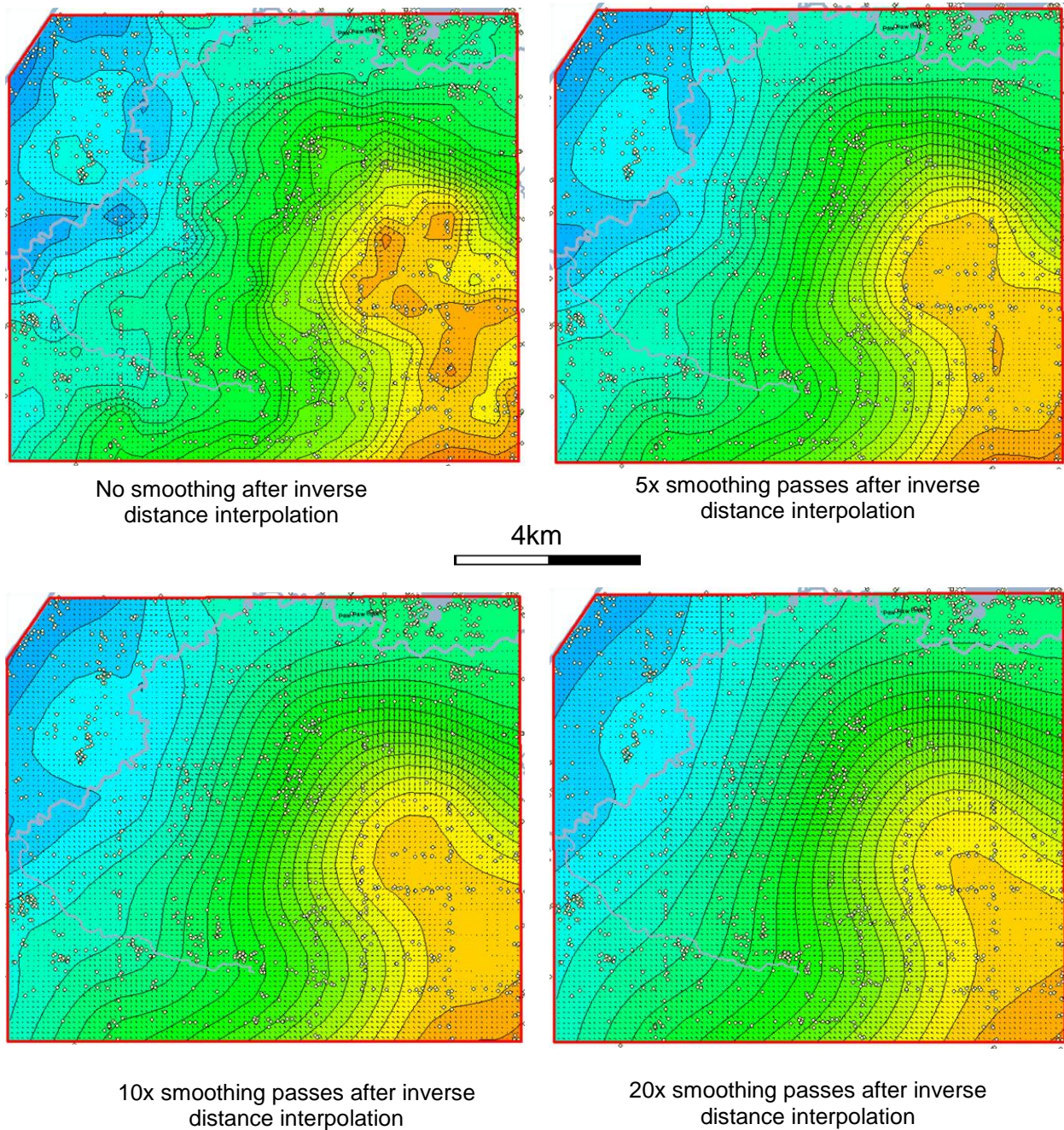


Figure 2.22 Different number of smoothing passes applied to a regional model after inverse distance interpolation of water wells data for drift aquifer. Contour interval is 2m. Blue color represents lower heads and orange higher. For this particular site, 10x smoothed surface was selected for particle tracking.

The data driven groundwater modeling approach was applied to delineate fen hydrology at different spatial scales. We developed a steady state mean flow model for the entire southern Michigan basin, 9 regional scale horizontal flow models around fen localities in varying geological settings, and 19 site-specific profile models for selected fens. Results from each of these models are presented in this chapter, with very brief discussions.

Statewide model has been discussed separately while the regional horizontal flow models and site specific profile models are discussed together. Some commonalities in different site models yielded insights into fen hydrology. Such commonalities have not been discussed in this chapter. The discussions of common results and their implications are carried out in detail in Chapter 4.

STATEWIDE MODEL

Lower half of Michigan's Lower Peninsula was modeled at the statewide scale which included all 150 known sites of prairie fens in the state.

The model grid had 360 x 212 cells. The size of grid cells was approximately 1 km² (1001.5m x 1001.5m). Source data for interpolation of SWL included water wells data with outliers beyond 2 standard deviations removed and SWL data generated for big inland lakes and streams (3rd and higher order) . The interpolation results were smoothed out by applying 50 passes of moving window as explained on page 58.

Statewide Hydrology and Occurrence of Fens

Figure 3.1 is a representation of groundwater surface, superimposed with the regional network of 3rd and higher order streams. Qualitatively looking at the map:

- Regional highs of groundwater are distinctly prominent around the headwaters of all major streams in the area.
- Most fen sites are distributed close to these regional groundwater highs.

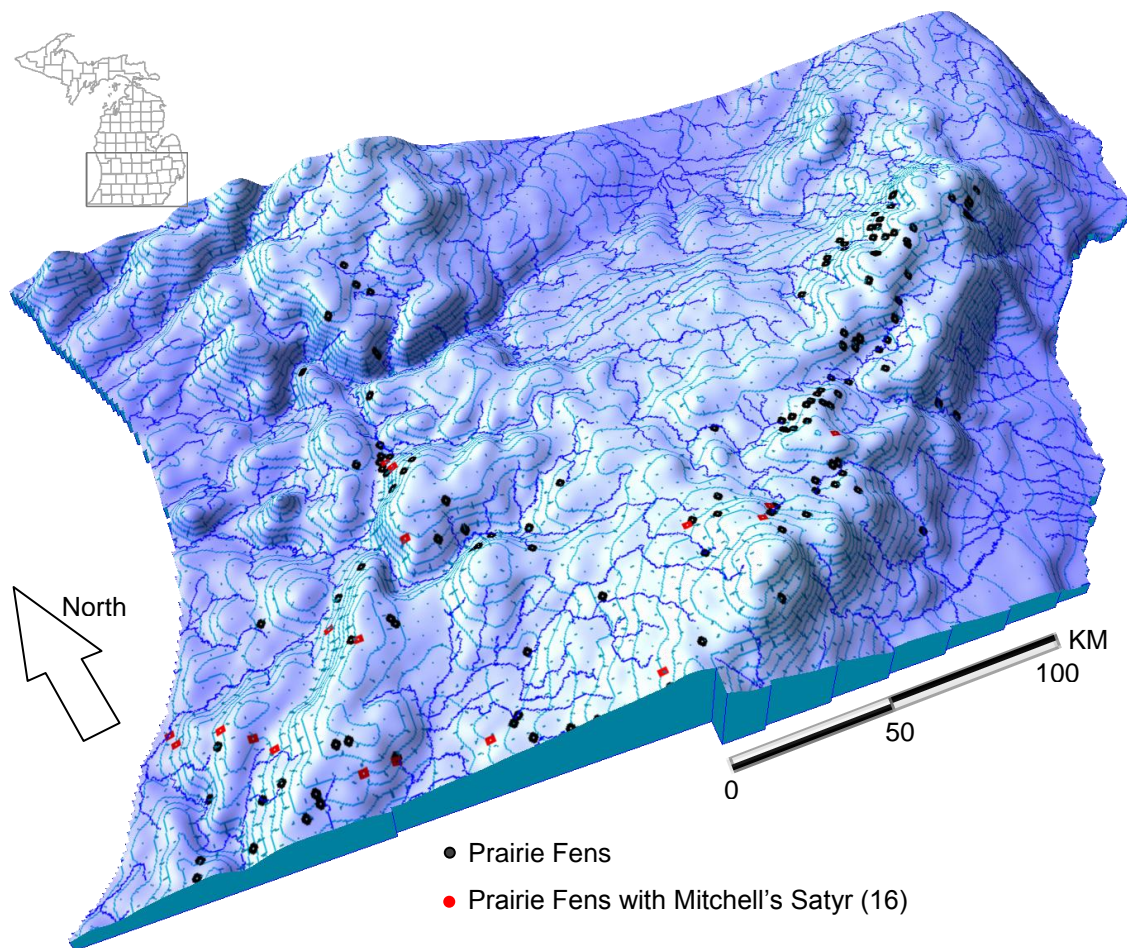


Figure 3.1 Surface and groundwater hydrology in relation to occurrence of fens. Relief and contours represent groundwater surface elevation which varies from 148.14m to 344.93m. Contour interval is 7m.

Flow Regime and Fen Occurrence Compared to Glacial Landforms

Except for 16 sites occurring in glacial till landforms and one occurring in coarse lacustrine deposits, other 133 sites occur in proglacial or ice-contact outwash. The occurrence of fen sites with respect to glacial landforms is illustrated in Figure 3.2. The relief surface represents regional groundwater profile.

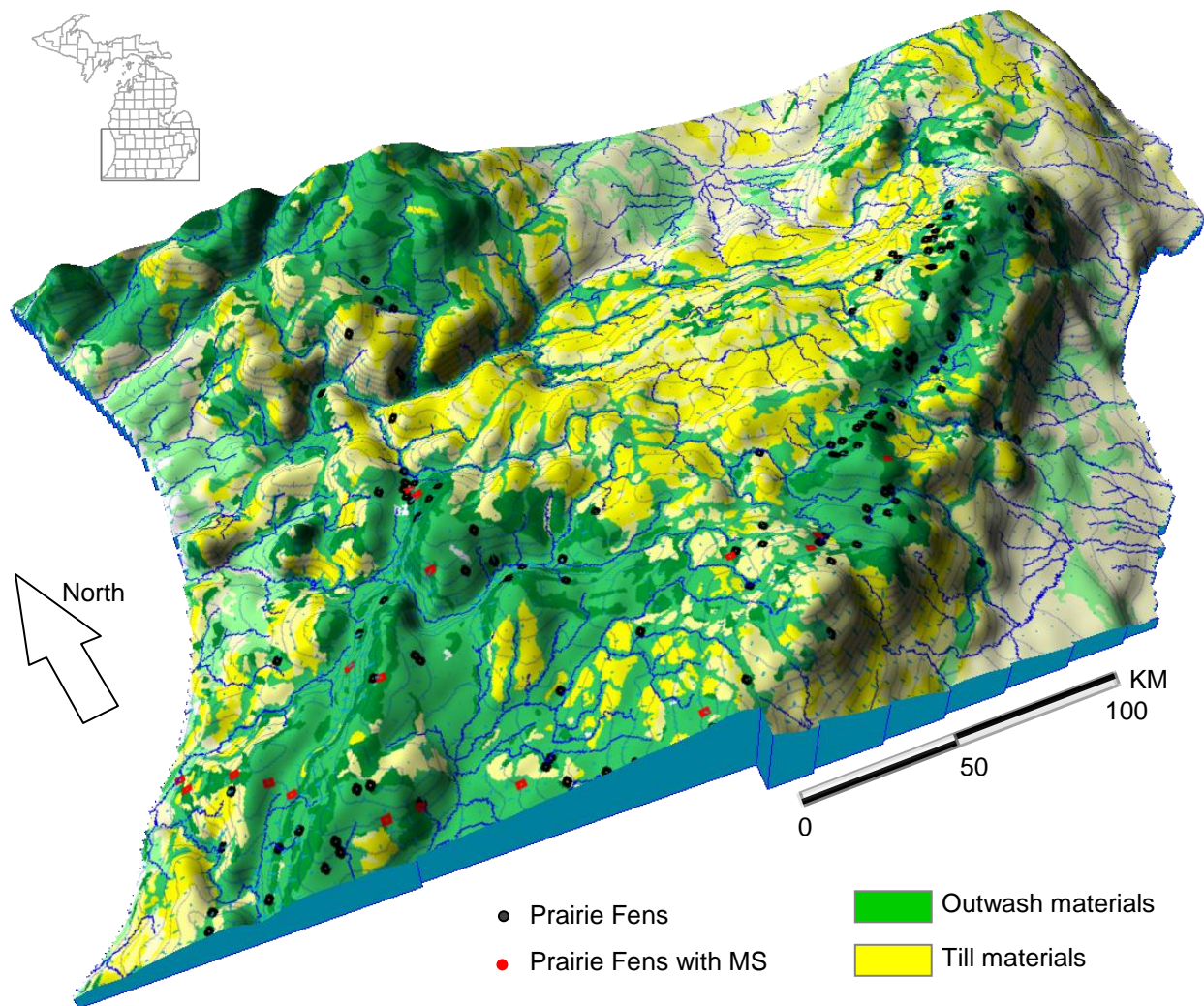


Figure 3.2 Occurrence of fens with respect to statewide groundwater hydrology and the glacial landforms. Relief and contours represent groundwater surface elevation which varies from 148.14m to 344.93m. Contour interval is 7m.

Statewide Regions of Significance for Source Groundwater

Significant sources of groundwater around the prairie fens across the state were identified as nine regional groundwater mounds near the head waters of major rivers and stream in the study area. The mounds are highlighted in Figure 3.3.

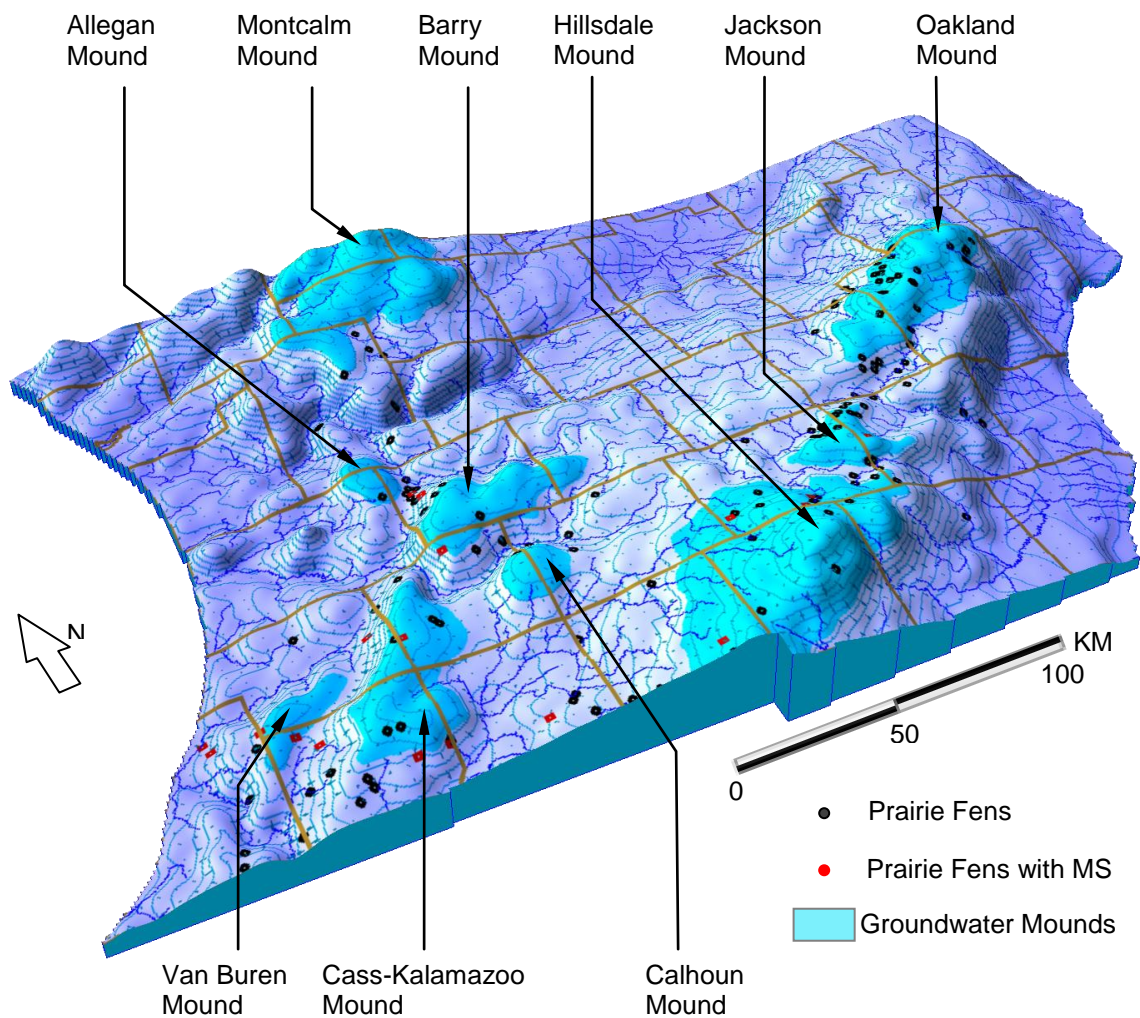


Figure 3.3 Source groundwater areas of regional significance for prairie fen sites across the state. Relief and contours represent groundwater surface elevation which varies from 148.14m to 344.93m. Contour interval is 7m.

For this study we named these mounds as 1) Montcalm Mound; 2) Allegan Mound; 3) Barry Mound; 4) Calhoun Mound; 5) Cass-Kalamazoo Mound; 6) Van Buren Mound; 7) Hillsdale Mound; 8) Jackson Mound; and 9) Oakland Mound.

SELECTION OF FEN SITES FOR DETAILED MODELING

Eighteen fen sites across the state were selected for detailed groundwater modeling. Each site was first modeled at regional scale in 2D horizontal plane to delineate regional groundwater flow paths leading to the fen site. A representative transect was then chosen along the regional flow paths for each site and modeled as 2D vertical profile. Selected sites within the state are highlighted in Figure 3.4.

The sites were selected based on their proximity to the regional groundwater mounds identified in the statewide model (Figure 3.3), their occurrences in different glacial landforms, and whether or not a site was occupied by MS. Some of the selected sites were either clustered or very close to each other. Such sites were modeled together within a single regional model, but their selected transects were still modeled separately for the vertical profiles.

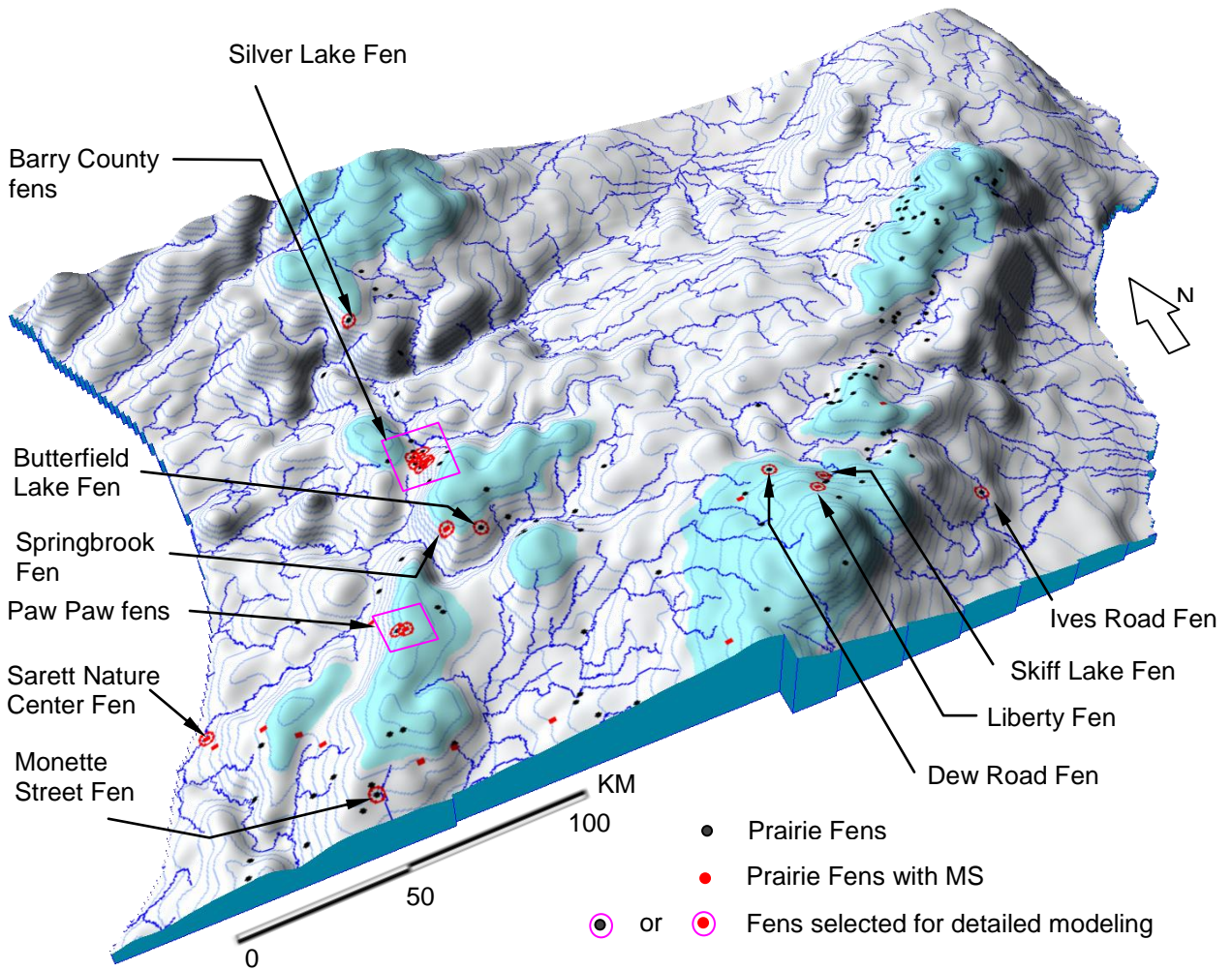


Figure 3.4 Fens selected for detailed regional groundwater modeling. Shaded relief and contours represent groundwater levels delineated at statewide scale varying from 148.14m to 344.93m. Contour interval is 7m.

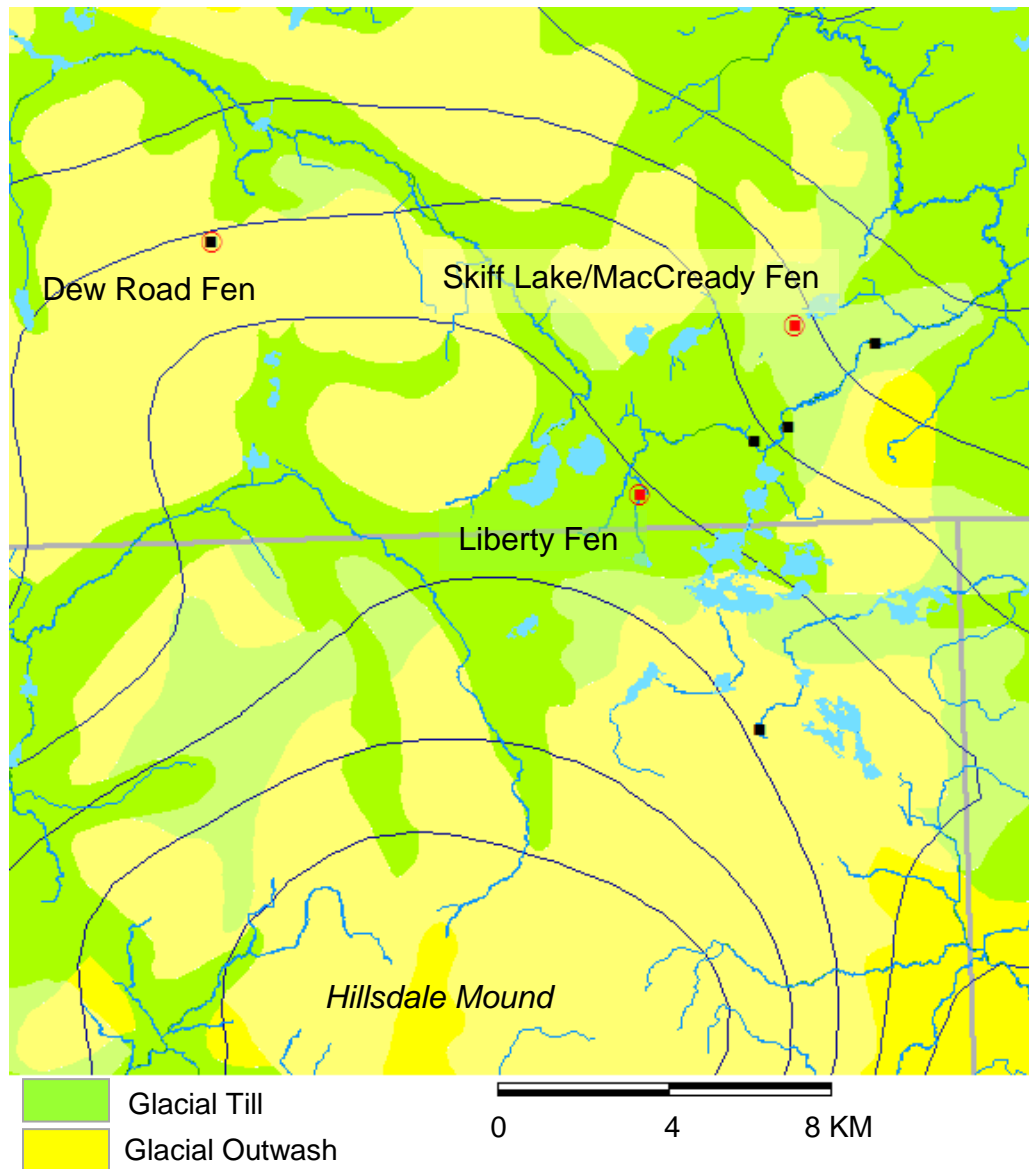


Figure 3.5 Selected fens in Jackson County. Contours at 7m interval represent groundwater delineation from statewide model.

Fens selected in Jackson County occur in glacial outwash along the slopes of the Hillsdale Groundwater Mound as shown in Figure 3.5. The sites include Liberty Fen, Skiff Lake/MacCready Fen and Dew Road Fen. Liberty and Skiff Lake fens have MS occurrence. Dew Road fen is one of the few fens occurring in glacial till landforms.

Ives road fen in Lenawee County was selected for detailed modeling because of its unique location, much farther from the regional mounds, and occurring in a narrow band of glacial outwash along Raisin River valley as shown in Figure 3.6.

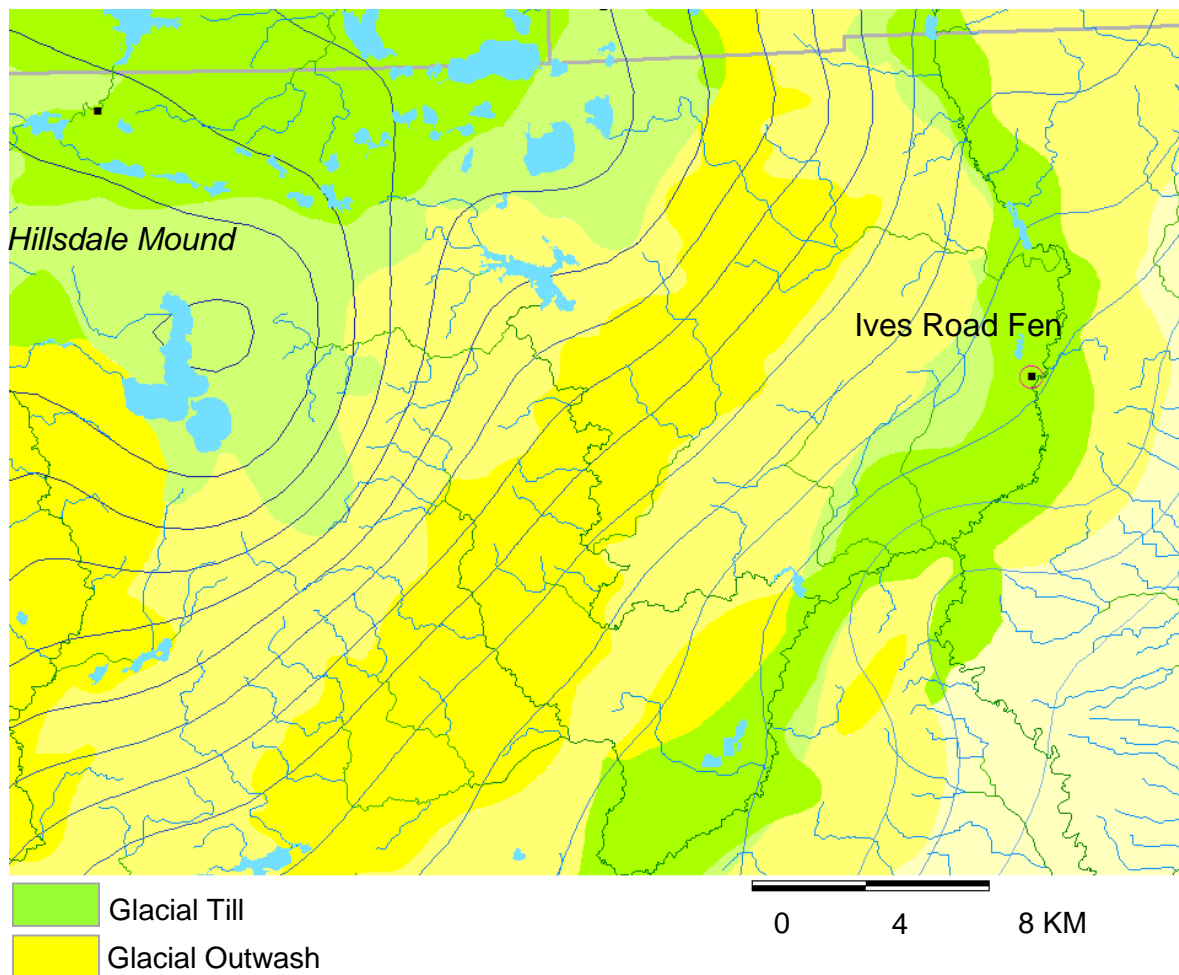


Figure 3.6 Ives road fen located in a narrow band of glacial outwash along Raisin River. Contours at 7m interval represent groundwater delineation from statewide model.

A cluster of fens occur between Barry and Allegan groundwater mounds within glacial outwash in Barry County as shown in Figure 3.7. Turner Creek Wetlands Fen, McKibben Fen, Yankee Spring Fen, Hill Creek Fen, Hall Lake Fen, McDonald Lake Fen and Bowens Mill Fen were selected from the cluster. First three fens in the group have MS occurrence.

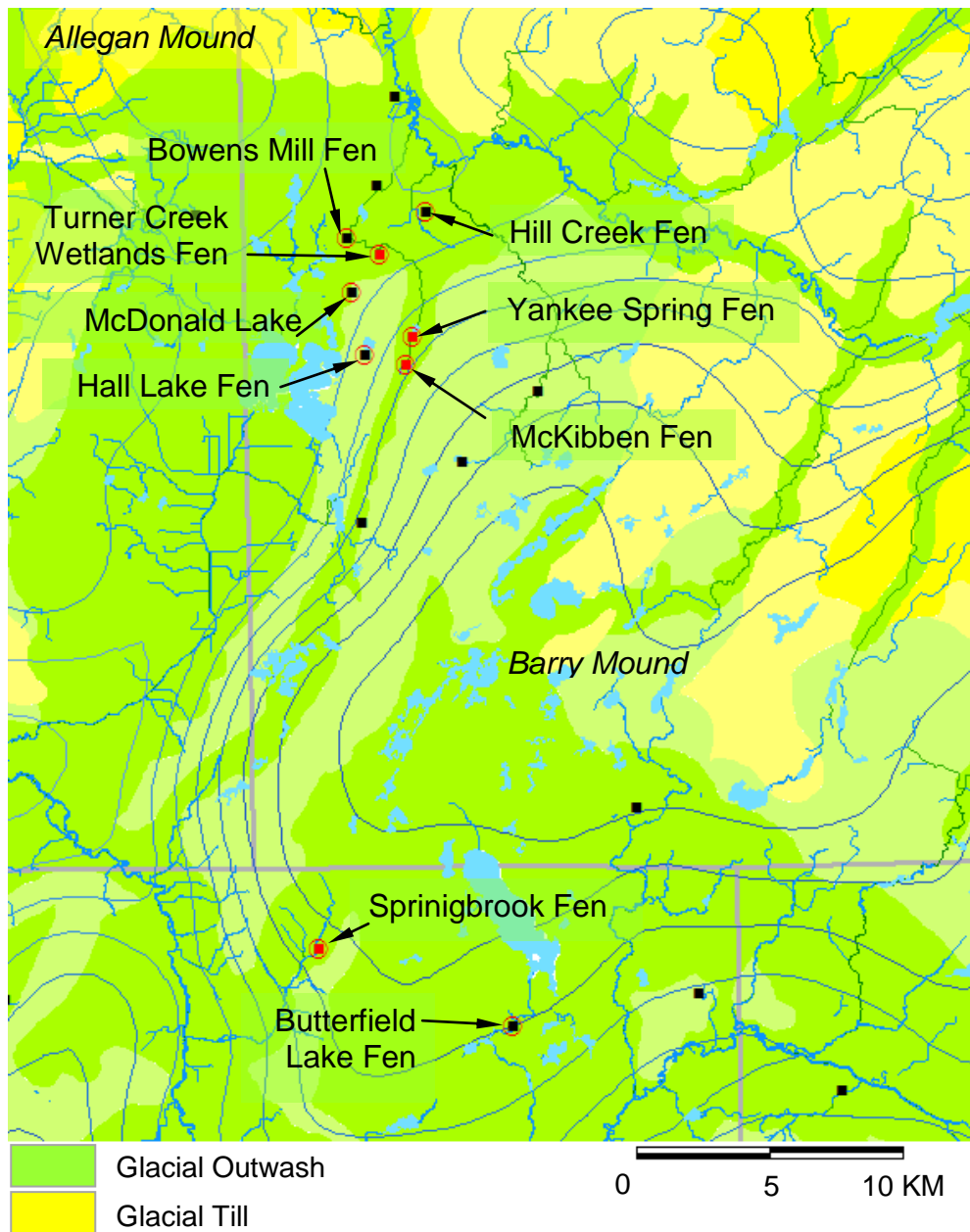


Figure 3.7 Cluster of fens between Barry and Allegan Mounds. Contours at 7m interval represent statewide groundwater.

Springbrook Fen and Butterfield Lake Fen in Kalamazoo County, also shown in Figure 3.7, were selected on the southern slope of Barry Groundwater Mound. Springbrook fen has MS occurrence. Sarett Nature Center fen in Berrien County was selected for being the only prairie fen occurring in coarse lacustrine deposits and relatively away from regional groundwater

mounds. Silver Lake fen in Kent County was selected for being one of the few fens occurring in glacial till rather than coarse glacial deposits. Monette Street Fen in Cass County was selected for its large size, high ecological ranking and its regional proximity to Cass-Kalamazoo Mound. Paw Paw Lake Fen and Paw Paw Prairie Fen were selected in Kalamazoo/Allegan counties for being in close proximity of each other, one with MS occurrence and one without. These two fens are located very close to the apex of Cass-Kalamazoo Mound. Groundwater models for each of these fen sites are presented as follows.

REGIONAL AND PROFILE MODELS FOR SELECTED SITES

Barry State Game Area Group of Fens

Located relatively closer to each other, there exists a cluster of fens between the Barry and Allegan Groundwater Mounds. Following fens from this cluster were selected for regional modeling. Ecological ranking or EORANK (NatureServe 2002) of the fens are given in parentheses:

- Hill Creek Fen (B)
- Turner Creek Wetlands Fen (BC)
- Bowens Mill Fen (C)
- McDonalds Lake Fen (C)
- Yankee Spring Fen (BC)
- Hall Lake Fen (C)
- McKibben Fen (C)

The cluster of above fens occurs in glacial outwash deposits overlaying Marshall Sandstone. The average outwash thickness around the cluster is 60m, varying between 25m and 150m. The fens and their surface catchment areas are shown on 30m/10m DEM relief in Figure 3.8. MS occurrence has been reported at Turner Creek Fen, McKibben Fen and Yankee Spring Fen.

Barry State Game Area site has shallow groundwater, deep glacial drift, and distinct transmissive bedrock aquifer systems. Each of these systems was separately evaluated in the regional model and then correlated in profile models for the individual fen sites.

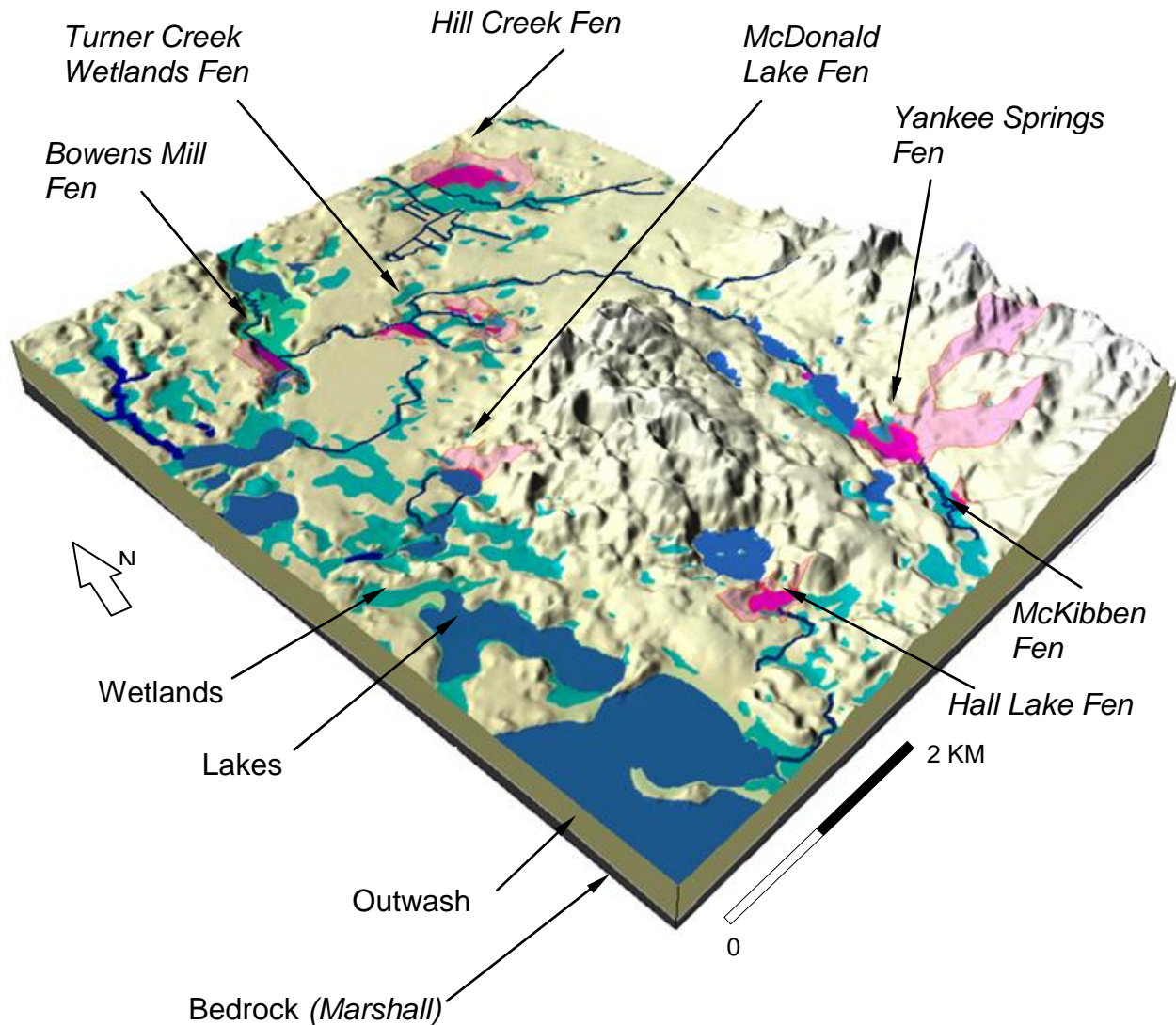


Figure 3.8 Cluster of fens in Barry State Game Area. The shaded relief represents topography derived from 10m DEM which varies from 223.22m to 342.78m.

Regional Groundwater Model for Fens Cluster

Regional model was selected over an area of 15.77 km by 16.12 km which included all selected fens. Model area was divided into the 300x313 grid cells, with the cell size of 51.59m. The cluster of fens occurs in significantly thick glacial outwash aquifer overlying a transmissive bedrock formation – Marshall Sandstone. Water wells data in the model area was available for

both the glacial drift as well as bedrock. SWL was separately delineated for drift and sandstone formations, using respective wells data.

Figure 3.9 shows SWL delineation for drift aquifer, derived from water wells data of drift wells and taking large surface water bodies into account. Groundwater capture zones were estimated using reverse particle tracking using groundwater head surface in the drift aquifer. The estimation suggests the fen sites may be connected to Allegan and Barry Groundwater mounds, between 5 and 12 km from the fen sites.

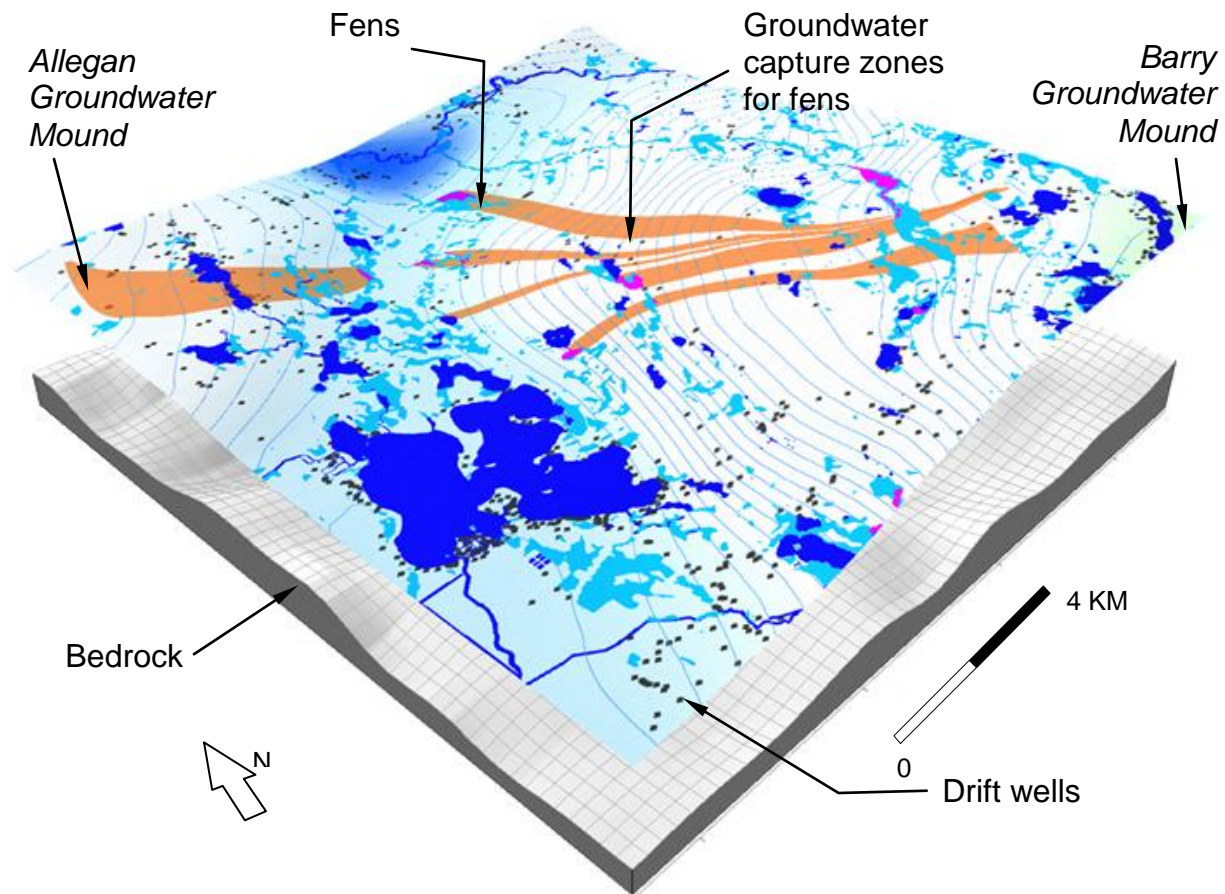


Figure 3.9 The contours at 2m interval and shaded relief represent regional groundwater head around Barry State Game Area in the drift aquifer, varying between 220 m and 279 m.

Figure 3.10 shows SWL delineation for bedrock aquifer. This delineation is based only on the bedrock wells data only, with consideration of surface water features. Bedrock flow system seems to converge to major surface water features along northeast-southwest direction from eastern and western up hills. This pattern gives a strong indication of bedrock upwelling in this area. Likely zone of upwelling from bedrock aquifer is highlighted in the figure. In Figure 3.11, both drift and bedrock SWL surfaces are presented for comparison.

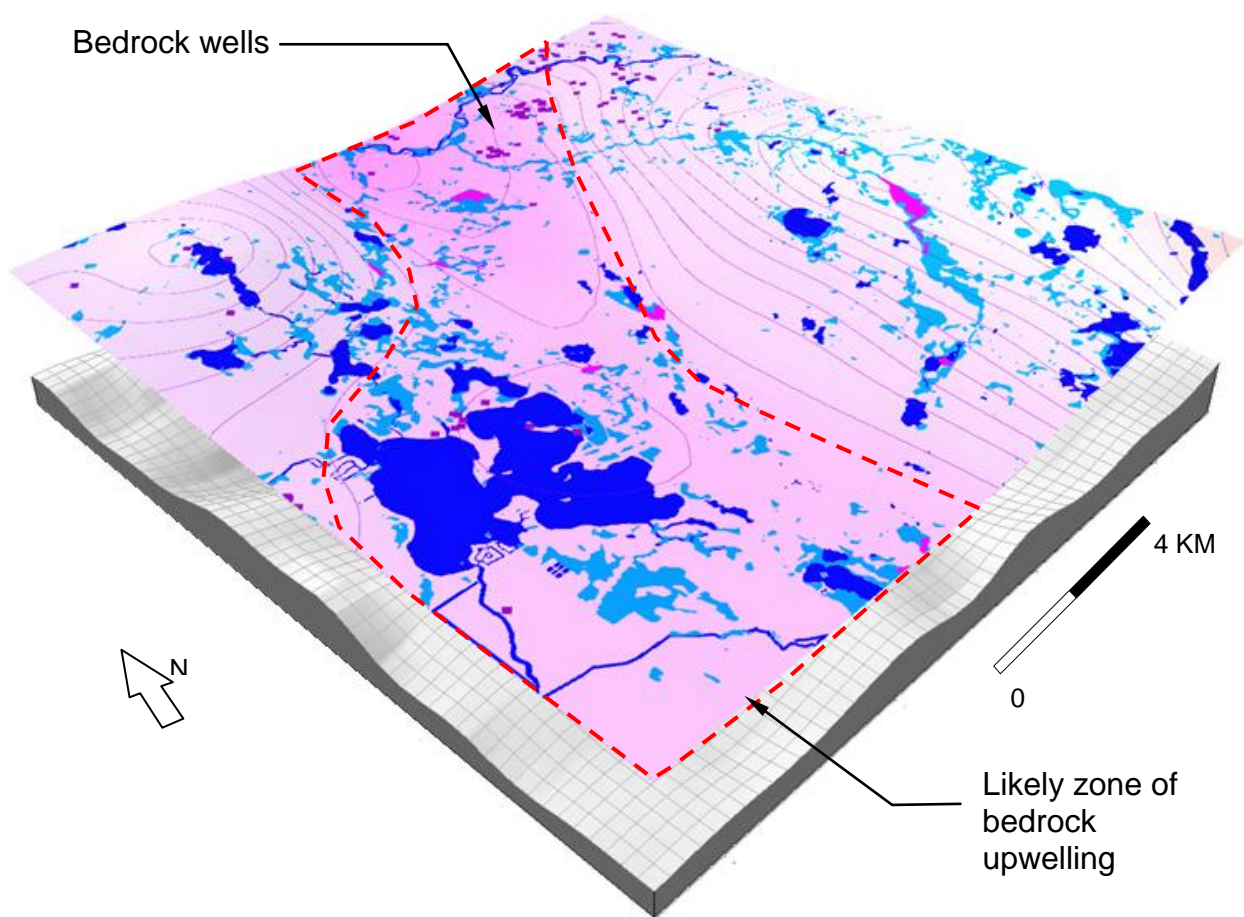


Figure 3.10 The contours at 2m interval and shaded relief represent regional groundwater head around Barry State Game Area in the drift aquifer, varying between 221 m and 259 m.

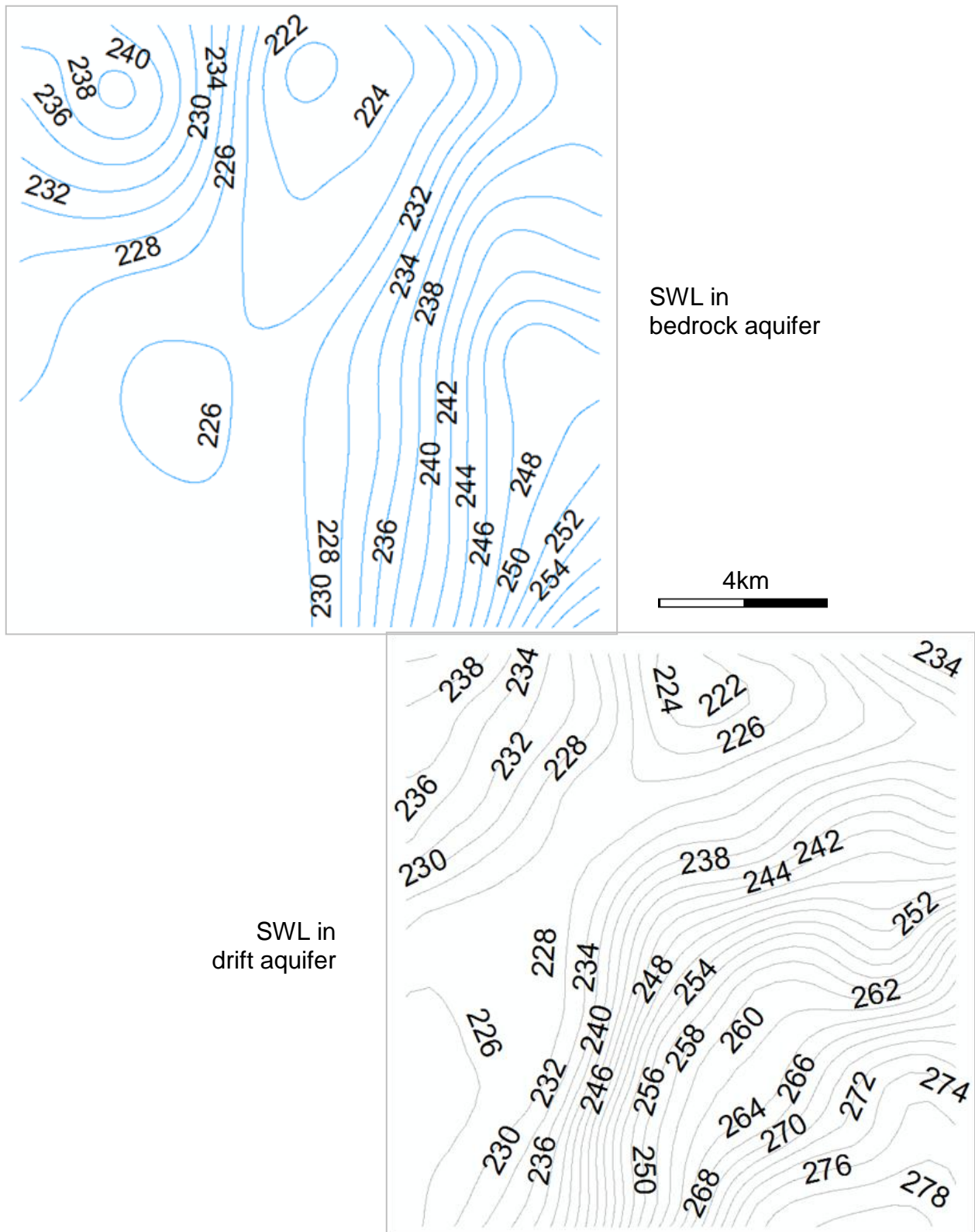


Figure 3.11 Comparison of Bedrock and drift SWL surfaces in Barry State Game Area. Contour labels represent elevation (m).

For most parts of the model area SWL in drift seems higher than that of bedrock; however, bedrock SWL seems systematically higher in the groundwater discharge zones across the model. This pattern suggests that drift aquifer is recharging the bedrock in the higher elevations and the bedrock is discharging groundwater in the lower elevations. This also suggests that the two aquifers are connected.

Figure 3.12 shows bedrock well-logs across a few cross sections through the model area. There seem to be clay layers in some parts of the drift and missing in others. Corresponding to the discharge zones the clay seems particularly missing in the well lithologies. This reinforces the possibility that the two aquifers are connected and, despite occurrence of clay within the drift, there seems no continuous layer separating the bedrock and drift aquifers.

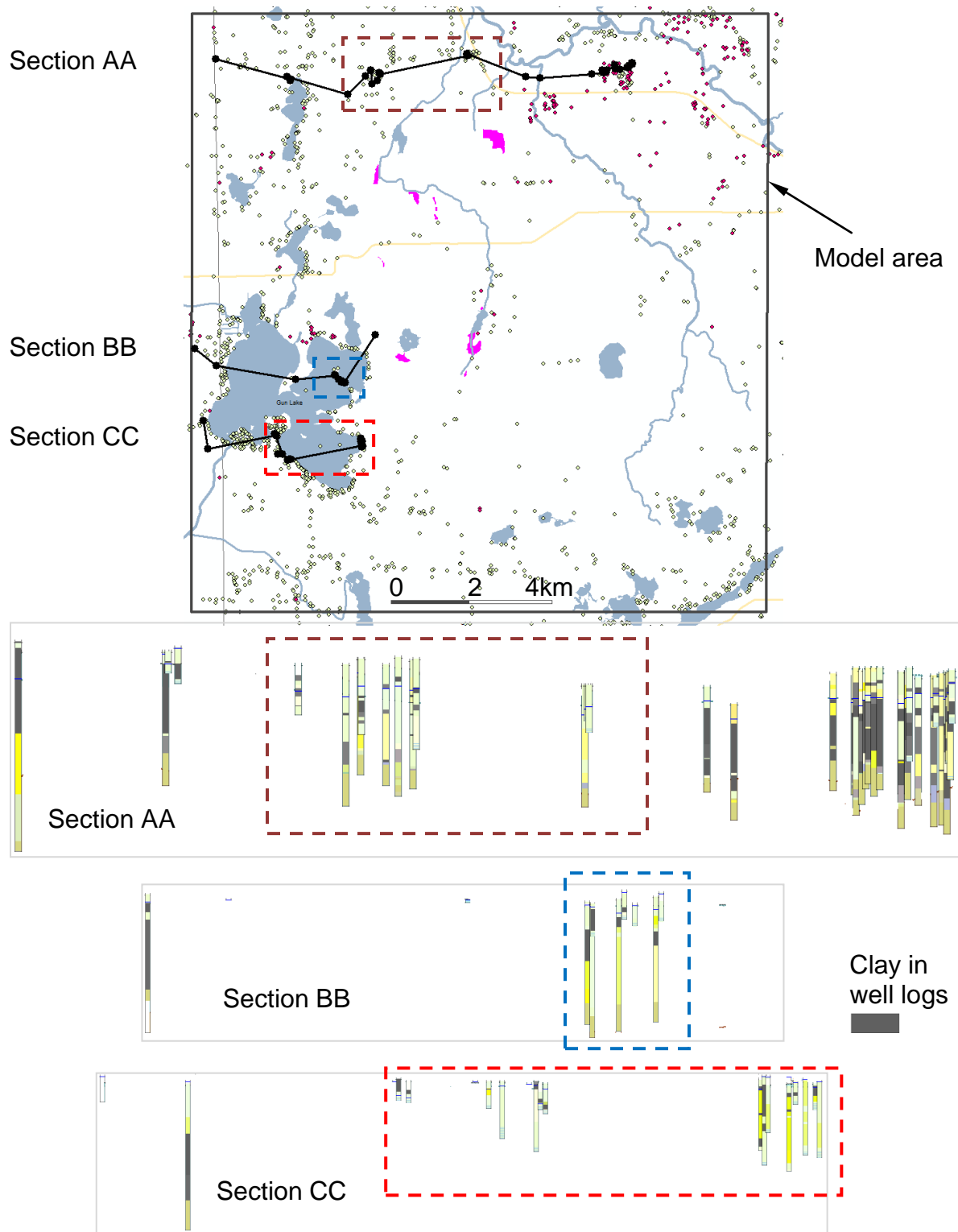


Figure 3.12 Distribution of clay in well logs across selected sections in model area

In Figure 3.13, the groundwater contribution zones are superimposed on surface topography and geological land forms. The groundwater capture zones seem to converge to the regional groundwater mounds, crossing over one or two regional watersheds on their way.

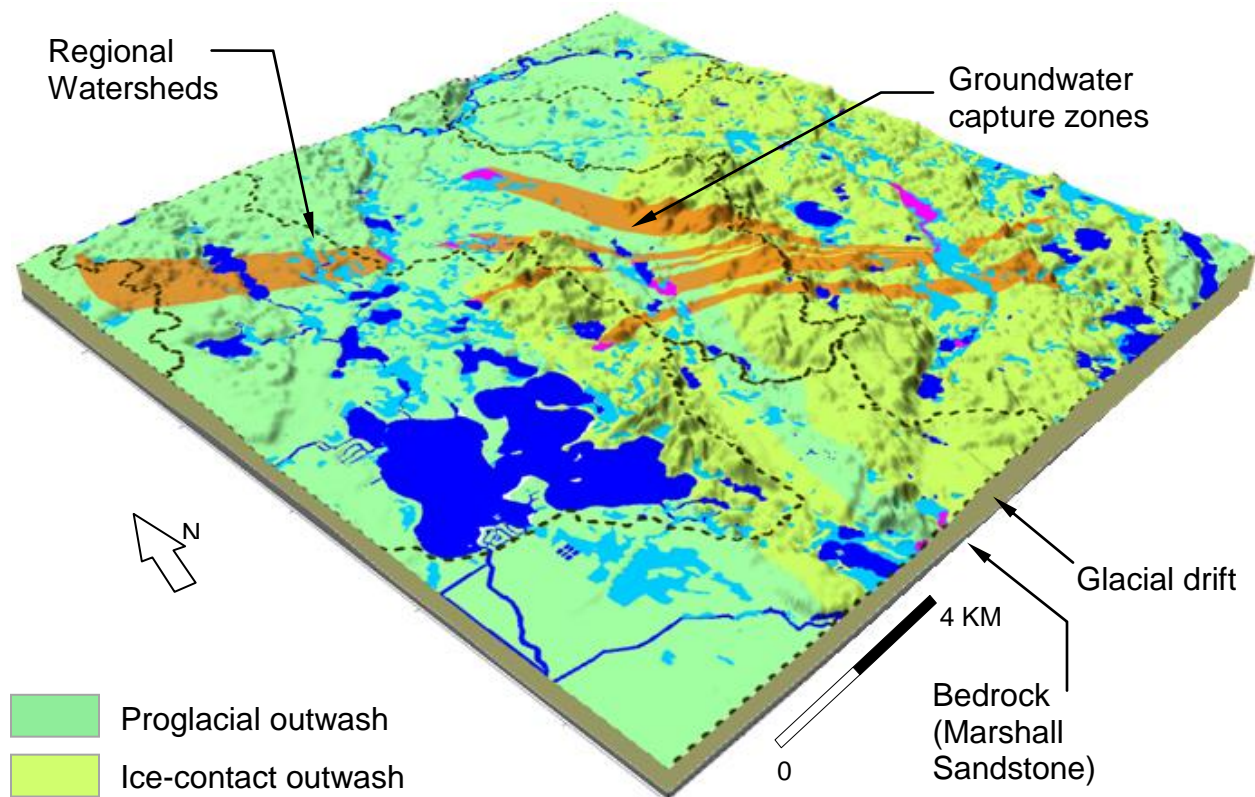


Figure 3.13 The shaded relief represent surface topography in the region which varies in elevation from 241.06m to 298.58m.

Groundwater Profile Model – Hill Creek Fen

Well logs along the capture zone of Hill Creek Fen are shown in Figure 3.14. The logs do not reveal existence of continuous clay layers in any portion along the capture zone. A two-layer profile model was conceptualized with glacial drift layer overlying Marshall Sandstone, Barry Mound being the regional source at one end, and Hill Creek being the regional sink at the other. The profile model is shown in Figure 3.15. The model suggests that delivery of groundwater to the fen is through upwelling of deep groundwater flow system which has its source

approximately 6 km south of the fen site just across the surface regional watershed. The model also shows that there is upwelling of shallower groundwater closer to the fen. This upwelling water is feeding the wetlands and stream just south of the fen. Deep groundwater from Barry Groundwater Mound is upwelling into the stream north of the fen and does not seem to directly contribute to the fen.

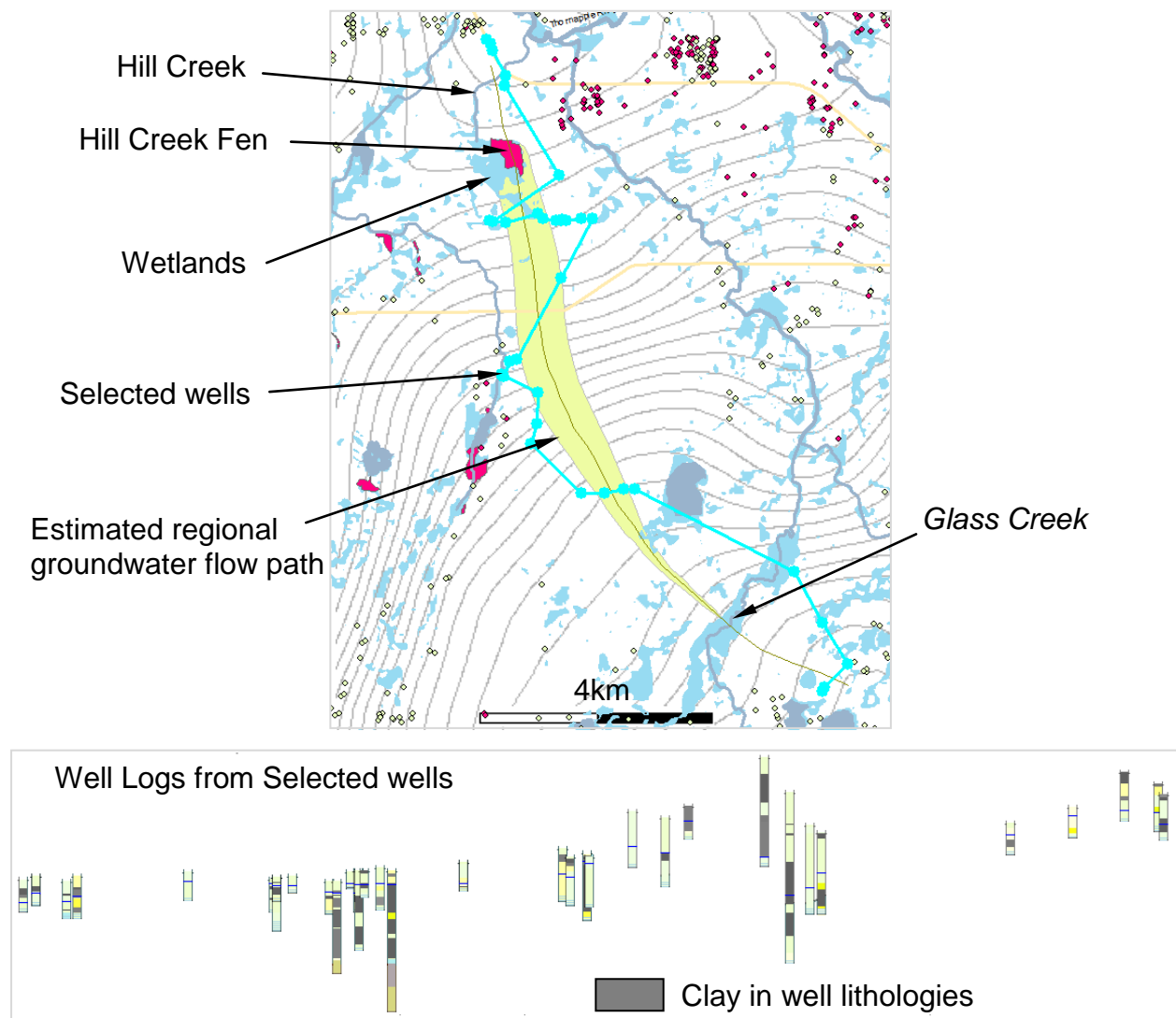


Figure 3.14 Well location and well logs along Hill Creek Fen capture zone. Contours at 2m interval show SWL for deep drift.

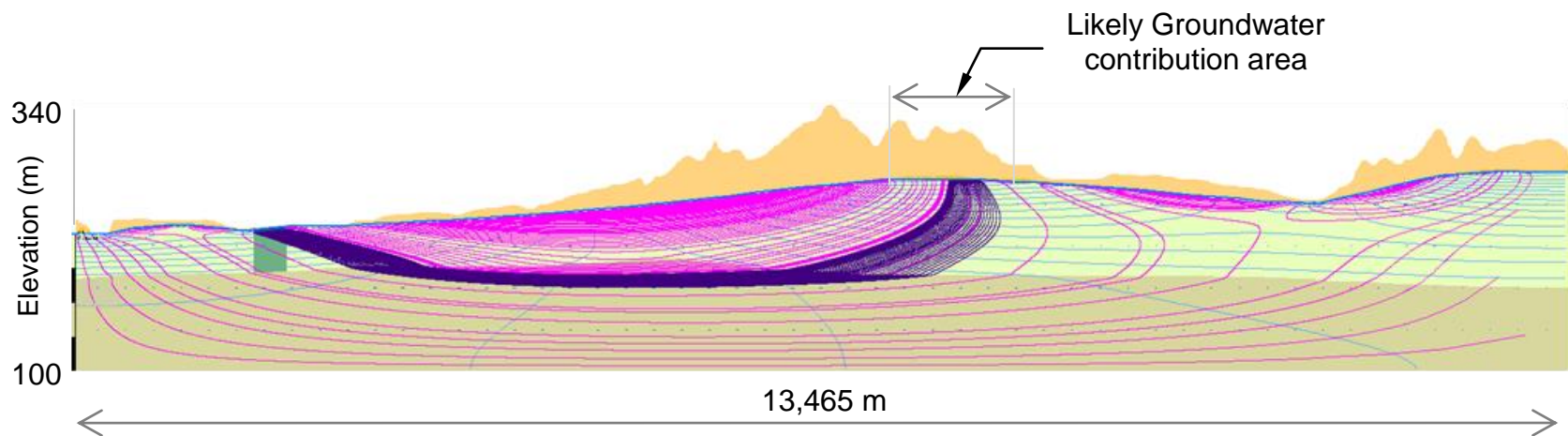
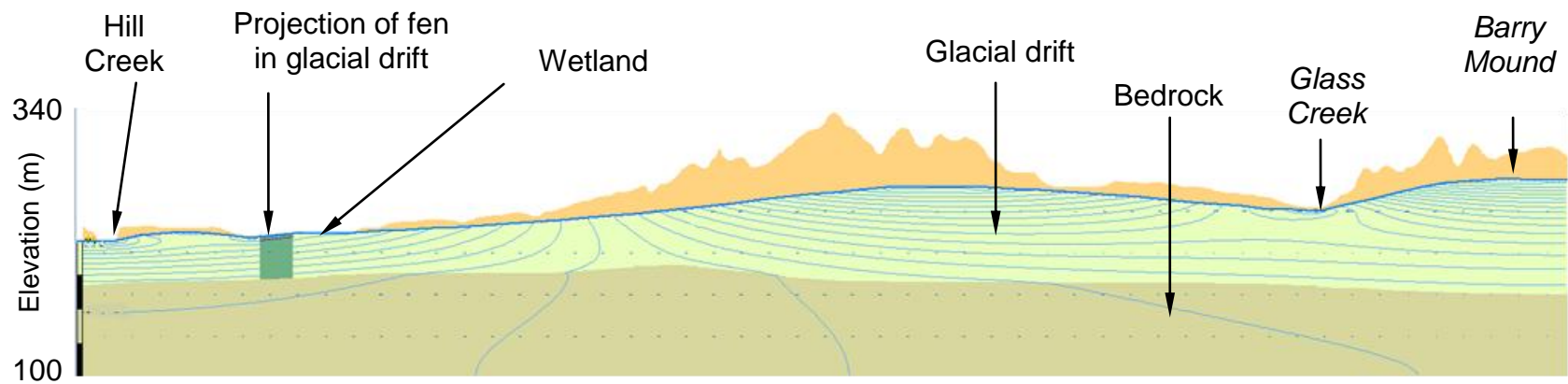


Figure 3.15 Profile Model for Hill Creek Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 1.86m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Groundwater Profile Model – Turner Creek Wetlands Fen

Turner Creek Wetlands Fen comprises a major area attached to Turner Creek and three smaller parts in the south. Well logs along the capture zone of the fen are shown in Figure 3.16. The logs do not reveal any structural discontinuities in the drift. A two-layer profile model was conceptualized with glacial drift layer overlying Marshall Sandstone, Barry Mound being the regional source at one end and lower reach of Turner Creek being the regional sink at the other end. The model, in Figure 3.17, shows groundwater upwelling into the smaller parts of the fen from glacial drift, and in the larger part from the bedrock. The source water recharge comes from a sub-regional groundwater mound between Glass Creek and Turner Creek, approximately 6 km from the fen site. It appears that shallow systems are not contributing much to the fen.

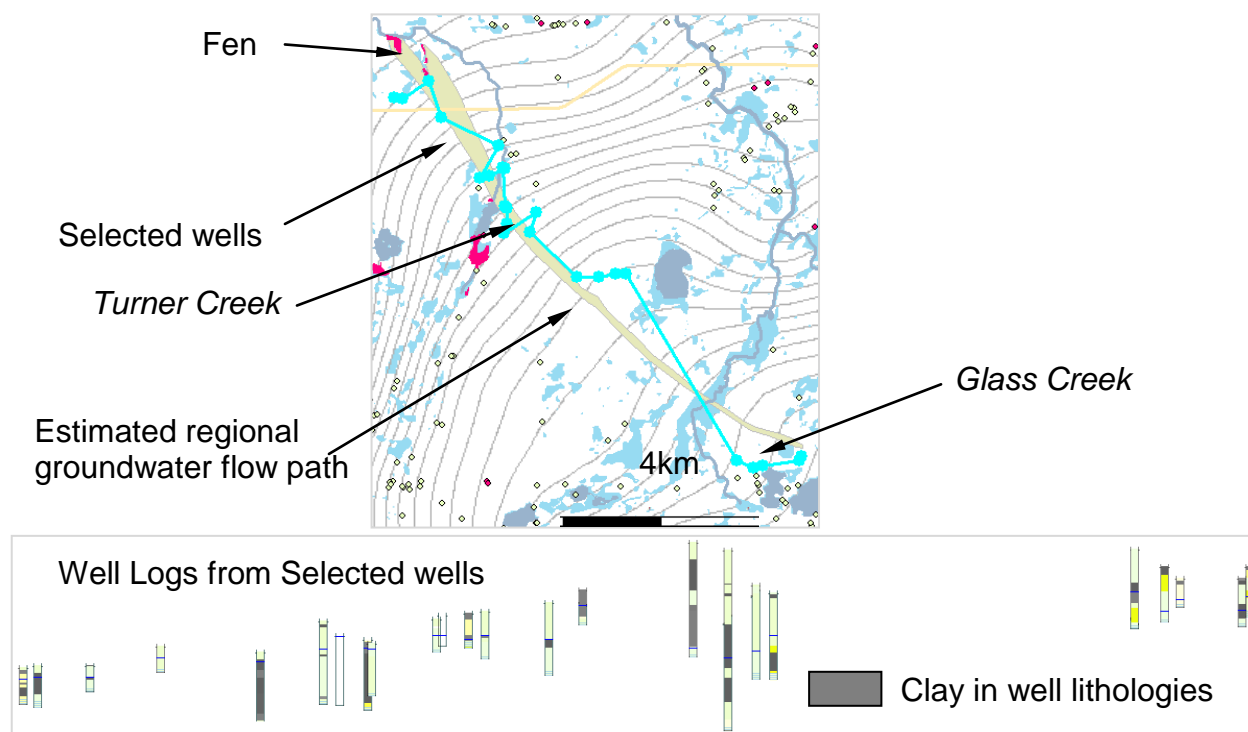


Figure 3.16 Wells and well logs along Turner Creek Wetlands Fen capture zone. Contours at 2m interval show SWL for drift.

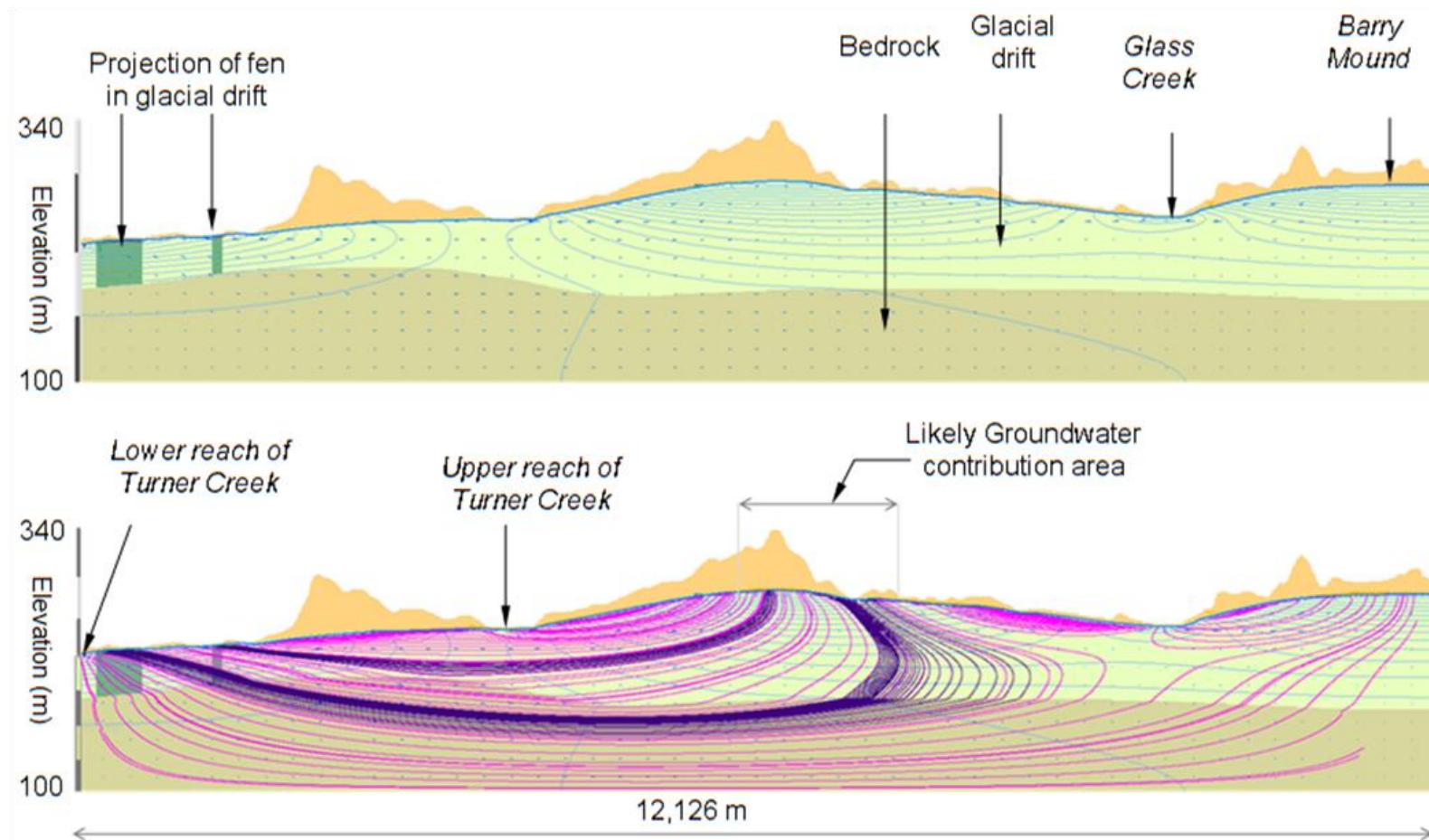


Figure 3.17 Profile Model for Turner Creek Wetlands Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 1.90m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Groundwater Profile Model – Bowens Mill Fen

Well logs along the capture zone of Bowens Mill Fen are shown in Figure 3.18 which reveals a pocket of clay within the glacial drift. Two separate profile models for the site were made – one with clay pocket and one without. In both models, the profiles were conceptualized with glacial drift layer overlying Marshall Sandstone, Allegan Mound being the regional source at one end and Turner Creek with adjacent wetlands being regional sink at the other end. With slight variations, Figure 3.19, both models predict that the fen may be receiving groundwater from both the shallow and the deep systems. The shallow system may extend up to 600 m westwards from the fen site. The deeper system may be receiving its recharge from the Allegan Mound, approximately 6 km from the fen site, upwelling into the fen from the bedrock aquifer.

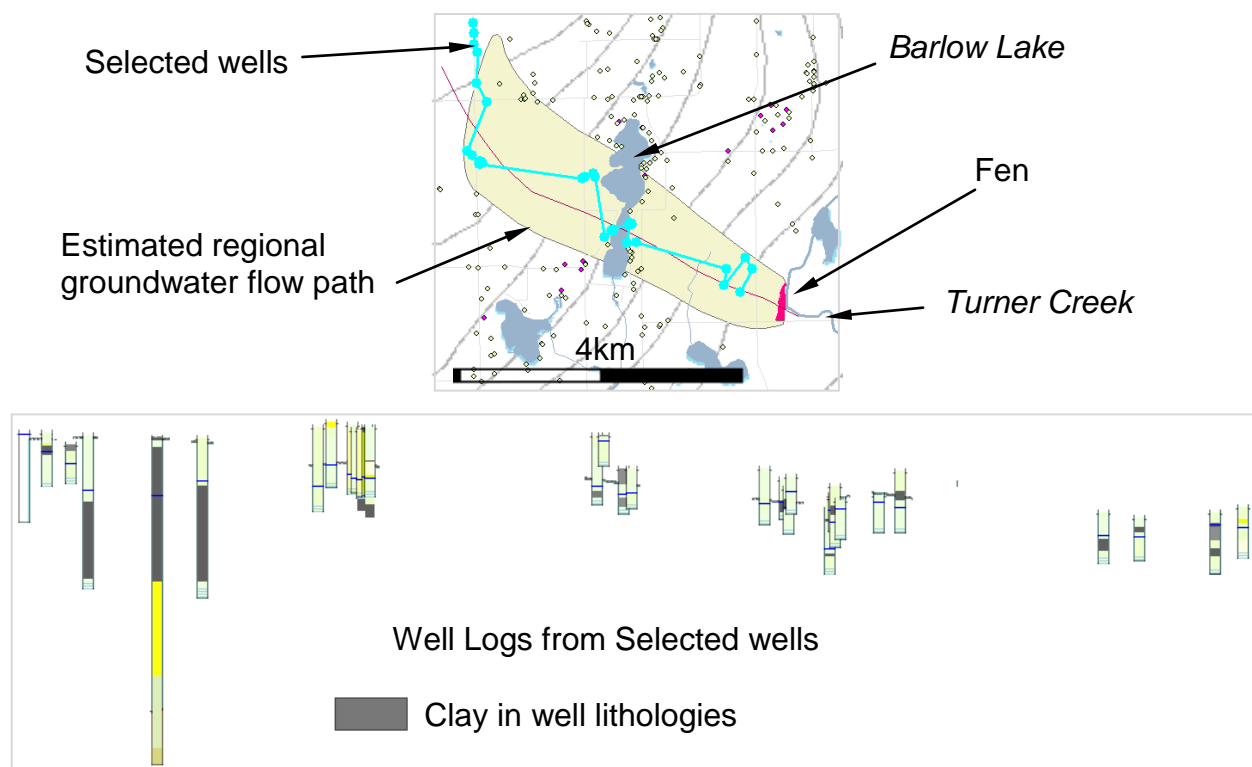


Figure 3.18 Well locations and well logs along Bowens Mill Fen capture zone. Contours at 2m interval show SWL for drift.

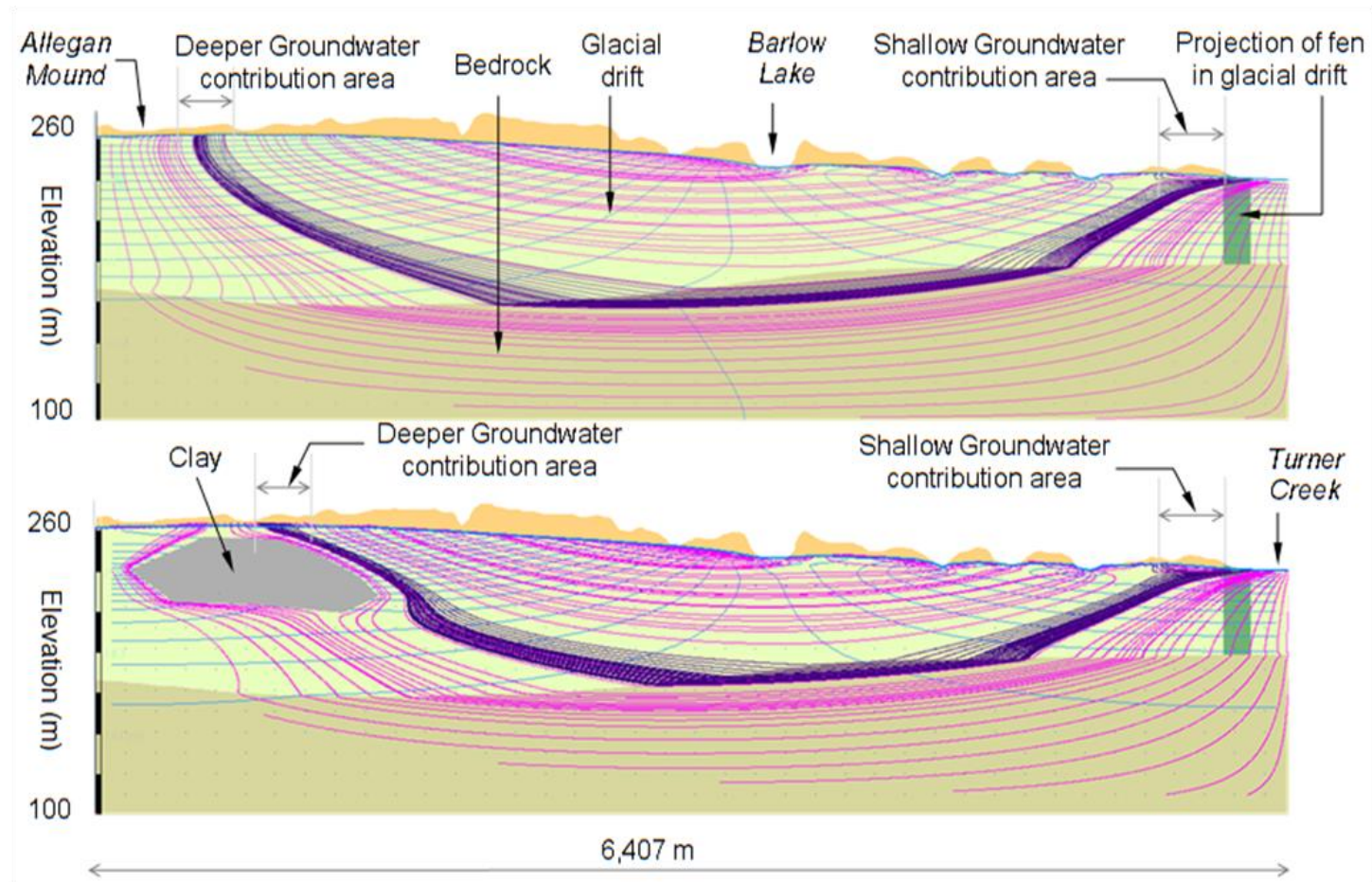


Figure 3.19 Profile Model for Bowens Mill Fen with clay lenses in the glacial drift [bottom] and without [top]. Light blue lines show groundwater head contours at 0.77m interval. Reverse particle tracking shows estimated groundwater flow regime (pink) and likely source water paths for the fen (purple).

Groundwater Profile Model – McDonalds Lake Fen

Well logs along the capture zone of McDonalds Lake Fen are shown in Figure 3.20. The logs do not reveal structural discontinuities in the drift. A two-layer profile model was conceptualized with glacial drift layer overlying Marshall Sandstone, Barry Mound being the regional source at one end and McDonald Lake with adjacent wetlands being the regional sink at the other end. The model, shown in Figure 3.21, predicts that the fen may be receiving groundwater from the deeper groundwater system connected to a sub-regional groundwater mound between Deep Lake and Glass Creek, approximately 5 km from the fen location. The model also suggests that upwelling water in the fen may not come in contact with the bedrock.

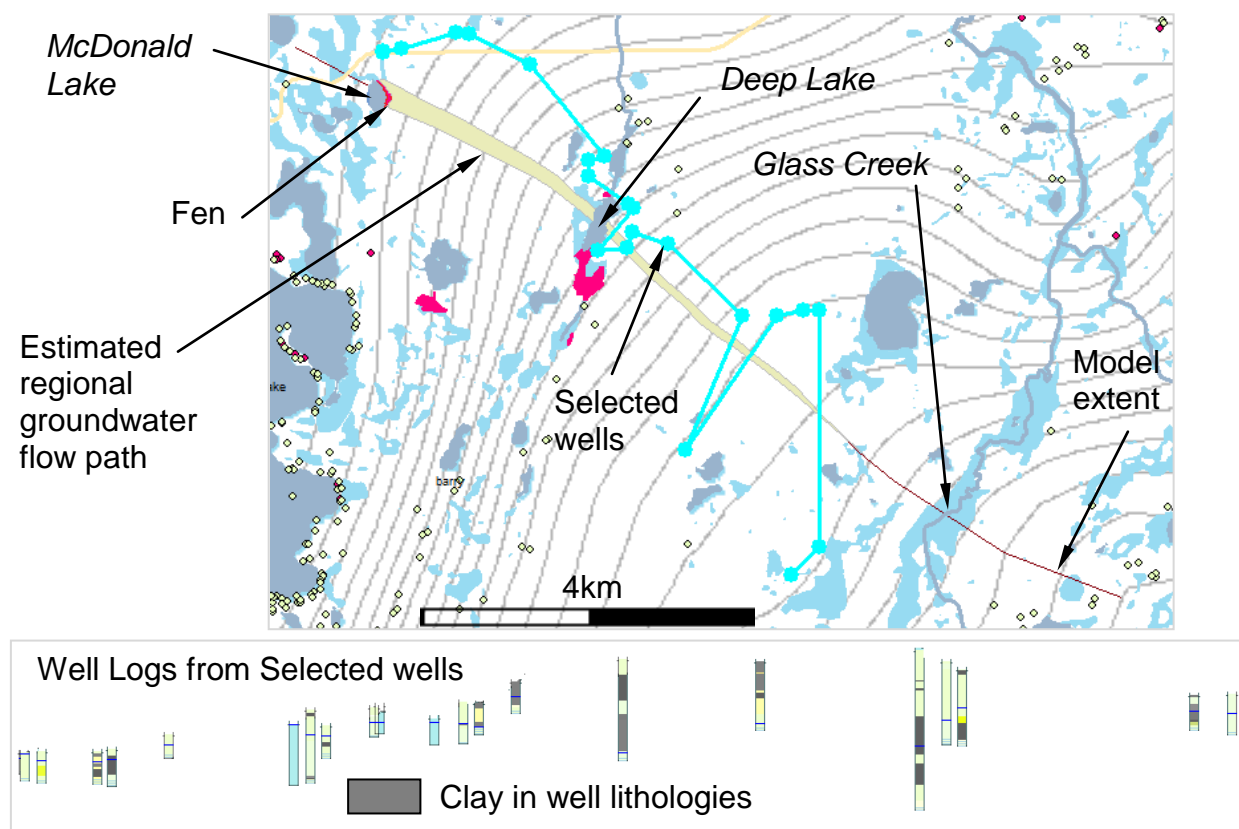


Figure 3.20 Well locations and well logs along McDonalds Lake Fen capture zone. Contours at 2m interval show SWL for drift.

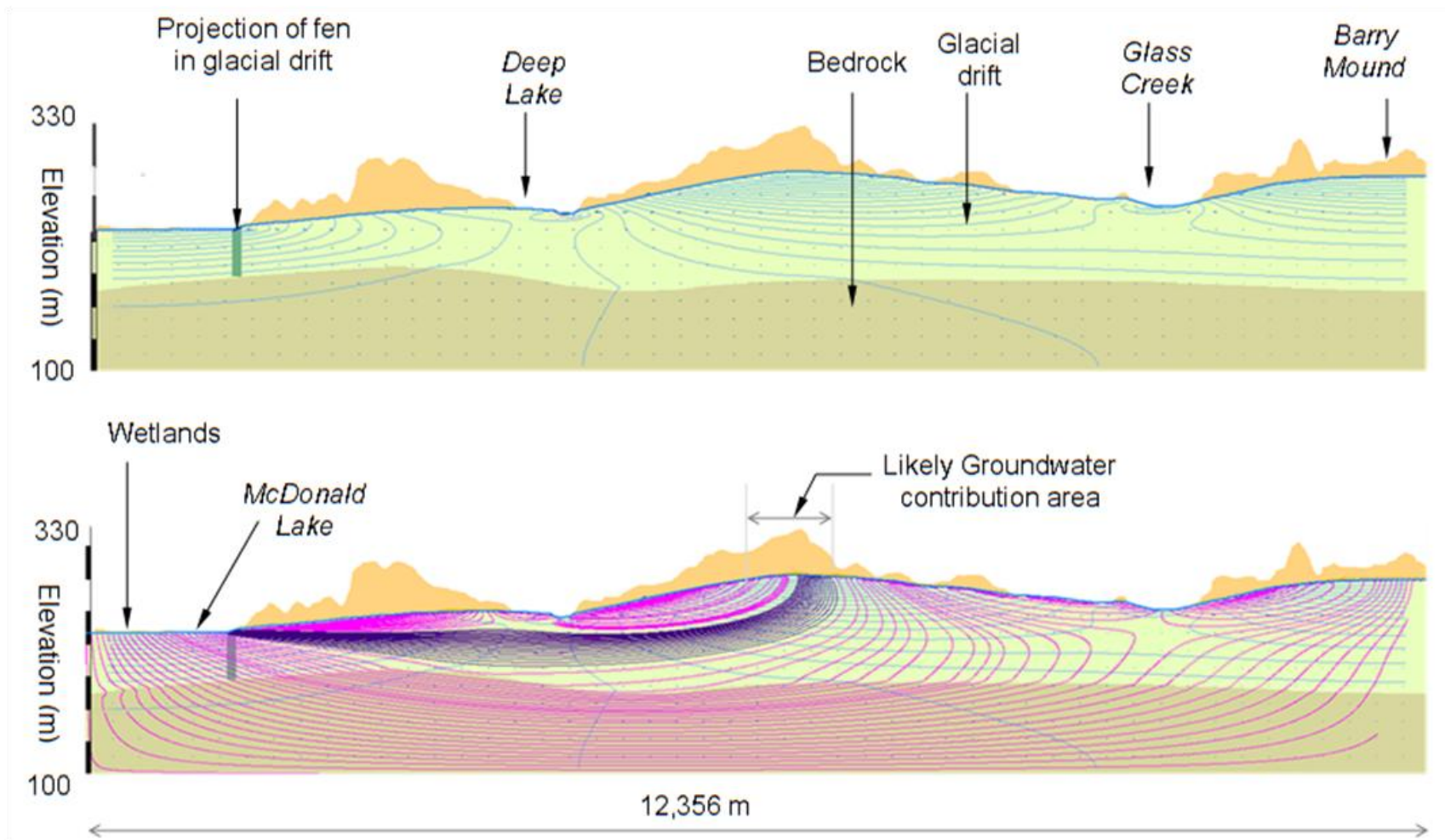


Figure 3.21 Profile Model for McDonald Lake Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 1.83m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Groundwater Profile Model – Yankee Spring Fen

Well logs along the capture zone of Yankee Spring Fen are shown in Figure 3.22. The logs do not reveal any structural discontinuities in the drift closer to the fen site. A two-layer profile model was conceptualized with glacial drift layer overlying Marshall Sandstone, Barry Mound being the regional source at one end and Gun Lake being regional sink at the other end. The model, in Figure 3.23, suggests that the fen receives water from the adjacent shallow system which extends all the way to the apex of the sub-regional groundwater mound approximately 1.8 km from the fen site. The model also suggests that upwelling water in the fen does not come in contact with the bedrock. The fen does not seem to receive water from the deeper systems.

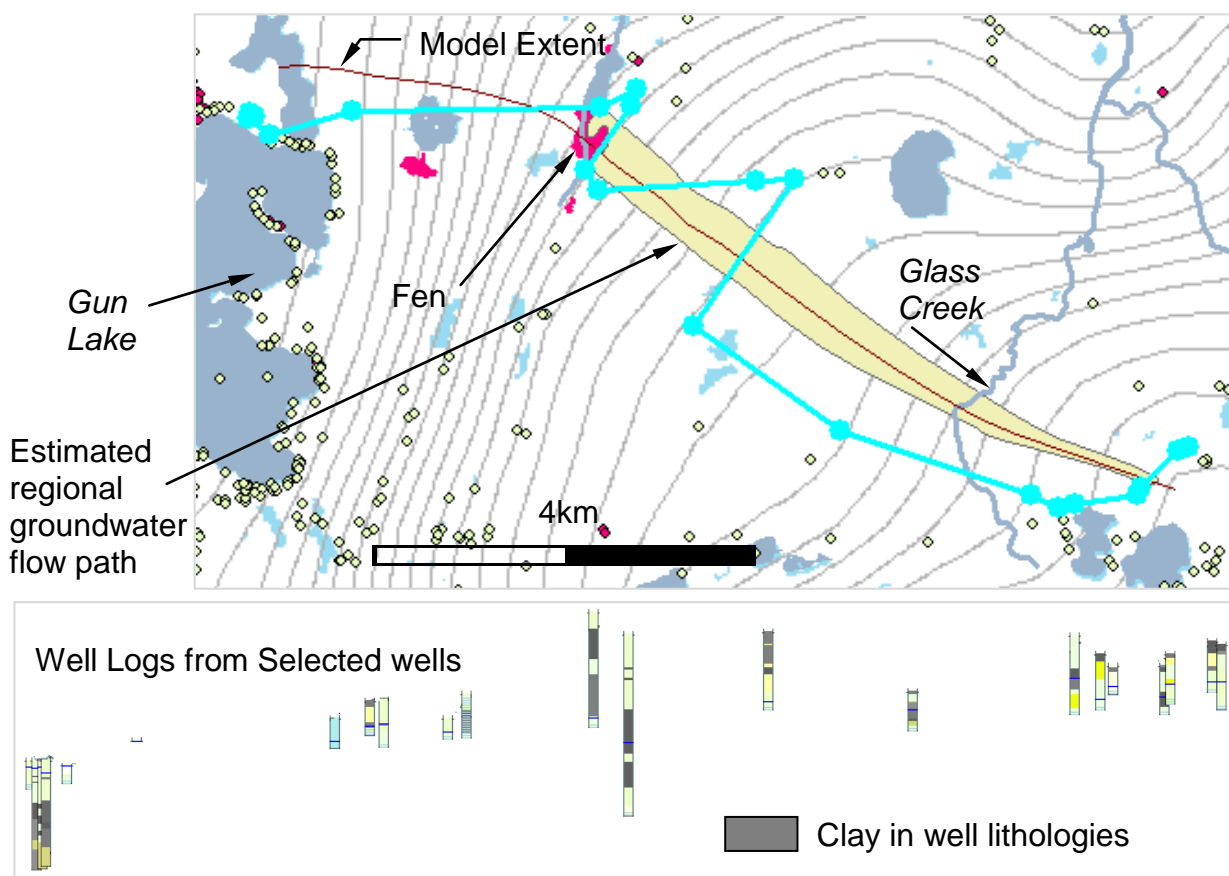


Figure 3.22 Well locations and well logs along Yankee Spring Fen capture zone. Contours at 2m interval show SWL for drift.

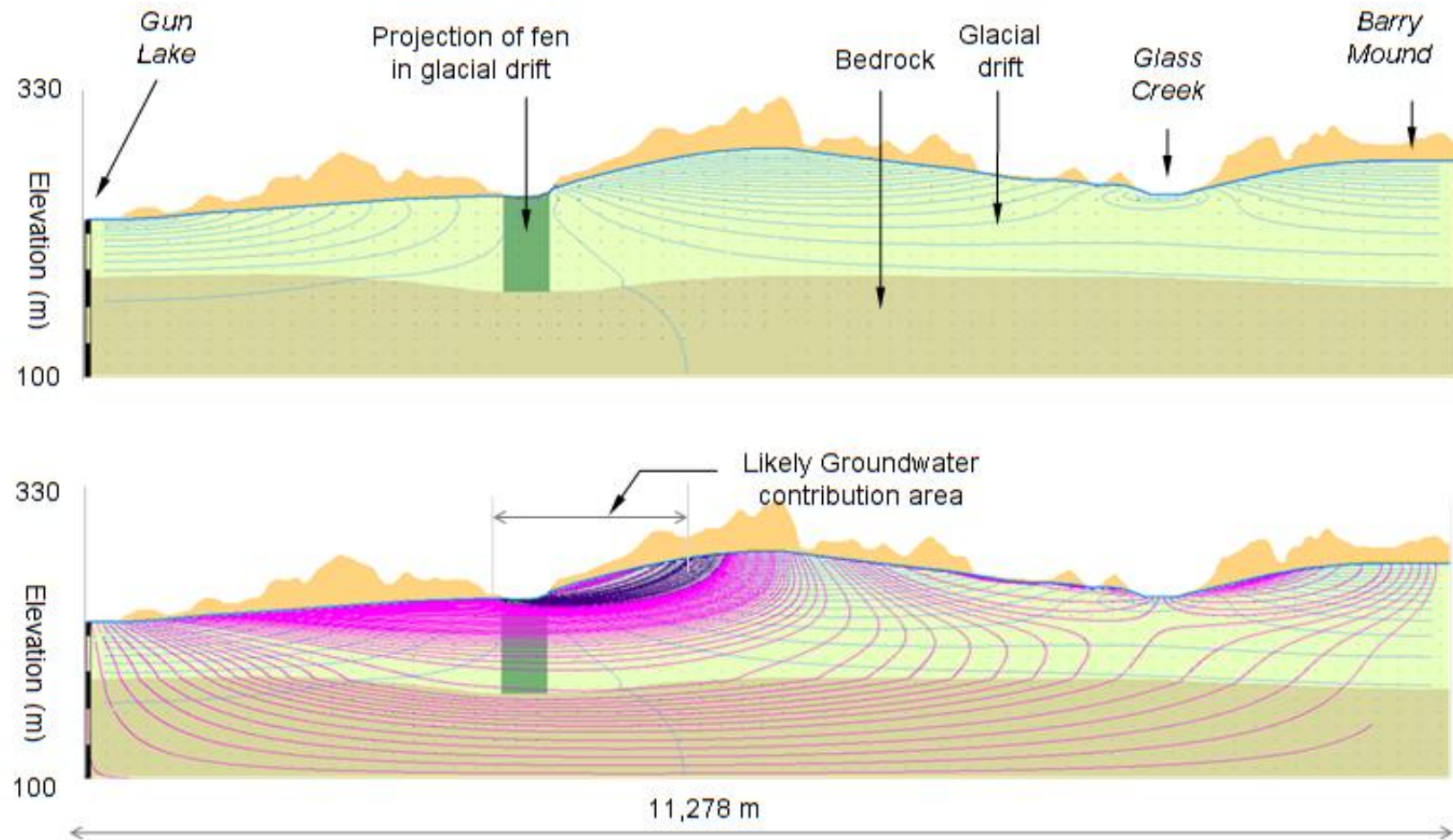


Figure 3.23 Profile Model for Yankee Spring Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 1.92m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Groundwater Profile Model – Hall Lake Fen and McKibben Fen

Hall Lake Fen and McKibben Fen share the same regional capture zone as shown in Figure 3.24. Well logs along the capture zone are also shown which do not reveal any structural discontinuities in the drift closer to the fen site. A two-layer profile model was conceptualized with glacial drift layer overlying Marshall Sandstone, Barry Mound being the regional source at one end and Gun Lake being regional sink at the other end. The model, shown in Figure 3.25, predicts that the McKibben Fen may be receiving groundwater from the adjacent shallow system while Hall Lake Fen receives water both from the adjacent shallow system as well as deeper upwelling. The groundwater feeding the fens does not seem to come in contact with bedrock.

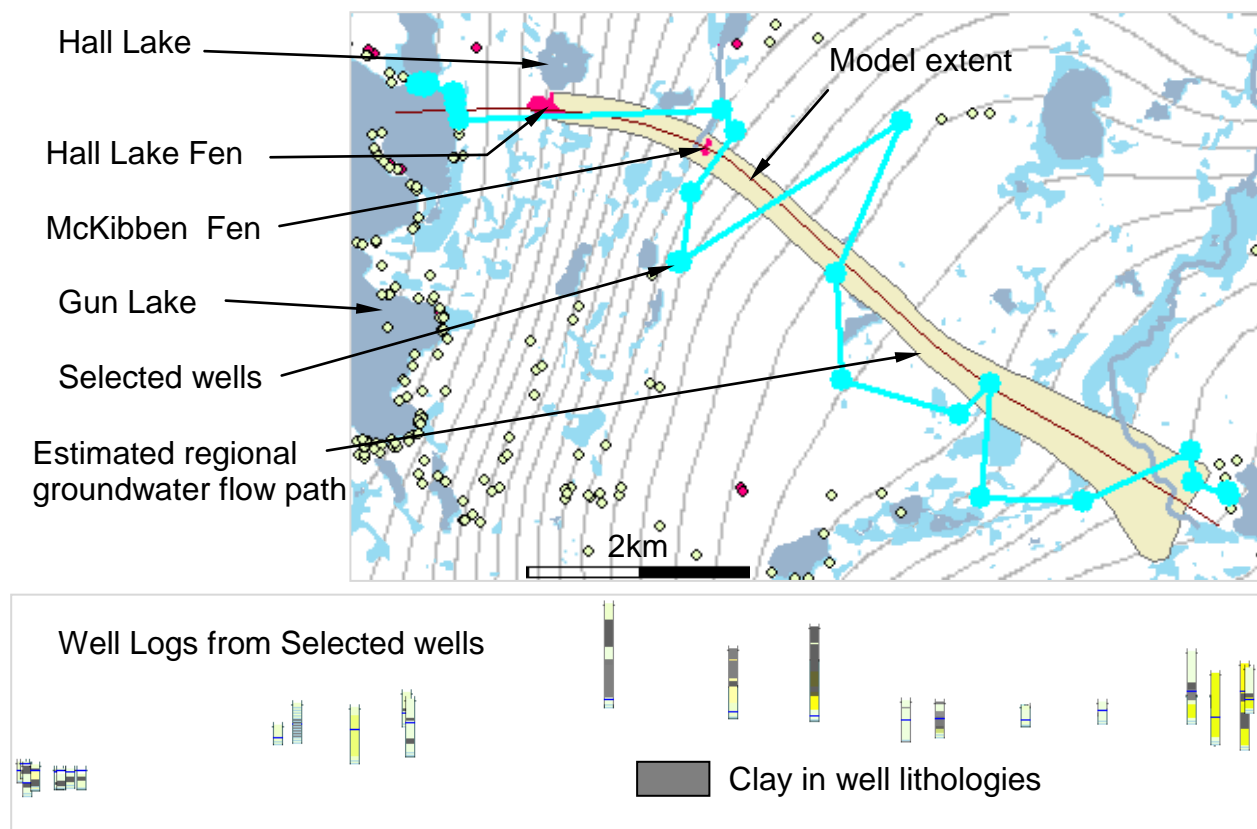


Figure 3.24 Well locations and well logs along Hall Lake Fen and McKibben Fen capture zone.

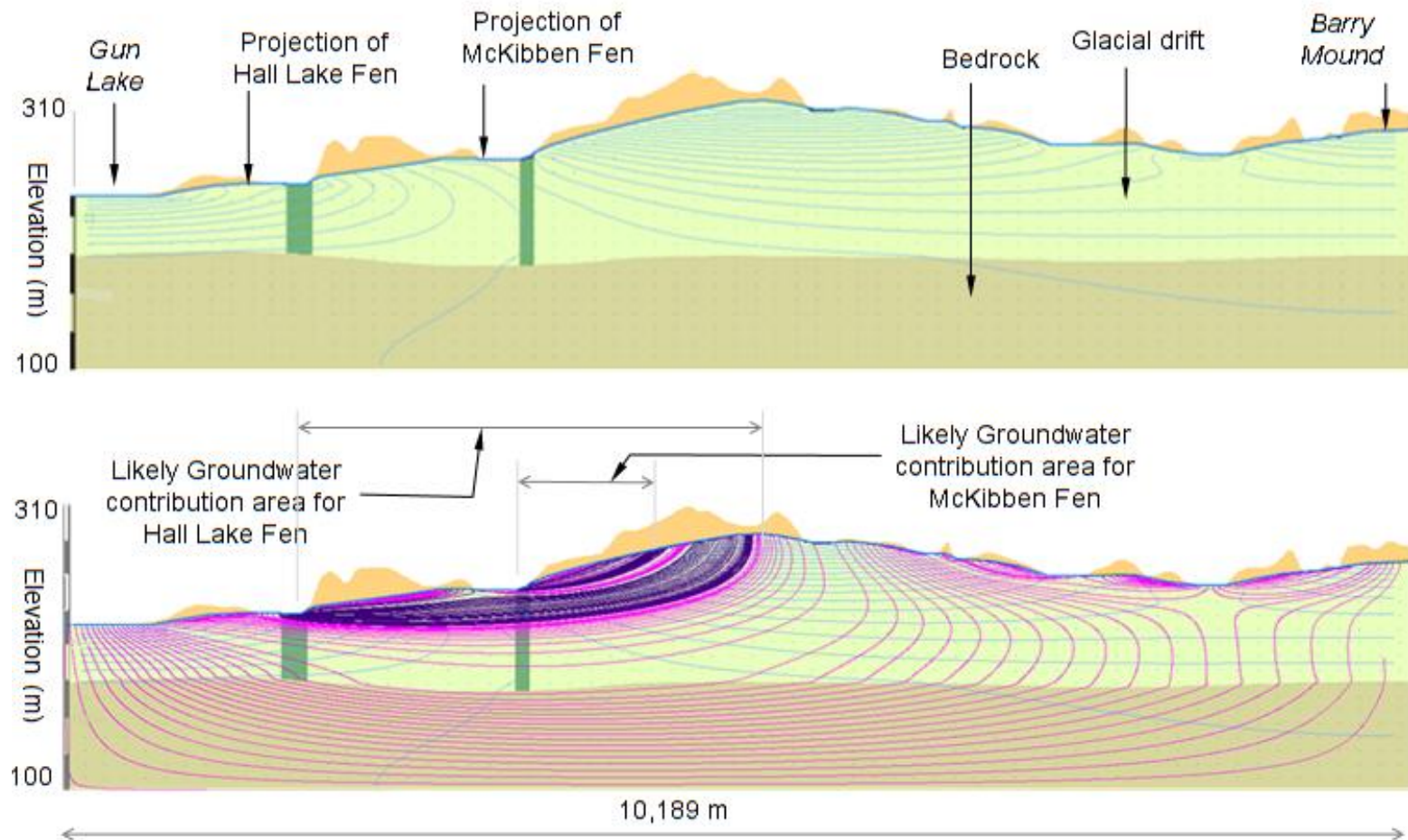


Figure 3.25 Profile Model for Hall Lake Fen and McKibben Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 2.30m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Liberty Fen and Skiff Lake/MacCready Fen

Liberty Fen occurs in proglacial outwash at the headwaters of Grand River where the river is only a first order stream. Bedrock formation under the glacial drift is Marshall Sandstone – a very transmissive formation. Average thickness of glacial drift in the area is 21m, with maximum 38m and minimum 12m. The fen and its surface catchment area are shown on 10m DEM relief in Figure 3.26. EORANK of the fen is ‘A’. MS occurrence has been reported at Liberty Fen.

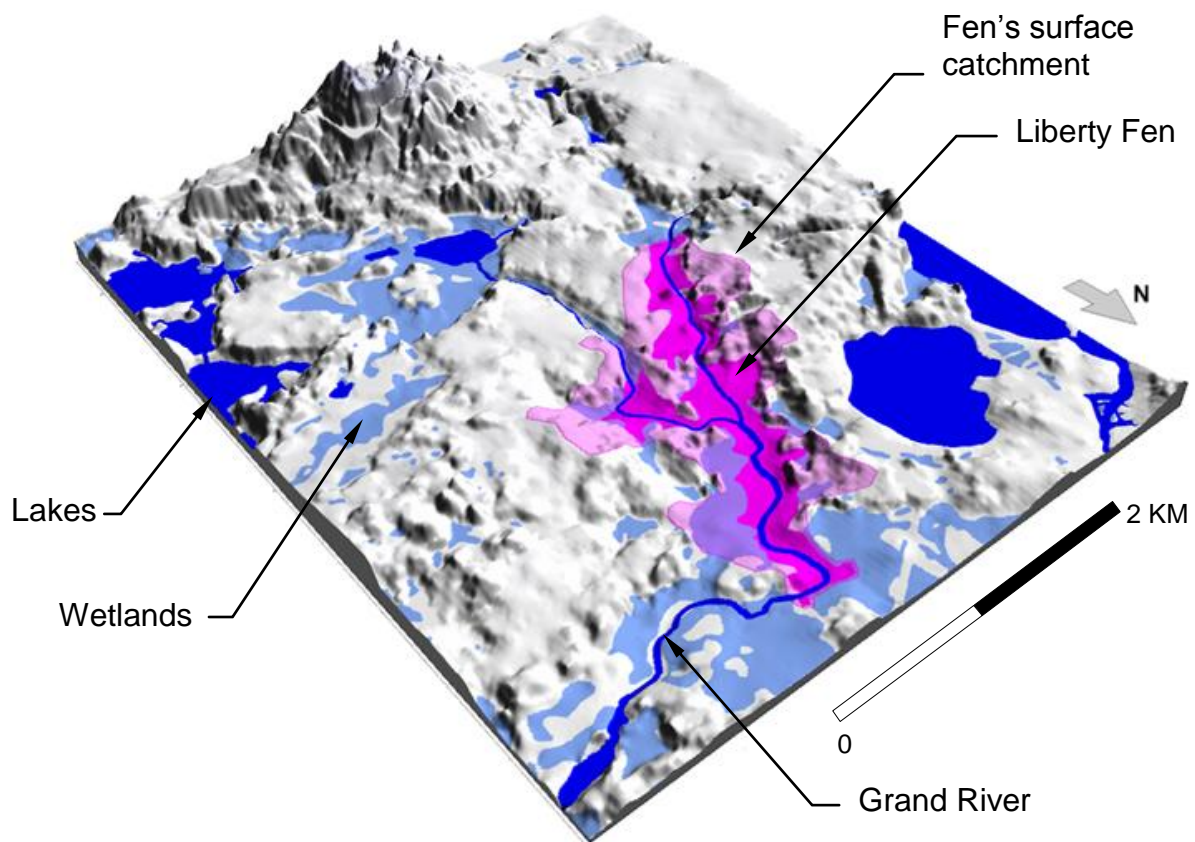


Figure 3.26 Liberty Fen. The shaded relief represent surface relief derived from 10m/30m DEM. Surface elevation varies between 310.69m and 384.31m.

Skiff Lake Fen occurs on the southwestern side and MacCready Fen occurs on the northeastern side of Skiff Lake. Both fens occur in proglacial outwash. Bedrock formation under the glacial drift is Marshall Sandstone – a very transmissive formation. Average thickness of glacial drift in the area is 24m, with maximum 58m and minimum 6m. The fen and its surface catchment area are shown on 10m DEM relief in Figure 3.27. A prominent esker runs along the northwestern extent of MacCready Fen. EORANK of the fen is ‘BC’. MS occurrence has been reported at Skiff Lake Fen but not at MacCready Fen.

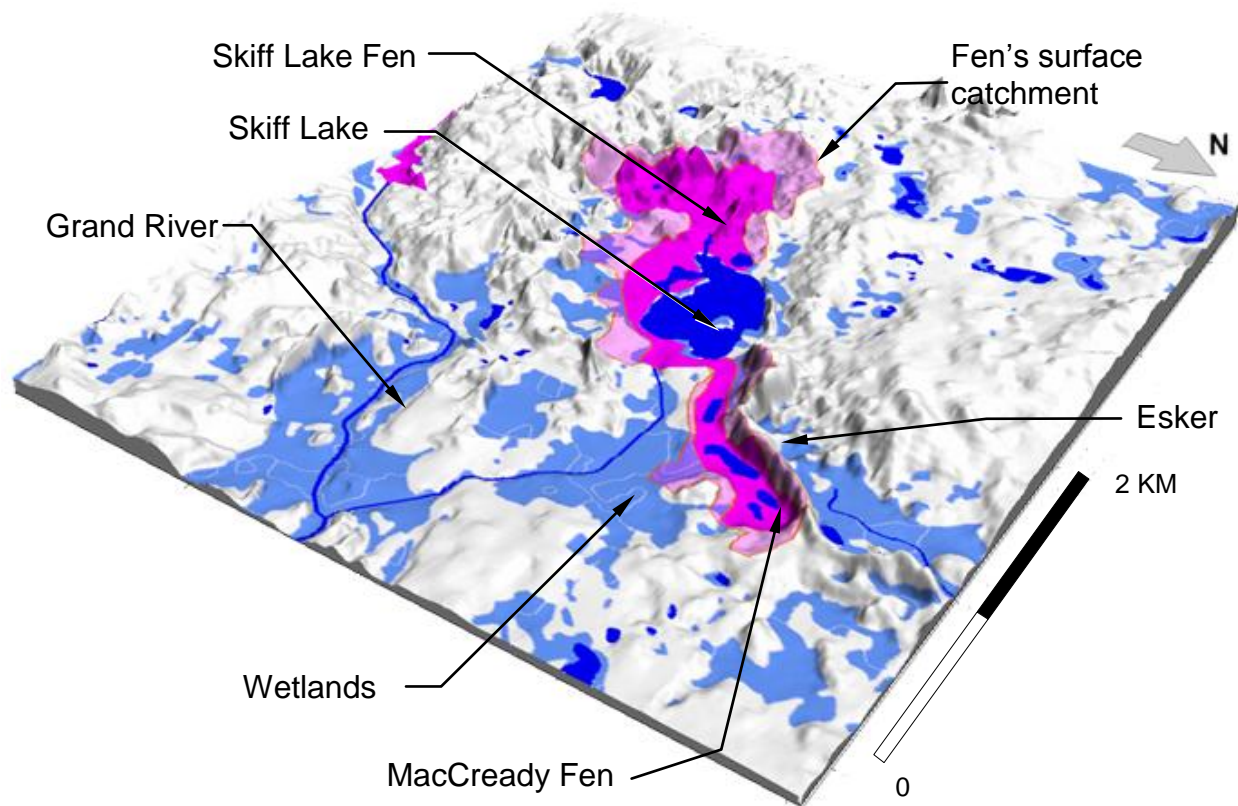


Figure 3.27 Skiff Lake and MacCready Fens. The shaded relief represent surface relief derived from 10m/30m DEM. Surface elevation varies between 294.77m and 346.75m.

Regional Groundwater Model

Liberty Fen and Skiff Lake/MacCready Fen were both covered in the same regional model. Model area of 16.12 km by 19.97 km was divided into the 300x375 grid cells, with the cell size of 53.40 m. The model area consists of thin glacial outwash deposits overlying a shallow bedrock formation – Marshall Sandstone, which is very transmissive. Marshall Sandstone is underlain by impervious Coldwater Shale formation. Static water level (SWL) was ascertained using bedrock wells and surface water data from large streams/lakes. Delineated zones of groundwater contribution to the fens are shown in Figure 3.28.

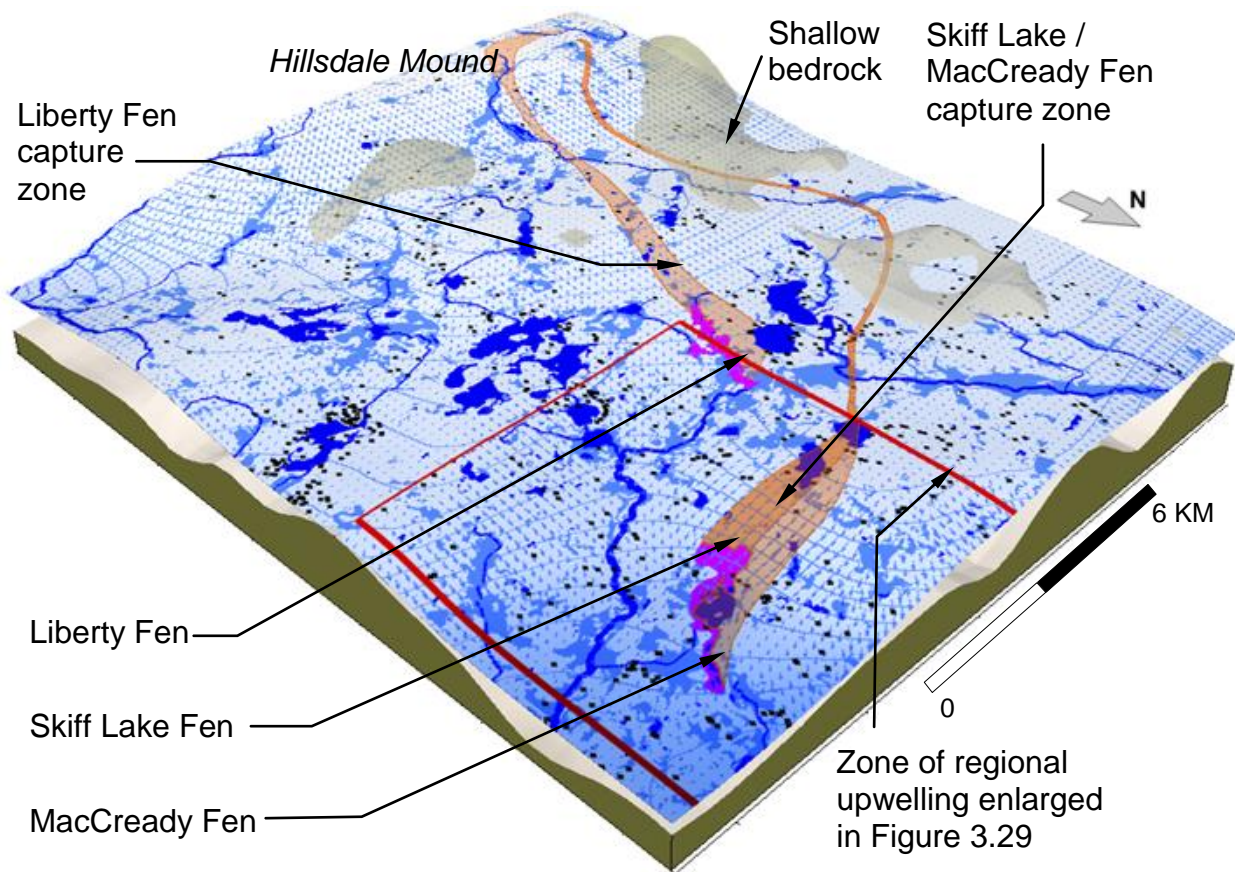


Figure 3.28 The contours at 2m interval and shaded relief represent regional scale delineation of groundwater surface around Liberty Fen and Skiff Lake Fen which varies in elevation from 292.92m to 347.14m.

The exception was made to include surface water data while delineating SWL from bedrock wells because of the shallow proximity of bedrock to the surface.

Reverse particle tracking was used to delineate groundwater capture zones for the selected fen sites in the model. Flow paths leading to all fen sites in the area seemed to originate from Hillsdale Groundwater Mound in the south-west of the model area, between 12 and 18 km from the respective fen sites. Residence time for the regional flow paths were estimated between 70 and 100 years.

The regional model shows bending of contours in the north-eastern part of the model which implies convergence of regional flow in this area. Since Marshall Sandstone is underlain by less transmissive shale, the convergence of flow suggests possibility of upwelling in this area.

Regional Groundwater Upwelling

The likely upwelling area as highlighted in Figure 3.28 was modeled in more detail to ascertain regional upwelling. SWL was separately delineated for this area using bedrock wells only (i.e., without taking into consideration any surface water features). SWL delineated by bedrock wells, as shown in Figure 3.29, also showed strong convergence of regional flow in this zone. The flow paths on either sides of the fen complex were oriented almost perpendicular to each other.

During a site visit to this area, three artesian wells were observed around Skiff Lake / MacCready fen sites. Exact locations of these wells are marked in Figure 3.29. The presence of artesian wells within the convergence zone suggested by the model provides qualitative validation of regional groundwater upwelling in the area – suggesting that fens may also be benefitting from this source.

Please also refer to Chapter 4, Figure 4.1 and Figure 4.2 for discussion on regional flow convergence observed around other fen sites in this study.

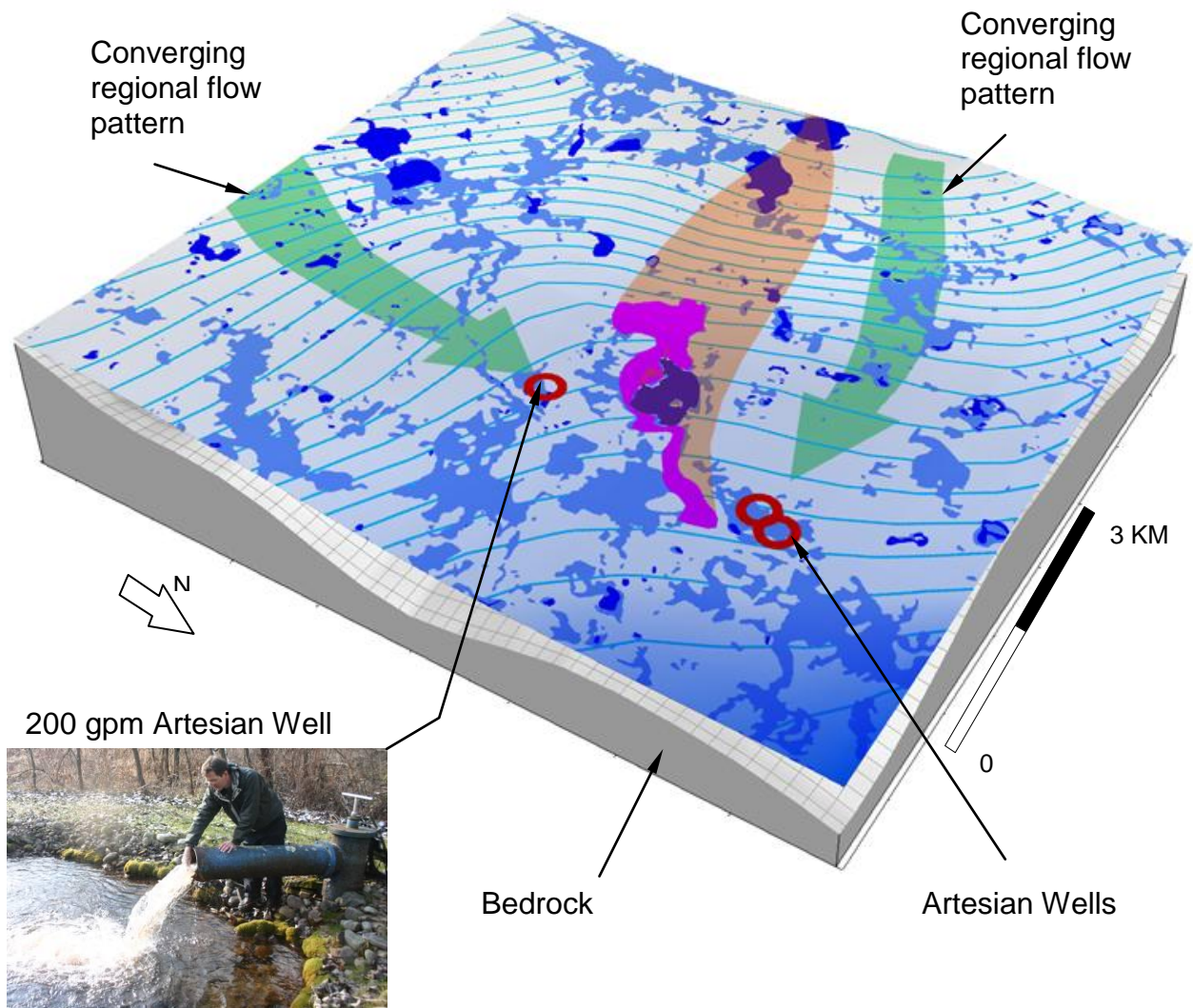


Figure 3.29 Zone of regional upwelling around Skiff Lake/MacCready Fens and locations of artesian wells in the area. Contours at 1.05m interval and relief represent groundwater head surface delineated by interpolating bedrock wells data.

In Figure 3.30, the groundwater contribution zones are superimposed on surface topography and geological land forms. The two fen sites occur within the glacial outwash. The capture zones extend beyond the regional surface water catchments.

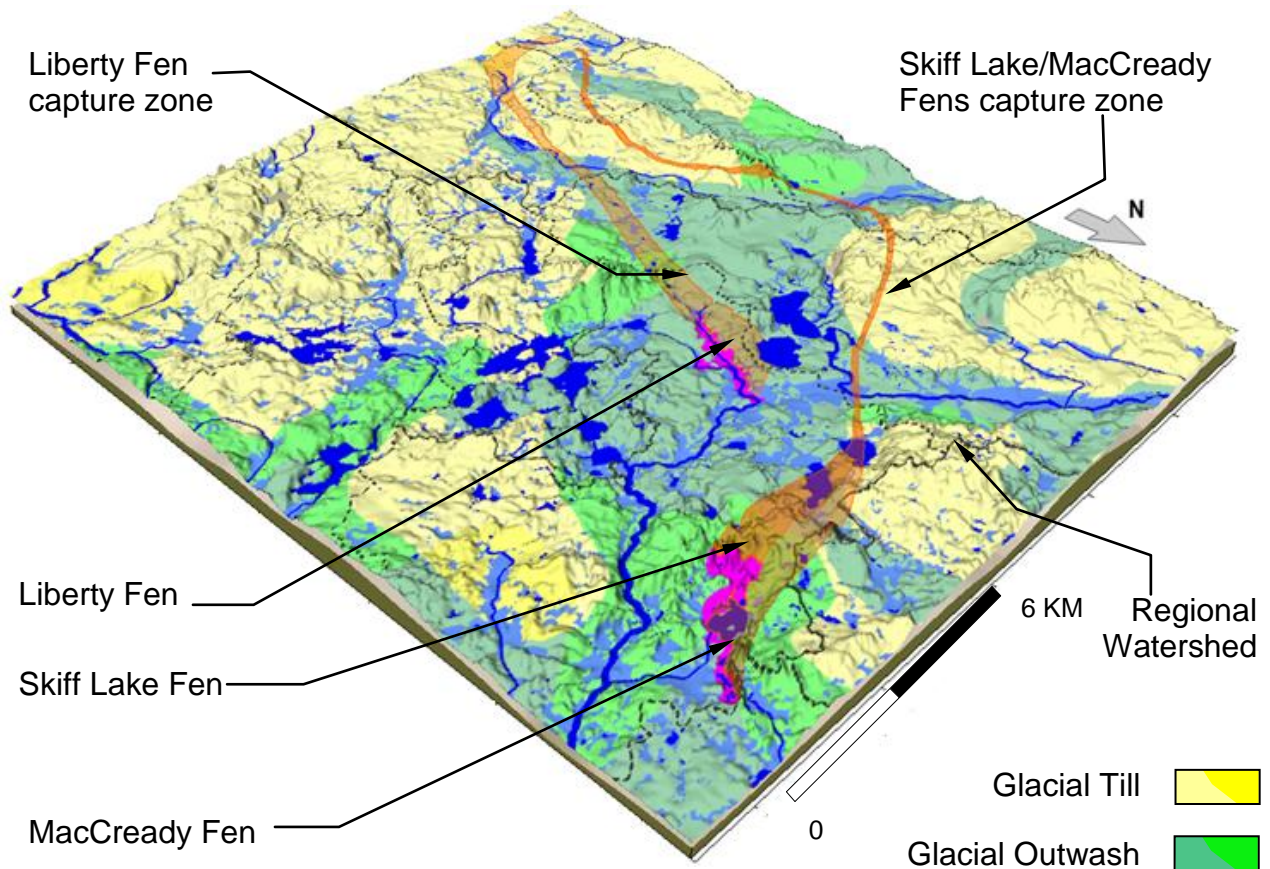


Figure 3.30 The shaded relief represents surface topography in the region which varies in elevation from 296.27m to 387.36m.

Local Flow Systems

Estimation of contribution areas of local/shallow flow systems were also made for the two fen sites as shown in Figure 3.31 and Figure 3.32. The models for local flow systems suggest that local flow may be contributing to the fens from all around. The residence times for local flow systems at the two sites was estimated by using range of effective porosity from 0.1 to 0.3

in Equation 2.1. The estimated times varied between 1 and 3 years for the local systems. In case of Liberty Fen, local high groundwater areas to the south of the fen seem to be connected to the fen. The local system to the north of the fen has relatively small gradients. However, it can be readily seen that these local highs across the flatter gradients may be contributing to the flatter areas right next to the fen site, and therefore, may be indirectly providing water to the fen.

The profile model explained in the next section only captures the local flow details along the selected section. Detailed estimates for local flow systems for other modeled sites in this study area are not presented.

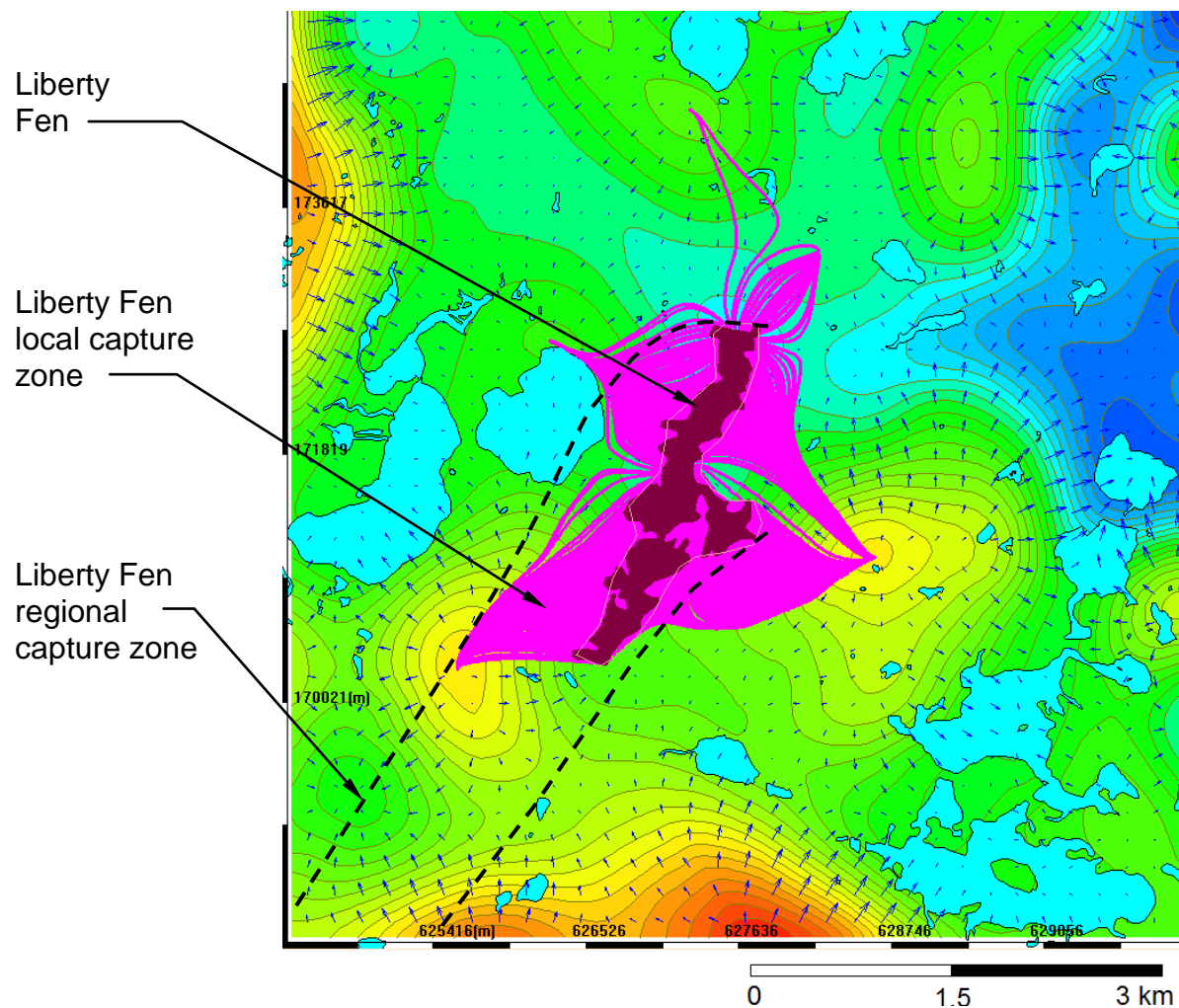


Figure 3.31 Local flow system around Liberty fen.

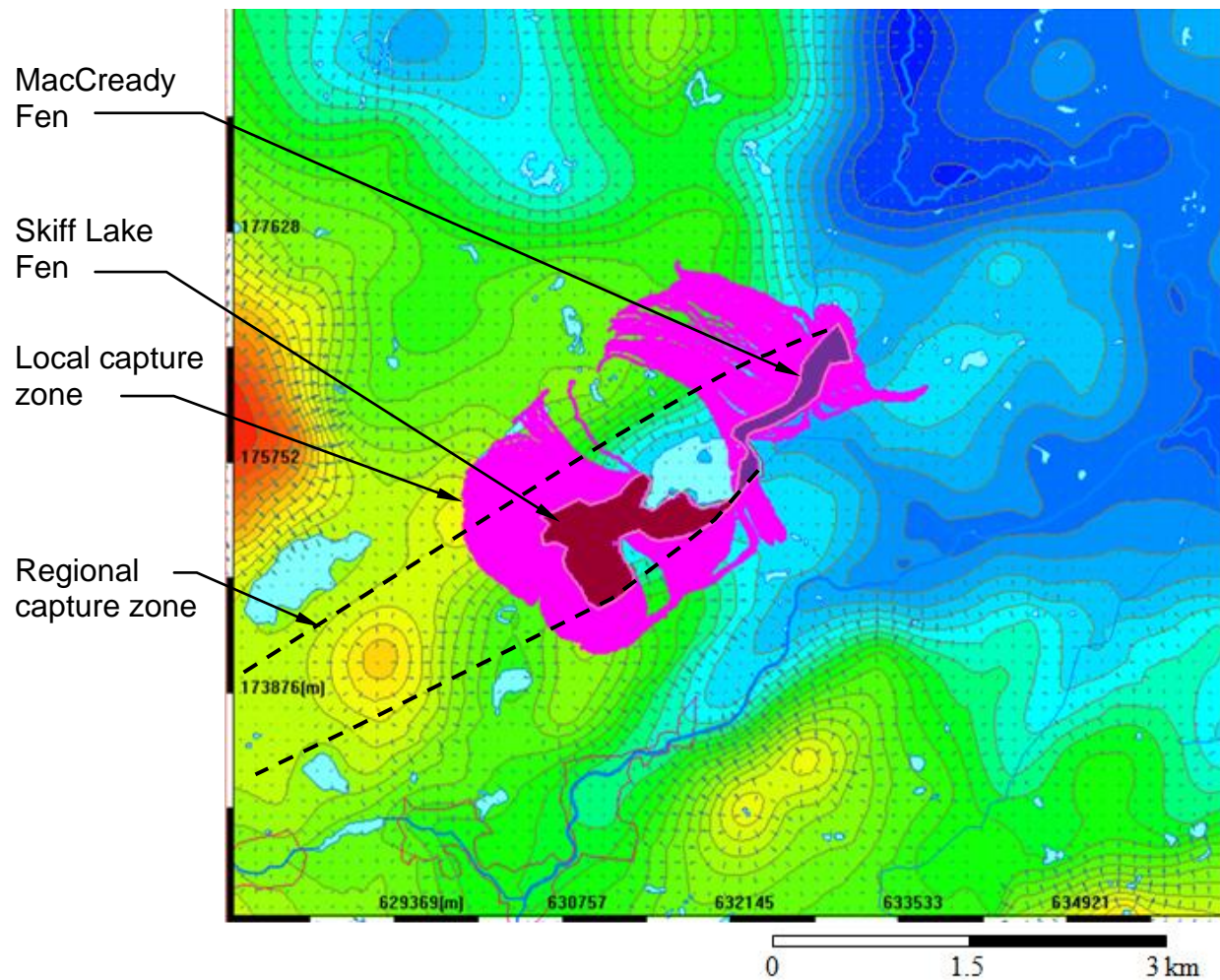


Figure 3.32 Local flow systems around Skiff Lake/MacCready fens.

Groundwater Profile Model – Liberty Fen

The profile section selected across the fen and its regional capture zone is shown in Figure 3.33. The section starts in the south at the top of Hillsdale Groundwater Mound, runs through the delineated groundwater capture zone of Liberty Fen, and extends further north-east of the fen, ending close to the Grand River - the regional sink in the area.

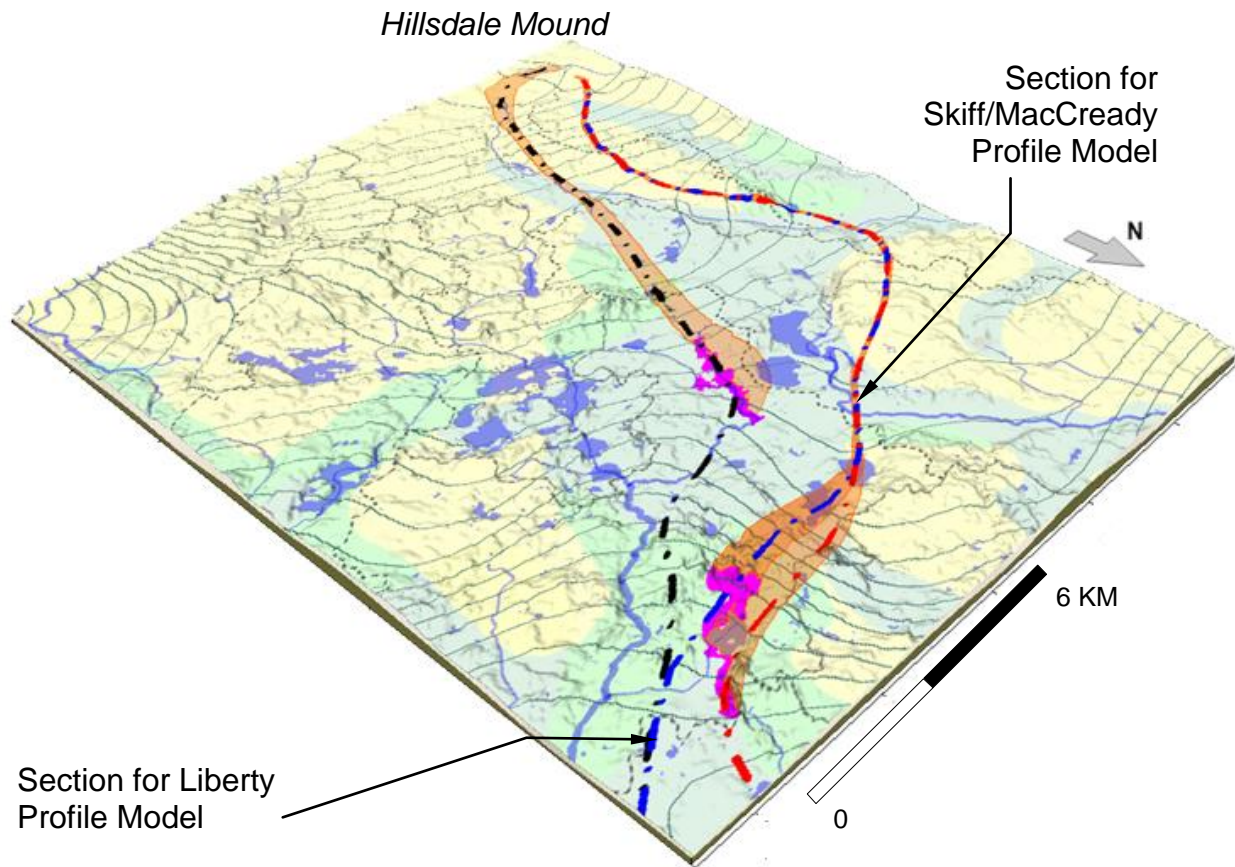


Figure 3.33 Selected sections for profile models. Shaded relief represents topography and contours represent regional SWL at 2m interval.

Profile model for Liberty Fen is shown in Figure 3.34. The model shows that the regional groundwater in the capture zone delineated in the horizontal model flows mostly in the bedrock – Marshall Formation, underneath the glacial drift. Some upwelling from bedrock into the fen seems likely and its source may be linked to a recharge area around a sub-regional surface watershed. The shallow system and drift aquifer, extending approximately 4.8 km from the fen seems to be contributing most groundwater system to the fen site.

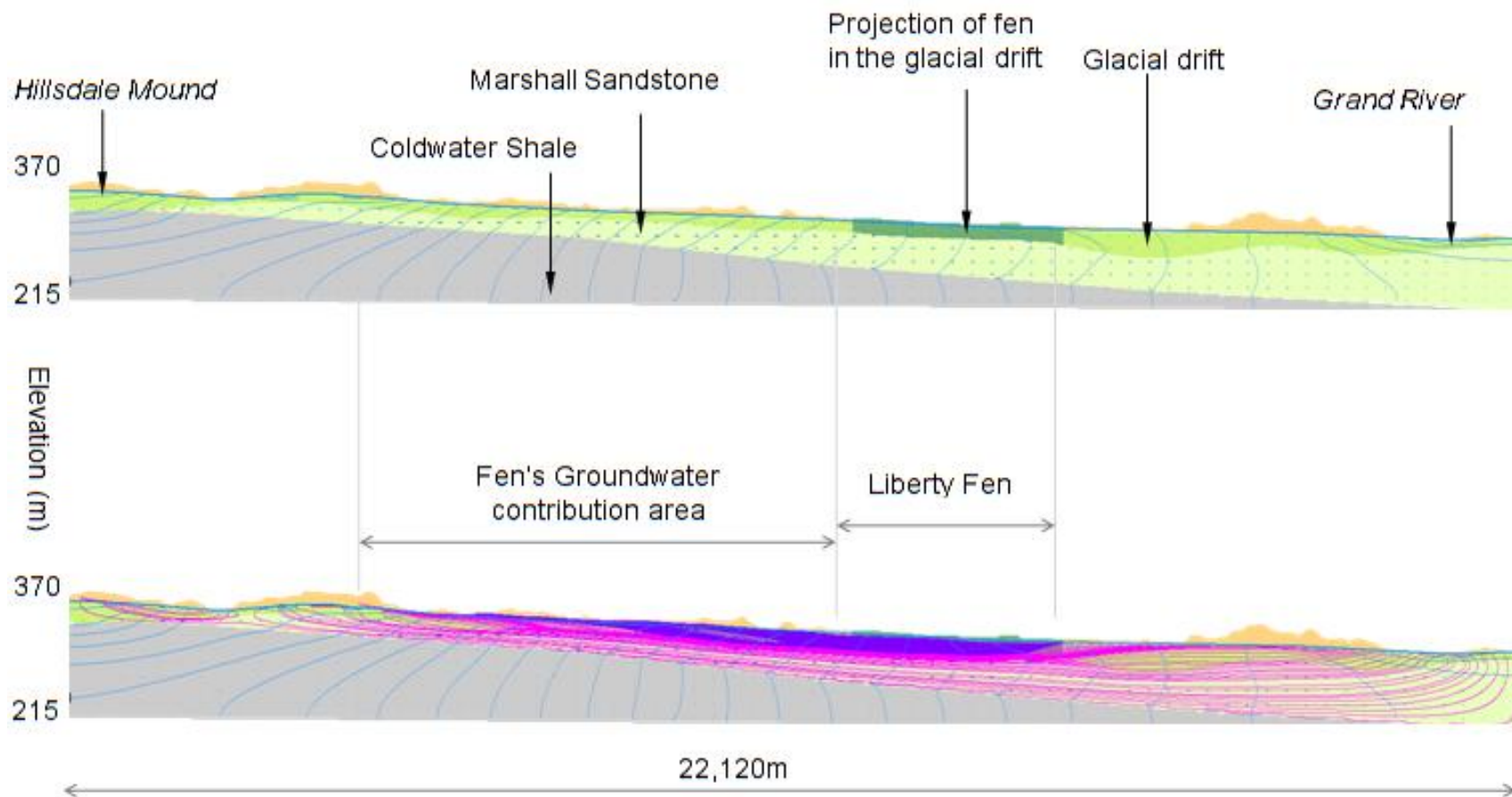


Figure 3.34 Profile Model for Liberty Fen. Geological layers along the profile and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 1.85m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water areas (purple) [bottom].

Groundwater Profile Model – Skiff Lake/MacCready Fen

The profile section selected across the fen and its regional capture zone is shown in Figure 3.33. The section starts in the south at the top of Hillsdale Groundwater Mound, runs through the delineated groundwater capture zone of Skiff Lake/MacCready Fens, through the fen sites and ending close to the Grand River - the regional sink in the area.

Profile model for Skiff Lake/MacCready Fens is shown in Figure 3.35. The model suggests that Skiff Lake Fen may be receiving groundwater from both shallow and deep aquifer systems. The shallow system in drift aquifer feeding the fen may extend from the fen site to approximately 3.5km to the west. Groundwater feeding the fen from the deeper Marshall formation may have its recharge area approximately 11 km from the fen sites in the south-west direction. Recharge from this zone is also feeding MacCready Fen.

It appears from the profile model in Figure 3.35 that MacCready Fen is getting all its water only from the deeper bedrock aquifer only. However, it is very important to keep in mind the local horizontal flow model shown in Figure 3.32 which suggests that the direction of local flow to MacCready fen is almost perpendicular to the regional flow direction along which the profile model was built. The profile model, therefore, does not show the local flow component to the fen. It appears from the local horizontal flow model that wetland and adjacent hills to the north of the fen may be the sources of shallow groundwater contribution to the fen. This case typically highlights the 3D nature of flow systems in the area.

The profile model shows regional connection and the possibility that part of groundwater discharge at MacCready fen may even be linked to the recharge areas at Hillsdale Mound, 22 km from the fen site. The model also shows that most of deeper groundwater flow from Hillsdale Mound bypasses the fens and ends up in Grand River.

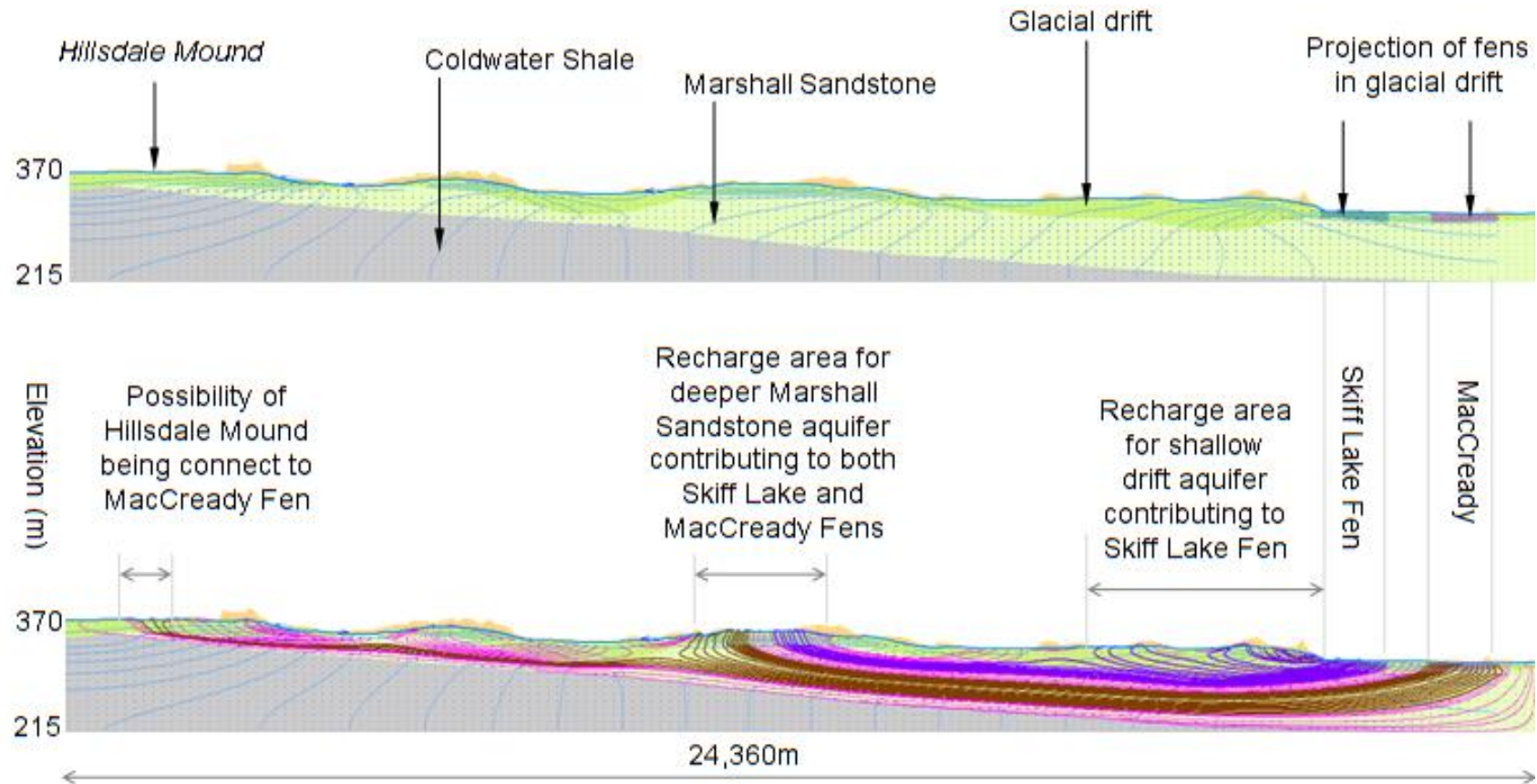


Figure 3.35 Profile Model for Skiff Lake/Maccready Fens. Geological layers along the profile and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 1.88m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water areas for Skiff Lake (purple) and MacCready (brown) fens [bottom].

Ives Road Fen

Ives Road Fen is one of the few prairie fens occurring far away from regional groundwater mounds and in relative isolation compared to nearby fens. It occurs in proglacial outwash deposits along Raisin River. Bedrock formation under the outwash is Coldwater Shale. Average thickness of outwash is 56m, with maximum 79m and minimum 37m around the fen. The bedrock almost pinches to the surface about 800m to the west of the fen. The fen and its surface catchment area are shown on 10m DEM relief in Figure 3.36. EORANK of the fen is 'A'. MS occurrence has not been reported at this site.

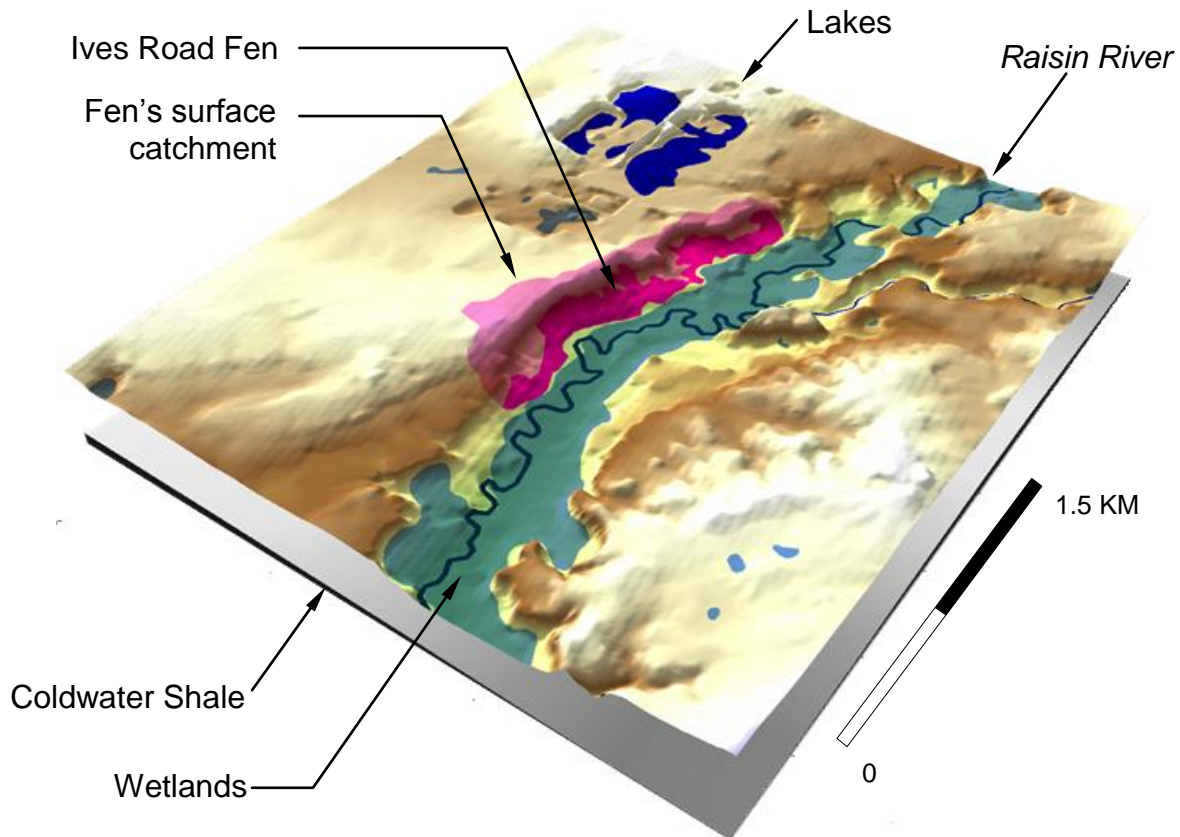


Figure 3.36 Ives Road Fen along the Raisin River valley. The shaded relief represents topography derived from 10m/30m DEM which varies from 218.98m to 253.64m.

Regional Groundwater Model

Regional model for Ives Road Fen was selected over an area of 23.26 km by 15.66 km. The area was divided into the 450x304 grid cells, with the cell size of 51.69 m. Static water level (SWL) and other modeling parameters were ascertained as explained in methodology. Reverse particle tracking was used to delineate groundwater capture zone for the fen site in the model. The delineated zone is shown in Figure 3.37.

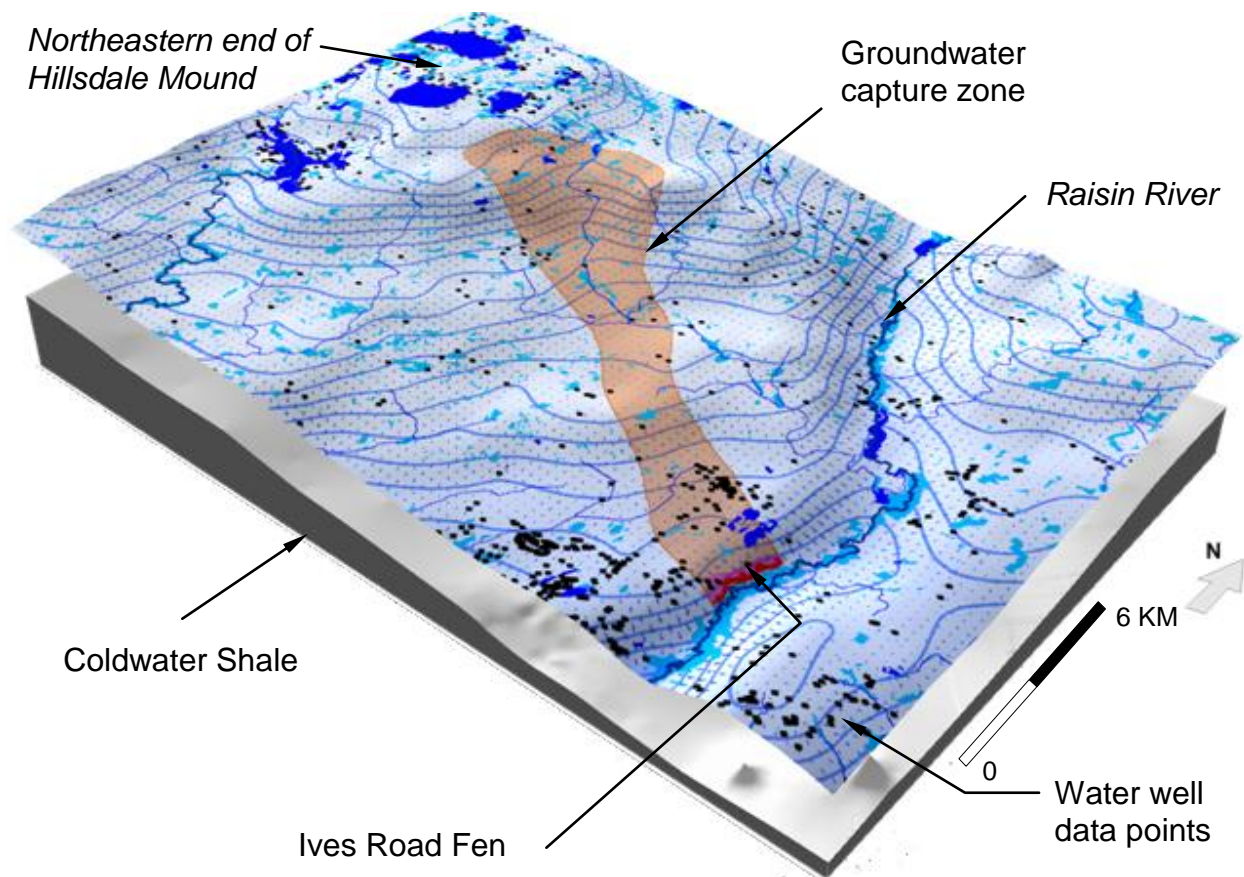


Figure 3.37 The contours at 3m interval and shaded relief represent regional scale delineation of groundwater surface around Ives Road Fen which varies in elevation from 217.40m to 295.15m.

The model shows that the contribution zone may be connected to the north eastern end of Hillsdale Groundwater Mound, approximately 16 km to the northwest from the fen site. In Figure 3.38, the groundwater contribution zone is superimposed on surface topography and geological land forms. The fen occurs in a narrow strip of glacial outwash along the Raisin River valley. The groundwater contribution area, approximately perpendicular to the river valley extends across the till plains all the way to another zone of glacial outwash as shown in the northwest corner of the model. This area coincides with the northeastern end of the Hillsdale Groundwater Mound. A few first order streams crisscross the capture zone in the till plains. A few wetlands and lakes also occur over the capture zone.

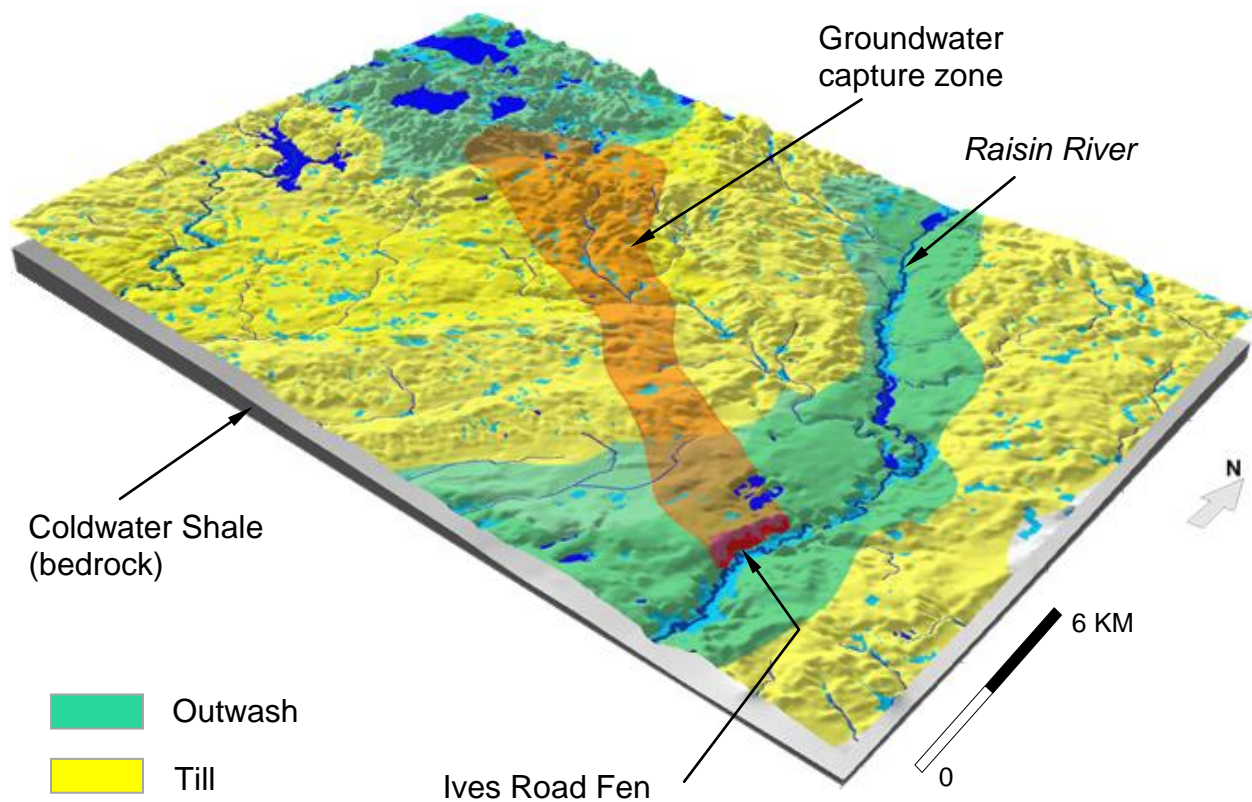


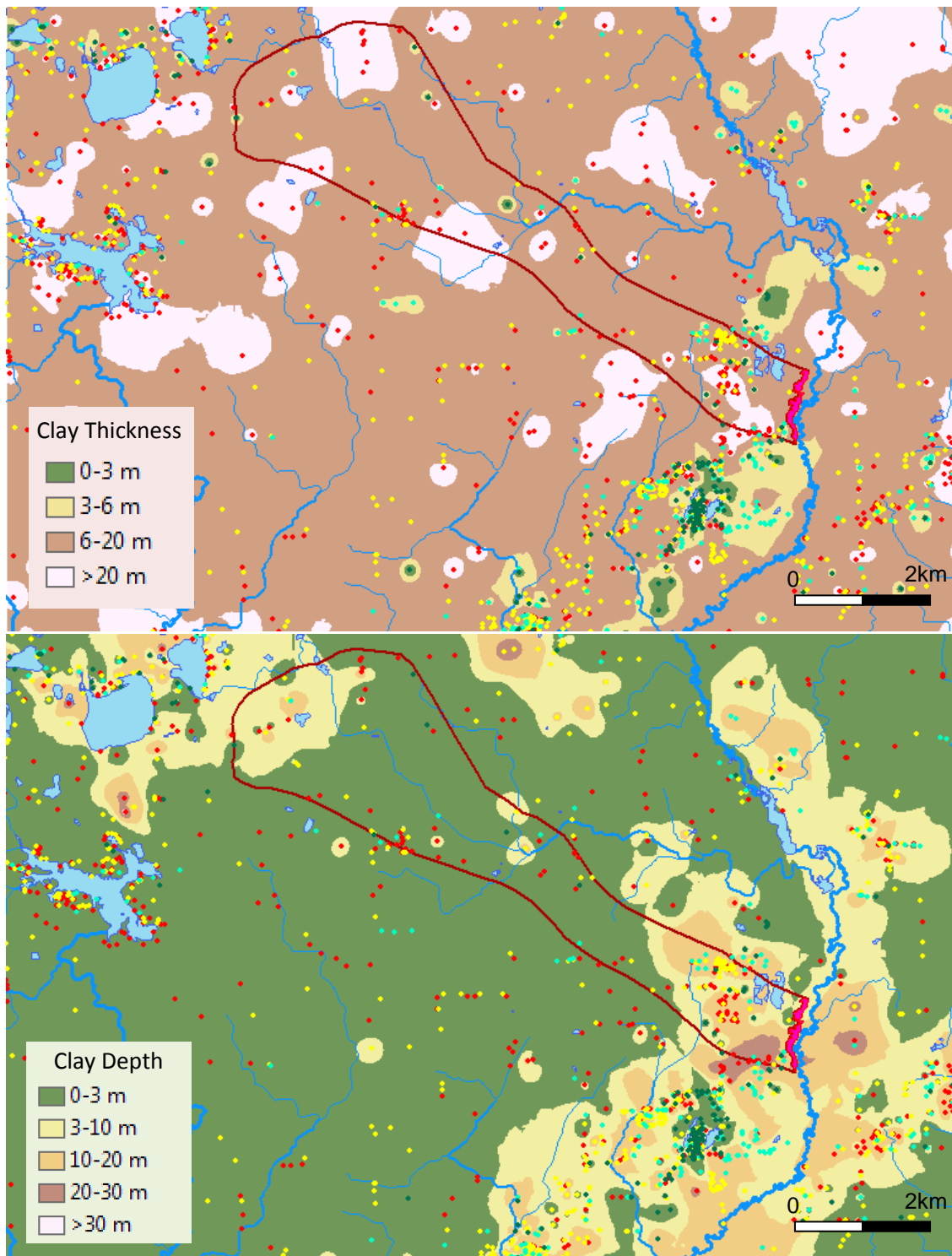
Figure 3.38 The shaded relief represents surface topography, varying in elevation from 217.42m to 332.32m. Glacial landforms in the area are represented by different colors.

Groundwater Profile Model

Analysis of lithology from the well logs around Ives Road Site revealed a thick and continuous layer of clay close to the ground surface, extending west of the fen location for approximately 15 km. Geostatistical interpolation of thickness of the clay layer and its depth from the surface is shown in Figure 3.39. The clay layer is close to the surface in the central portion of the fen's groundwater capture zone while it is buried deeper in outwash deposits at its either ends. Closer to Raisin River valley the top of the layer seems to have been eroded by the river and replaced by outwash deposits. The layer becomes thinner, and even seems missing at places, especially in the vicinity of the fen.

Thick deposits of glacial drift to the west of Raisin River overlay Coldwater Shale formation which may be considered as impervious for modeling purposes. The presence of a large number of water wells in the area indicates a productive aquifer underneath the clay layer within more transmissive outwash deposits from earlier glaciations. Gaps in the clay layer closer to Raisin River connect the older outwash with the recent outwash deposits in the river valley.

A representative vertical section for the capture zone was inferred from this data analysis as illustrated in Figure 3.40. The conceptual profile model for Ives Road Fen site was based on this section. North eastern extent of Hillsdale Groundwater Mound (coinciding with the north western end of the capture zone) was taken as regional recharge area while Raisin River was taken as the regional sink. Confined aquifer conditions were assumed under the continuous clay layer. Gaps in clay layers were added within the outwash deposits along Raisin River.



Clay thickness reported in wells logs is color coded as follows:

- 0-3m
- 3-6m
- 6-15m
- >15m

Figure 3.39 Thickness [top] and depth [bottom] of clay deposits interpolated from water wells data.

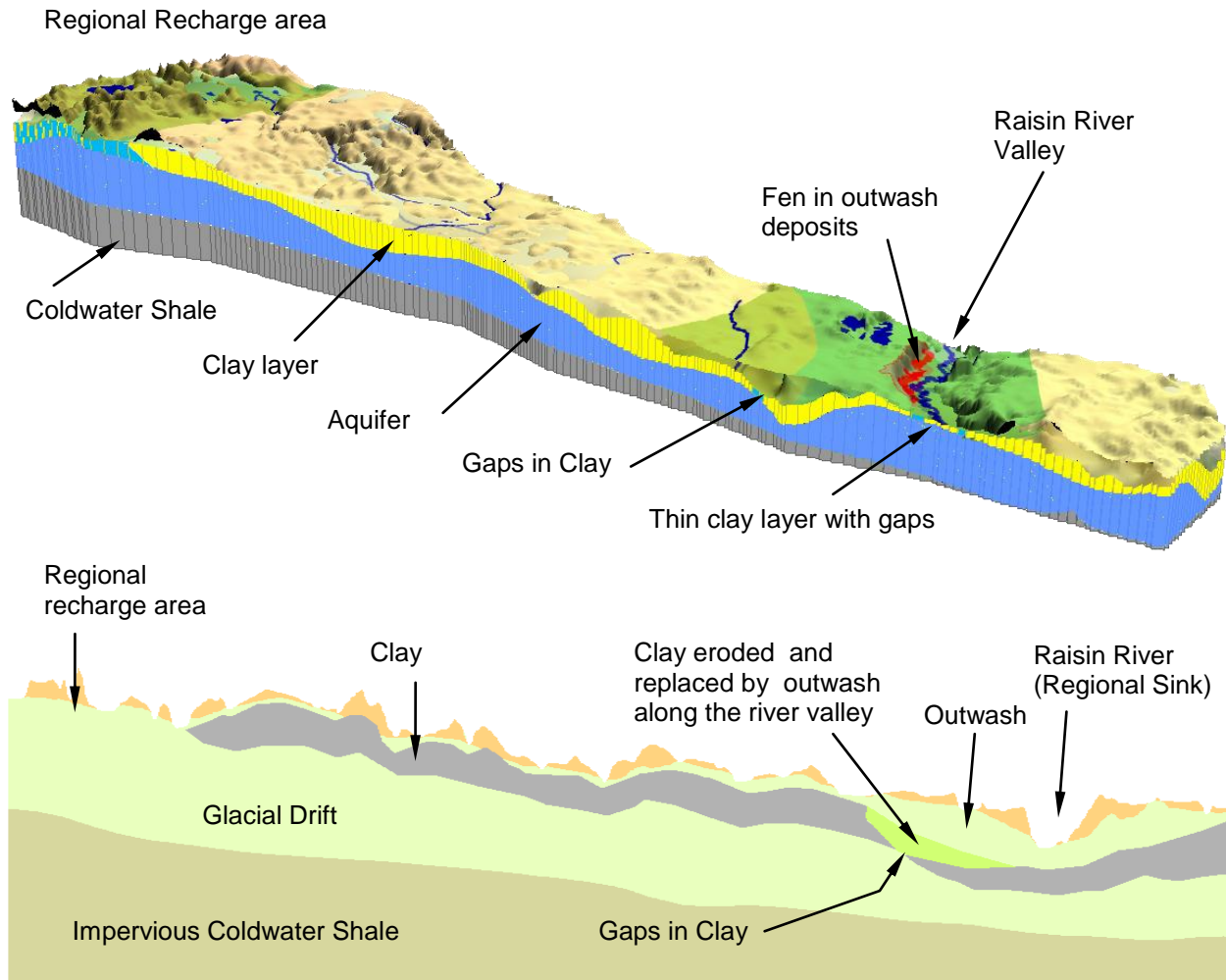


Figure 3.40 Perspective visualization based on data [top] and conceptual profile [bottom] of Ives Road regional groundwater capture zone.

Groundwater profile model for Ives Road Fen is shown in Figure 3.41. The model predicts groundwater flow from the northeastern end of Hillsdale Groundwater Mound, 15.5 km from the fen, seeping beneath the clay layer and upwelling into the glacial outwash in Raisin River valley. It seems possible that this regional flow is also upwelling into the fen. The model also shows that the fen receives water from the outwash deposits, with capture zone extending up to 3km west from the fen.

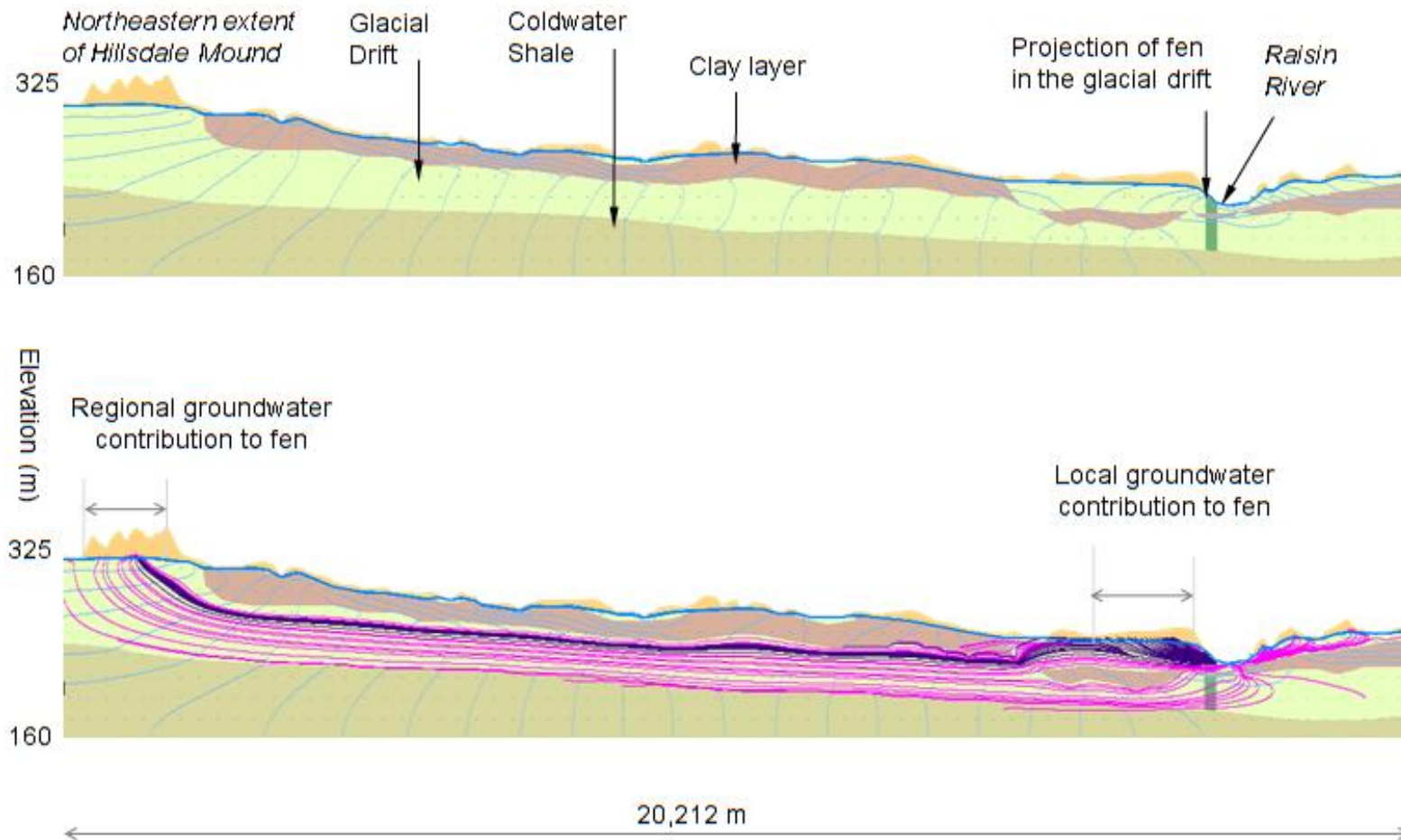


Figure 3.41 Profile Model for Ives Road Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 2.84m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Sarett Nature Center Fen

Sarett Nature Center Fen is the only known prairie fen occurring in the coarse lacustrine deposits overlying shale bedrock. Average thickness of glacial deposits around the fen is 54m, with maximum 65m and minimum 45m. The fen occurs along Paw Paw River valley besides a large complex of wetlands. The fen and its surface catchment area are shown on 10m DEM relief in Figure 3.42. EORANK of the fen is 'C'. MS occurrence has been reported at this site.

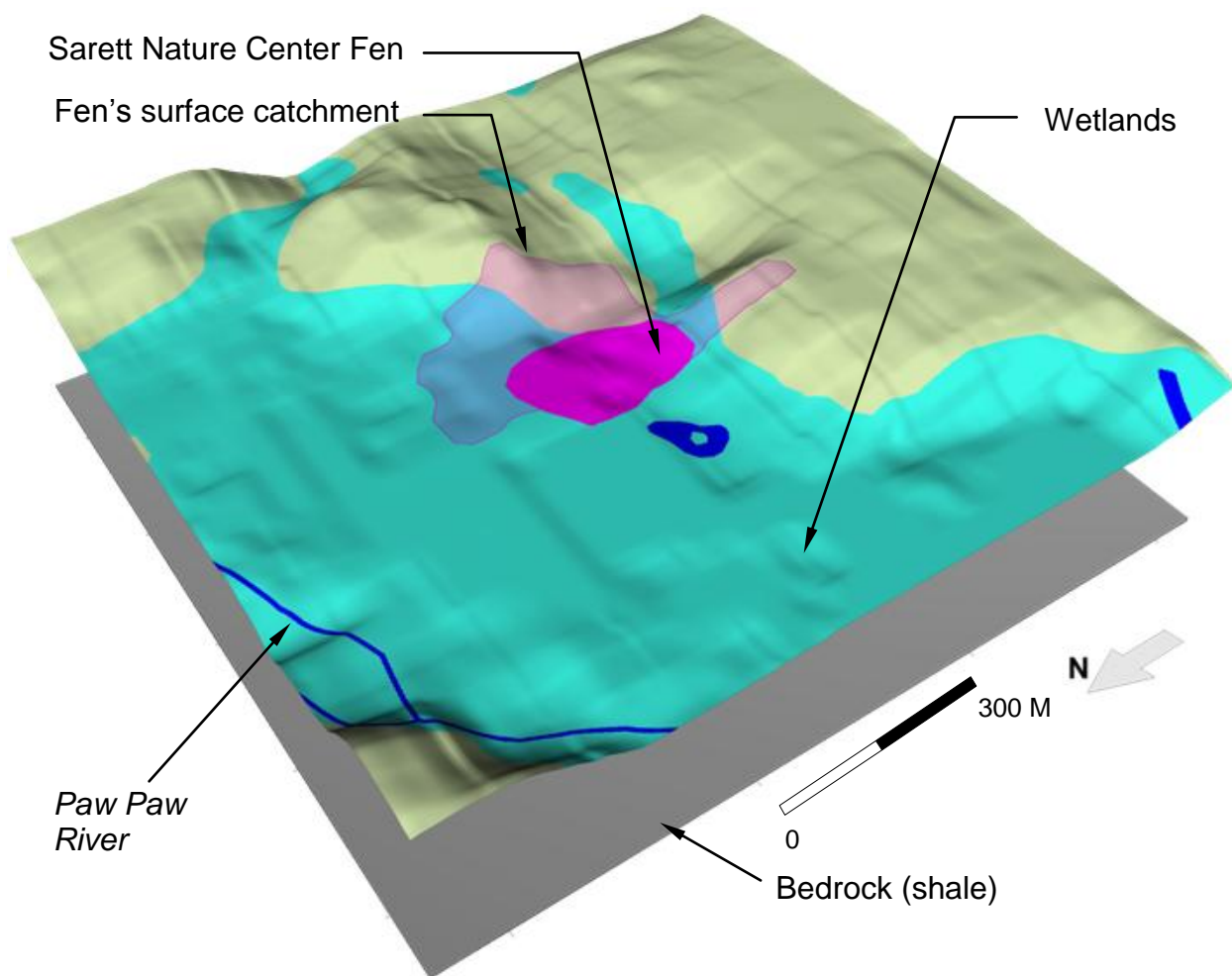


Figure 3.42 Sarett Nature Center Fen along the Paw Paw River valley. The shaded relief represents topography derived from 10m DEM which varies from 176.75m to 198.44m.

Regional Groundwater Model

Regional model for Sarett Nature Center Fen was selected over an area of 12.78 km by 10.91 km. The area was divided into the 300x261 grid cells, with the cell size of 41.14 m. Static water level (SWL) and other modeling parameters were ascertained as explained in methodology. Reverse particle tracking to delineate groundwater capture zone for the fen site suggests the fen sites may be connected to a sub-regional groundwater mound 8km away. The delineated zone is shown in Figure 3.43. Bending of regional contours closer to the fen location suggests regional flow convergence and possibility of regional upwelling in the area. Please also refer to Figure 4.2 for more discussion.

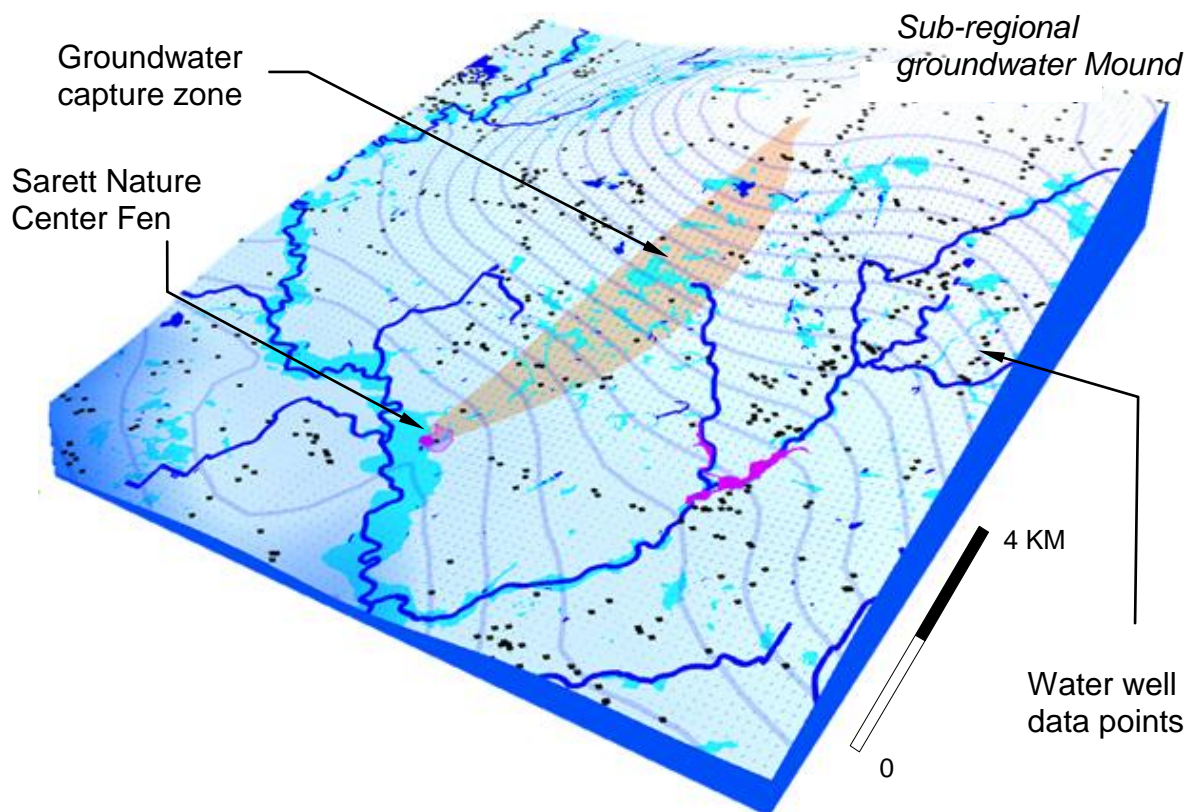


Figure 3.43 The contours at 2m interval and shaded relief represent regional groundwater head/surface around Sarett Nature Center Fen which varies from 176.30m to 218.42m.

The model shows that the contribution zone may be connected to a sub-regional groundwater mound approximately 8 km to the east. In Figure 3.44, the groundwater contribution zones are superimposed on surface topography and geological land forms. The fen occurs in the lacustrine coarse deposits while the capture zone extends through the glacial till and outwash materials all the way to a regional watershed boundary. Many wetlands and a lake occur within the capture zone.

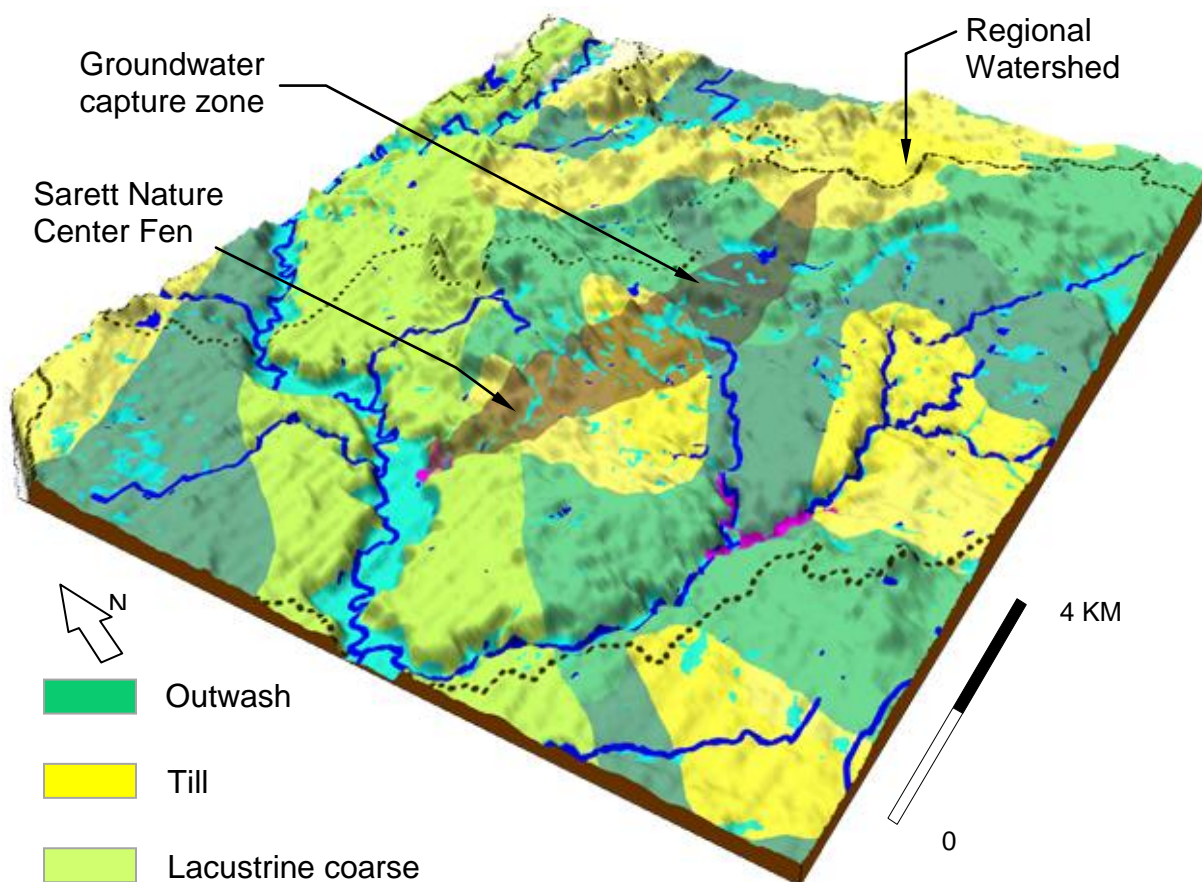


Figure 3.44 The shaded relief represent surface topography in the region which varies in elevation from 176.31m to 256.95m.

Groundwater Profile Model

Analysis of lithology from the well logs around Sarett Nature Center Fen in Figure 3.45 revealed a continuous layer of clay, coinciding with approximately 2.7 km of the glacial till to the east of the fen. The estimated extent and thickness of this clay layer was incorporated in the profile model as shown in Figure 3.46. The model predicts groundwater flow from the sub-regional groundwater mound beneath the clay layer and upwelling into Paw Paw River. It seems possible that part of this regional flow is also upwelling into the fen. The model suggests that the fen receives water from the sub-regional groundwater mound approximately 7.5 km east, through deep upwelling from beneath the clay layer and also from shallow groundwater in the adjacent coarse lacustrine deposits extending 700m to the east from the fen.

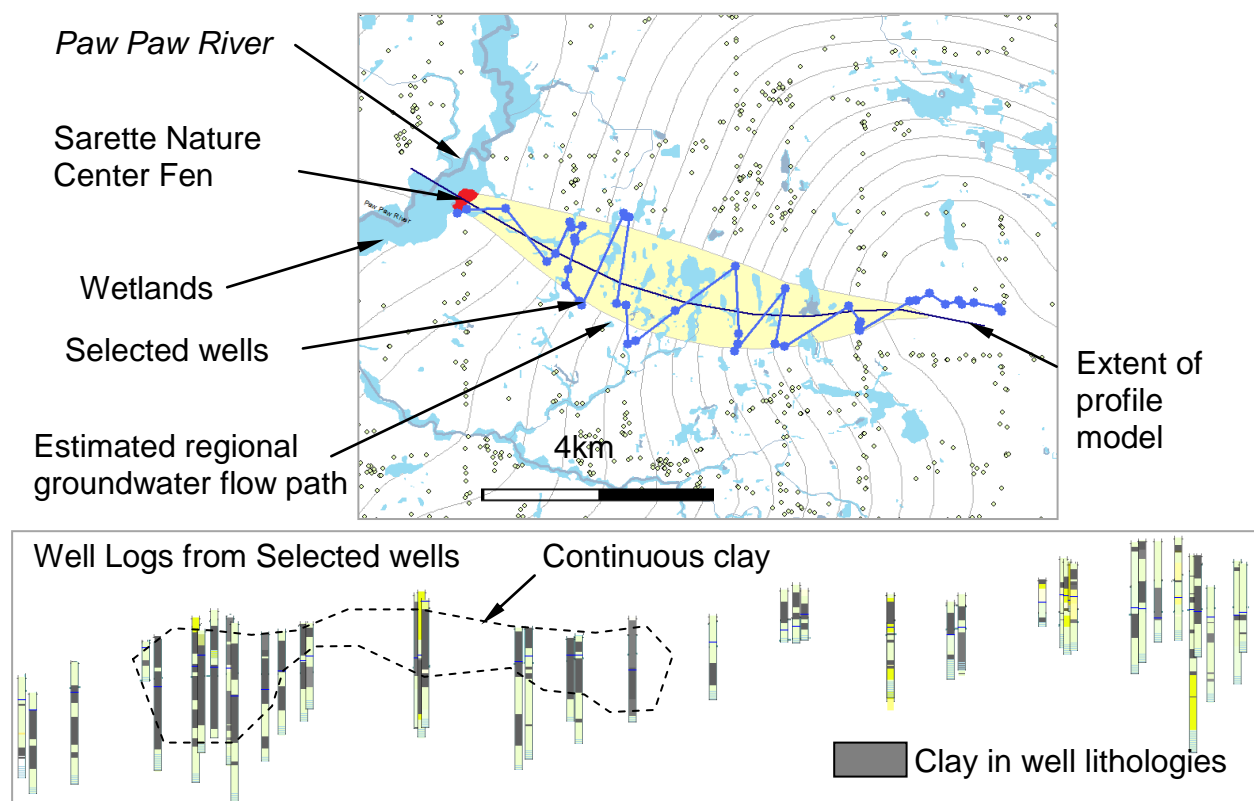


Figure 3.45 Well location and well logs along Sarett Nature Center Fen capture zone. Contours at 2m interval show SWL for drift.

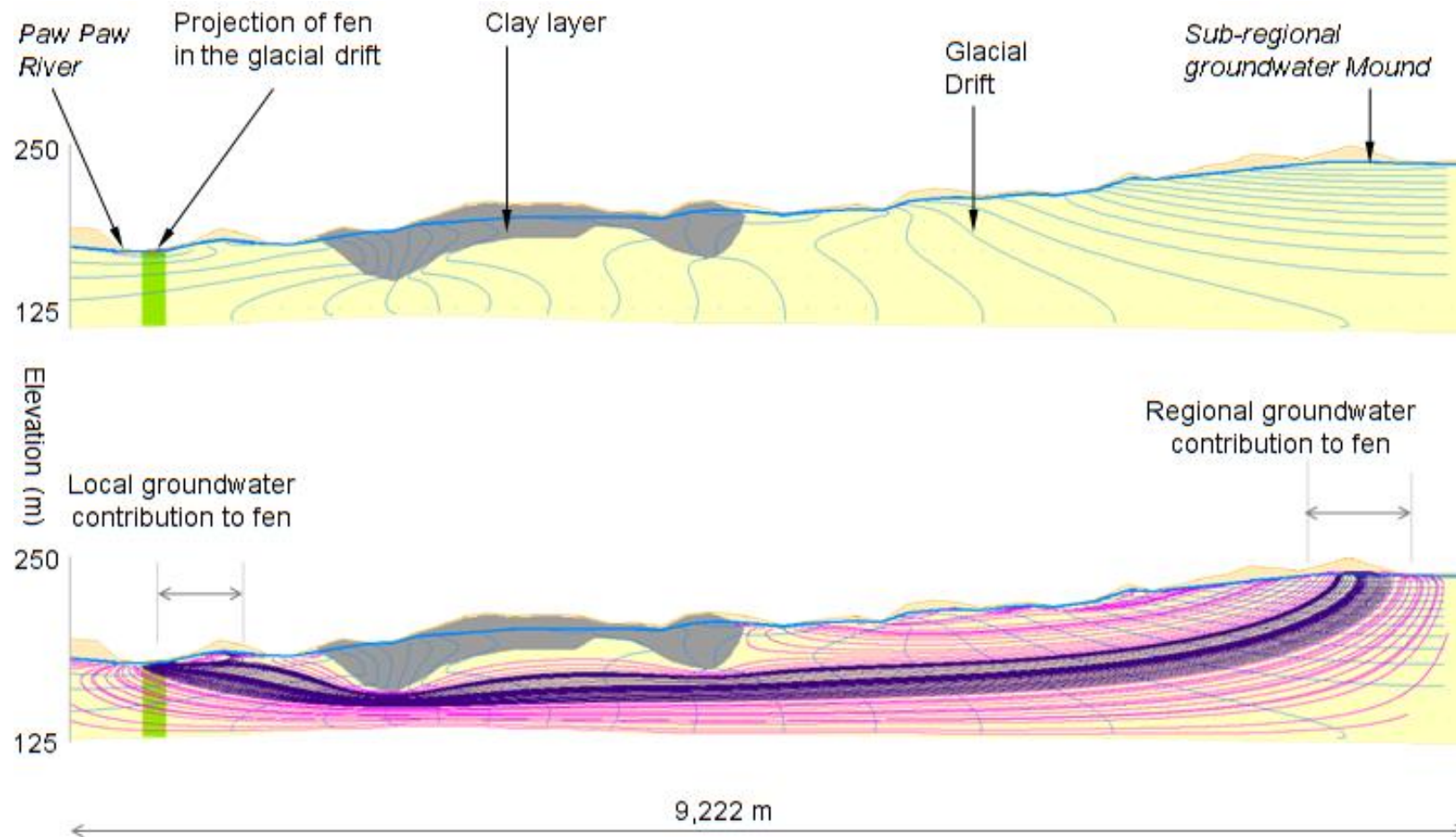


Figure 3.46 Profile Model for Sarett Nature Center Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 1.84m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Paw Paw Lake Fen and Paw Paw Prairie Fen

Paw Paw Lake Fen and Paw Paw Prairie Fen occur very close to the northern apex Cass-Kalamazoo Groundwater Mound. Located along headwaters of Paw Paw River, the fens occur in glacial outwash where drift thickness is 100m or more. Paw Paw Prairie Fen occurs in proglacial outwash while Paw Paw Lake fen occurs in ice contact outwash. The fens and their surface catchment areas are shown on 10m DEM relief in Figure 3.47. EORANK of Paw Paw Lake Fen is 'B' and MS occurrence has been reported at this site. EORANK of Paw Paw Prairie Fen is 'BC' and MS occurrence has not been reported at this site. However, this site is a candidate for re-introduction of MS.

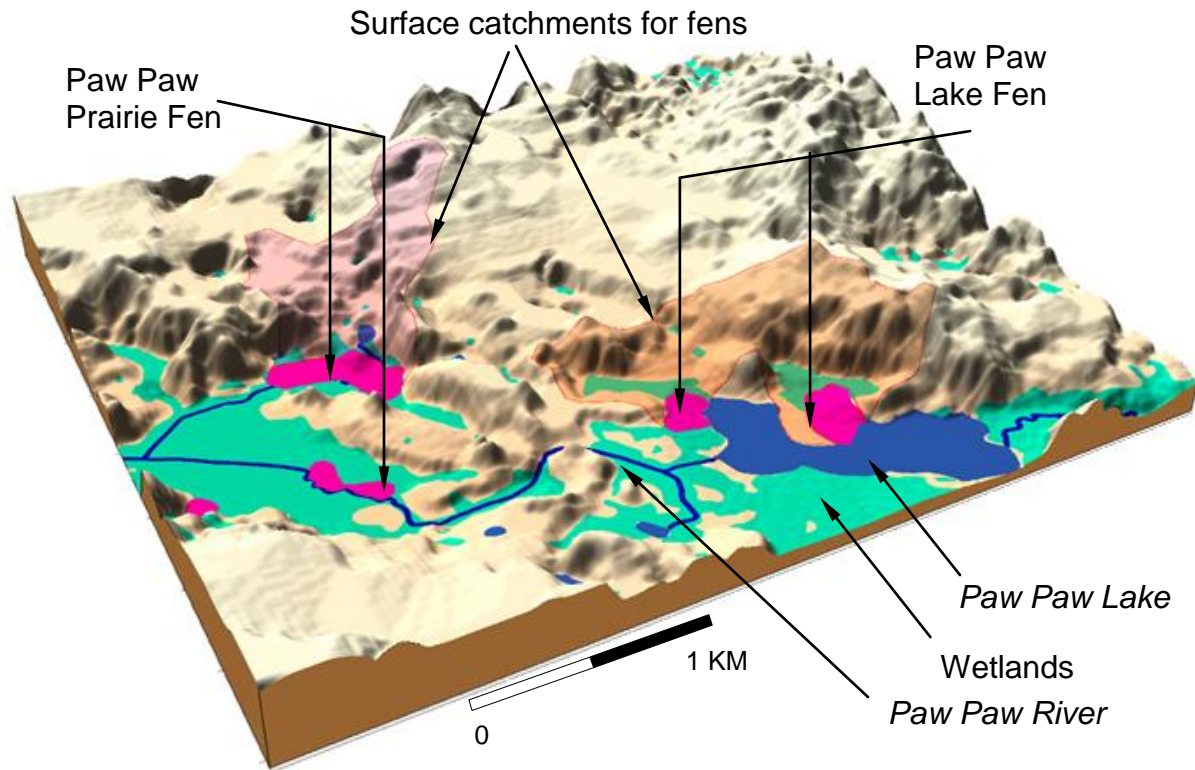


Figure 3.47 Paw Paw Lake Fen and Paw Paw Prairie Fen along Paw Paw River. The shaded relief represents topography derived from 10m DEM which varies from 261.74m to 316.91m.

Regional Groundwater Model

Paw Paw Lake Fen and Paw Paw Prairie Fen were both covered in the same regional model. Model area of 10.34 km by 8.90 km was divided into 300x285 grid cells, with the cell size of 34.49 m. SWL for the model was ascertained from water wells records in the drift aquifer and taking into consideration major surface water features in the area. The model area is situated in thick glacial deposits overlying less transmissive shale. Strong bending of regional groundwater in drift deposits suggests possibility of regional upwelling in the area.

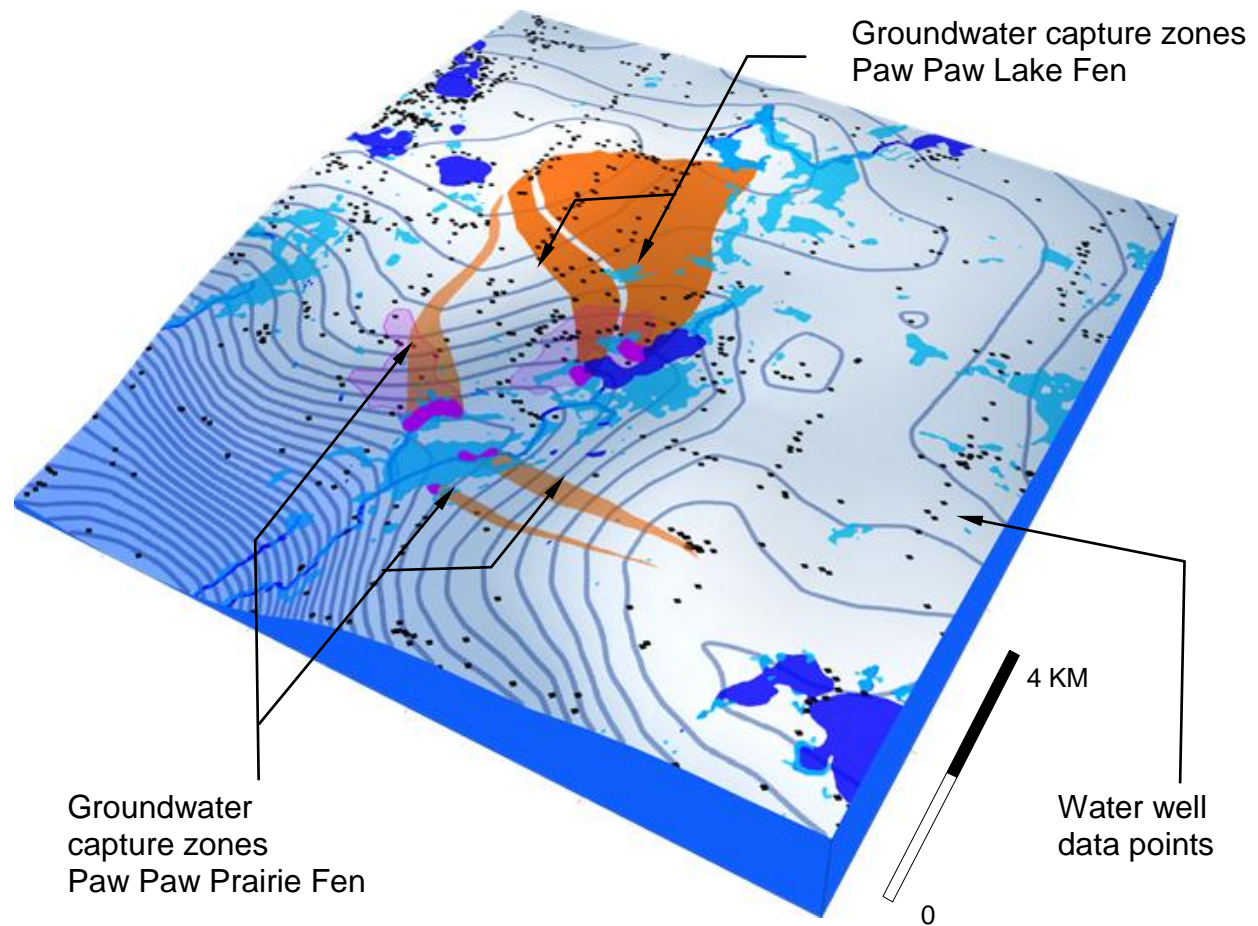


Figure 3.48 The contours at 1m interval and shaded relief represent regional scale delineation of groundwater surface around Paw Paw Fens which varies in elevation from 243.60m to 273.48m.

The bending pattern of contours was reproduced along the same stretch even when no surface water data was taken into consideration as shown in Figure 4.1. Although the upwelling seems to be directed to surface water bodies in the area, there seems a strong possibility that the fens, located within the likely upwelling zones, are also benefitting from the regional upwelling which can make a more steady and robust source of groundwater for fens.

In Figure 3.49, the groundwater contribution zones are superimposed on surface topography and geological land forms.

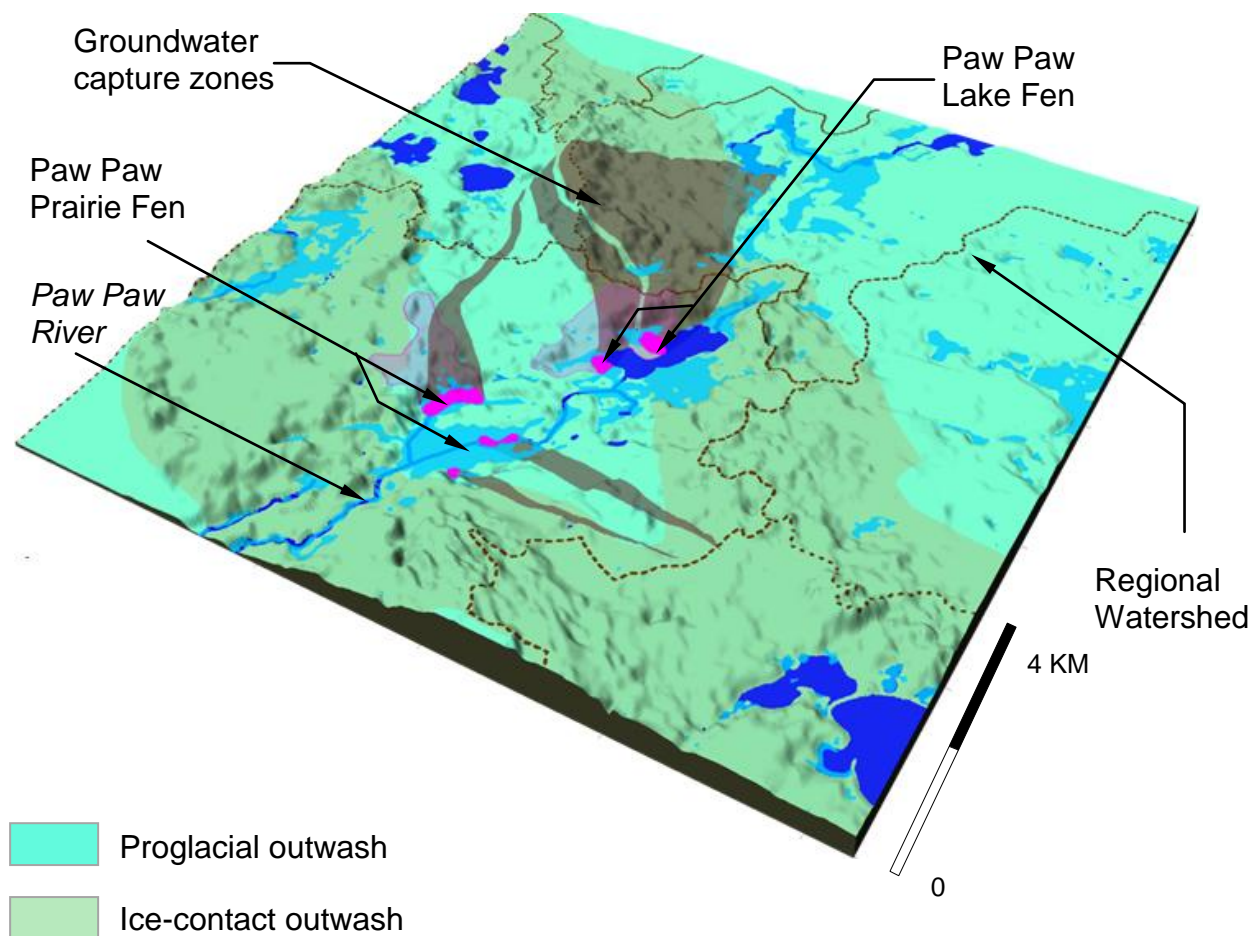


Figure 3.49 The shaded relief represent surface topography in the region which varies in elevation from 243.64m to 321.76m.

Likely zones of groundwater contribution on the northern side of Paw Paw River extend beyond the river watershed. The fen locations seem to be connected to groundwater sources on either sides of the river. The model shows that the contribution zones extend beyond the surface water catchment areas of the fens and may be connected to sub-regional groundwater mounds between 3 and 4 km from the respective fen locations.

Groundwater Profile Model – Paw Paw Lake Fen

Analysis of lithology from the well logs around Paw Paw Lake Fen within its delineated capture zone did not reveal continuous clay lenses within the glacial drift. The profile section was selected as shown in Figure 3.50. Cass-Kalamazoo Groundwater Mound at the eastern end of profile was taken as regional source and Paw Paw Lake/River complex on the west as the regional sink. Profile for the fen is shown in Figure 3.51. The model suggests that the fen receives water from the adjacent shallow system as well as deeper regional and sub-regional systems. The model also shows that most of the deeper flow from Cass-Kalamazoo Groundwater Mound is going to Paw Paw Lake but part of this deep regional flow is also providing water to the fen.

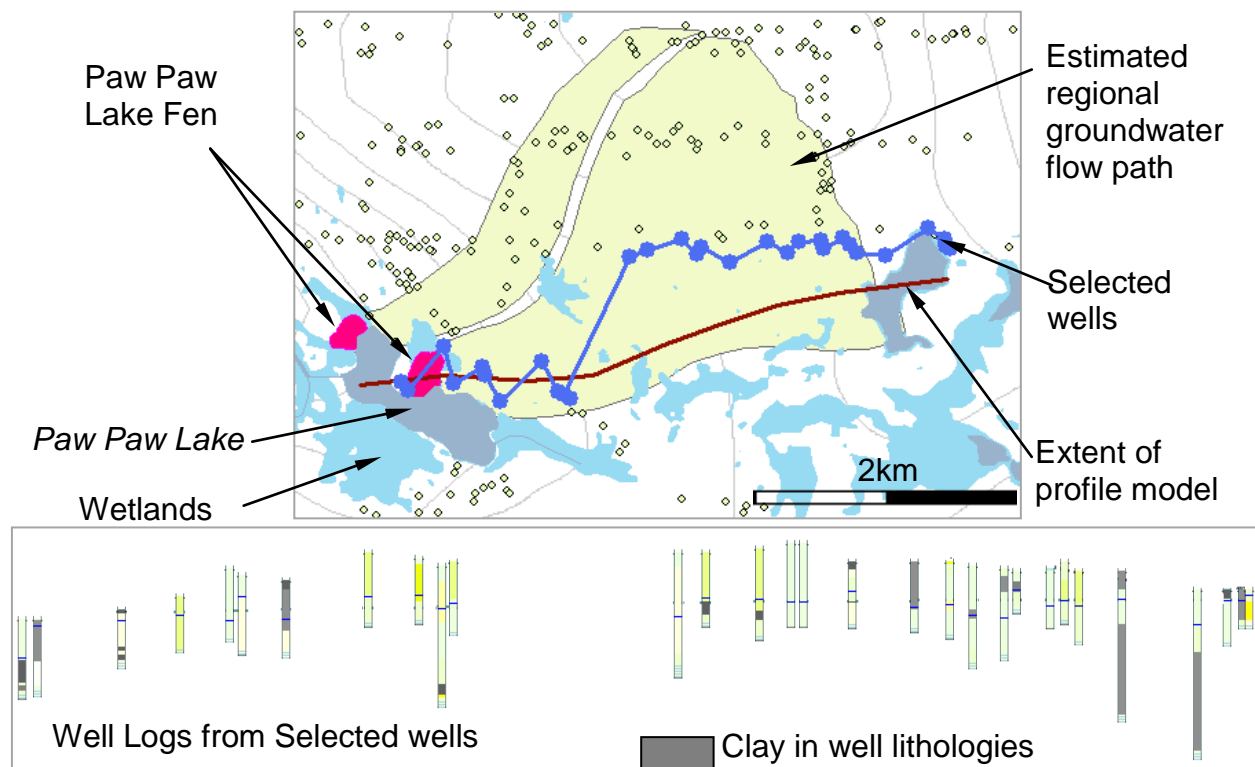


Figure 3.50 Well location and well logs along Paw Paw Lake Fen capture zone. Contours at 1m interval show SWL for drift.

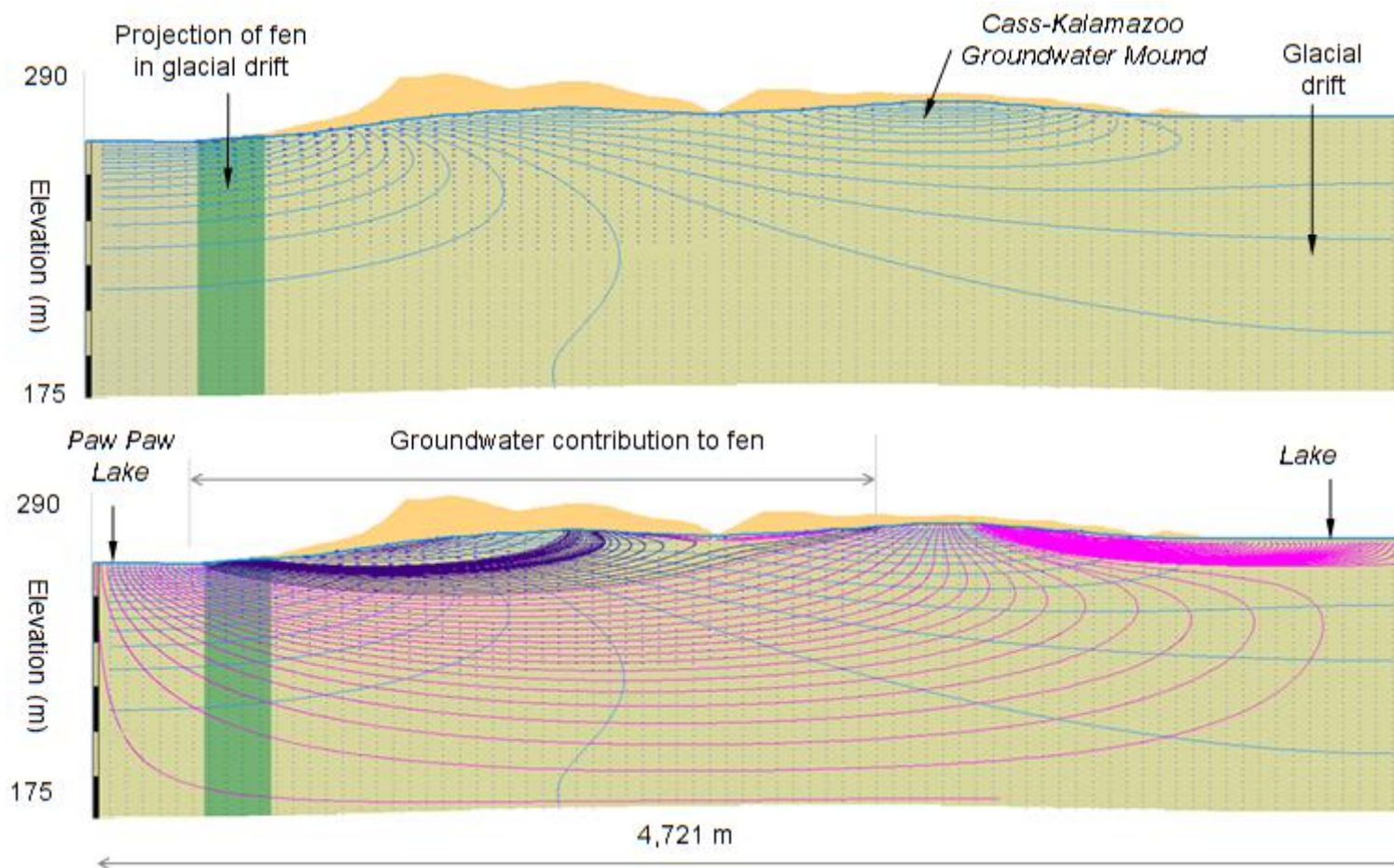


Figure 3.51 Profile Model for Paw Paw Lake Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 0.48m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Groundwater Profile Model – Paw Paw Prairie Fen (67th Street)

Paw Paw Prairie Fen symmetrically occurs on either banks of Paw Paw River. The capture zones from either sides extend in opposite directions as shown in Figure 3.49. A single profile model was built to cover both parts of the fen. Analysis of lithology from the well logs along the chosen profile, as shown in Figure 3.52, did not reveal continuous clay lenses within the glacial drift. The profile model is shown in Figure 3.53. Regional and sub-regional groundwater mounds at either ends of the profile serve as sources and Paw Paw River in the middle serves as the sink. The model predicts that wetlands adjacent to both parts of the fen receive water from the shallow groundwater systems whereas the fen receives upwelling groundwater from the deeper system connected to regional/sub-regional groundwater mounds.

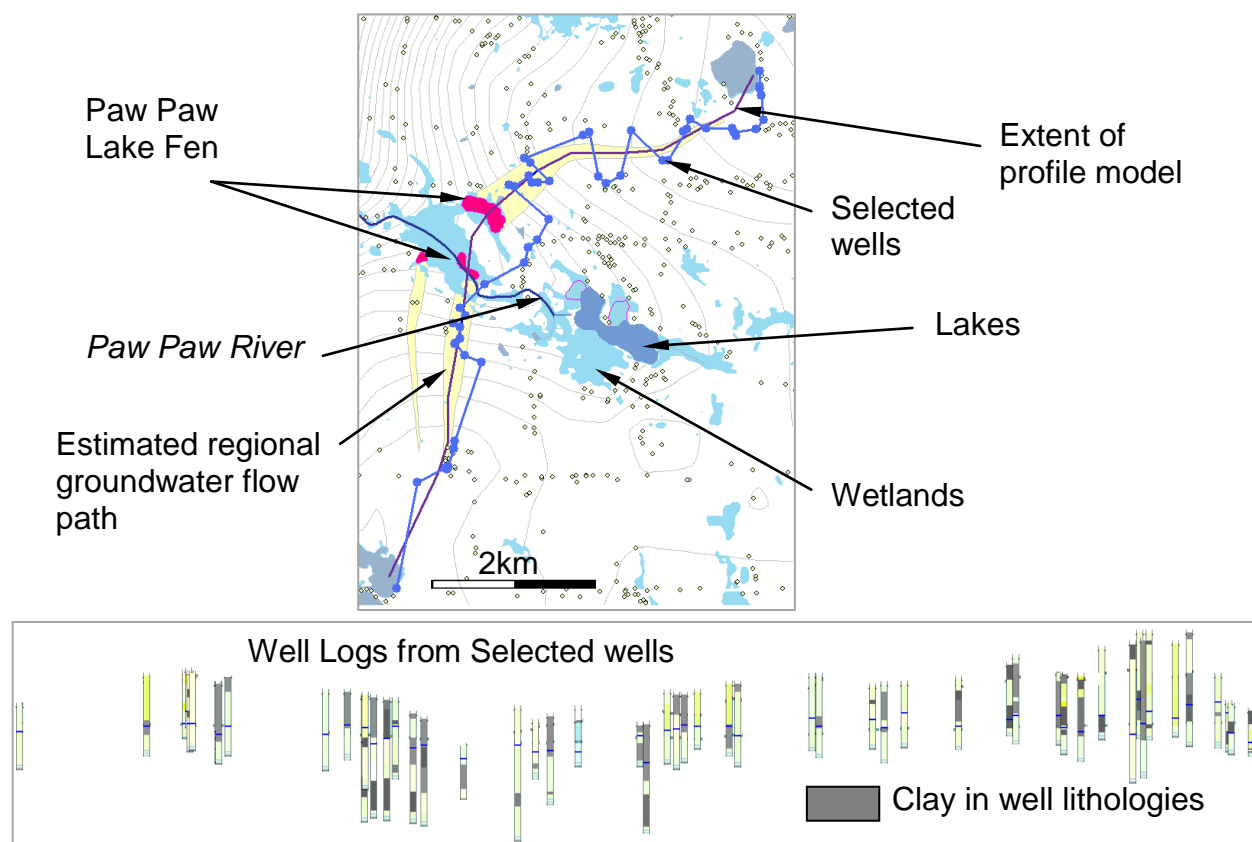


Figure 3.52 Well location and well logs along Paw Paw Prairie Fen capture zone. Contours at 1m interval show SWL for drift.

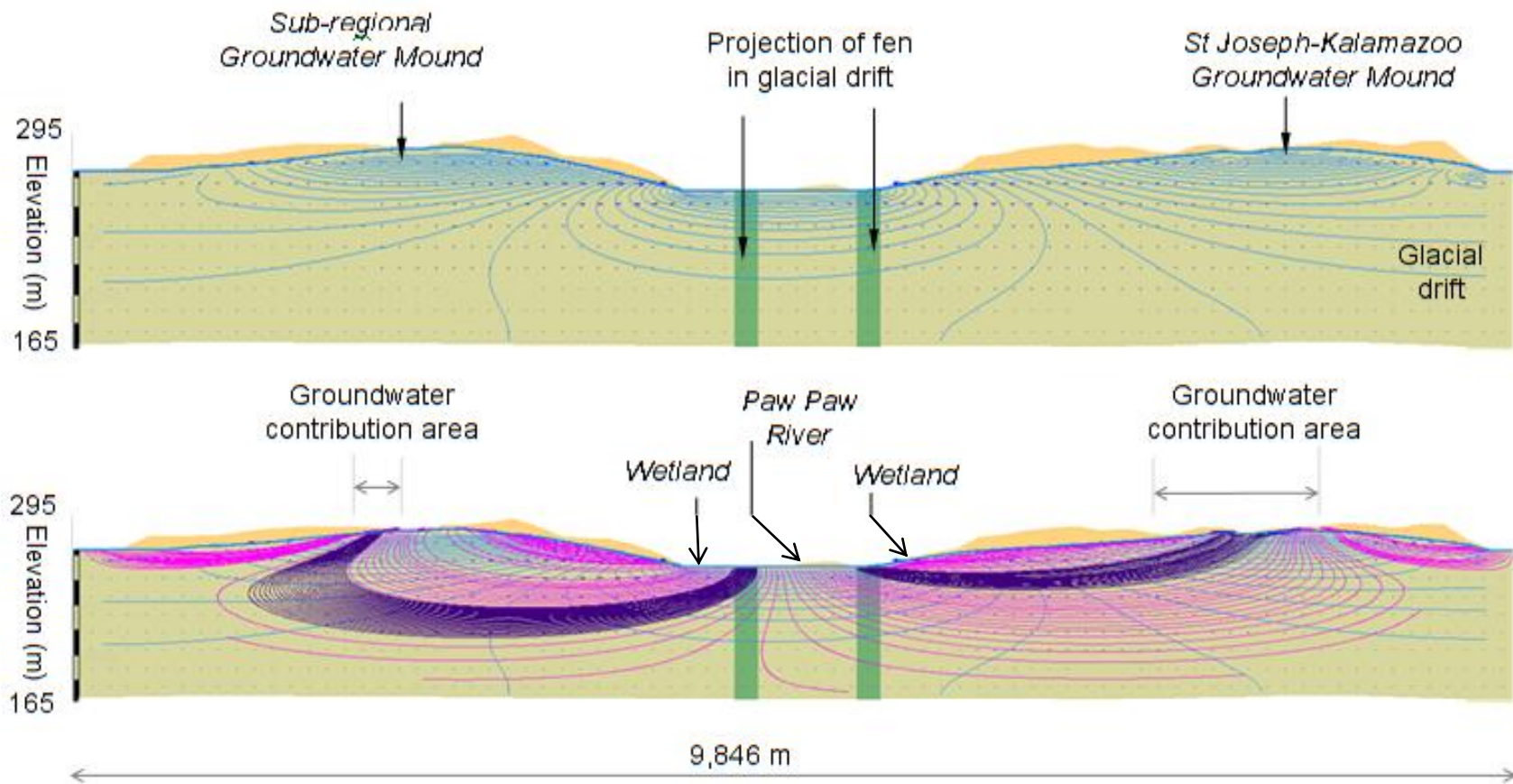


Figure 3.53 Profile Model for Paw Paw Prairie Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 0.84m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom]

Monette St Fen

Monette St Fen is one of the largest prairie fens in Michigan occurring in proglacial outwash overlying shale bedrock. The average drift thickness around the fen site is 87m, varying between 112m and 83m. The fen and its surface catchment area are shown on 10m DEM relief in Figure 3.54. EORANK of the fen is 'A?'. MS occurrence has not been reported at this site.

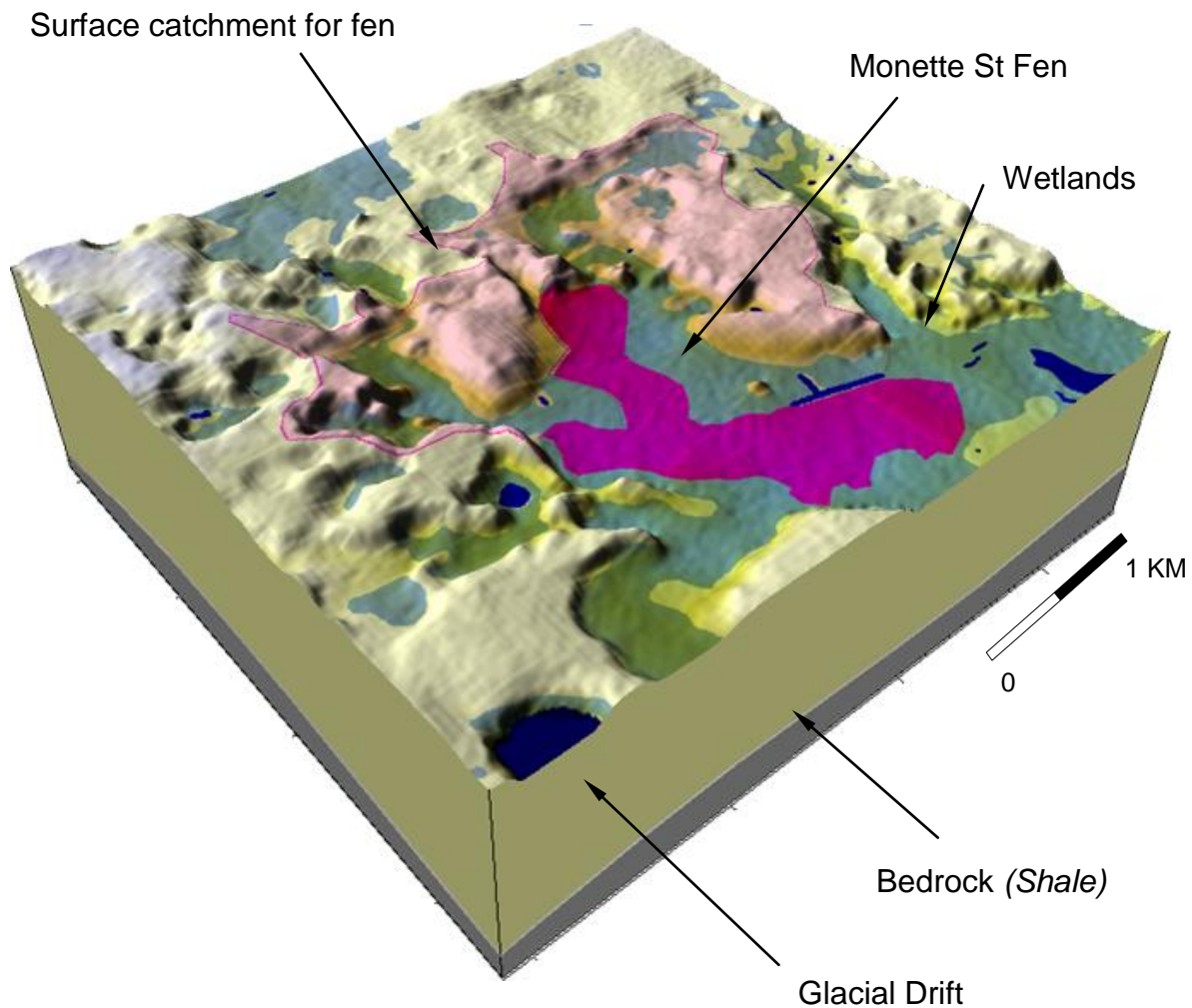


Figure 3.54 Monette St Fen. The shaded relief represents topography derived from 10m DEM varying from 241.03m to 261.10m.

Regional Groundwater Model

Regional model for Monette Street Fen was selected over an area of 8.76 km by 10.22 km. Model area was divided into the 300x285 grid cells, with the cell size of 29.04 m. Static water level (SWL) and other modeling parameters were ascertained as explained in methodology. Reverse particle tracking was used to delineate groundwater capture zone for the fen. Delineated zone of groundwater contribution to the fen is shown in Figure 3.55.

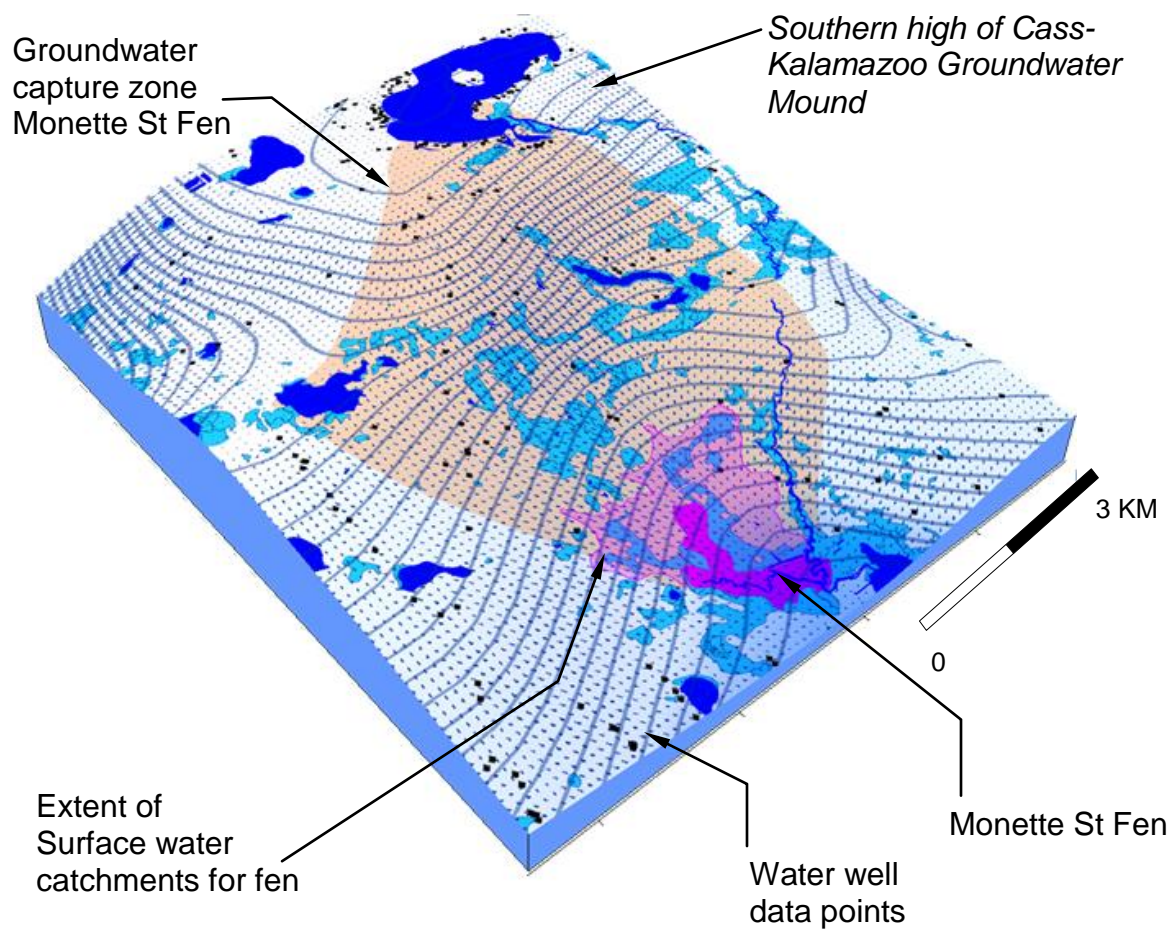


Figure 3.55 The contours at 0.61m interval and shaded relief represent regional scale delineation of groundwater surface around Monette St Fen which varies in elevation from 241m to 260m.

The model suggests that the contribution zone may be connected the southern high of Cass-Kalamazoo Groundwater Mound approximately 6 km to the north of the fen site. Strong bending of regional contours closer to the fen sites location suggests regional flow convergence and possibility of regional upwelling in the area. Please also refer to Figure 4.2 for more discussion. In Figure 3.56, the groundwater contribution zones are superimposed on surface topography and geological land forms. The fen occurs in proglacial outwash and has a few wetlands within its surface water catchment area.

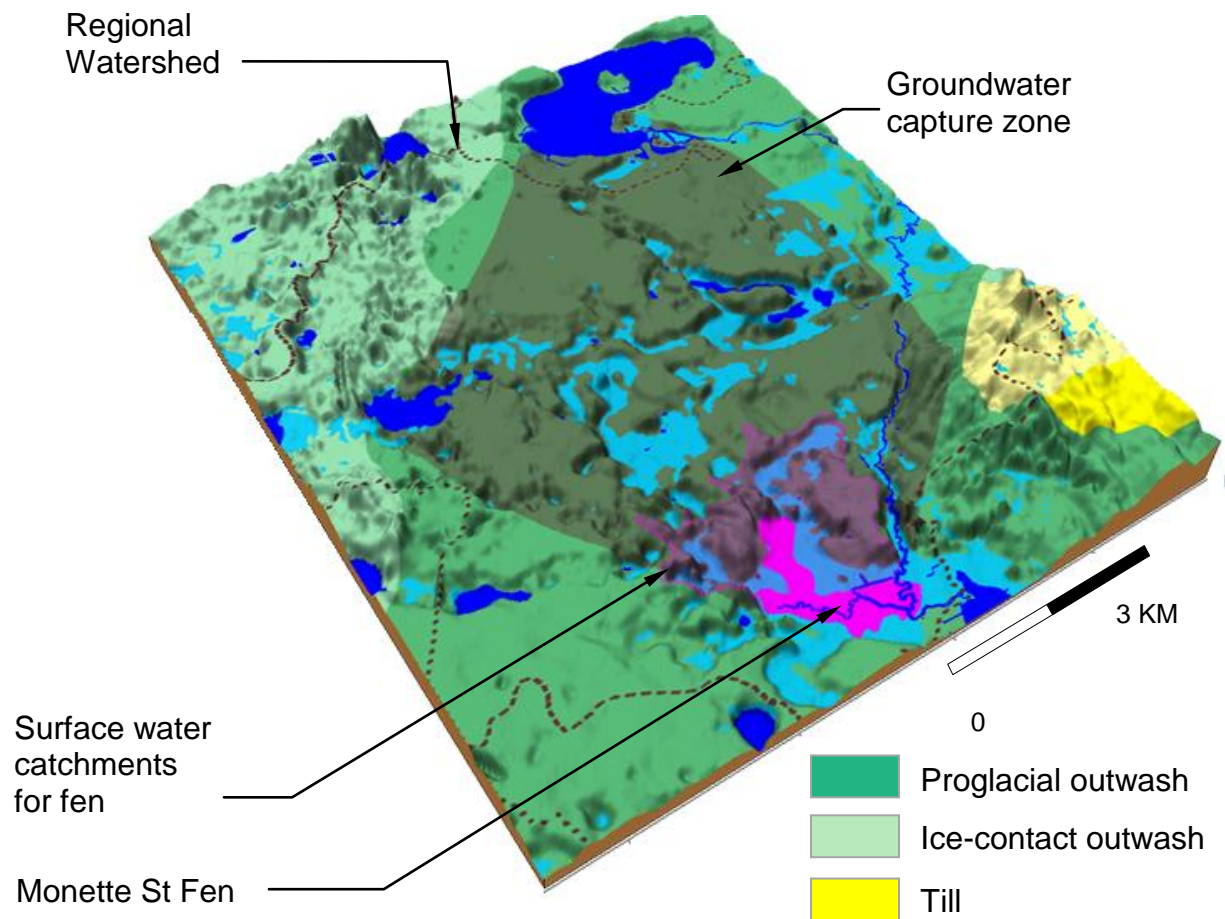


Figure 3.56 The shaded relief represent surface topography in the region varying in elevation from 241.06m to 298.58m.

Groundwater Profile Model

Well logs along the capture zone of Monette St Fen are shown in Figure 3.57 which do not reveal any structural discontinuities within the drift. The drift is overlying shale formations which were considered as impervious. The profile model was conceptualized as single layer of drift as shown in Figure 3.58, with Diamond Lake as the regional source at the northern end and the complex of Christina Lake and adjacent wetlands as the regional sink. The model predicts that the fen may be receiving groundwater from a sub-regional recharge area approximately 7 km to the north of the fen. The fen receives water through deep upwelling. Shallow groundwater systems do not seem to contribute directly to the fen, but instead feed the adjacent wetlands around the fen site.

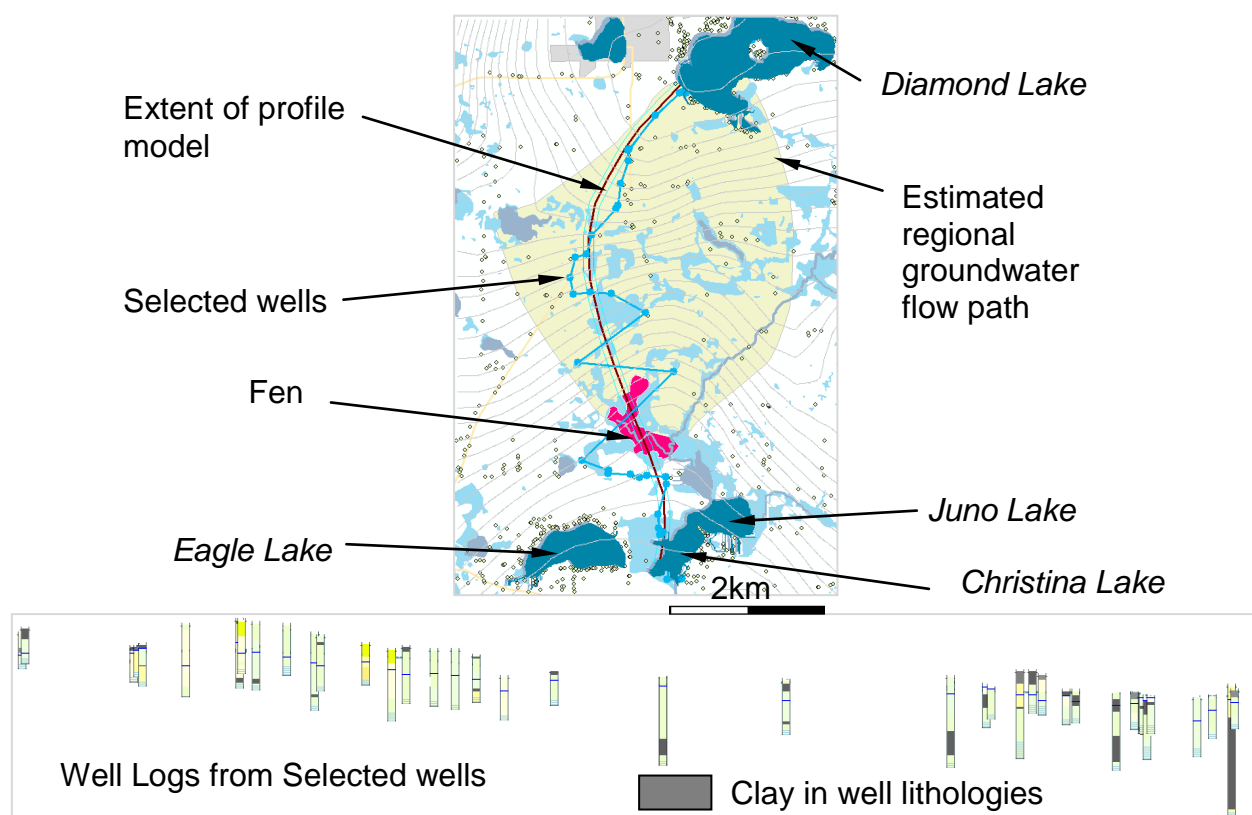


Figure 3.57 Well locations and well logs along Monette St Fen capture zone. Contours at 0.61m interval show SWL for drift.

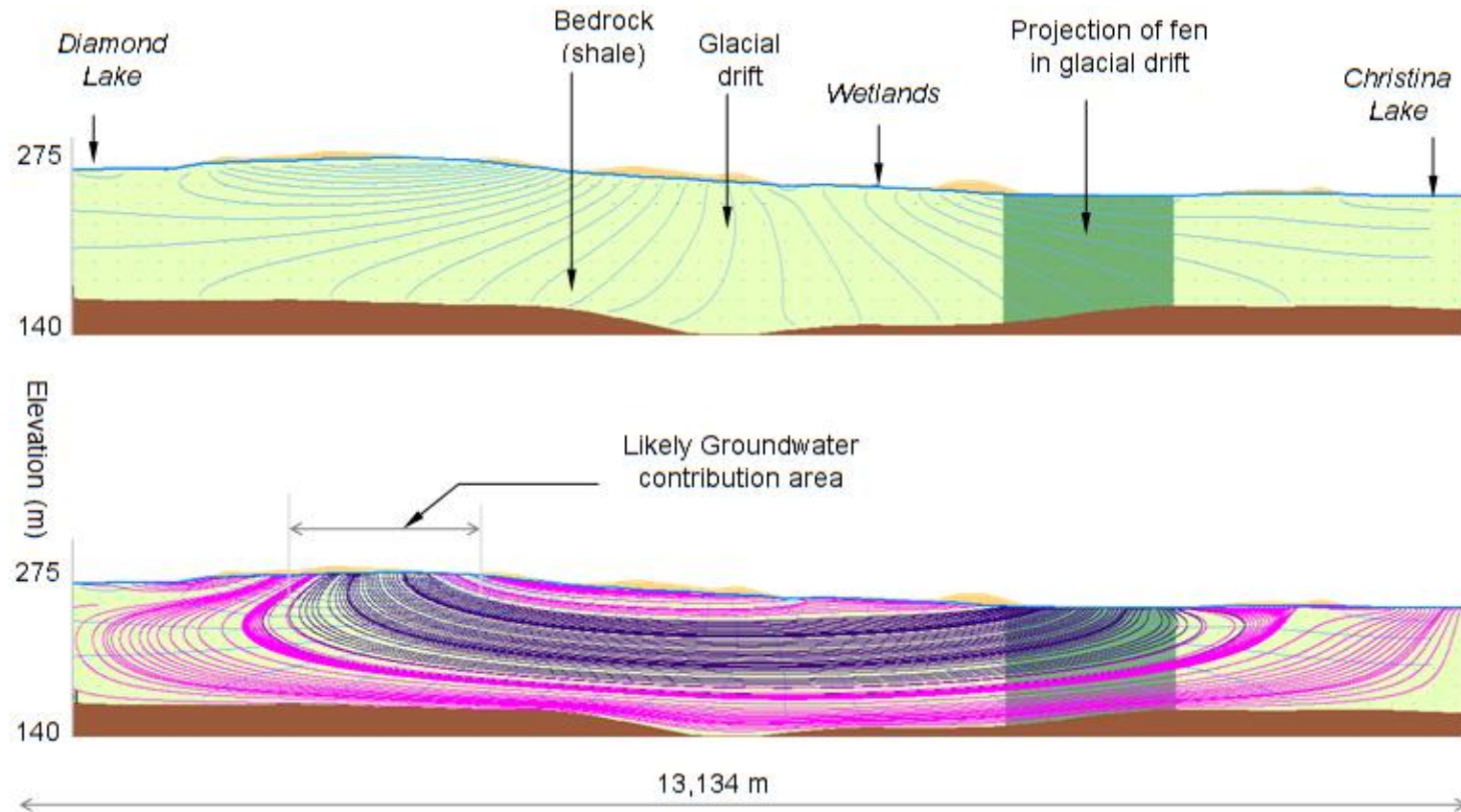


Figure 3.58 Profile Model for Monette St Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 0.90m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Springbrook Fen and Butterfield Lake Fen

Springbrook Fen occurs in proglacial outwash besides the eastern bank of Spring Brook – a first order stream, within a wetlands complex which runs alongside the stream. The fen and its surface catchment area are shown on 10m DEM relief in Figure 3.59. EORANK of the fen is ‘C’. MS occurrence has been reported at this site.

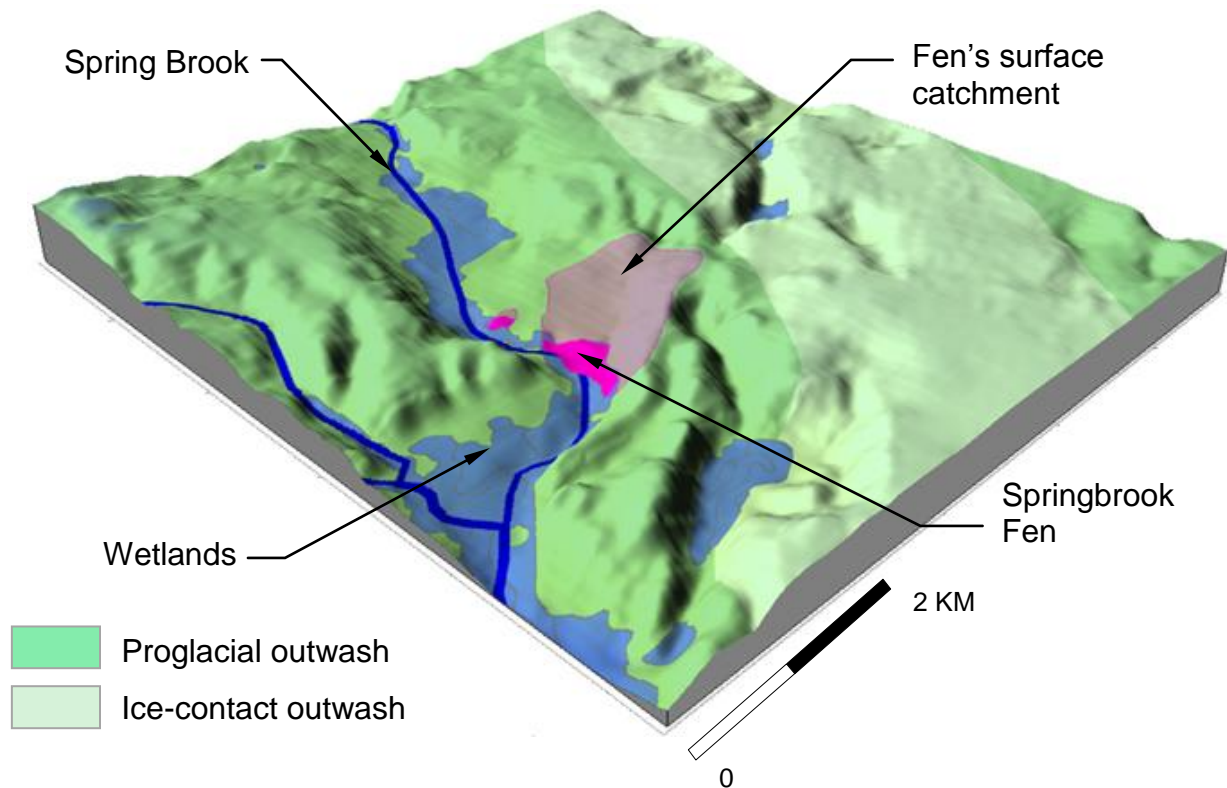


Figure 3.59 Springbrook Fen. The shaded relief represent surface relief derived from 30m/10m DEM. Surface elevation varies between 255.36m and 293.80m.

Butterfield Lake Fen occurs in proglacial outwash adjacent to southern edges of Butterfield Lake and along either banks of Gull Creek – a first order stream. The relief around the fen is hummocky and dominated by a complex of wetlands along Gull Creek. The fen and its surface catchment area are shown on 10m DEM relief in Figure 3.60. EORANK of the fen is ‘CD’. MS occurrence has not been reported at this site.

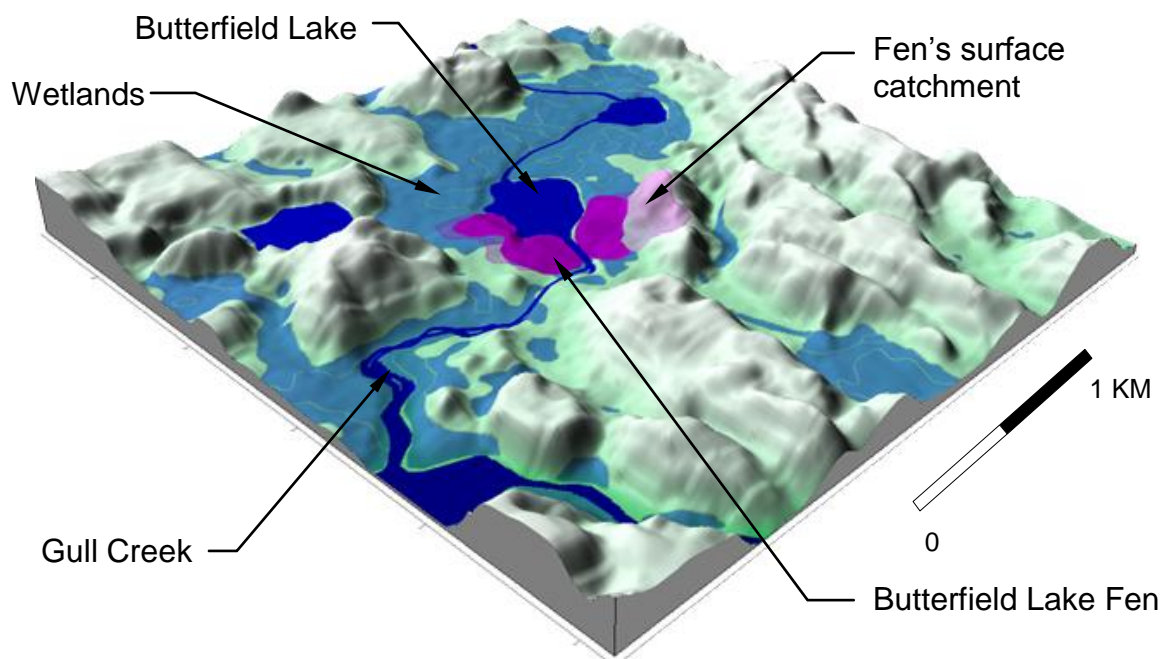


Figure 3.60 Butterfield Lake Fen. The shaded relief represent surface relief derived from 30m/10m DEM. Surface elevation varies between 256.49m and 282.75m.

Regional Groundwater Model

Being in the close vicinity of each other, the two fens were covered in a single regional model over an area of 12.94 km by 16.28 km. The model area was divided into the 250x313 grid cells, with the cell size of 51.68 m. Static water level (SWL) and other modeling parameters were ascertained as explained in methodology. Reverse particle tracking was used to delineate

groundwater capture zones for the two fen sites in the model. Delineated zones of groundwater contribution to the fens are shown in Figure 3.61.

The model suggests that the contribution zone for Butterfield Lake Fen extends to Barry Groundwater Mound, going through Gull Lake. Gull Lake in the region is a flow through lake which may also be receiving groundwater input from Barry Groundwater Mound (from north) and discharging water to the aquifer (from south). From the regional picture it appears that Butterfield Lake Fen may be directly or indirectly linked to Barry Groundwater Mound. For Springbrook Fen, the model suggests that it may be connected to Barry Groundwater Mound. Bending of regional contours closer to the fen site suggests regional flow convergence and possibility of regional upwelling in the area. Please also refer to Figure 4.2 for more discussion.

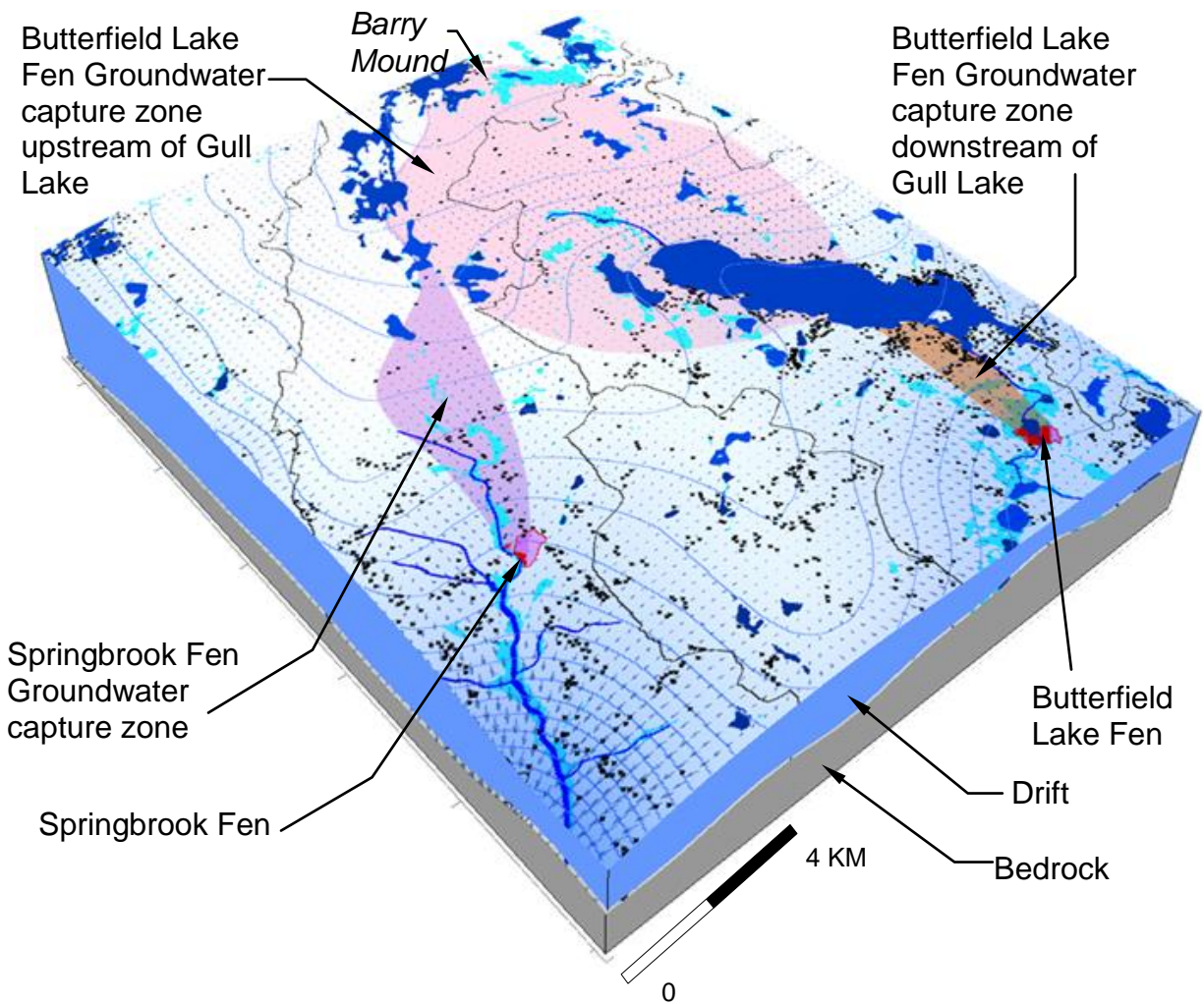


Figure 3.61 The contours at 2m interval and shaded relief represent regional scale delineation of groundwater surface around Springbrook and Butterfield Lake fens. The SWL elevation ranges from 240.36m to 281.64m.

In Figure 3.62, the groundwater contribution zones are superimposed on surface topography and geological land forms. Groundwater capture zones of both fens remain confined to their respective regional watersheds. The glacial drift thickness in the region varies between 24m and 123m with an average of 70m. The drift thickness is more in the northwest of the model

area and lesser in the southeast. The drift in the area comprises outwash deposits. Both fens occur in proglacial outwash.

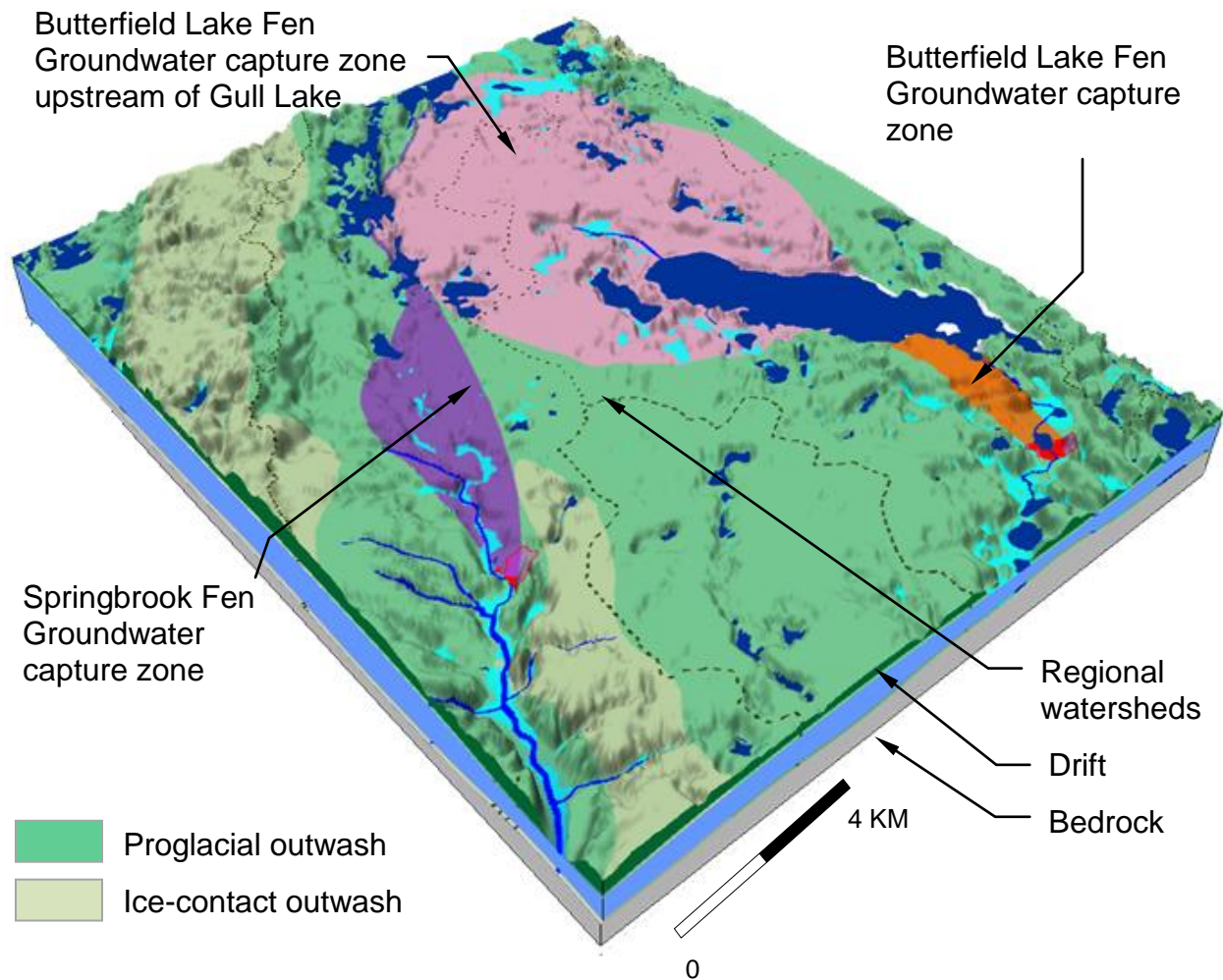


Figure 3.62 The shaded relief represent surface topography in the region which varies in elevation from 240.36m to 321.27m.

Outwash deposits in the region are underlain by two different bedrock formations. The formations are Coldwater Shale and Marshall Sandstone as shown in Figure 3.63. While Marshall Sandstone is considered very pervious formation, Coldwater Shale is considered almost

impervious. Both fens occur over Coldwater Shale but their capture zones extend over to the Marshall formation.

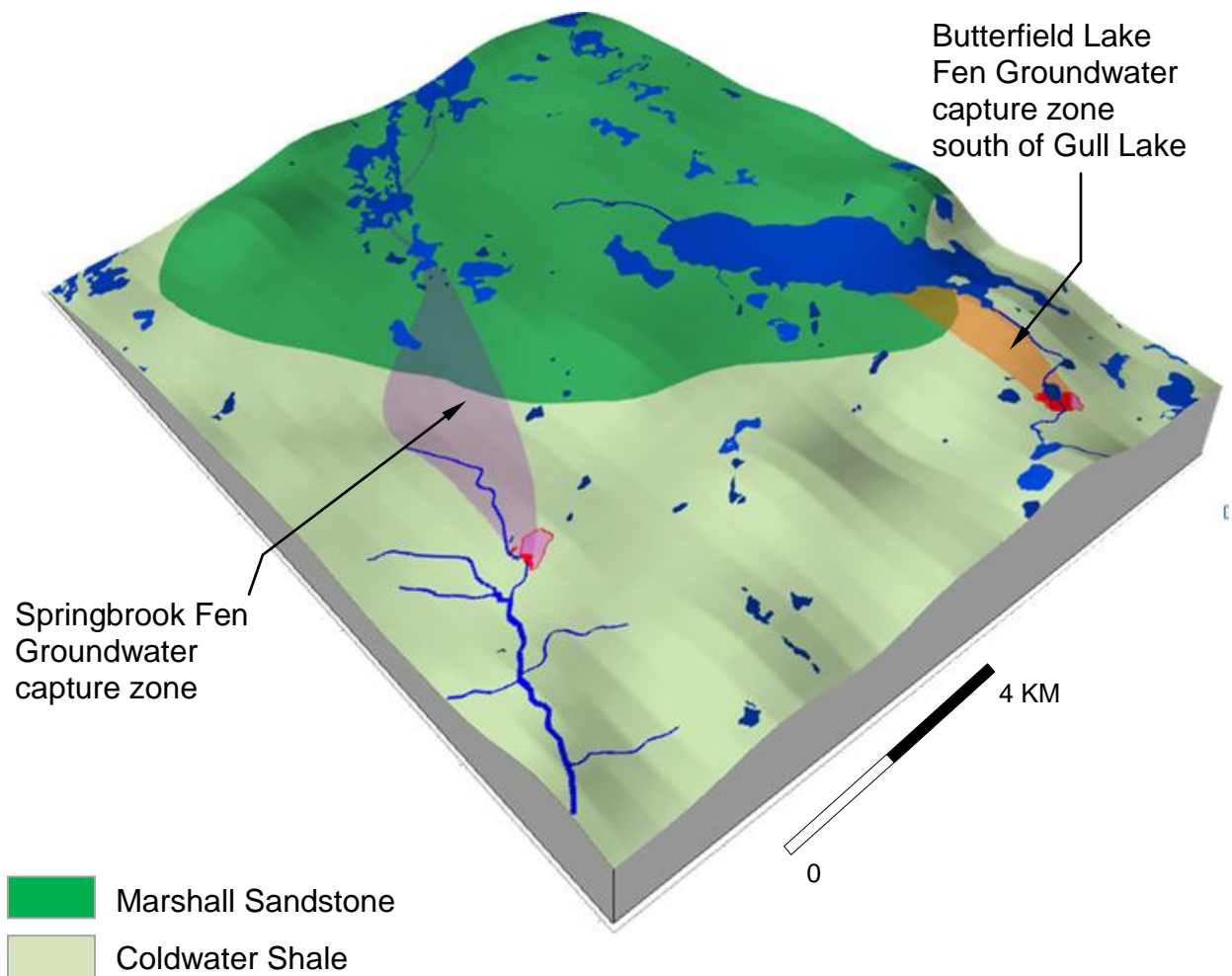


Figure 3.63 The shaded relief represent bedrock surface in the region which varies in elevation from 175m to 238m. Bedrock formations in the area are represented by different colors. Both fens occur in drift deposits over Coldwater Shale.

Groundwater Profile Model – Springbrook Fen

Well logs along the capture zone of Springbrook Fen are shown in Figure 3.64 which do not reveal any structural discontinuities within the drift. The profile model was conceptualized as

a layer of drift overlying bedrock (sandstone and shale formations), as shown in Figure 3.65, with Barry Groundwater Mound as the regional source at the northern end. Steep regional groundwater gradient (Figure 3.61) at the southern end of the profile was modeled as constant head to allow boundary outflow. The model predicts that the fen may be receiving groundwater from shallow systems immediately adjacent to it, extending up to 4 km northward from the fen. The deeper systems from the Barry Groundwater Mound seem to bypass the fen.

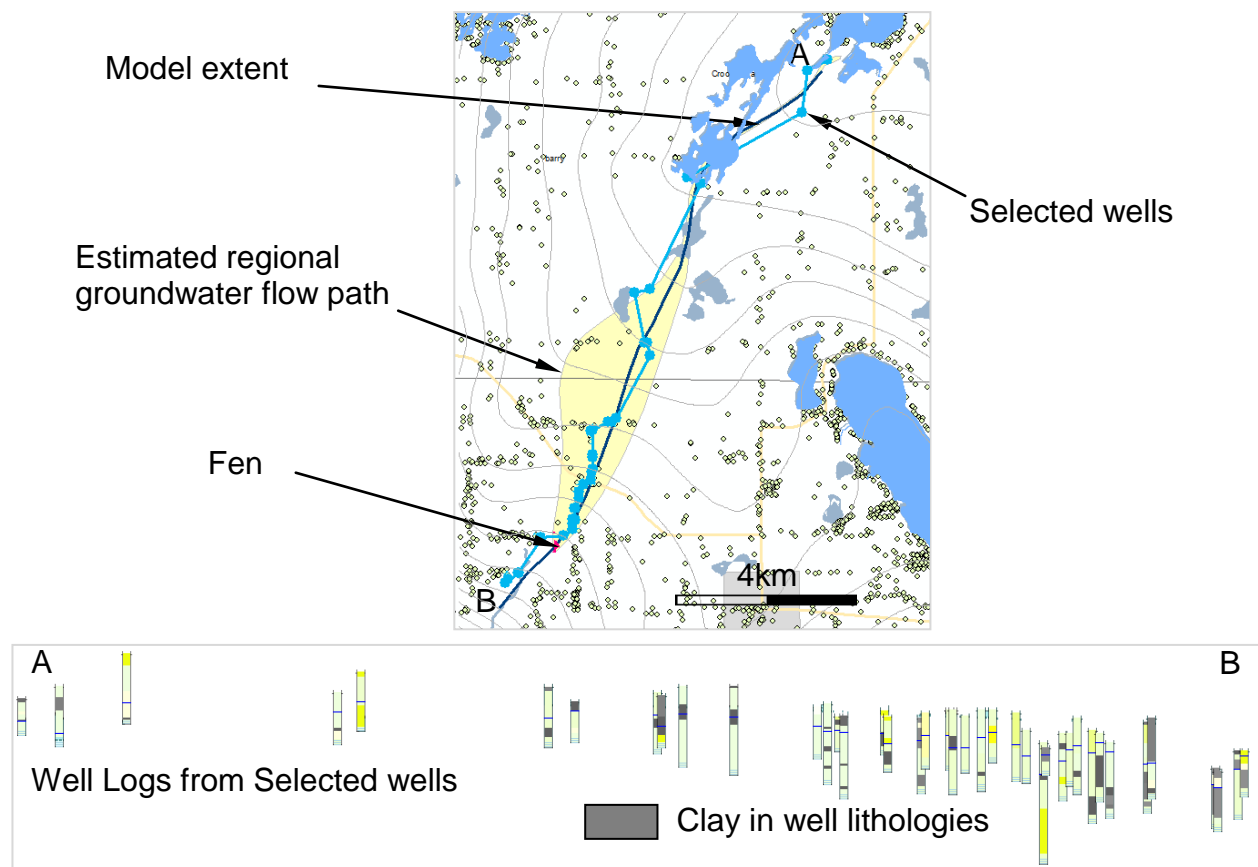


Figure 3.64 Well locations and well logs along Springbrook Fen capture zone. Contours at 2m interval show SWL for drift.

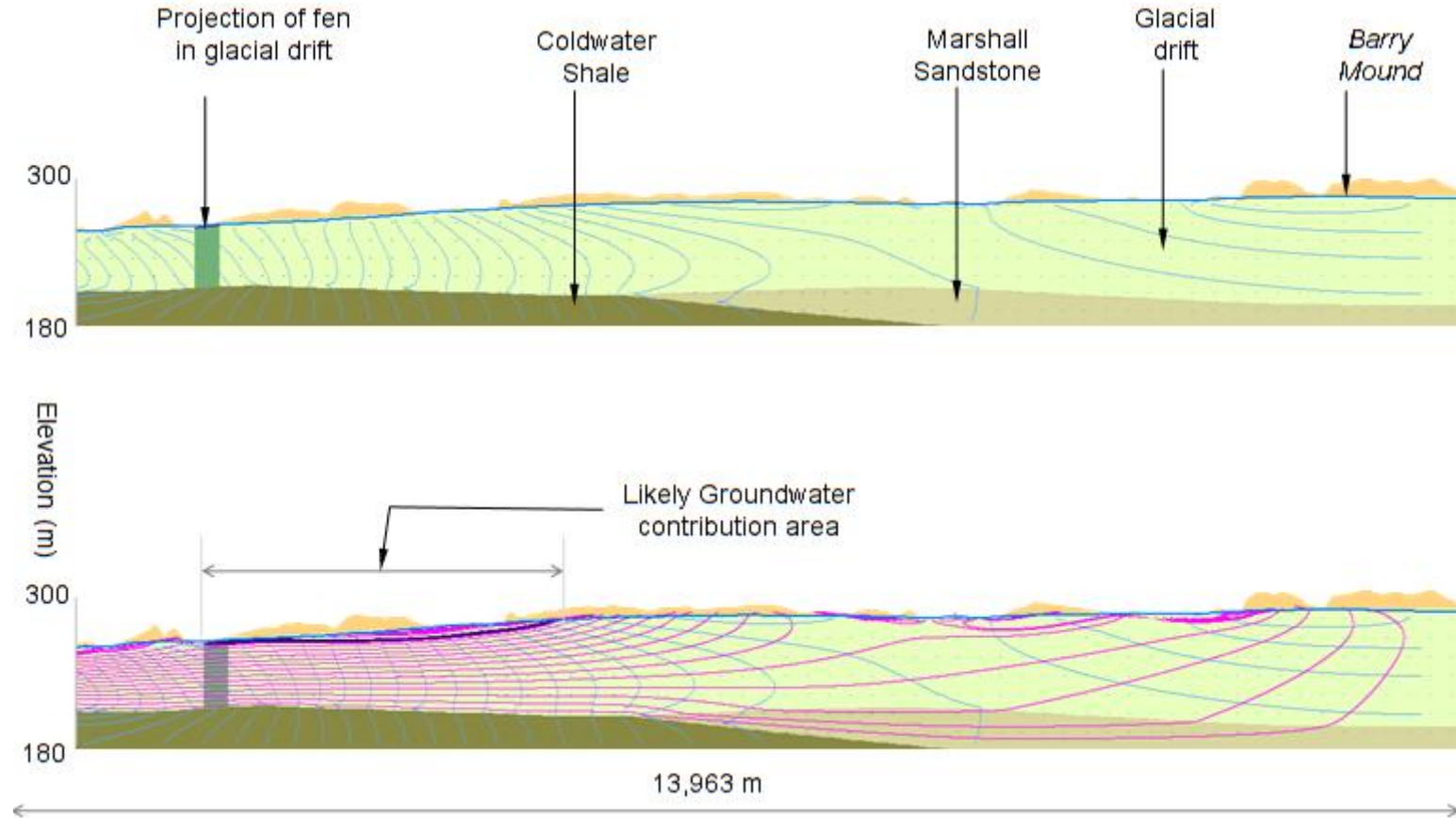


Figure 3.65 Profile Model for Springbrook Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 1.02m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Groundwater Profile Model – Butterfield Lake Fen

Well logs along the capture zone of Butterfield Lake Fen are shown in Figure 3.66 which do not reveal any structural discontinuities within the drift. The profile model was conceptualized as a layer of drift overlying bedrock (sandstone and shale formations), as shown in Figure 3.67, with Barry Groundwater Mound as the regional source at the northern end. Steep regional groundwater gradient (Figure 3.61) at the southern end of the profile was modeled as constant head to allow boundary outflow. The model predicts that the fen may be receiving groundwater from deeper system, upwelling from Marshall Formation and connected to Barry Groundwater Mound approximately 12 km northward from the fen, bypassing Gull Lake. The shallow systems around the fen may be contributing to wetlands and lakes adjacent to the fen.

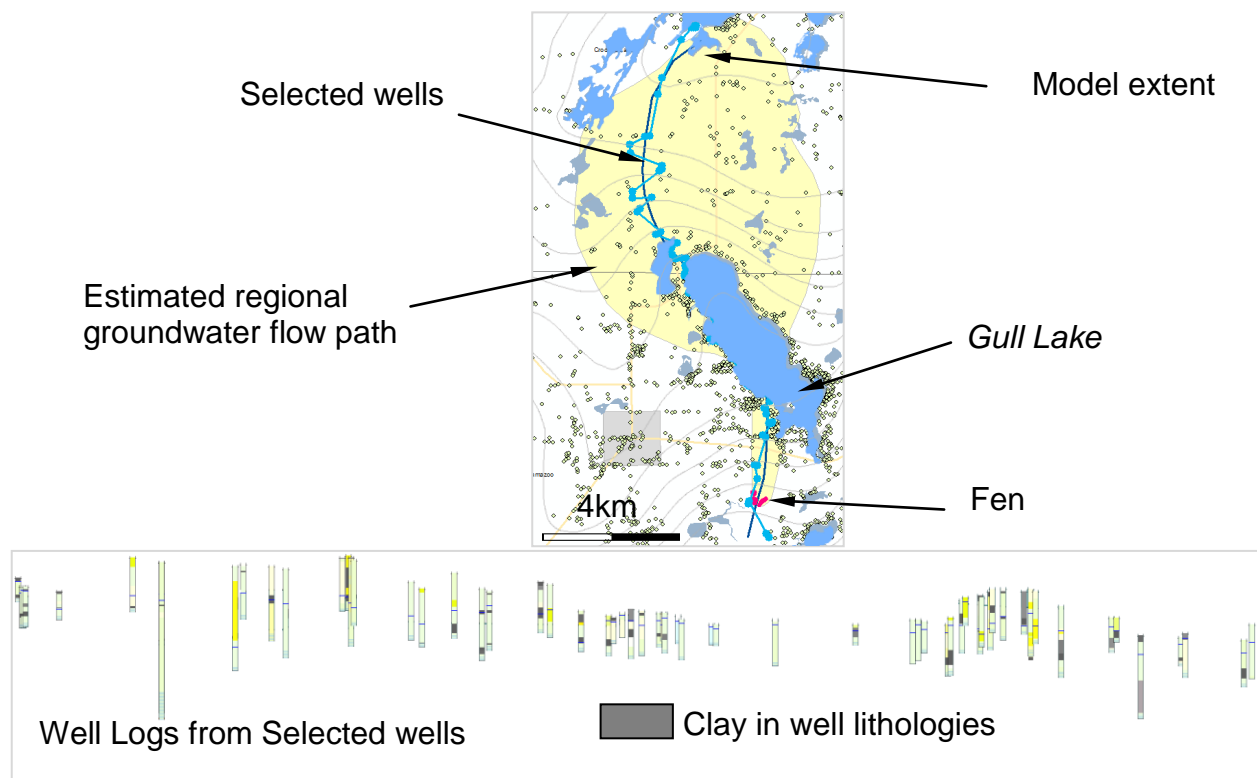


Figure 3.66 Well locations and well logs along Butterfield Lake Fen. Contours at 2m interval show SWL for drift.

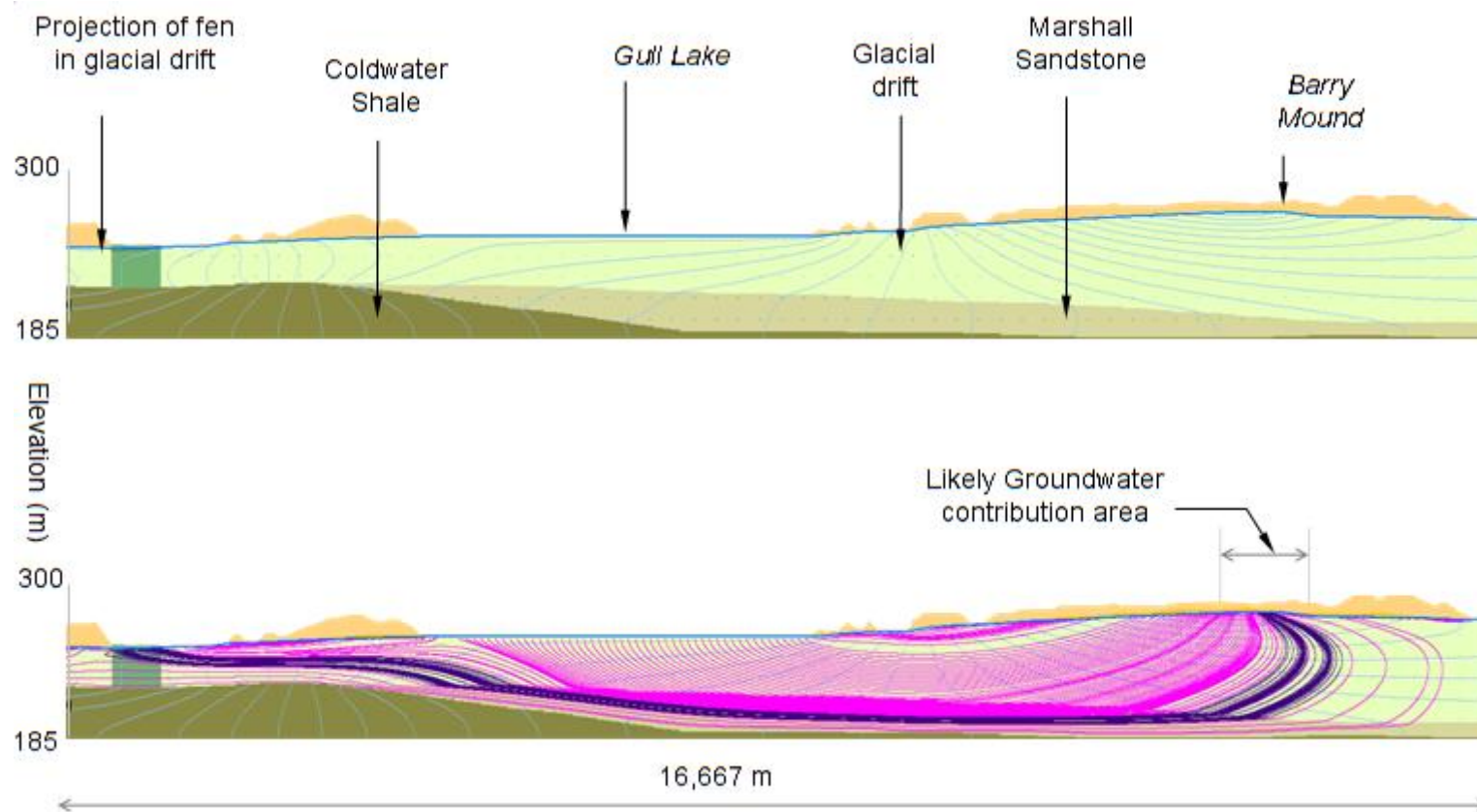


Figure 3.67 Profile Model for Butterfield Lake Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 0.99m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water (purple) [bottom].

Dew Road Fen

Dew Road Fen is one of the few prairie fens occurring in ice marginal till. The fen is adjacent to a wetlands complex. Bedrock formation under the glacial drift is Marshall Sandstone. Average thickness of glacial drift around the fen is 31m, with maximum 71m and minimum 1m. The bedrock almost pinches to the surface about 800m to the west of the fen. The fen and its surface catchment area are shown on 10m DEM relief in Figure 3.68. EORANK of the fen is 'C'. MS occurrence has not been reported at this site.

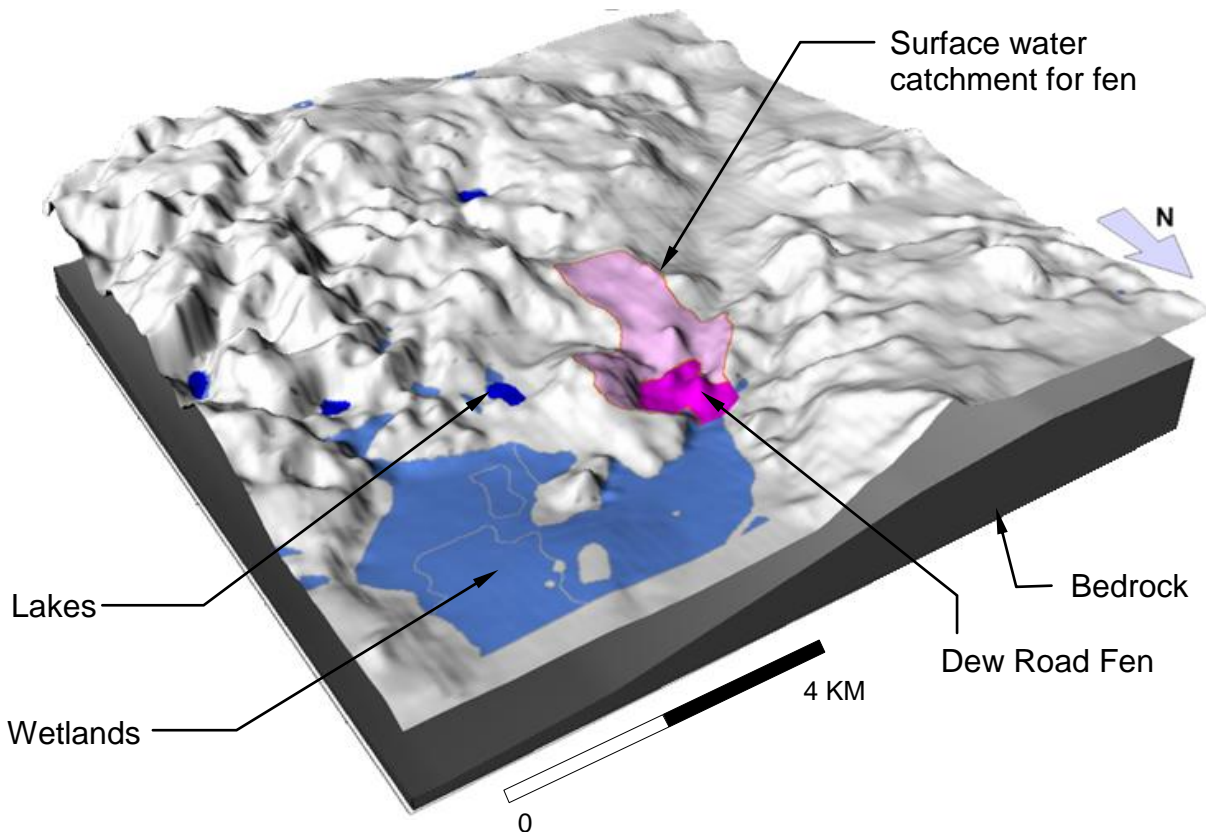


Figure 3.68 Dew Road Fen. The shaded relief represent surface topography derived from 30m/10m DEM. Surface elevation varies between 309.46m and 363.80m.

Regional Groundwater Model

Regional model for Dew Road Fen was selected over an area of 5.94 km by 6.99 km. The area was divided into the 120x140 grid cells, with the cell size of 49.89 m. Static water level (SWL) and other modeling parameters were ascertained as explained in methodology. Reverse particle tracking was used to delineate groundwater capture zone for the fen. Delineated zones of groundwater contribution to the fens are shown in Figure 3.69.

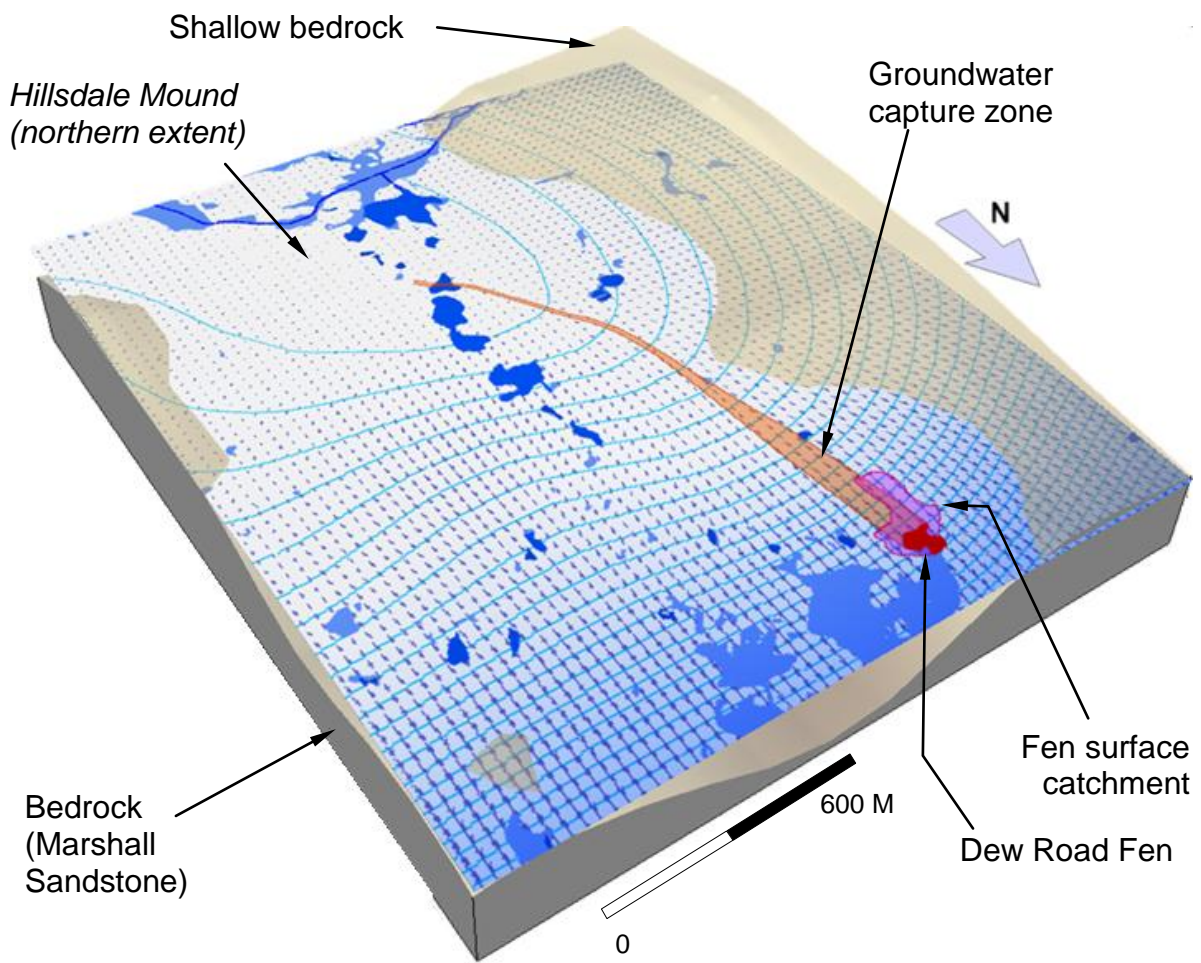


Figure 3.69 The contours at 0.5m interval and shaded relief represent regional scale delineation of groundwater surface around Dew Road Fen which varies in elevation from 306.59m to 321.97m.

The model shows that the contribution zone extends beyond the surface water catchment area of the fen and may be connected to the northern end of Hillsdale Groundwater Mound, approximately 5 km to the south from the fen site. In Figure 3.70, the groundwater contribution zone is superimposed on surface topography and geological land forms. The contribution area extends across the till plains all the way to a zone of glacial outwash in another surface watershed. Fen's surface catchment is small and short compared to the delineated capture zone.

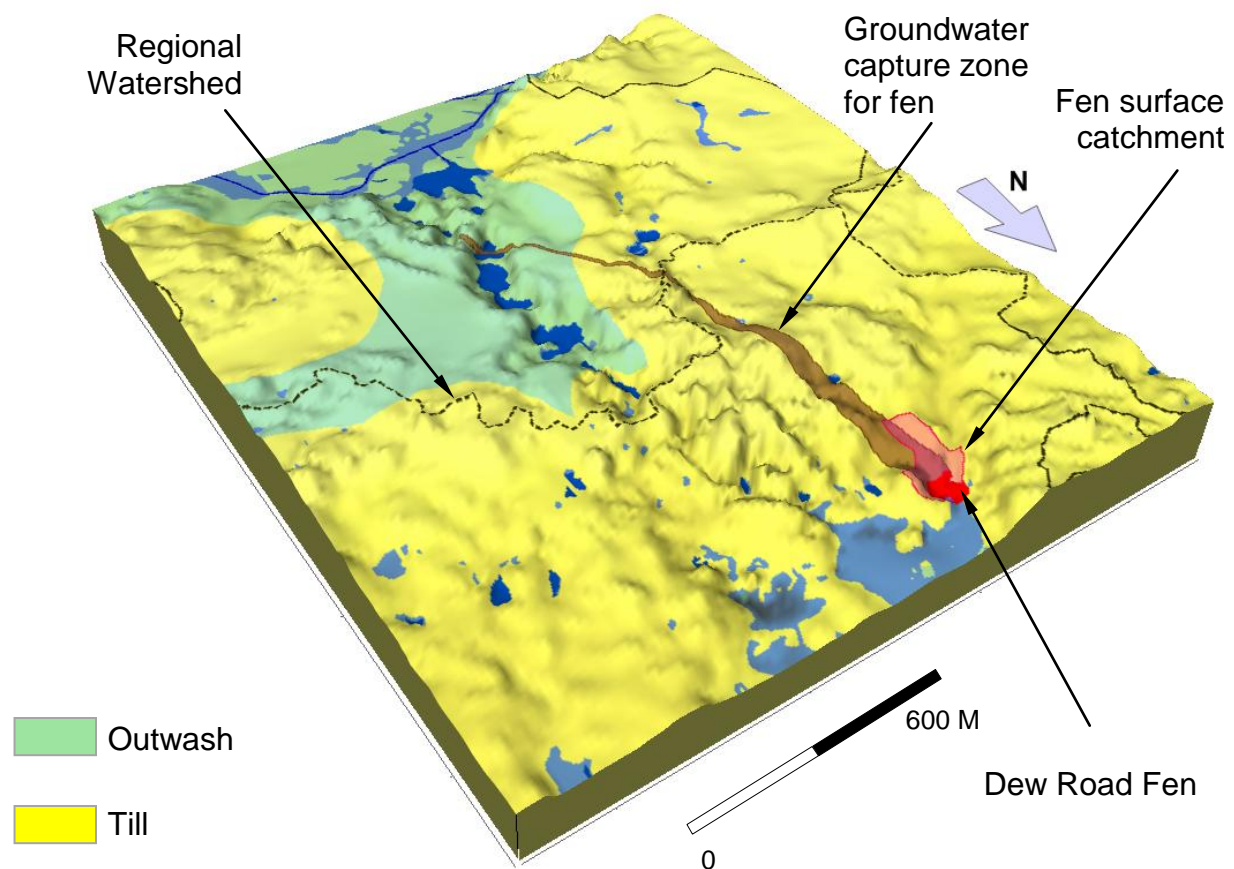


Figure 3.70 The shaded relief represents surface topography around Dew Road Fen which varies in elevation from 309.40m to 362.92m. The fen occurs in ice-contact till while the capture zone extends south to glacial outwash deposits.

Groundwater Profile Model

The profile section selected across the fen and its regional capture zone is shown in Figure 3.71. The section starts at Hillsdale Mound, being the regional source and ends at the large wetlands complex just north of the fen, where a very steep regional gradient exists. This end the profile was hence modeled as constant head to simulate boundary flow due to steep gradient.

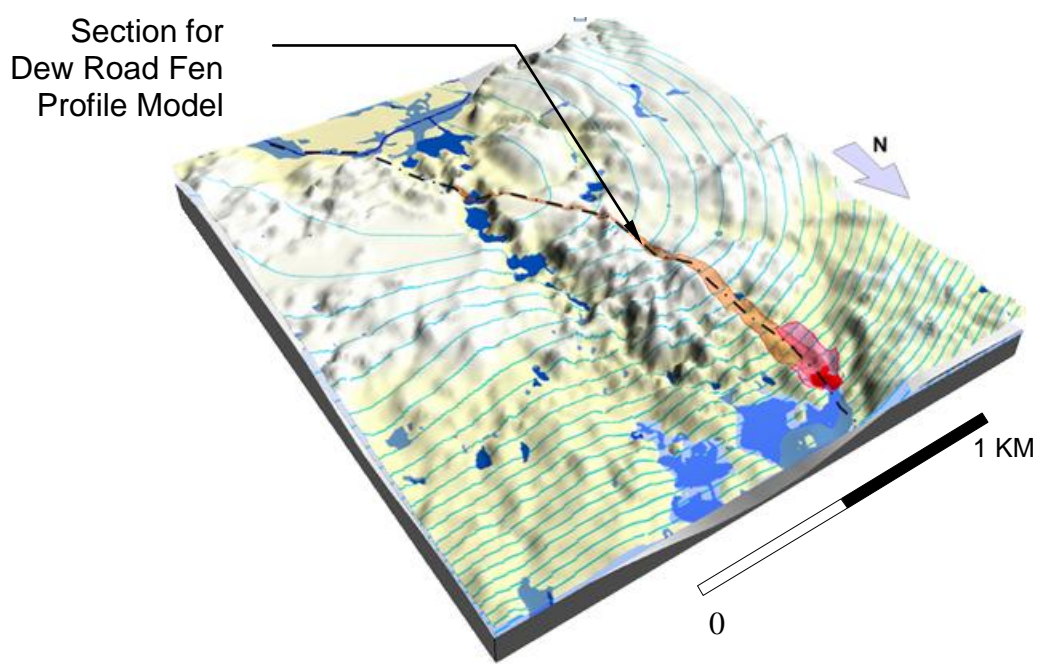


Figure 3.71 Section for profile model. Shaded relief represents topography and contours at 0.5m interval represent regional SWL.

Profile model for Dew Road Fen is shown in Figure 3.72. The model shows that the fen may not be connected to the regional system, drawing water only from the adjacent shallow groundwater system extending approximately 1.5 km to the south from the fen. The regional flow does not seem to up-well into the ice-marginal till or into the fen but bypasses the site flowing through the Marshall formation.

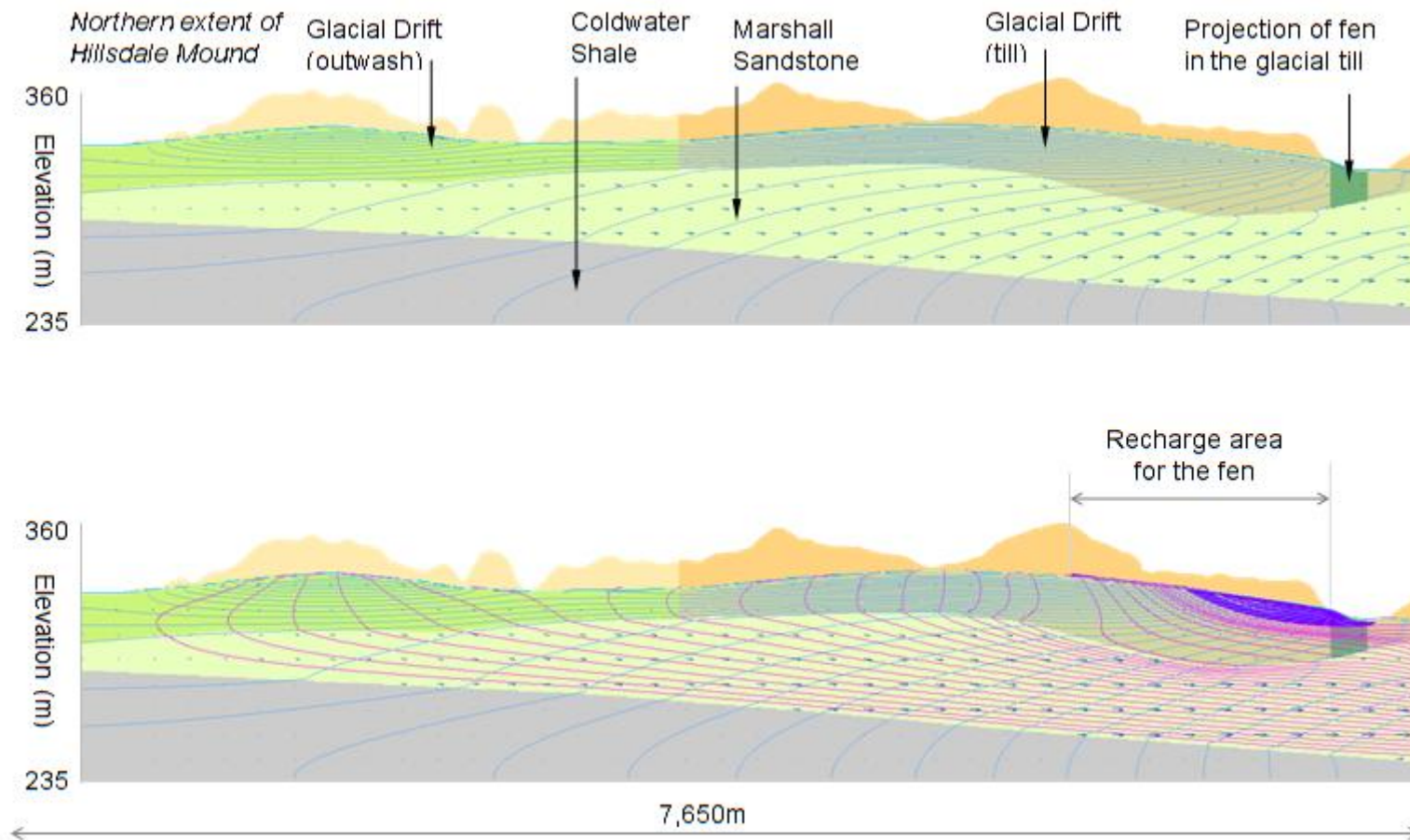


Figure 3.72 Profile Model for Dew Road Fen. Geological layers and delineation of groundwater head and velocity [top]. Light blue lines show groundwater head contours at 0.84m interval. Reverse particle tracking to estimate groundwater flow regime (pink) and likely fen's source water area (purple) [bottom].

Silver Lake Fen

Silver Lake Fen is one of the few prairie fens in Michigan occurring in ice marginal till. The average drift thickness around the fen site is 110m, varying between 85m and 140m. The fen and its surface catchment area are shown on 10m DEM relief in Figure 3.73. EORANK of the fen is 'CD'. MS occurrence has not been reported at this site.

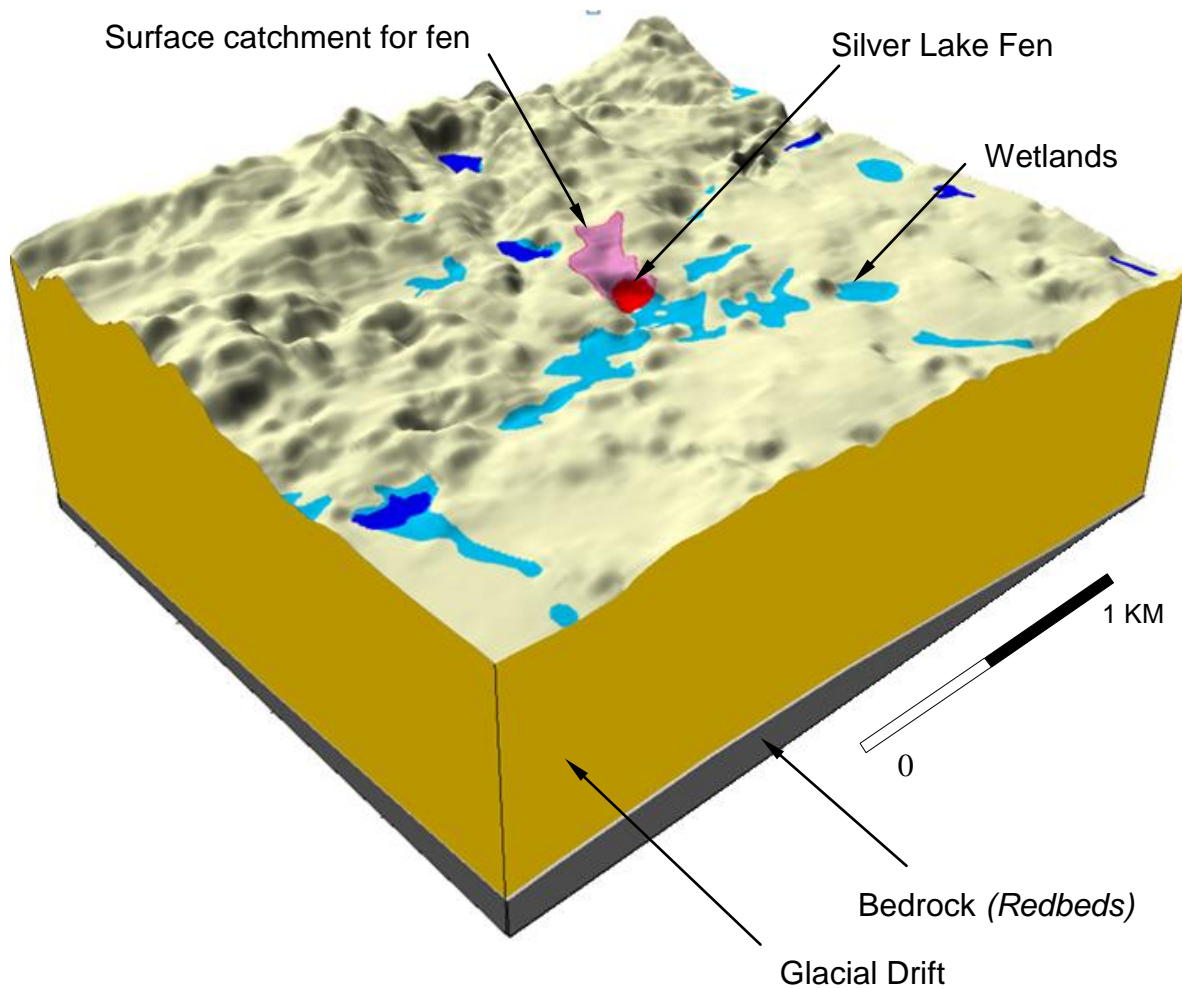


Figure 3.73 Silver Lake Fen. The shaded relief represents topography derived from 30m/10m DEM which varies from 260.55m to 303.04m.

Regional Groundwater Model

Regional model for Silver Lake North Fen was selected over an area of 8.68 km by 7.49 km, divided into 300x259 grid cells, with the cell size of 29.03 m. Static water level (SWL) and other modeling parameters were ascertained as explained in methodology. Reverse particle tracking was used to delineate groundwater capture zone for the fen site in the model. Delineated zone of groundwater contribution to the fen is shown in Figure 3.74. The model shows that the contribution zones may be connected to a sub-regional groundwater mound approximately 3 km to the north from the fen location.

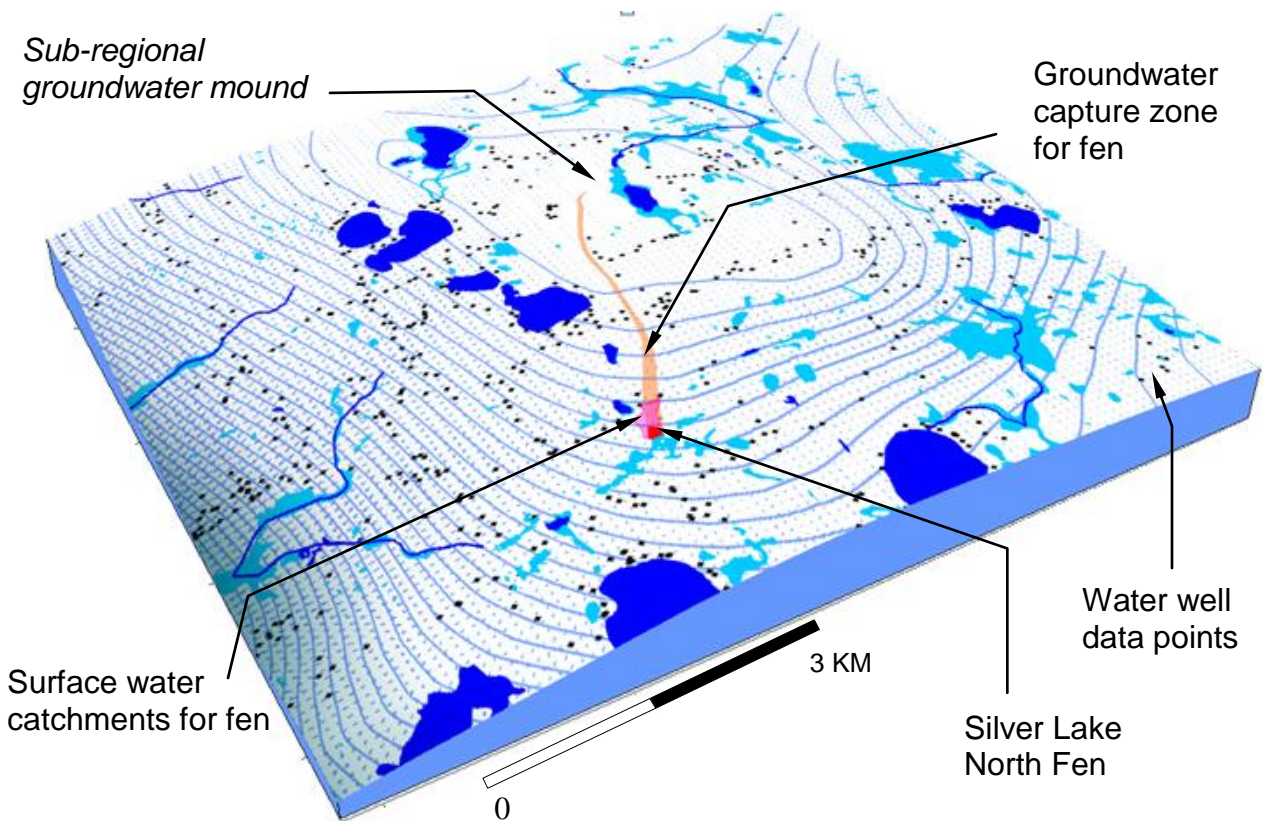


Figure 3.74 The contours at 1.16m interval and shaded relief represent regional scale delineation of groundwater surface around Silver Lake Fen which varies in elevation from 240.50m to 266.36m.

In Figure 3.75, the groundwater contribution zones are superimposed on surface topography and geological land forms. The model shows a narrow groundwater capture zone extending north, culminating just across the regional watershed.

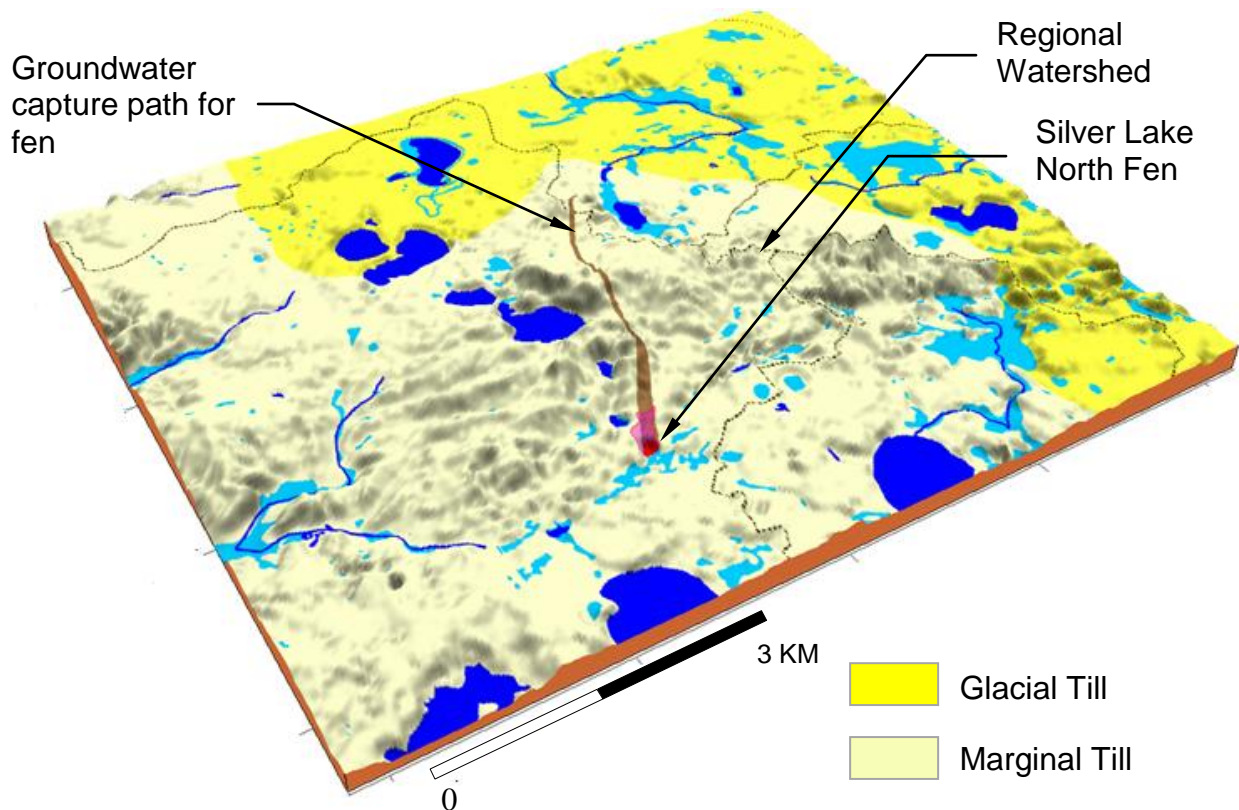


Figure 3.75 The shaded relief represent surface topography in the region which varies in elevation from 240.51m to 310.94m. Glacial landforms in the area are represented by different colors. The fen occurs in glacial till.

Groundwater Profile Model

Analysis of lithology from the well logs around Silver Lake Fen did not reveal continuous clay lenses within the glacial drift as shown in Figure 3.76. The model's profile section starts in the north at a sub-regional groundwater mound acting as source and ends at the wetlands complex just south of the fen, where a very steep regional gradient exists. This end the

profile was hence modeled as constant head to simulate boundary flow due to steep gradient. The profile model is shown in Figure 3.77. The model predicts that the fen receives water from the adjacent shallow system which extends all the way to the apex of the sub-regional groundwater mound approximately 2.3 km from the fen site. The fen does not seem to receive water from the deeper systems. The model also shows that the deeper regional flow of groundwater flow bypasses the fen.

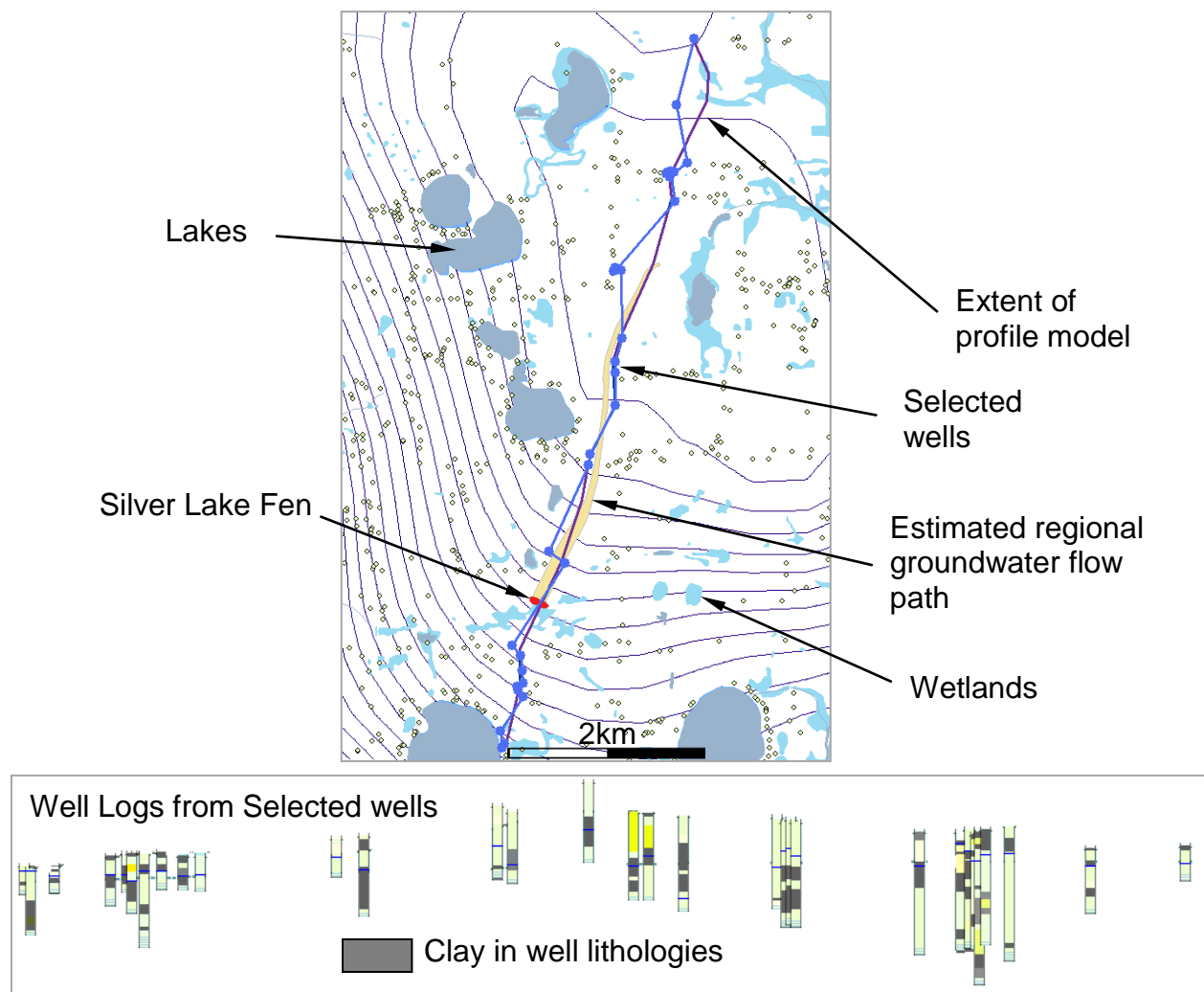


Figure 3.76 Well location and well logs along Silver Lake Fen capture zone. Contours at 1.16m interval show SWL for drift.

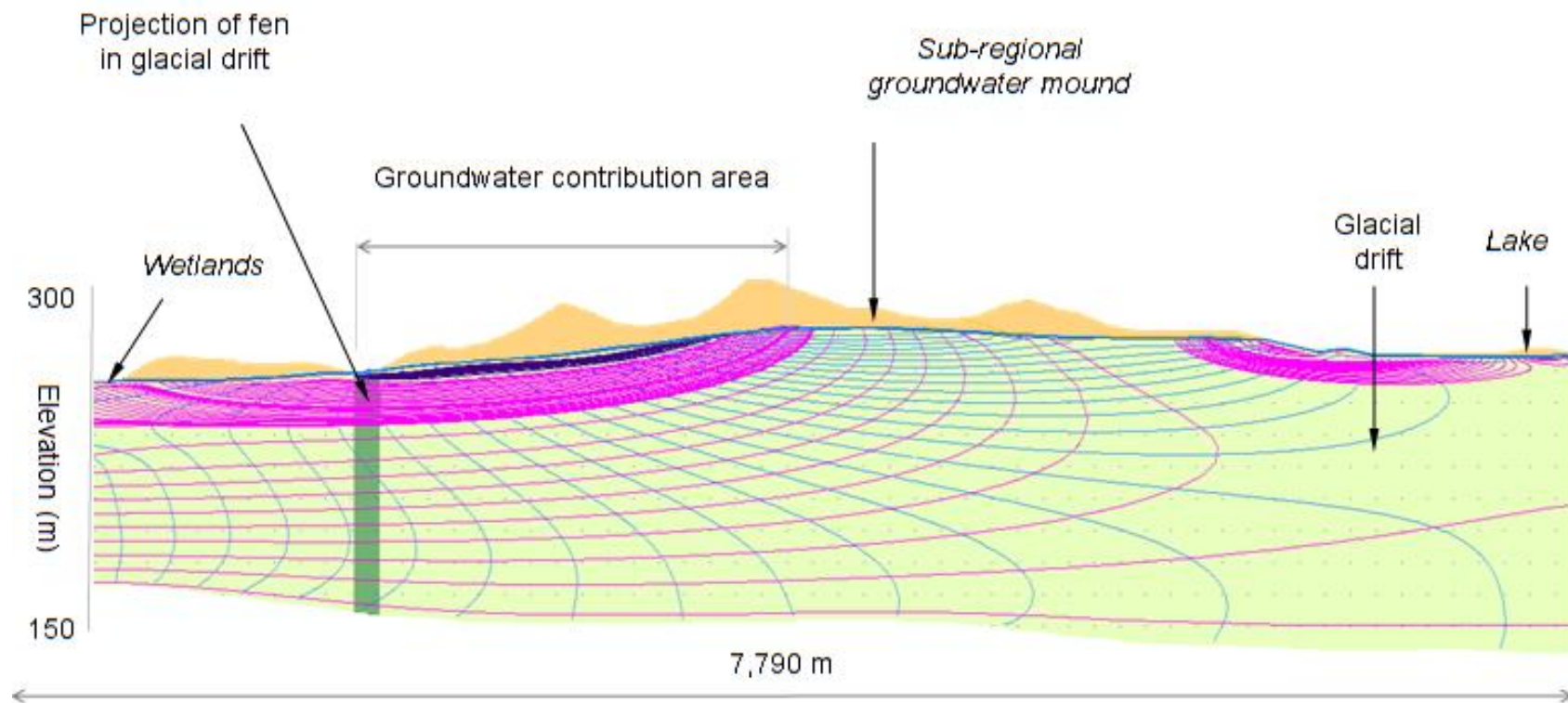


Figure 3.77 Profile Model for Silver Lake Fen. Groundwater flow lines show estimated groundwater flow regime (pink) and likely source water paths for the fen (purple). Light blue lines show groundwater head contours at 0.74m interval.

BASIN-WIDE GROUNDWATER PICTURE

Statewide models revealed the larger picture of groundwater flow regime across the southern half of Michigan's Lower Peninsula. Most fen sites seem to be occurring around the regional groundwater mounds identified in the models. All major rivers in the modeled area also seemed to have their headwaters emerging around the groundwater mounds. The placement of mounds as well as the occurrence of fens generally coincides with the interlobate regions – comprising mostly of pervious glacial outwash materials which have higher potential for receiving groundwater recharge and contain more pore space for aquifer storage. Also refer to Figure 3.2 and Figure 3.3.

REGIONAL UPWELLING

Horizontal flow models for some regions showed very strong convergence of regional groundwater flow around the areas where fens were located. These models were first developed using water wells data and taking large surface features into account. For some of the regions showing particularly strong regional convergence, flow models were also made using only the water wells data without taking into account the surface water features to ascertain if water wells data alone also reveal a pattern of regional convergence. Some flow models, based entirely on water wells data still suggested strong regional flow convergence around the fen locations. The examples of 5 such regions are shown in Figure 4.1 and Figure 4.2 (also refer to Figure 3.28, Figure 3.43, Figure 3.48, Figure 3.61, and Figure 3.55 for the same sites where regional flow

pattern was based on water wells data as well as large surface water data). Such strong signals already suggest possibility of groundwater upwelling from the regional system. The flow convergence though seems directed to a bigger surface water body such as a stream or a lake, the fens sites within this ‘zone of convergence’ also seemed benefitting from the regional system.

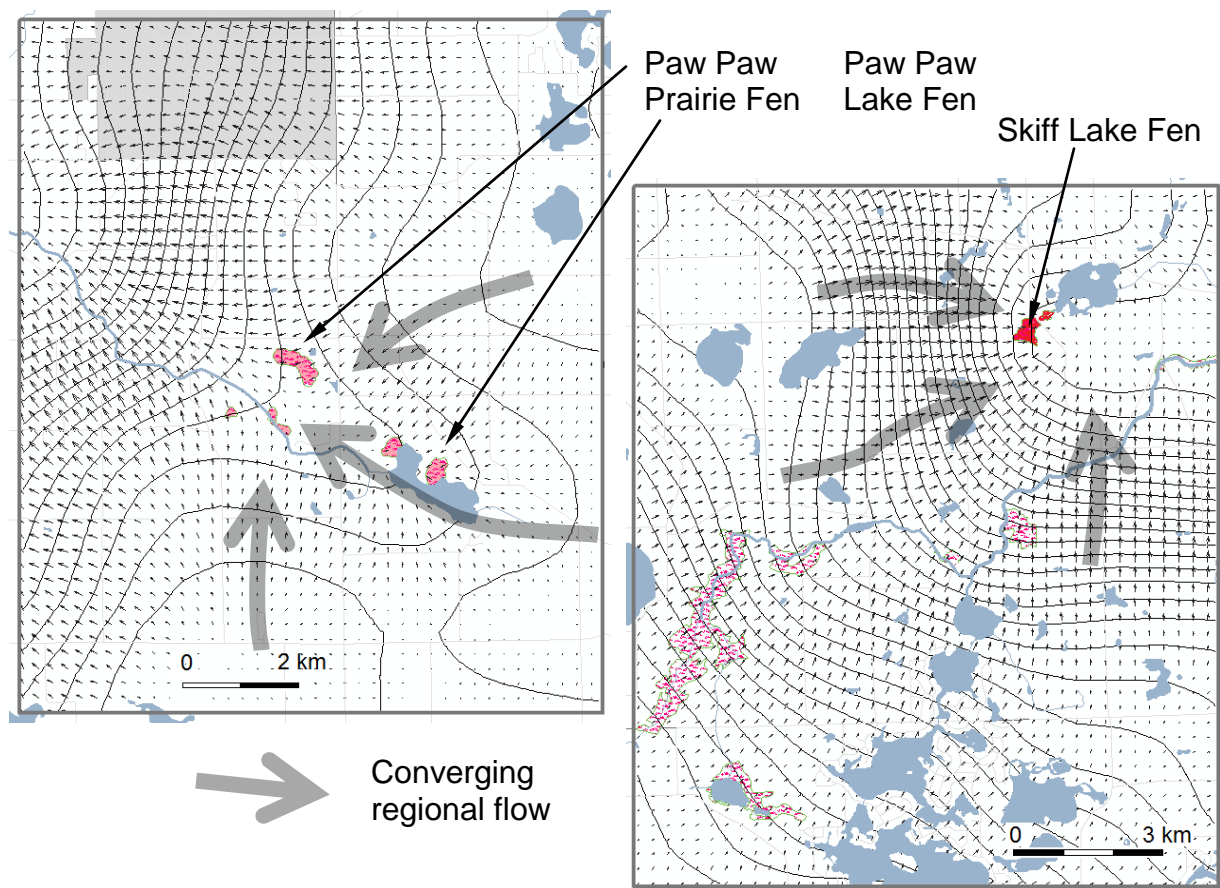


Figure 4.1 Strong regional groundwater flow convergence shown by water wells data around Paw Paw Lake and Paw Paw Prairie fens (left) and Skiff Lake fen (right).

Many modeled sites which did not reveal clear ‘convergence zones of regional flow’ around the fen locations still showed components of regional upwelling through profile models. Profile models, therefore, were helpful in assessing the possibility of regional connections, especially when they were not readily apparent from the horizontal flow models.

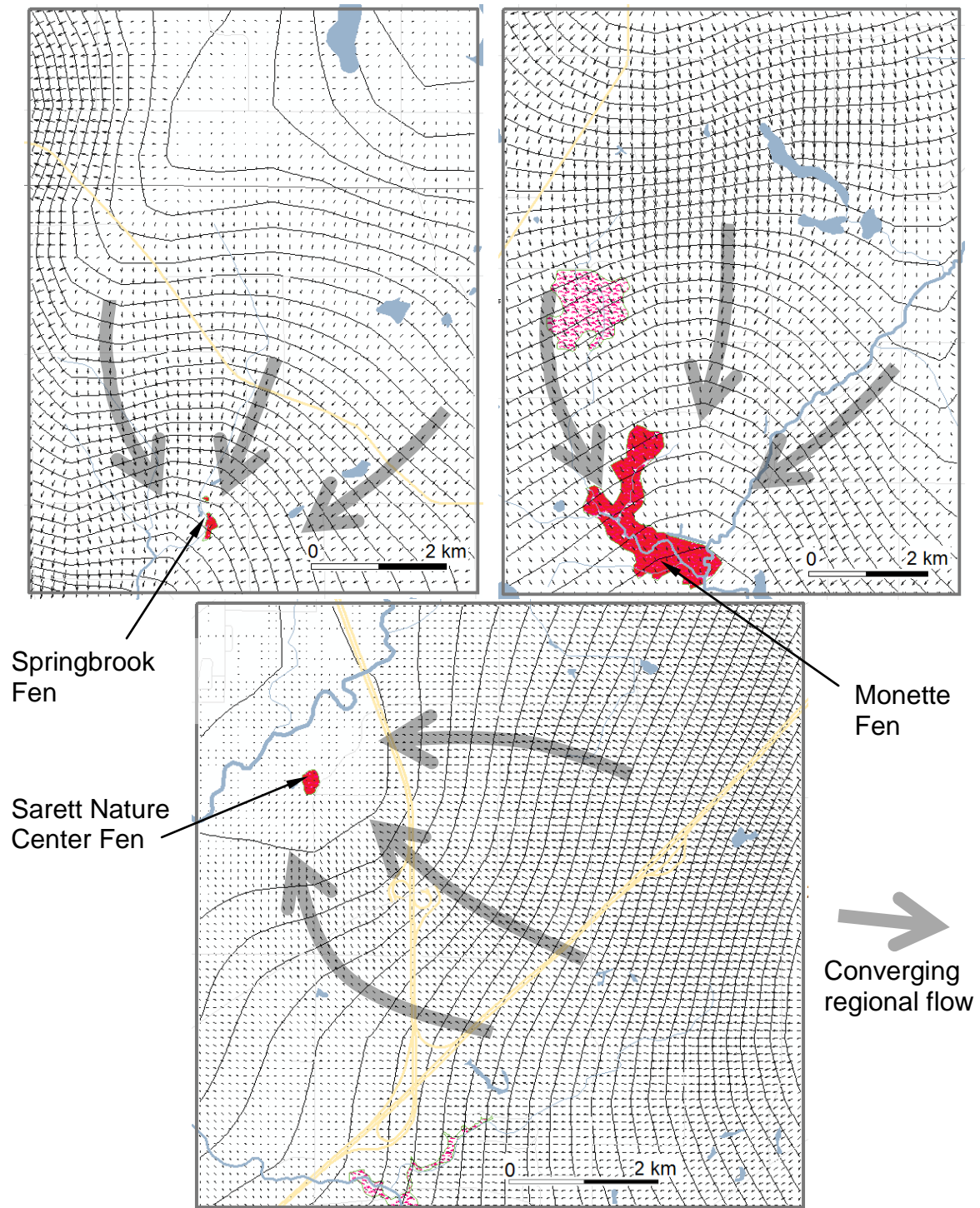


Figure 4.2 Strong regional groundwater flow convergence shown by water wells data around Springbrook fen (top left), Monette fen (top right) and Sarett Nature Center fen (bottom).

SOURCE WATER AREAS FOR FEN SITES

This study identified likely groundwater sources feeding the prairie fen sites across the state. Based on the modeling results, the source water areas for the fen sites may be divided into three main categories as explained below. The models have also shown that a single site could be connected to more than one source water areas.

Local Sources

Wetlands, lakes and stream close to a fen site (from a few 100 meters to a couple of kilometers at the most) may act as source water for the groundwater seeping into the fen. Such sources, though close to the fen, were found to be separated from the fen sites by small topographic ridges. The ridges prevent the direct runoff from these surface sources into the fen. Consequently, the surface runoff into these local sources turns into ‘groundwater’ as it seeps underneath the topographic ridges. The ridges are mostly made up of coarse glacial landforms such as kames or eskers. Of the 19 fen sites modeled in this study, 13 sites seemed to be receiving groundwater from their nearby local sources. Also see Table 4.I.

Sub-Regional Sources

Surface waters such as wetlands/lakes/streams or recharge areas in the uplands, far from a fen site (from a couple of kilometers to about ten kilometers), may act as source water for the groundwater seeping into the fen. Since these areas are not immediately adjacent to the fen sites, they may not be easily identified as source water to a particular site without the knowledge of regional groundwater dynamics. Of the 19 fen sites modeled in this study, 8 sites seemed to be receiving groundwater from sub-regional sources. Also see Table 4.I.

Regional Sources

Regional recharge areas between the river basins with sizeable groundwater mounds, far away from a fen site (tens of kilometers away), may act as source water for the groundwater seeping into the fen. Generally such sources are huge and may be connected to more than one fen site. Without the knowledge of basin-scale flow regime, as well as site specific details around a fen site, it is difficult to ascertain whether a regional source might be connected to a particular fen site. Of the 19 fen sites modeled in this study, 6 sites seemed to be receiving groundwater from regional sources. Also see Table 4.I.

DELIVERY MECHANISMS OF GROUNDWATER AT FENS SITES

Profile models in the study implied distinct delivery mechanisms linking source water areas to the fen sites. These mechanisms are explained as follows. Also refer to Table 4.I and Figure 4.10 through Figure 4.13 for examples of delivery mechanism from the modeled sites.

Shallow Connections

Groundwater recharge from local hills and surface water in lakes/wetlands at higher elevations adjacent to a fen may seep into the fen through shallow, and relatively short, groundwater flow paths. Figure 4.3 shows the schematic representation of an adjacent shallow connection.

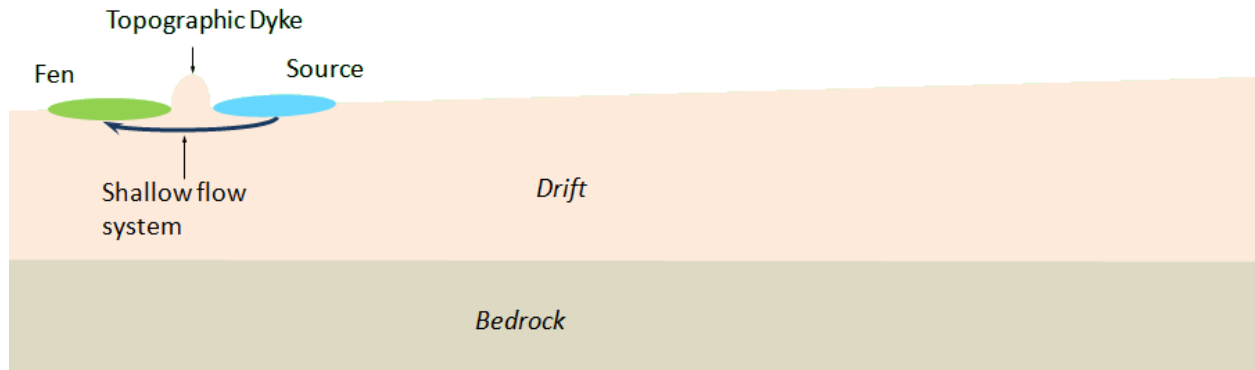


Figure 4.3 Delivery mechanism – adjacent shallow connections.

The topography around the fen is often such that a natural ‘topographic dyke’ forms on their upstream sides, preventing significant direct runoff into the fen. Surface runoff due to the dykes is mostly diverted away from the fen, generally accumulating in an adjacent lake/wetland. The lake/wetland, if higher than the fen, may be hydraulically connected to the fen through a shallow connection. We termed this special case of shallow connection as the “dyke effect” which essentially converts local precipitation/runoff into “groundwater” before it enters the fen. The source water in case of dyke effect is the local precipitation and runoff.

Deep Connections

A deep groundwater system, with its source far from the fen site, may be upwelling into a fen as illustrated in Figure 4.4. In this study, the delivery of groundwater to a fen site through deep upwelling is termed as ‘deep connection’. The path that the groundwater follows may (or may not) come in contact with deeper bedrock formations besides the deeper glacial drift deposits. Figure 4.4 shows the schematic representation of a deep connection.

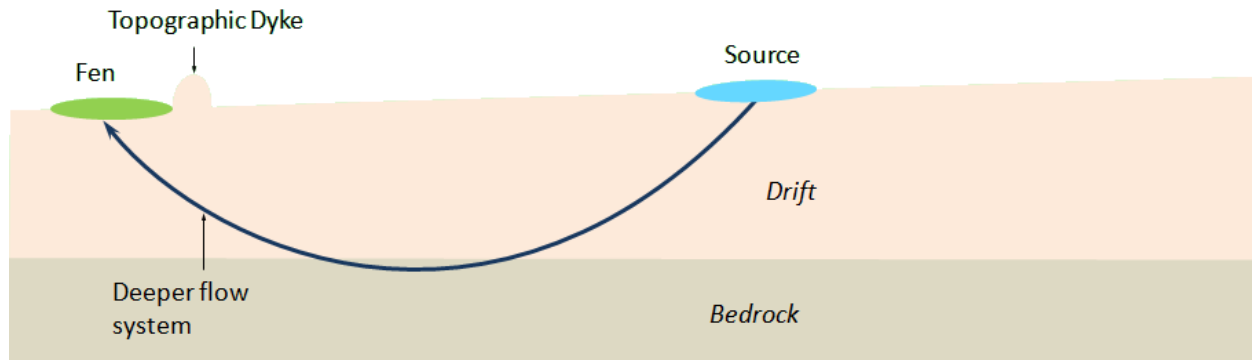


Figure 4.4 Delivery mechanism – deep connections.

Some fens seemed to have their groundwater source area tens of kilometers away from the site and are linked to an “unexpected” strong connection to the regional flow in addition to local flow. Shallow seeps/local hills may be more visible, but it is the regional flow paths that may be “pumping” steadily into these fens, through the deep aquifer, providing significant/continuous discharge of calcareous groundwater. Time scale of groundwater flow along flow paths leading to fens can be decades and therefore impacts of changing land use or climate on fens may be delayed, yet quite protracted once they are manifested.

The upwelling may be through deep glacial deposits and/or from the bedrock aquifers. Deep connections may be further sub-categorized into the following:

Local Upwelling

Source waters closer to a fen, upwelling into the fen through relatively shallower drift materials are termed as ‘local upwelling’ in this study as shown in Figure 4.5. Such sources are generally within 1 to 3 kilometers from the fen sites. The flow paths from the source to the fen run only through shallow drift materials.

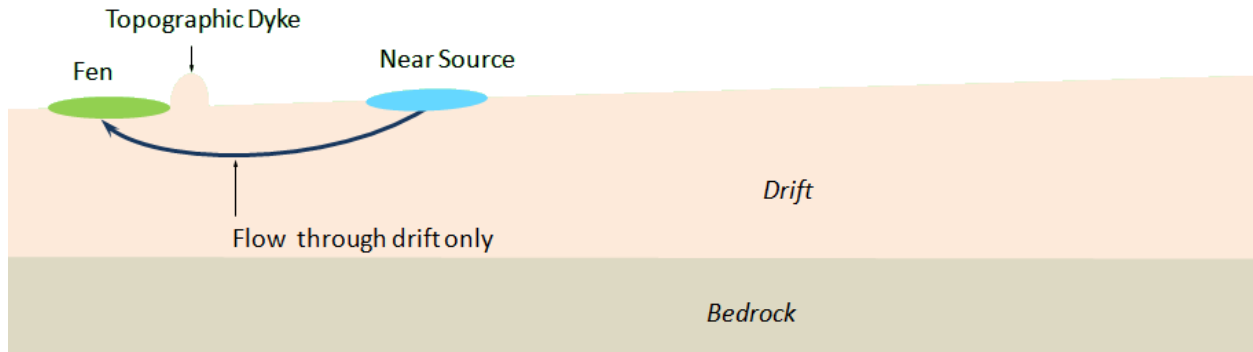


Figure 4.5 Upwelling - local source.

Sub-regional Upwelling

Distant sources of groundwater, upwelling through deeper drift materials and/or bedrock formations into a fen site, are termed as ‘sub-regional upwelling’ in this study as shown in Figure 4.6. These sources are generally between 5 to 10 kilometers from the fen sites. The flow paths from the source to the fen may run through deeper glacial drift and/or the bedrock formations.

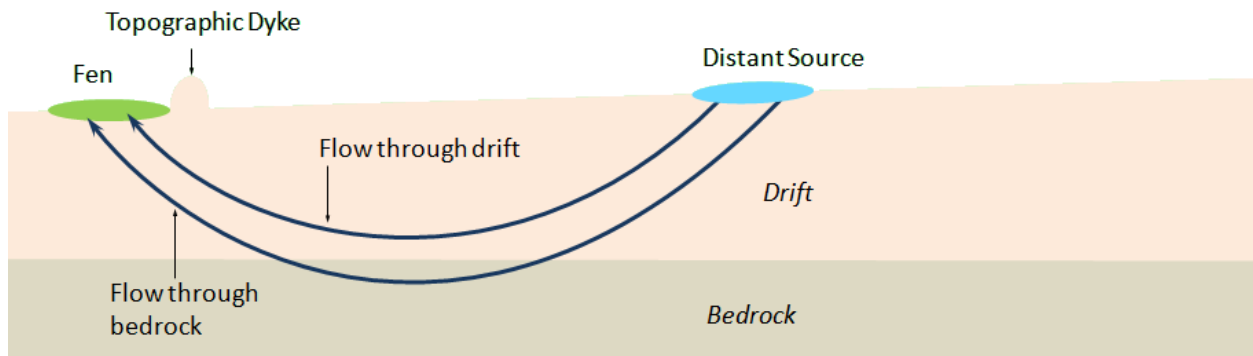


Figure 4.6 Upwelling - sub-regional source.

Regional Upwelling

Groundwater upwelling into a fen from a regional source after moving through deep glacial and/or bedrock formation is termed as ‘regional upwelling’ in this study as shown in Figure 4.7. These sources are generally over 10 km from the fen sites.

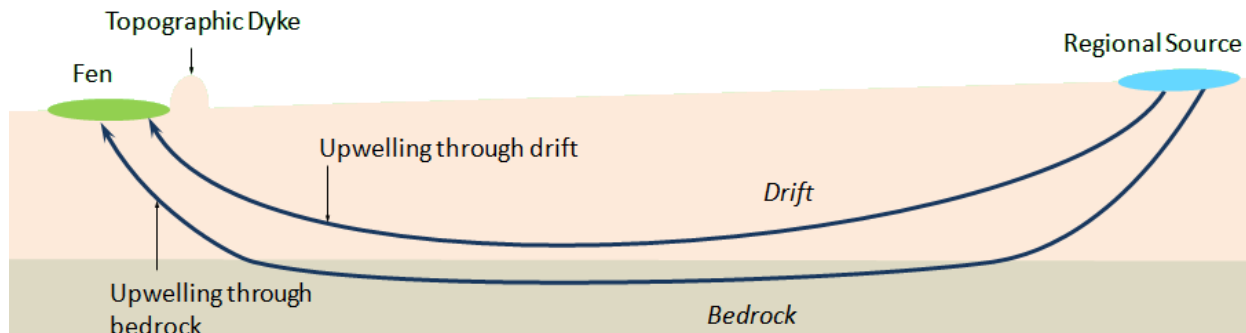


Figure 4.7 Upwelling - regional source.

Confined Connections

Glacial landforms in Michigan classified as till plains, at some locations, may be overlying pervious outwash from the earlier glaciations, creating sub-regional confined aquifers. As shown in Figure 4.8, while a source water area and a fen site may be located over unconfined aquifers, the groundwater flow path (or part or the path) between the source and the fen may be channeled through a confining clay layer before upwelling into the fen. Such a groundwater connection is termed as a ‘confined connection’ in this study.

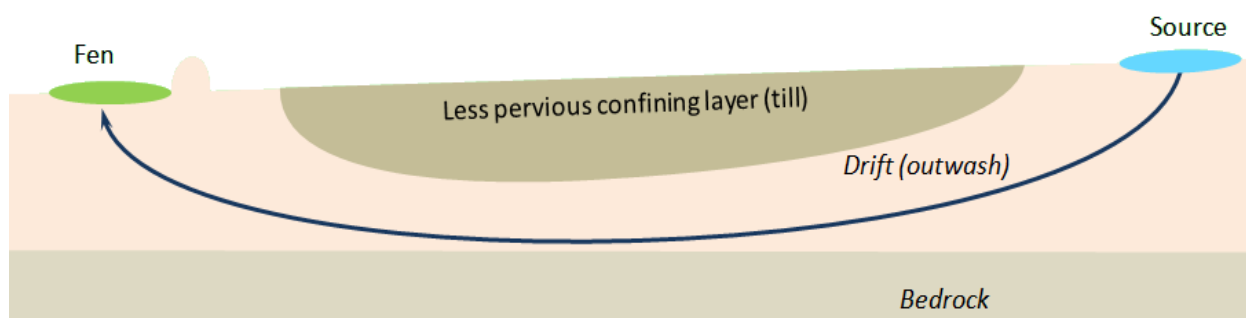


Figure 4.8 Delivery mechanism - confined connections.

Some fens seem spatially isolated from the ‘usual’ fen clusters in interlobate outwash region, but may be hydrologically connected to the regional recharge sources through confined connections over tens of kilometers. The residence times in confined connections can be in

decades. The till plains also provide natural protection to groundwater flow paths from land-use perturbations.

Cascading Connections

A groundwater source connected to a fen site may be dependent on one or more sources of surface water and/or groundwater. The fen connected to such a source would hence be indirectly dependent on other sources too as shown in Figure 4.9. Such indirect groundwater connections between the sources and the fen sites are termed as ‘cascading mechanisms’ in this study.

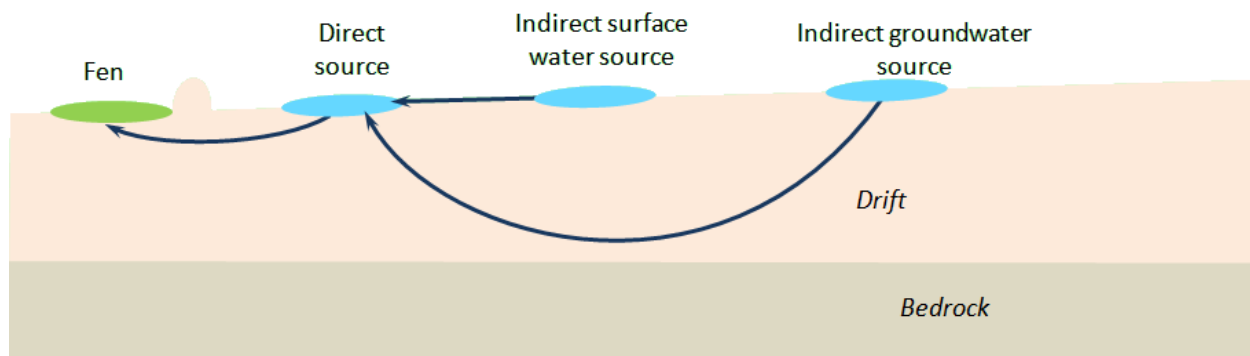


Figure 4.9 Delivery mechanism – cascading connections.

Just identifying a source area feeding the fen may not be enough when the identified source is further dependent on other sources. If a local source is dependent on a regional recharge zone far from the fen, then the regional zone cannot be ignored while managing the fen. Similarly, a surface water source connected to a fen is dependent on its surface catchment, making its entire catchment critical for the fen.

Following figures illustrate some examples from of the delivery mechanisms discussed above from the prairie fens investigated in this study.

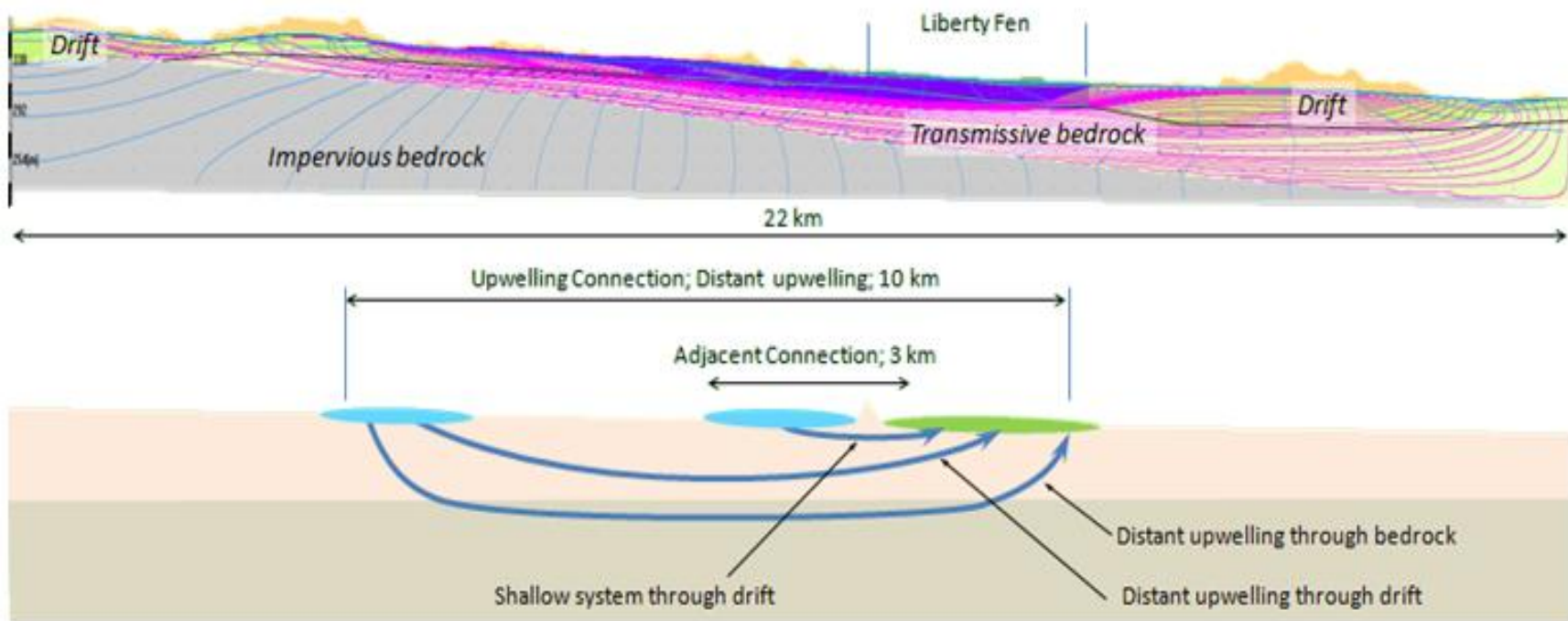


Figure 4.10 Example from Liberty Fen - the fen site exhibits sub-regional upwelling as well as shallow connections.

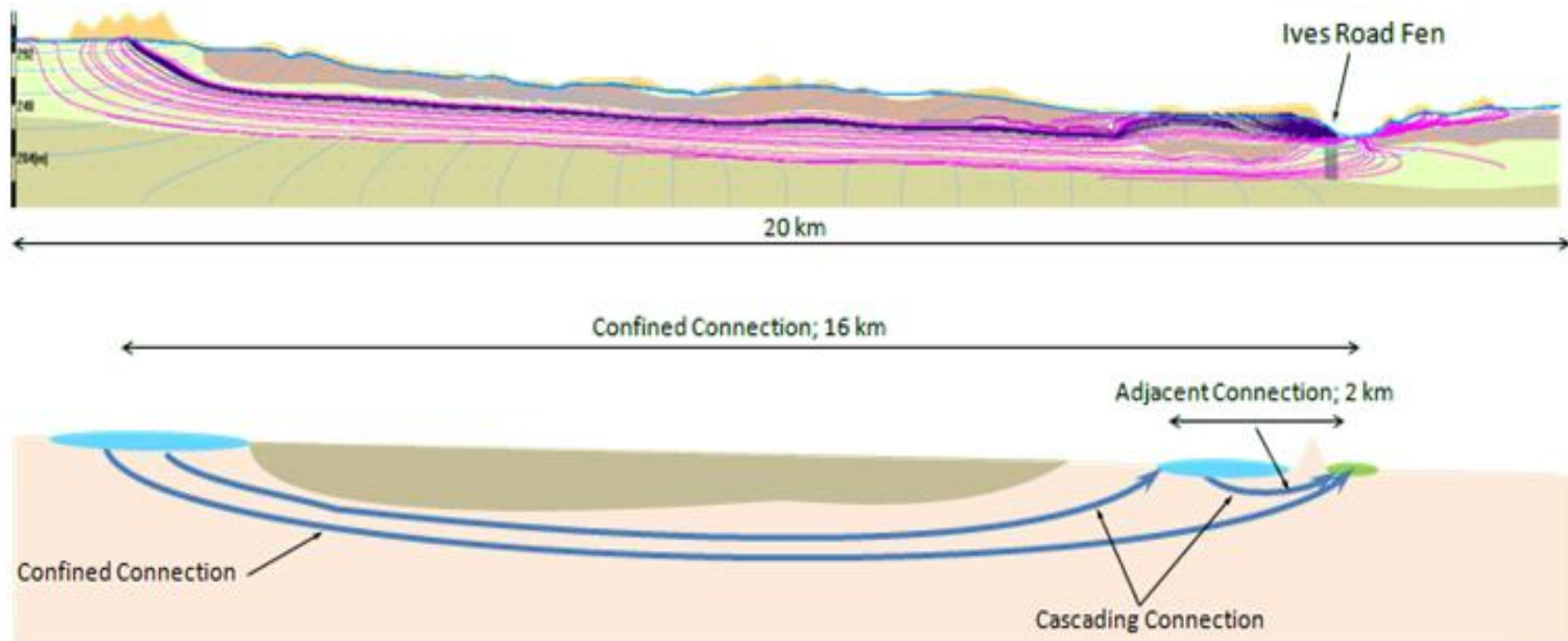


Figure 4.11 Example from Ives Road Fen - the fen site exhibits shallow, confined and cascading connections.

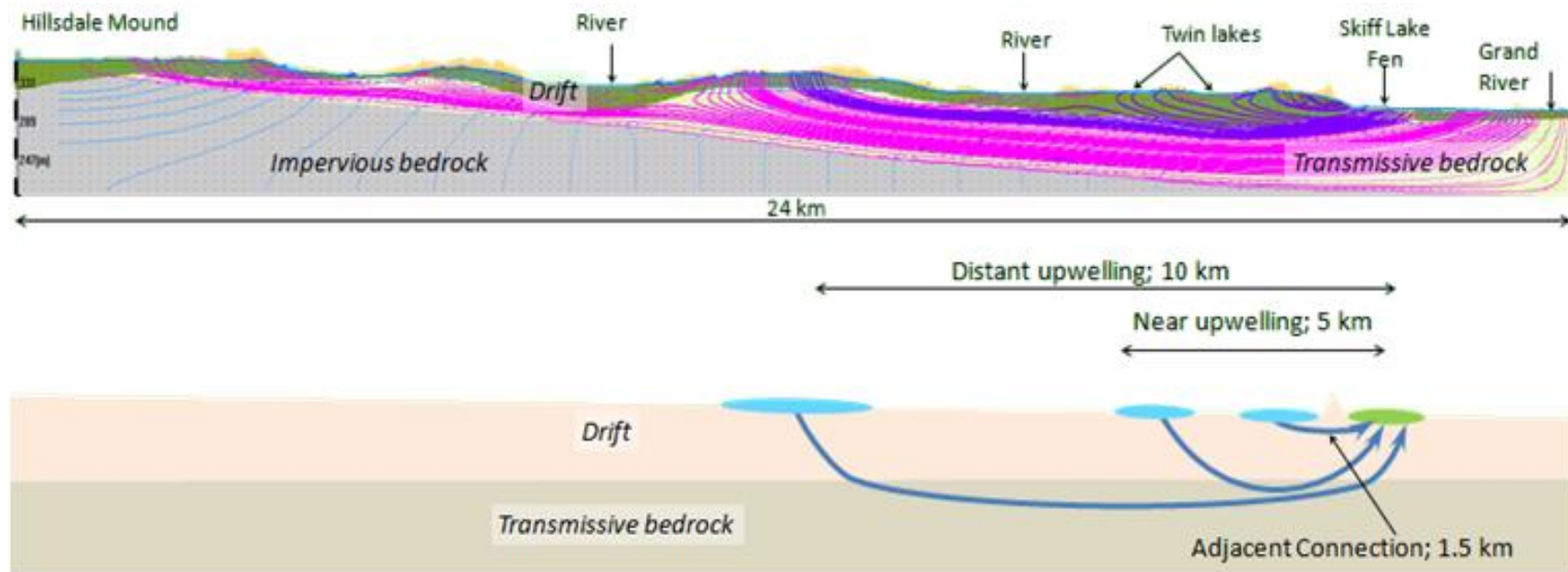


Figure 4.12 Example from Skiff Lake Fen - the fen site exhibits adjacent, local upwelling and sub-regional upwelling connections.

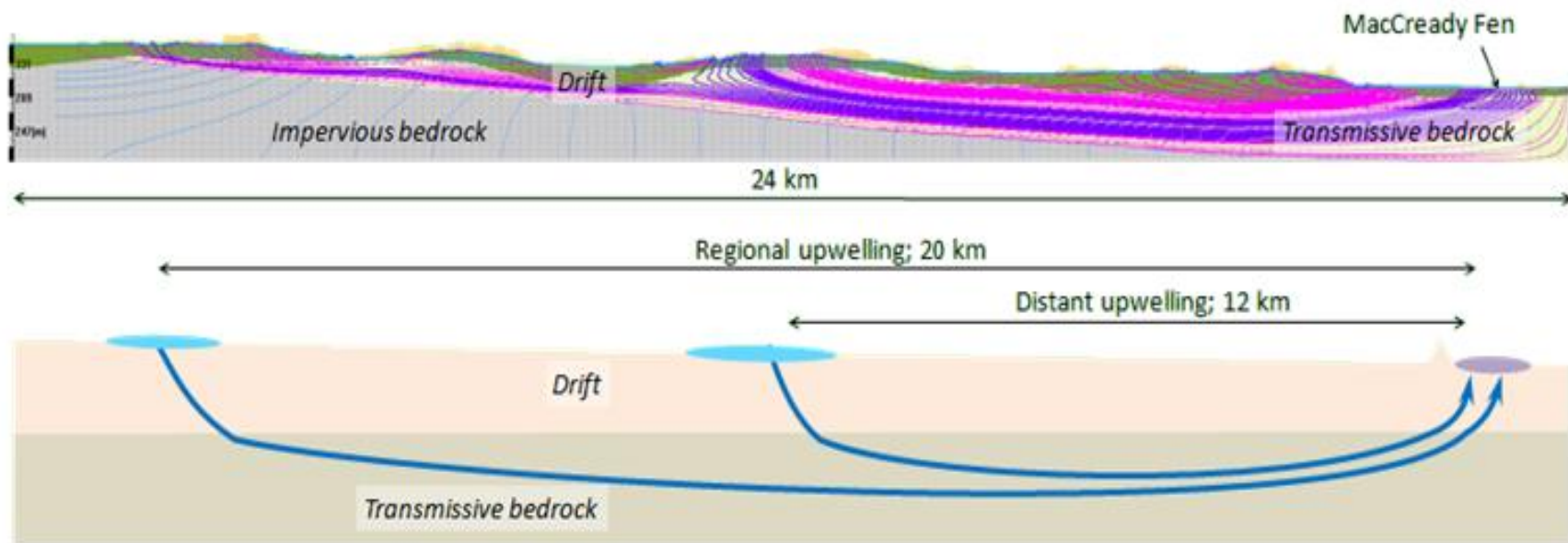


Figure 4.13 Example from MacCreedy Fen - the fen site exhibits regional and sub-regional upwelling connections.

Table 4.I shows the summary of investigated sites. Flow paths through drift aquifer are common to all 8 sites investigated with MS occurrence. Moreover, all but one of these sites (Turner Creek Fen) is not connected to the local shallow system. And all but one of the MS sites (McKibben Fen) does not seem to be receiving water from an upwelling connection, but this site is located very close to major sub-regional source.

Of the 19 modeled sites, six sites show little connection with the local shallow systems and seem mostly dependent on regional or sub-regional upwelling. Interestingly, none of these sites is connected to multiple sources of groundwater.

Of the 150 prairie fens in Michigan, only seven occur in glacial till. Two of these sites were included in detailed modeling. Both sites seem to exhibit only shallow connections to the local groundwater sources.

From the 8 modeled sites with MS occurrence, there seems no particular similarity in source water areas or delivery mechanisms. The ecological ranking (EO Rank) too does not exhibit any particular pattern/similarity with the groundwater delivery mechanism or source water areas.

Table 4.I Summary of modeled fen sites

Fen Site	Types of Sources & Connections				Flow- paths in Aquifer	Geological Landform	EO Rank	Satyr
	Adjacent	Upwelling	Confined	Cascading				
Liberty	L	S			D,B	PGO	A	Y
Skiff Lake	L	S,L			D,B	PGO	BC	Y
MacCready	L	R,S			D,B	PGO	-	
Dew Road	L				D	IMT	C	
Ives Road	L		R	R,L	D	PGO	A	
Butterfield		R			B	PGO	CD	
Spring-brook	L	L			D	PGO	C	Y
Paw Paw Lake	L	R			D	PGO	B	Y
Paw Paw Praire		R			D	ICO	BC	
Sarett	L	S,L	S		D	CL	C	Y
Monette		S			D	PGO	A?	
Silver Lake	L	L			D	IMT	CD	
Bowens M	L	R			D,B	PGO	C	
Turner Ck		S			D,B	PGO	BC	Y
Hill Creek		S			D	PGO	B	
McDonald		S			D	ICO	C	
Yankee Spring	L	L			D	PGO	BC	Y
Hall Lake	L	S		S,L	D	ICO	C	
McKibben	L				D	PGO	C	Y
Sources:	L = Local		S = Sub-regional		R = Regional			
Aquifers:	D = Drift		B = Bedrock					
Landforms:	PGO = Proglacial outwash		ICO = Ice-contact outwash					
	IMT = Ice marginal till		CL = Coarse lacustrine					
EO Ranks	As defined by Nature Serve (NatureServe 2002)							

MAJOR IMPLICATIONS OF FINDINGS

The above findings have various management implications. The regional sources of significance identified in the study need to be protected to preserve fens even when those are tens of kilometers away from the actual sites. Understanding of hydrological regime at statewide and regional scales can help coordinate statewide conservation efforts in a synergistic way to protect and manage prairie fens. The methodology presented in this research could also assist identify data needs and knowledge gaps at local and regional scales. The approach presented here for prairie fens may as well be applied to other groundwater dependent ecosystems.

Protection of Source Water Areas

Surface water bodies such as lakes and wetlands which make a groundwater source for a fen site need to be protected to protect the fen. A surface water body may be relatively small, but its surface water catchment may be large which might imply more regulatory limitations in the entire surface catchment of the source.

Groundwater contribution area for the source waters also need to be protected, however, unlike the surface catchment areas, which can be readily ascertained through topography, delineation of groundwater contribution areas would require hydrogeological investigations and/or modeling – making it expensive and time consuming.

Some regional and sub-regional groundwater sources may be linked to more than one fen site. Protecting such sources would protect multiple fen sites.

Fens connected to distant sources through distant and regional upwelling may have their source water areas in a distant and disjoint (from the fen) location. Yet, the capture zone in the

plan view may need to be protected to disrupt quality and quantity of groundwater within the path leading to the fen from the source.

Groundwater flow paths through the confined connections may be naturally protected through impervious layers between the fen and source water areas.

Basin Wide Perspective

Oakland Mound, Jackson Mound and parts of Hillsdale Mound identified in this study coincide with the Michigan Recharge area for southeastern Michigan as identified in a report by Michigan Department of Natural Resources and proposed as one of the Forest Legacy areas in the state (MDNR 2003). The comparison of delineation of groundwater mounds with proposed Forest Legacy area is shown in Figure 4.14. The areas delineated for mounds, therefore, are not only important of fens but also coincide with the known regions of ecological significance.

It is interesting to note in Figure 4.14 (bottom) that groundwater mounds are sitting across the regional surface water divides and are large enough to spread out in more than one political jurisdiction. The surface area over these mounds makes a contiguous region of hydrogeological and ecological significance overlapping political, topographic and hydrological boundaries. Hillsdale Mound, for example, spans seven counties in three states plus intersects watersheds of five major rivers in three different states (Grand, Kalamazoo, St. Joseph, Tiffin and Raisin rivers).

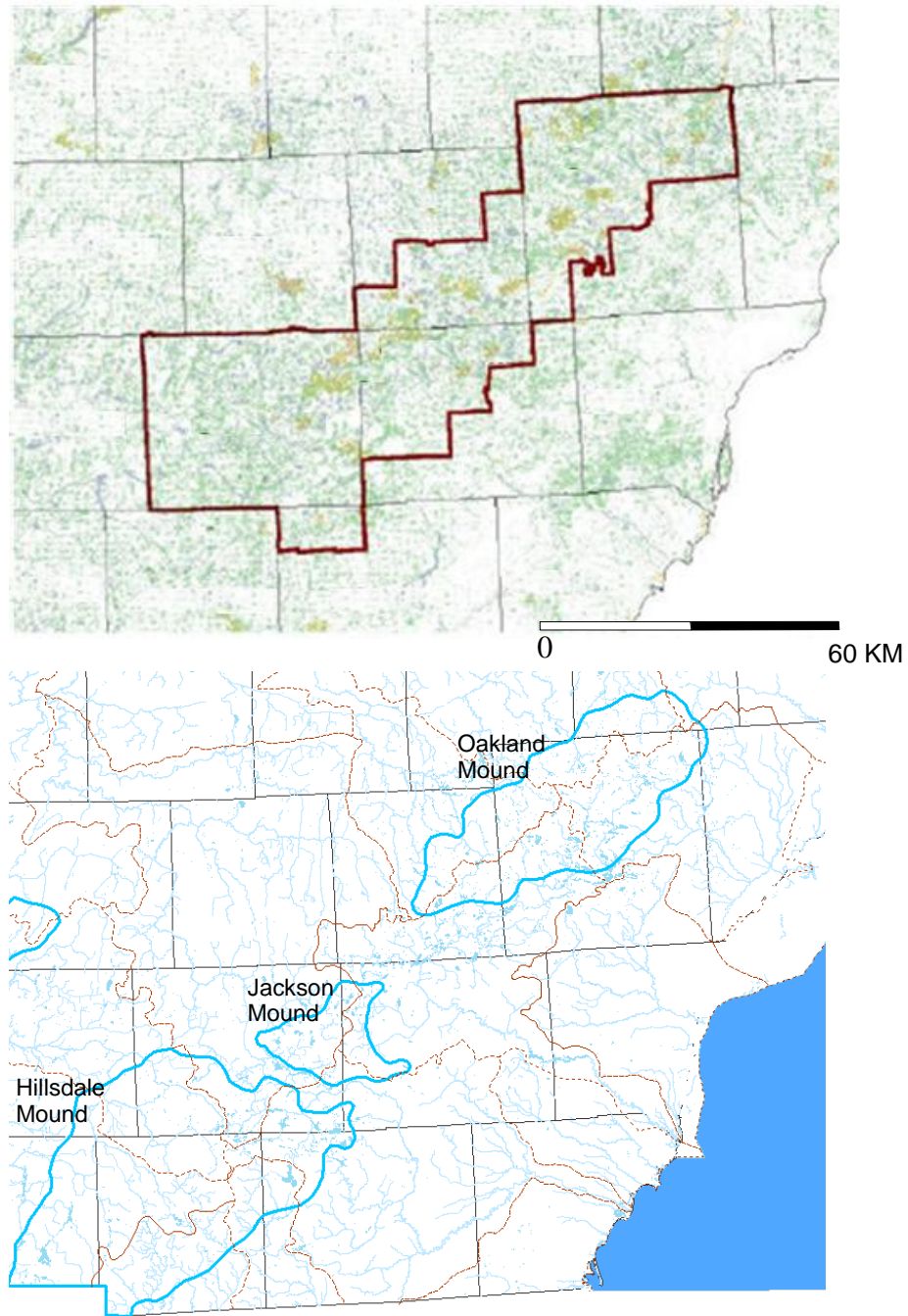


Figure 4.14 Michigan Recharge area proposed as Forest Legacy Area (MDNR 2003) [top]; Groundwater mounds in South-eastern Michigan [bottom] coincide with the proposed Forest Legacy Area.

Current paradigm of resource management along political boundaries is already outdated while the emerging trend of basin scale management (Environment Canada 2009; EU 2000; EU 2006; GLPF 1998; IJC 2009; NSW CMA 2004; Price et al. 2005; SOGW 2009) may also have to be given a thought for the situation where what happens within a buffer on the basin boundaries may not be best managed by dividing the critically important buffer zone along the topographic boundaries. The holistic management of these contiguous areas may pose administrative challenges whether managing areas along river basin boundaries or the political boundaries.

Another significance of the groundwater mounds identified in this study shows when glacial landforms are correlated to the occurrence of these mounds. The mounds generally coincide with the pervious glacial outwash deposits, flanked on either sides by less pervious surfaces made up by till plains and fine lacustrine landforms as shown in Figure 4.15. However, the presence of significant number of groundwater wells in the areas of till and fine lacustrine deposits indicates presence of more pervious glacial or bedrock formation under the till plains. While direct recharge to these aquifers through less pervious till layers may be limited, the groundwater mounds sitting between them in more pervious deposits and on higher elevations may be acting as the recharge ‘window’ to the aquifer systems in bedrocks/confined coarse glacial aquifers under the till plains and fine lacustrine surfaces. This possibility along Section AA’ in Figure 4.15 is shown in Figure 4.16 and can be explored further with more data and detailed modeling. The section was derived from GIS data.

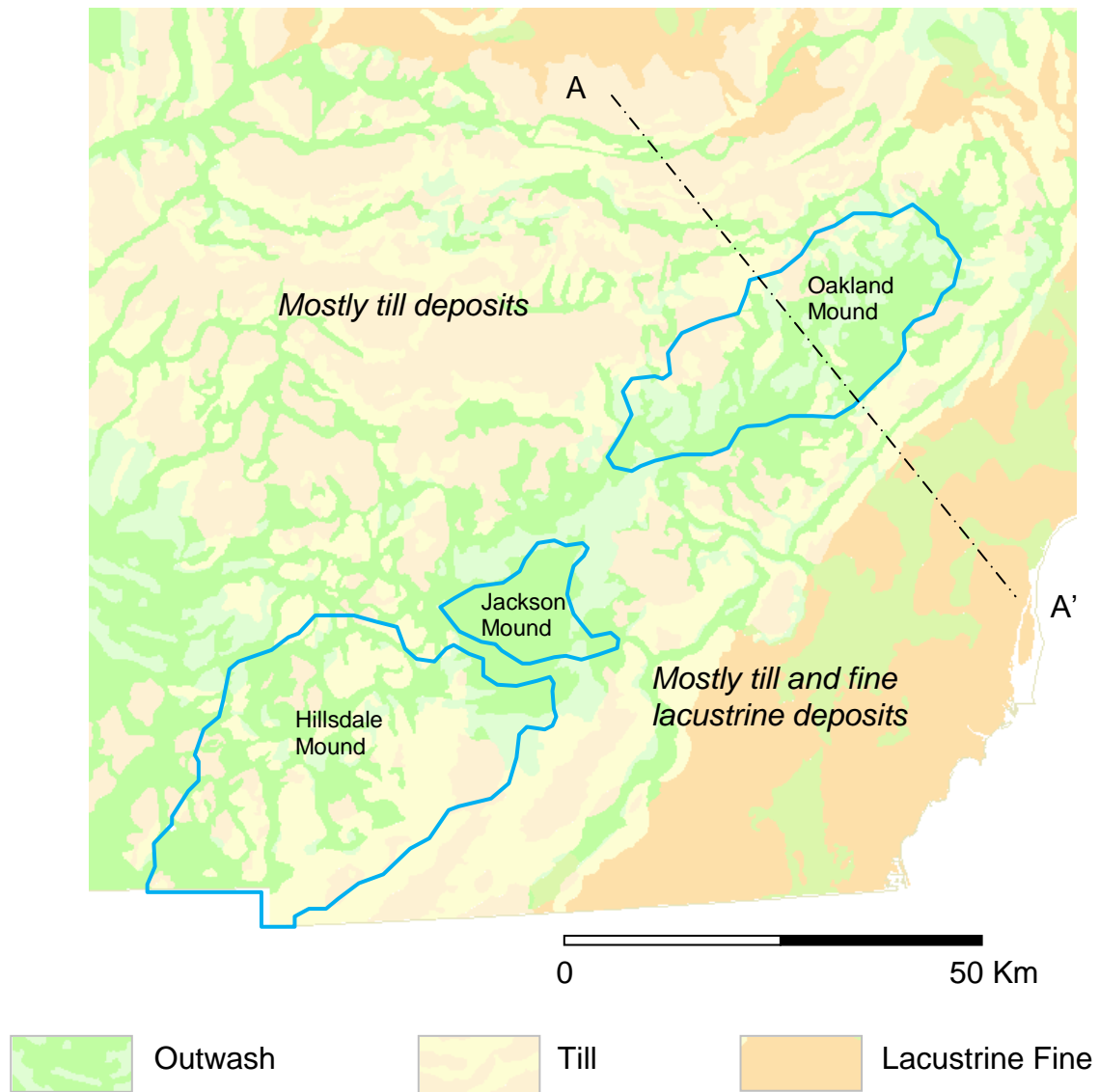


Figure 4.15 Glacial landforms and Michigan's recharge areas

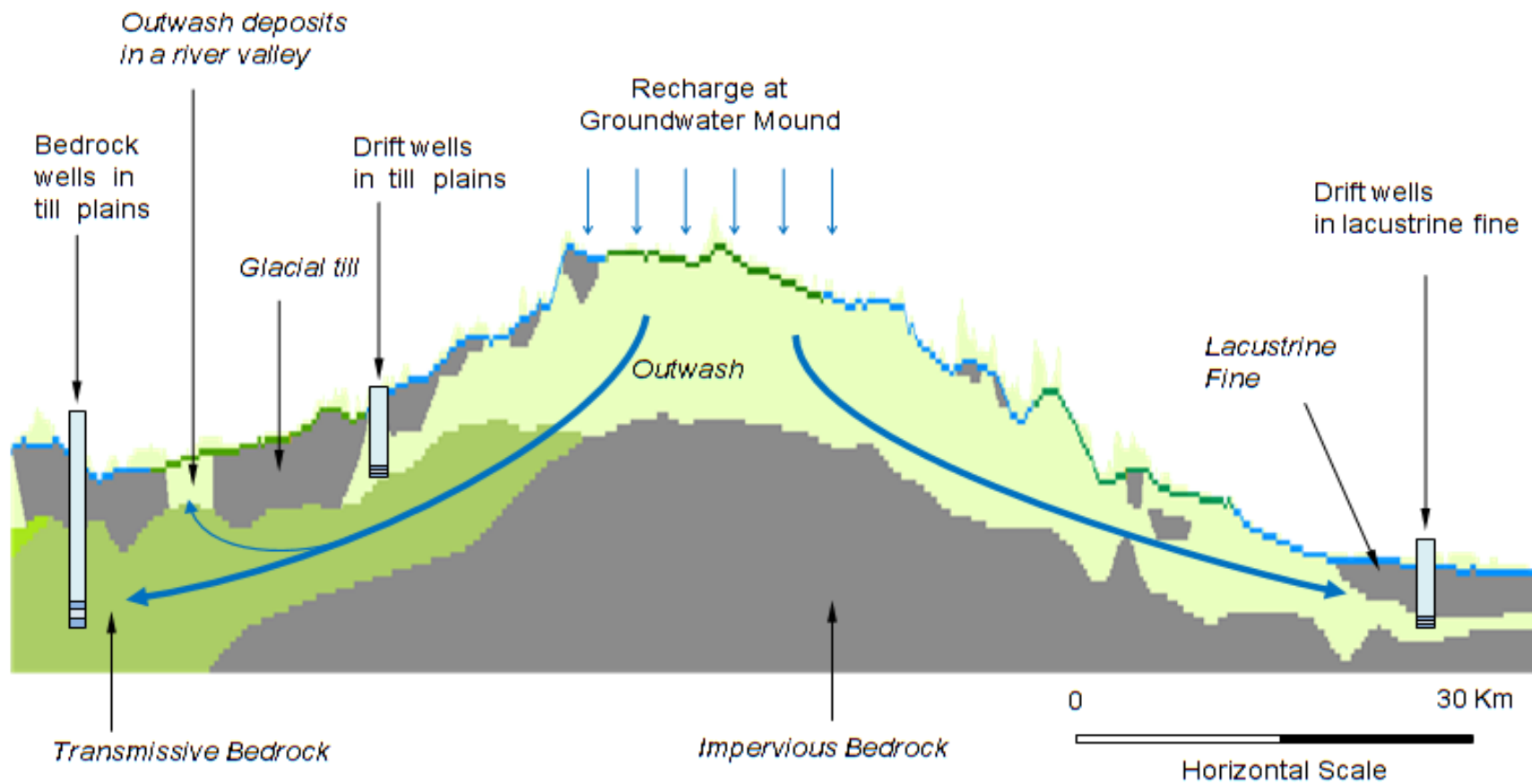


Figure 4.16 Recharge dynamics at basin-scale. Vertical exaggeration is 50x.

Policy, Management and Development

With source water areas of significance identified at regional scales, the *Policymakers* can make more informed decisions with regard to setting and enforcing laws and regulations for water resources management and to evaluate future land use management plans related to zoning and new developments. The *resource managers and planners* can become more effective in identifying/prioritizing areas/sites for monitoring, development, conservation, or protection. They can also be more effective in engaging the general public and informing high-level decision makers about the implications of a proposed development and the transport of contamination on source water areas. The *consultants* will be able to design more focused, cost effective analysis and monitoring networks to protect state's water resources and environment.

This research represents first systematic modeling study of prairie fen hydrology in Michigan, spanning across local, regional, and basin-wide scales, taking into account a large number of sites with diverse hydrogeological characteristics. We developed a basin-scale model for the entire southern Michigan basin, regional scale models for 9 regions, and site-specific models for 19 selected fens. We also developed vertical profile models to understand the groundwater delivery mechanisms from source waters to the fens sites. Following is the summary of significant findings from these multi-scale models.

SUMMARY OF SIGNIFICANT FINDINGS

- Although at local scale prairie fens look scattered, unrelated, or even accidental, on a regional scale they exhibit a clear, systematic pattern.
- The vast majority of the prairie fens are located around or at the foot of several large groundwater “mounds” at the intersection of major watersheds. These extensive mounds are critical, regional source water areas for Michigan’s aquifer systems, fens, and other groundwater-dependent ecosystems (e.g., cold water trout streams, and many unique plant and animal species);
- These critical regional mounds may play a disproportionally large role controlling the sustainability of groundwater resources and groundwater-dependent ecosystems and biodiversity in the Michigan basin;
- Groundwater flow patterns in the regional source water areas are complex and most fens are recharged from multiple groundwater sources.

- Prairie fens located seemingly far apart in different watersheds, different counties, or even different states may share the same regional source water areas.
- The data driven models reveal four distinct mechanisms of groundwater delivery into the fens:
 - *shallow connections* – groundwater recharge from local hills and surface water in lakes/wetlands at higher elevations adjacent to a fen may seep into the fen through shallow and relatively short groundwater flow paths. Time scale of groundwater flow along flow paths leading to fens can be up to a couple of years. The topography around the fens is often such that a natural ‘topographic dyke’ forms on their upstream sides, preventing significant direct runoff into the fen. This “dyke effect” essentially converts local precipitation/runoff into “groundwater” before it enters the fen.
 - *deep connections* - where source water recharge comes in contact with deeper glacial/bedrock formations before upwelling into the fen; Some fens seemed to have their groundwater source area tens of kilometers away from the site and are linked to an “unexpected” strong connection to the regional flow in addition to local flow. Shallow seeps/local hills may be more visible, but it is the regional flow paths that may be “pumping” steadily into these fens, through the deep aquifer, providing significant/continuous discharge of calcareous groundwater. Time scale of groundwater flow along flow paths leading to fens can be decades.
 - *confined connections* - where a distant source water recharge area gets connected to a fen through older outwash beds confined under recent till plains; Some fens seem spatially isolated from the ‘usual’ fen clusters in interlobate outwash region,

but these fens may be hydrologically connected to the regional recharge sources through confined connections over tens of kilometers. The residence times in confined connections can be in decades. The till plains also provide natural protection to groundwater flow paths from land-use perturbations.

- *cascading connections* - where groundwater sources directly linked to fens are dependent on other surface/sub-surface source waters; Just identifying a source area feeding the fen may not be enough when the identified source is further dependent on other sources. If a local source is dependent on a regional recharge zone far from the fen, then the regional zone cannot be ignored while managing the fen. Similarly, a surface water source connected to a fen is dependent on its surface catchment, making its entire catchment critical for the fen.
- groundwater flow times from regional/sub-regional source areas (5 to 25 km from the fen sites) to the fen sites ranged between 10 and 100 years; groundwater flow times from local source water areas (1 to 5 km from the fen sites) showed times ranging between 1 and 4 years; with timescales as these, the impacts of changing land use or climate on fens may be delayed, yet quite protracted once they are manifested.

SUMMARY OF IMPLICATIONS

Since water well records and other GIS data are now available for free virtually “anywhere”, our improved ability to use this data source creates new possibilities that have basin-wide implications for the management of fen ecosystems. By systematically making use of this readily available data, we have the potential to significantly reduce the cost of site characterization in the context of source water delineation and expand our “world view” by informing management practices from a “local site” to a “region”, a “watershed”, and ultimately

a “basin”, transforming “isolated, site-based actions” into “synergistic, multi-scale conservation”.

This research has significant practical implications and supports the need to reconsider the current priorities in prairie fen restoration strategies. In particular, the research suggests:

- Fen management must move beyond water’s (or ecosystem’s) edge to account for the impact of regional flow systems, if it is to be effective.
- Because of the connectivity of the basin’s groundwater systems, a few “smart” actions in key locations (e.g., regional source areas) could yield tremendous ecological return, with gains being more than additive.
- When we protect one strategic component(s) of a system, we are protecting many. When we protect fens and their upstream sources, we are also protecting other fens, aquifers, streams, lakes, fishes, and ultimately the Great Lakes
- A “damaged” or regionally-altered groundwater mound (e.g., by pollution, urbanization, agriculture, mining, climate change) could impact the entire water resource and ecological systems. Stressed fen communities can be an early warning for potentially much more grave consequences to come.
- The current often incongruent perspectives and fragmented responsibility of agencies make it difficult, if not impossible, to manage efficiently and holistically the entire fen ecosystem – the knowledge on regional hydrologic integrity of the systems would help inter-agency synergy.

Occurrence of fens in the regional aquifer recharge areas at the intersections of watershed boundaries implies that coordination across the river basins as well as the political divides and between water resources and ecological communities would be imperative for protection of fens.

This implies that management jurisdictions for protection of fens can neither be based on political boundaries nor can be based on (environmentally much preferred) river basin boundaries. A management approach across the river basins and political boundaries has to be thought of to protect the natural integrity in a holistic manner.

RELATING TO PREVIOUS WORK

Following is the comparison of the review of previous work, presented in Chapter 1, to the work conducted in this study, highlighting the improvements/additional contributions this study has made in the knowledge base related to modeling of fen hydrology.

- Both local and regional scales of groundwater dynamics were investigated in this study using the actual data. The nature of fen hydrology has long been recognized as multi-scale (Almendinger and Leete 1998b; GLPF 1998; Gorham 1957; Meyboom 1967; Siegel 1988; Wassen et al. 1990), however, groundwater models used to investigate hydrology of fens and wetland systems in most prior studies had been applied either at regional or at local scales only (Acreman et al. 2007; Acreman and Miller 2004; Batelaan et al. 2003; Cobb and Bradbury 2008; Gilvear et al. 1993; Grapes et al. 2006). In cases where regional dynamics had not been modeled, data limitation at large scales had been one of the major factors. The scales not addressed by models had mostly discussed by the authors only in an intuitive sense.
- This study is one of the first to focus on a larger number of fen sites in a large region making up a geographically contiguous flow regime, analyzing regional scales and also zooming in to local details for a large number of fen sites. Many previous studies have investigated hydrology for larger number of fens (Acreman 2004; Almendinger and Leete

1998b; Amon et al. 2002; Godwin et al. 2002; Halsey et al. 1997), however, these studies have generally investigated large scale regional dynamics surrounding many fen sites without zooming into the local details at specific sites. Few studies have covered both local and regional scales for multiple fen sites (Almendinger and Leete 1998b), but mostly these sites happen to be in disjoint regions, and therefore, a flow regime picture around a large number of sites had mostly been missing from these studies.

- To understand vertical dynamics of fen hydrology in a 3D sense, it is one of the first studies to choose vertical profiles based on horizontal delineation of flow paths, using data, rather than choosing them arbitrarily. Careful selection of boundary conditions for the profile models in this study were also based on the insights gained from the regional models for horizontal flow. Most prior studies which employed the use of vertical profile models have mostly chosen the profile sections arbitrary manner and have not connected the vertical flow dynamics to the regional flow systems (Bleuten et al. 2006; Grootjans et al. 2006; Loon et al. 2009).
- This study is one of the first to describe delivery mechanisms of groundwater to the fen sites using actual data at multiple scales, and have identified the fen sites exhibiting those mechanisms. Delivery or transfer mechanisms of groundwater from source water areas to the fens or wetlands have been discussed in previous studies (Acreman 2004; Amon et al. 2002; Meyboom 1967) but most of these studies have either used hypothetical situations in simulation models to explore the possibilities or have discussed the mechanisms with hydrogeologic intuition only.
- In this study we used statewide data to delineate subsurface hydrology across the river basins. The results from this study led to on-ground identification of source water areas

of regional significance. It has been well recognized that the focus of conservation of ecosystems should be shifted from the number of hectares lost or degraded to the alteration in environmental and hydrological variables at regional scale (GLPF 1998). Very few studies, however, have actually investigated connection of fen sites to the groundwater dynamics at river-basin scales. Most regional studies had been based on hydrologic intuition and judgments rather than the actual data at larger scales (Acreman 2004; Amon et al. 2002; Halsey et al. 1997). In many prior studies the conservation potential has been considered higher for the sites with less significant modifications in the recharge areas of their source waters (Bedford 1999; Koerselman 1989; Wassen et al. 1990; Winter 1998), but few studies have actually identified those source water areas, especially if they are regional in nature. Data limitations at multiple scales had mostly been the major limiting factor (Price and Waddington 2000).

- In this study we not only delineated basin-wide regional groundwater system for southern Michigan but also identified connections between regional and local groundwater sources for 19 selected fen sites using actual data at every scale of investigation. The likelihood that a fen receives groundwater from more than one flow systems has been intuitively discussed in many previous studies (Almendinger and Leete 1998a; Amon et al. 2002; Bedford 1999; Bedford and Godwin 2003), but it is difficult to find the work which actually shows such hydrological connections and delivery mechanisms at specific sites using actual data at multiple scales.
- This is one of the first studies in Michigan (Great Lakes region) which have vividly linked the local and regional dynamics of sub-surface flow regime to protect prairie fen ecosystems across the state by seamlessly integrating the local and regional scales. A

“Great Lake Expert’s Roundtable” (Great Lakes Protection Fund 1998) stressed to shift the focus of current conservation efforts for ecosystems, which are too disjointed and focused too much on local/visible symptoms, to protecting the underlying processes, the functionalities, and the fundamental biological engine. Not many studies could be found which have investigated the fundamental processes at multiple scales to help protect, restore or enhance knowledge on the underlying hydrological processes on which the ecosystems are dependent.

STRENGTHS AND LIMITATIONS OF THE STUDY

One of the major strengths of this study is the use of existing GIS-data which made multi-scale hydrological investigations/modeling possible in a cost effective manner. However, following are the major limitations which could not be adequately addressed in the models presented in this study:

Models Validation

Data from statewide GIS databases was used to built models and draw conclusions. However, no independent datasets were available to validate modeling results. Of all the sites presented in the study, site visits were made only to Liberty Fen, Skiff Lake Fen, MacCready Fen and Ives Road Fen. The visits aimed only getting the ‘look and feel’ of the sites rather than elaborate data collection. There were signs of upwelling of groundwater in lakes and streams. Artesian wells were observed in the area. Presence of marl deposits suggested groundwater from bedrock formations feeding the streams and lakes. Vegetation observed in some lakes/wetlands was typically ‘groundwater fed’ (observed by Dr. Steve Hamilton – from Kellogg Biological Station). Though these observations seemed consistent with the modeling results, it was not

possible within the study resources to further investigate and collect sufficient data that could be used to validate modeling results.

Limitations of Profile Models

The profile models presented in the study are part ‘data-driven’ and part ‘process-driven’. The boundary conditions and water-table profiles in the models were acquired from data interpolation, while the particle tracking were based on process based simulations. The profiles were selected along the regional flow trends with an underlying assumption that no flow takes place across the profile. The shallow systems, however, were not always flowing parallel to the deeper systems, rendering the profile models less certain for the shallow systems. Careful consideration was given to this limitation while building the models and interpreting the results. For example, a shallow water-table mound would flow in all directions, but within the profile model, it is only allowed to flow parallel to the profile, thus forcing more water along the profile than it would actually do. Attempts were made to identify such situations along the chosen profiles. Where possible, the water-table profiles acquired from data were modified to mitigate anticipated variations and/or considerations were made while interpreting the model predictions. Consequently:

- water balance estimates along the profiles were not done for the models, nor the proportions volume of water from multiple sources seeping into the fens estimated as they could be highly uncertain without independent validation data; and,
- flow patterns presented in the profile models, therefore, are more qualitative in nature and may be taken as ‘likely possibilities’ along a profile rather than predicted flow.

Moreover, no measured data were available on porosity of glacial landforms or the bedrocks which was critical to establish travel times of groundwater from the sources to the fen sites. Using a range of porosity values between 0.1 and 0.3, travel times were estimated in the models which only present a possible range. Without validation data, predicted travel times of groundwater from a source to a site may be in a wide range of error.

Local or shallow flow systems connected to the fens were not adequately represented along the profile models because the profiles were chosen along the major regional flow lines while the local systems' flow paths were all around the fens. The profile models only captured the local systems along the major regional flow paths.

Prescribed head boundaries driving the vertical flow in the profile models were obtained from the delineation of local/shallow flow systems around the fen sites. These systems were indirectly delineated by matching surface elevation data to a number of wetlands, lakes and streams around the fens. This methodology may not be possible where surface water features are not extensively available. Luckily for fen, they mostly exist in hummocky topographies surrounded by lots of valleys and depressions filled with water.

Given all the shortcomings identified above, this study may be taken as a 'first-cut' investigation which only employed the available data and revealed the probable source water areas and possible delivery mechanisms of groundwater to the fen sites. The models from this study can be used to guide multi-scale site specific investigations/data collections to validate these models.

RECOMMENDATIONS FOR FURTHER STUDY

In this study we modeled only 19 of the 150 prairie fen sites in the state, out of which only 8 were those with MS occurrence. It is recommended to model all of the remaining fen sites and identify possible source water areas across the state. With all sites modeled, the hydrological and other characteristics of sites with MS can be compared with other sites and statistical inferences could be drawn to recommend sites for re-introduction of species and to protect the existing sites.

The existing data from GIS databases can bring us thus far. Site specific data on fen chemistry and outflow may be collected to validate source water locations and do the water balance analyses to determine the share of groundwater contribution from multiple sources.

When all fen sites across the state are modeled, a complete inventory of fen sites can be made with following information:

- What is the groundwater contributing area for this fen?
- Is there a strong regional source connected to the site?
- How long does it take for water originating from the regional source to reach the fen?
- How many other fens share this same regional source?
- How is the regional water quality in this area?
- Which fens seem to be hydrologically more sustainable?
- Where should we monitor to be most effective in protecting a fen?
- Where should we monitor to be most effective in protecting a large group of fens that share the same regional source?
- What is the land use pattern in the groundwater contributing areas? What potential contamination sources exist in these areas?

- How will the contamination spread if a spill occurs? How fast? Will it impact the fens?

For the fens which were historically occupied by MS, following may be investigated:

- What has changed hydrologically at this site?
- What common changes do fens historically occupied by MS share?

There are possibilities of discovering correlation of fen hydrology with its other characteristics (e.g. EO Rank), but such correlations were not explored because the number of modeled sites were too few to yield statistically significant conclusions. Better statistical conclusions may be drawn from a full inventory of modeled sites, such as:

- Is a high quality fen often associated with a very small surface water catchment?
- What type of topography and geological conditions create the most stable groundwater environment?
- How does local and regional hydrology interact to control the ecological integrity of a fen ecosystem?

CLOSING REMARKS

This study was aimed at investigating subsurface hydrology for prairie fens in southern Michigan so that these unique ecosystems can be protected with more informed science. In the process we investigated the hydrology at multiple scales and modeled 19 sites in detail. Existing GIS datasets were used for groundwater modeling. The systematic, multi-scale study yielded critical insights that support the need to consider linkages between local and regional flow regimes.

The basin wide connections in sub-surface hydrology found in this study, on one hand, pose new challenges and require a paradigm shift in the way the fen sites are currently being managed, but on the other hand, these findings open up new opportunities for integrating and coordinating conservation efforts between different agencies in a holistic and synergistic way. Administratively more coordinated and scientifically more informed conservation activities will benefit the regional resources on the whole.

With current advancements in databases and computing power, there lies an opportunity that is unprecedented to protect and manage our ecological future and systematically enhance the conservation effort of the Great Lakes States and beyond.

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