

**Delineation of areas contributing groundwater to springs and wetlands
supporting the Hine's Emerald Dragonfly, Door County, WI**

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By

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Abstract

The coastal springs and wetlands of Door County, Wisconsin, provide rich habitat for the highly endangered Hine's emerald dragonfly. Understanding the source of groundwater discharging at the springs is critical to evaluating how local land-use decisions might impact the springs and to future efforts at groundwater and spring protection. This study delineated surface areas contributing groundwater to eleven sites understood to be critical Hine's habitat in Door County. Delineations used a combination of soil water-balance modeling and simple groundwater flow modeling to determine contributing areas. Contributing areas ranged in size from 0.2 to 11.4 square miles. Shallow groundwater flows through a fractured dolomite aquifer. Predicted groundwater velocities are extremely high (up to 40 ft/day) and residence times can be quite short (less than two years at most sites). Geochemical and isotopic data collected at several springs are consistent with model results. The scope of the project did not allow detailed study at any one site, but instead focused on an overview study of many sites. The results represent a starting point for more refined studies at specific critical sites.

Introduction

Background

The coastal springs and wetlands of Door County, Wisconsin, provide rich habitat for the highly endangered Hine's emerald dragonfly. The U.S. Fish and Wildlife Service, Wisconsin Department of Natural Resources, the Nature Conservancy, and biologists from the University of South Dakota are all actively engaged in research and other actions to better understand and protect the Hine's emerald. Despite these efforts, a significant risk to the Hines emerald has remained poorly understood. Development and disturbance in upgradient recharge areas has the potential to alter groundwater flow to the springs and wetlands that provide habitat for the Hine's emerald. Understanding, maintaining, and protecting groundwater flow to these coastal areas is essential for protection of the species. Delineating areas contributing water to the springs is the first step in this process.

This study has developed preliminary estimates of the areas contributing groundwater recharge that may affect eleven different Hine's emerald dragonfly habitats in Door County (Figure 1). Recharge-area delineations include a combination of water-balance and groundwater-flow modeling supported with field measurements of water levels and baseflows. We estimated groundwater recharge rates using a GIS-linked soil-water budget model. Contributing-area delineations were made using a series of relatively simple groundwater flow models calibrated to field measurements of surface water and groundwater levels and surface-water discharges. Measurements of spring chemistry, temperature, and isotopic indicators assisted in verifying model results and will provide baseline data currently lacking at the Hine's emerald sites.

Dragonfly ecology

The Hine's emerald dragonfly was federally listed as an endangered species in 1995. It is currently known to exist in only four states (Illinois, Michigan, Missouri, and Wisconsin) and was recently found in Ontario. Its habitat is largely restricted to spring-fed wetlands in areas of dolomite bedrock. The survival of the species has been threatened by habitat destruction, degradation and fragmentation.

Adult female dragonflies lay eggs in water or mud. When the eggs hatch the larvae spend up to five years in small streams and wetlands. Only after this multi-year period as larvae dwelling in shallow surface water do they transform into adults that are recognizable as dragonflies. This adult stage is comparatively brief, lasting no more than six weeks in a period from June through August. They capture prey in flight, feeding actively during daylight hours. Adults require complex wetlands with a forest edge and cool shallow water for foraging, roosting, and reproducing.

Acknowledgments

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Hydrogeology

Door County's principal aquifer is composed of fractured, solution-weathered Silurian age dolomite. Extensive research has been conducted on the hydrogeology of the aquifer (e.g., Sherrill, 1978; Bradbury, 1989; Bradbury and Muldoon, 1992; Muldoon and others,

2001). The dolomite strata dip gently to the east, thickening from just tens of feet in the extreme southwest on the Green Bay shore to as much as 500 ft along Lake Michigan in the northeast of the county. Soil cover over the dolomite is frequently very thin, particularly in upland areas, and rainfall and snowmelt can infiltrate rapidly. Soil thicknesses increase in occasional buried bedrock valleys, particularly along the Lake Michigan shoreline. North of Sturgeon Bay, springs, streams and wetlands are typically restricted to these depressions in the bedrock surface.

The dolomite is very permeable but has relatively little storage. Recharge is conducted rapidly into the aquifer by vertical joints. Groundwater moves laterally along bedding plane fractures, many of which have been enlarged by rock dissolution. Muldoon and others (2001) showed that discrete near-horizontal zones of high permeability may be continuous over distances of as much as 10 miles.

Groundwater discharge occurs in springs, wetlands and into Lake Michigan and Green Bay. The majority of springs in Door County occur as focused discharge through a loose cover of sediment into a spring pool or stream bed. The visible turbulence in the sand or peat is commonly called a boil. Door County's springs have not been studied in detail, though it is assumed that most occur where highly permeable bedding plane fractures or joints intersect the bedrock surface. In many of the Hine's emerald habitats, we infer that a bedding plane fracture opens to a buried depression in the bedrock surface. The nature and volume of these springs suggests that they are not regional discharge points receiving far-field recharge transported as deeply circulating groundwater. We consider it more likely that most identified springs receive relatively local recharge conveyed in the shallower intervals of the dolomite aquifer.

Study Methods

Site selection

This study focused on eleven wetlands in Door County that are either confirmed or probable habitats for the Hine's emerald dragonfly (Figure 1). Other suspected habitats occur in Door County but were not included in this study. The physical bounds of each site were determined by the Wisconsin Department of Natural Resources and Dr. Daniel Soluk of the University of South Dakota. The sites vary in size from discrete spring complexes of several hundred square feet, to many mile-square wetland complexes known to include numerous breeding sites. Each site is described in more detail later in this report.

We divided the habitats in this study into two tiers based on site importance (Table 1). The bulk of field data collection and project resources were allocated to the first tier sites. The field data permitted more detailed model design and calibration, therefore contributing area estimates for these sites carry more confidence. Modeling of second tier sites made the best use of available data resources, but are in general less rigorously calibrated and therefore carry less confidence.

Table 1 Studied Habitats in Door County

| First Tier Sites | Second Tier Sites |
|----------------------------------|-----------------------------|
| Mink River Estuary | Big Marsh/Washington Island |
| Three Springs Creek | Ephraim Swamp |
| North Bay Marsh | Arbter Lake |
| Reiboldts Creek/Ridges Sanctuary | Kellner Fen |
| Baileys Harbor Swamp | Gardner Swamp |
| Piel Creek | |

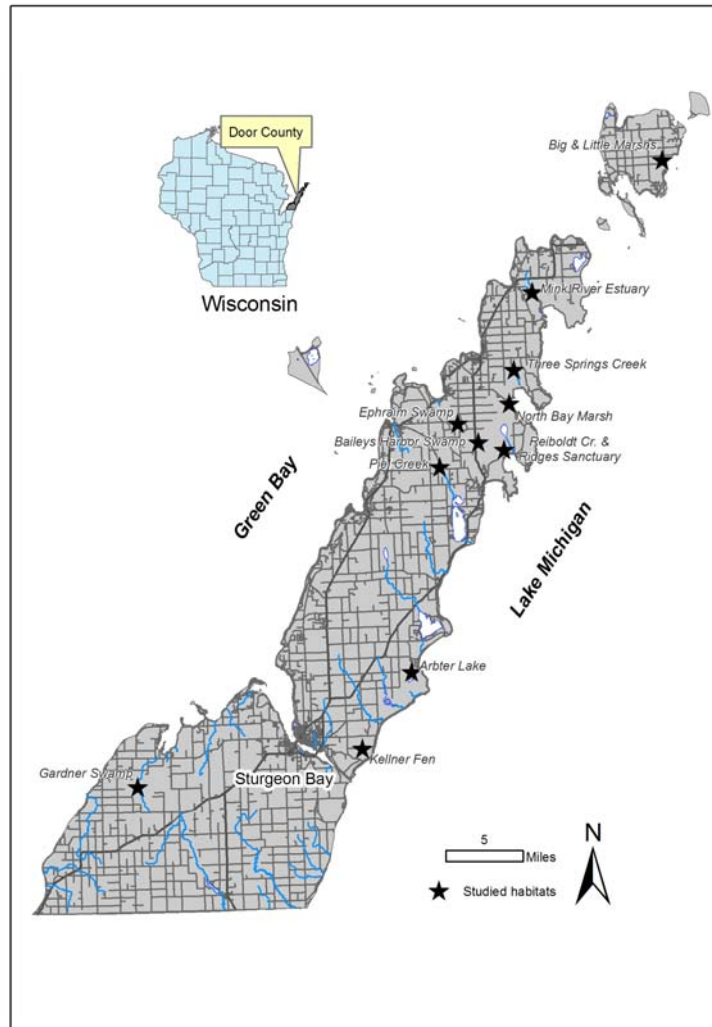


Figure 1. Locations of Hine's emerald dragonfly sites investigated in Door County.

Field investigations

We carried out a variety of field investigations designed to assist in model design and calibration, and to improve our understanding of the hydrogeologic system at the HED habitats. The major field tasks included habitat reconnaissance, stream-flow gauging, groundwater-level measurement, and spring sampling. Stream gauging and water-level measurement were focused near the first tier sites in northern Door County. Gauging was completed using an electromagnetic flow-meter. Water-level measurements were taken using a sonic water-level probe. The sonic probe allowed easy measurement of private water wells without the risks of contamination and tangling associated with a tape.

Laboratory samples were collected at only three HED habitats where focused spring discharge made it feasible to collect samples of discharge water and not standing surface water. Samples from these locations (Mink River, Three Springs Creek and upper Reiboldt Creek) were collected in both late November/early December and in early April. Samples were submitted to the University of Wisconsin Soil & Plant Analysis Lab in Madison for analysis of major ions, and to the Environmental Isotope Laboratory at the University of Waterloo, Ontario, for analysis of tritium, oxygen-18 and deuterium.

The WGNHS also completed a geophysical survey near the Reiboldts Creek habitat in the vicinity of Old Lime Kiln Road, in order to better understand the nature of the bedrock surface beneath the wetland habitat. The geophysical study is discussed in an appendix to this report.

Files relating to the field investigations have been archived at the WGNHS as a product of this study and are available for use by others. The files include further explanation and detailed results.

Recharge estimation

To estimate the quantity and spatial distribution of recharge we applied a soil-water balance model divided into daily time steps across a spatial grid (Dripps and Bradbury, 2007). The model uses common GIS coverages as inputs: soil hydrologic group, available water storage, land use, and overland flow direction. The flow-direction input was derived from a highly detailed digital elevation model that we generated using LIDAR (LIght Detection And Ranging) data furnished by Door County. We ran the model for the entire county on a 50-foot grid spacing, simulating recharge with daily precipitation and temperature data for four different years that approximated the median annual precipitation (2 different years), and the first and third quartiles (1 year each). Climatic data were acquired from the Wisconsin State Climatology Office in Madison. The model output for each run predicted cumulative monthly and annual and groundwater recharge for each cell. The two median model runs were averaged for the results and maps presented in this report. The accuracy of the predicted recharge values remains uncertain and are suspected to be biased low (i.e., more recharge is occurring than predicted). However, the model output is useful at identifying spatial trends and regions of preferential recharge. For ease of use by the public, the numerical recharge results have been simplified into a three-level system of recharge potential: low (0-3.75 in/year), medium (3.75 - 4.75 in/year) and high (greater than 4.75 in/year). The

statistical distribution of recharge predicted by the model is biased by numerous unreasonably high values (a model defect). However, the qualitative high/medium/low designations approximately divide the predicted recharge into thirds by area.

The recharge model files have been archived at the WGNHS as a product of this study and are available for use by others. The files include further explanation of model design and implementation.

Groundwater modeling

To estimate the contributing area for each Hine's emerald dragonfly habitat, we developed a series of groundwater flow models constructed using the GFLOW groundwater modeling code. GFLOW (<http://www.haitjema.com/>) simulates steady groundwater flow in two dimensions using mathematical analytic elements (linesinks) to represent hydrologic features such as wells, streams, wetlands, and springs.

To simulate groundwater flow in Door County, we constructed four different models representing: 1) Washington Island, 2) northern Door County from the Piel Creek habitat north to the Mink River habitat, 3) central Door County encompassing the Arbter Lake and Kelner Fen habitats, and 4) southern Door County encompassing Gardner Swamp. The northern Door County model included each of the first-tier sites, and was the most detailed in construction and calibration.

Models included streams and lakes as line sinks, digitized as a simplified map-view of the study area. Line sinks are assigned elevations, extracted from the digital elevation model, or interpreted from USGS 7.5 minute topographic maps. Models were divided into zones (termed inhomogeneities in the GFLOW environment) in order to vary hydraulic parameters. Zone areas were generally defined to reflect distinct terrains such as wetlands and uplands where recharge and aggregate hydraulic conductivity would be expected to differ.

Models were calibrated to match head and surface-water flux targets. Head targets included water-level data gathered for this study, data extracted from investigation reports of various contaminated sites in the county, and data reported by the USGS in their online database. The majority of surface water flux targets were based on field measurements made for this study in the late summer and fall of 2006. Additional gauging data was acquired from the WDNR's *2003-2004 Door Peninsula Baseline Monitoring Report*.

GFLOW models are powerful tools; however, they require great simplification of the true hydrogeologic complexity and assume steady-state flow. Door County's groundwater system has significant seasonal transience and vastly more heterogeneity than a computer model can represent, particularly at a regional scale. It should be recognized that no single groundwater model can be relied on to fully represent a hydrogeologic system. For this project, a confident estimate of contributing areas required multiple scenarios, not just one model. For each model area, a dry season and wet season model were created to bracket potential seasonal fluctuations. For the first-tier habitats, we

completed three dry season and three wet season models, each considered a reasonable representation of the groundwater system. The differences between the model estimates in the various scenarios represent both seasonal variation and uncertainty in the model design and calibration.

The models were calibrated using the automated parameter estimation routine PEST (Dougherty, 2004). Several realizations were completed for each model. For the northern Door County model, three different low-season calibrations were performed with varying bounds set on allowable recharge. To simulate wet-season conditions, recharge was raised in each simulation in increments until wet-season head calibration targets were reached. Because far fewer reliable calibration targets were available for wet-season conditions, a systematic calibration at wet-season conditions was not possible. In total, the northern Door model area is represented by six different model realizations, three dry-season and three wet season. The other models areas (each for 2nd tier sites) each include two model realizations, one dry-season and one wet-season.

Contributing areas for the habitats were estimated in each model realization using reverse particle tracking. GFLOW traces the path of groundwater backwards from a designated point to wherever it entered the aquifer as recharge. By this method it is possible to bound the area in which recharge entering the aquifer may discharge into a discrete habitat area. Figure 2 illustrates the contributing areas predicted for six simulations at the North Bay Marsh habitat. Each area in the figure represents the results of one simulation using different but equally reasonable sets of model parameters. The predicted areas typically varied only slightly between model realizations, with the greatest variation occurring at the upgradient extremes. The estimated contributing areas shown in this report are aggregate areas, encompassing the areas predicted in all model realizations. Figure 2 illustrates the process for designating the aggregate contributing area (shown with dashed line). Aggregate areas encompass the areas predicted in each simulation. Where contributing areas thinned to less than 100 ft in width, the peaks were excluded. Model uncertainty was too great to justifiably include areas at that level of detail. Aggregate contributing areas include the region between the upgradient peaks. We assume that seasonal shifts in water table are gradual and therefore that the upgradient peaks sweep across the upgradient region between the predicted extremes.

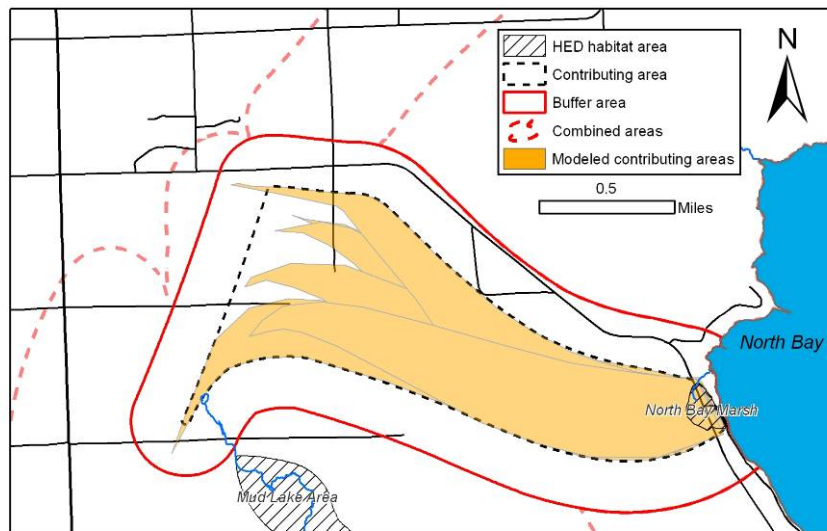


Figure 2. Contributing area for the North Bay site, illustrating the results of several model simulations and aggregated area. See text for details.

Results

Modeling results

The primary product of this study is a series of eleven contributing area maps developed for the Hines emerald dragonfly habitats (Appendix A, figures A1-A11). The areas shown in the appendix figures are also available as GIS files for incorporation into other geographic images. Each figure contains two views of the same region, illustrating different aspects of the study findings. The top views show recharge potential, and the bottom views show water table contours. The following section describes the elements shown in the figures, and discusses how they should be interpreted.

Wetland evaluated (hatched region). The wetland area evaluated is a region containing one or more HED larval habitats, as designated by the WDNR or Dr. Daniel Soluk of the University of South Dakota. Each area contains one or more locations of groundwater discharge, either focused at springs or distributed in wetlands or along streams. In the models, all groundwater flow that enters these areas is considered potential groundwater discharge that may affect HED habitat.

Contributing area (dashed black line). The contributing area is the model-predicted contributing area for a given HED habitat area. It encompasses the regions predicted by all model simulations for that habitat. Water infiltrating into the ground in the contributing area may potentially discharge within the respective HED habitat. Groundwater pumping, bedrock blasting, contaminant release or physical alterations to the hydrologic setting (such as construction projects that may increase impervious area or construction of detention basins) may affect the quantity and quality of water discharging in the HED habitats. Because of model limitations, it cannot be said that all water

infiltrating in this region will discharge within the habitat. Though it cannot be quantified, we expect that the closer a location within the area is to the habitat, the more probable it is that infiltration occurring there will impact the habitat.

Buffer areas (solid red line). The buffer area is a region extending 1000 feet beyond the contributing area. Though the area within this buffer was not predicted to be a contributing area by any model simulation, we recommend considering the buffer as potential contributing area. There are two major reasons for creating this buffer: 1) The model is imperfect and may potentially be in error on the scale of 1000 feet; and 2) In many instances rainfall or snowmelt occurring outside the contributing area may travel into the region as runoff (in road ditches, for instance) and infiltrate within the contributing areas.

Combined areas (dashed red line; only present on some figures). The combined areas show the aggregate contributing area and buffer for all HED habitats. The combined area is not present on figures showing isolated habitats, such as the Mink River. In the region between Baileys Harbor and Sister Bay, however, the contributing areas and buffers for the different habitats in that area commonly adjoin or overlap. Overlap occurs because we are including the results of multiple simulations. In these overlapping areas, infiltration may reasonably discharge at more than one habitat.

Recharge potential (color shading in top figure). Recharge potential is a qualitative representation of the recharge model output. Given evenly distributed precipitation and snowmelt, the three levels of recharge potential (high, medium and low) indicate the amount of water that is expected to infiltrate and recharge groundwater. Areas of high recharge potential (orange) are typically areas of thin soil cover, where the greatest infiltration rates are expected. Low recharge potential areas (blue) typically have thicker soil and greater density of vegetation, and therefore are expected to significantly reduce the quantity of groundwater recharge. Medium recharge areas are intermediate. The high/medium/low categories are also intended to rank the particular regions within the contributing areas according to the risk they may pose to the HED habitat.

Water table contours (blue dashed lines in bottom figures). The water table contours show the model-predicted water table from the dry season calibration. For the northern Door County models (from Piel Creek north to Mink River), the water tables are generated from the best of three different models calibrated to dry season targets. Contour elevations are in feet above Mean Sea Level.

The estimated contributing areas varied from as little as 0.4 square miles (Arbter Lake) to 11.4 square miles (Reiboldt Creek and Ridges Sanctuary). Table 2 indicates the size of the contributing areas. Table 2 also gives a qualitative assessment of the variability of the contributing areas between scenarios – the difference in the areas predicted by model scenarios run with dry-season recharge, wet-season recharge, or alternate calibrations. High variability suggests that the predicted result is highly sensitive to seasonal variation or to slight changes in model parameters, and thus carries greater uncertainty than models

in which the predicted contributing area remained essentially the same in all model scenarios.

Table 2. Summary of contributing area estimates for HED habitats.

| Habitat (contributing area size) | Tier | Scenario variation | Comments |
|---|------|-----------------------|---|
| Piel Creek (0.9 square miles) | 1 | high | The habitat is a wetland at the head of Piel Creek. Though the predicted contributing area is relatively consistent among scenarios, the models frequently predict that the habitat is dry (receives no discharge) in dry seasons. Seasonal variation is great here, and may not be adequately represented by the models. |
| Mink River Estuary (5.2 square miles) | 1 | low | The habitat includes a large wetland with many springs. The habitat area was extended to the mouth of estuary based on observations of D. Soluk. The habitat receives surface water from the Mink River north of the contributing area in wet seasons; dry season model scenarios show the river dry north of Highway 42. |
| Three Springs Creek (1.2 square miles) | 1 | high | The habitat includes a major spring complex that forms the perennial head of Three Springs Creek. Some model scenarios show all flow entering from the southwest (i.e., the northwest contributing area lobe is absent). The habitat receives surface water from the upper reaches of Three Springs Creek in wet seasons. |
| North Bay Marsh (0.9 square miles) | 1 | medium | The habitat includes a wetland adjacent to North Bay. Discharge to this wetland may cease in the driest months. Scenario variation is greatest at the upgradient maximum; near-field estimates are consistent. |
| Reiboldt Creek and Ridges Sanctuary (11.4 square miles) | 1 | medium | The habitat includes a large region of spring-fed wetlands containing numerous important HED habitats. Scenario variation is greatest at the upgradient maxima; near-field estimates are more consistent. Most potential surface water inputs are fully contained in the groundwater contributing area. |
| Ephraim Swamp (1.6 square miles) | 2 | high | The habitat forms part of the Ephraim Swamp. The hydrologic setting of the habitat is not well understood and may not be adequately represented in the models. Scenarios show greatest variation in the southern lobe of the contributing area. |
| Baileys Harbor Swamp (3.5 square miles) | 1 | medium | The habitat is a wetland. Scenario variation is greatest in the southern lobe of the contributing area. Surface water may enter the habitat from the upper reaches of the Baileys Harbor Swamp (west of Highway 57). |

Table 2. (continued)

| Habitat (contributing area size) | Tier | Scenario variation | Comments |
|--|------|--------------------|--|
| Big & Little Marshes, Washington Island (0.6 square miles) | 2 | low | The area includes two spring-fed wetland habitats: Big and Little Marshes. The areas are not contiguous, but are treated here as a single habitat for simplicity. There are no surface water inputs to either habitat. |
| Arbter Lake (0.4 square miles) | 2 | low | The habitat is a lake in a wetland. Some surface water may enter the habitat through streams entering from north of the lake. |
| Kelner Fen (0.9 square miles) | 2 | low | The habitat is a fen. There are no known surface water inputs to the habitat. |
| Gardner Swamp (9.1 square miles) | 2 | low | The habitat is within a large wetland complex, and contains a northern region south of Fox Road, and a smaller southern region north of Highway K. The two units are treated as contiguous within the model. |

Chemical and isotopic results

Water chemistry. The major-ion water chemistry of the three springs sampled for this project is typical of carbonate-rock terrains, and similar to groundwater in other parts of Door County (Table 3). The water is dominated by calcium, magnesium, and bicarbonate ions, with minor amounts of sodium, potassium, and sulfate. The springs were sampled twice, once in December, 2006 and once in April, 2007. Spring temperatures are typical of Door County groundwater. Minor differences in chemistry between these two sample dates are consistent with the conceptual model of rapid recharge and relatively short flow paths to the springs. Concentrations of most constituents are slightly lower in April than in December, consistent with more rapid recharge and consequent dilution of groundwater in the Spring. The chloride and nitrate levels are worth noting. Chloride levels are higher in December than in April, probably as a result of highway salting for ice removal in December. The presence of nitrate shows that near-surface land use has impacted spring water quality. Nitrate levels are higher in April than in December, possibly a consequence of Spring fertilizer applications. Both these temporal changes suggest rapid recharge and rapid lateral groundwater flow to the springs. This temporal variability shows that the springs are sensitive to changes in local land-use practices.

Isotopes. Analyses of environmental isotopes from water samples collected at three Hine’s emerald sites are consistent with the conceptual model of young groundwater moving rapidly along relatively short flow paths. Isotopes of hydrogen (²H, deuterium; ³H, tritium) and oxygen (¹⁸O, oxygen-18) occur naturally in the environment and are considered to be conservative tracers because they move as part of the water molecule, H₂O. Tritium (³H) is an unstable radioactive isotope that entered the water cycle in elevated quantities during and following atmospheric atomic weapons testing during the 1960s. Tritium is measured in tritium units, TU. During the 1960s, tritium in precipitation exceeded several thousand TU, and decreased through time due to

radioactive decay. Because of its short half-life (12.4 years), tritium has been used to date the “age” (time since recharge) of relatively young (< 50 years) groundwater. Since atmospheric testing ceased, background tritium levels in precipitation have decayed to about 10 TU, and tritium continues to decay once the water enters the subsurface. Accordingly, any groundwater that contains tritium above 1 TU is now considered to be quite young (recharged in less than 10 years), and groundwater that contains tritium near 10 TU must have been recharged in the past one or two years.

Table 3. Major ion and field parameters for springs. Top: field parameters; middle: major cations; bottom; major anions.

| location | pH | | temperature | | electrical conductivity | |
|---------------|-------|-------|-------------|-------|-------------------------|-------|
| | units | | °C | | uS/cm | |
| | Dec | April | Dec | April | Dec | April |
| Mink River | 7.05 | 7.21 | 8.4 | 9.4 | 678 | 623 |
| Three Springs | 7.09 | 7.33 | 9.4 | 8.7 | 594 | 457 |
| Lime Kiln Rd | 7.19 | 7.65 | 7.5 | 7.9 | 592 | 528 |

| location | K | | Ca | | Mg | | Na | |
|---------------|-----|-------|-----|-------|-----|-------|-----|-------|
| | ppm | | ppm | | ppm | | ppm | |
| | Dec | April | Dec | April | Dec | April | Dec | April |
| Mink River | 0.9 | 0.9 | 82 | 67 | 37 | 33 | 7.4 | 4.7 |
| Three Springs | 0.9 | 0.8 | 67 | 52 | 32 | 26 | 3.9 | 2.0 |
| Lime Kiln Rd | 1.6 | 1.5 | 68 | 56 | 32 | 27 | 4.1 | 4.8 |

| location | Cl | | NO ₃ | | SO ₄ | | Alkalinity | |
|---------------|------|-------|-----------------|-------|-----------------|-------|----------------------------|-------|
| | ppm | | ppm | | ppm | | as mg CaCO ₃ /L | |
| | Dec | April | Dec | April | Dec | April | Dec | April |
| Mink River | 15.1 | 10.5 | 1.7 | 4.2 | 14.1 | 12.8 | 250 | 342 |
| Three Springs | 10.4 | 5.8 | 1.4 | 6.0 | 15.7 | 13.4 | 225 | 267 |
| Lime Kiln Rd | 10.7 | 9.8 | 3.2 | 4.3 | 14.2 | 13.6 | 250 | 109 |

Tritium concentrations at the three springs sampled for this project ranged from 8.9 to 11 TU (Table 4). Differences between the two sampling dates are probably due to seasonal differences in atmospheric tritium input. The range is about what is expected for tritium in recent precipitation, and suggests that water discharging at the springs is very young, certainly no older than 5 years.

Oxygen-18 (¹⁸O) and deuterium (²H) are stable isotopes that do not decay radioactively. Instead, the water composition of these isotopes changes by fractional distillation of

water vapor as water evaporates or precipitates. Concentrations of ^{18}O and ^2H are expressed as δ (‰) values compared to standard mean ocean water, abbreviated SMOW. Although both isotopes vary seasonally due to temperature and evaporation and precipitation in air masses, the ratio of ^{18}O to ^2H in precipitation remains fairly constant. This relationship, called the meteoric water line (MWL), varies slightly from location to location. In general, groundwater recharged directly from precipitation should have an ^{18}O : ^2H signature that falls on the local meteoric water line. Water samples that plot to the right of the MWL are interpreted as originating from surface water, where free-surface evaporation has occurred. Rayne, Bradbury, and Muldoon (2001) collected isotope data from wells and surface water features in Door County and showed that water from Green Bay and Lake Michigan plotted significantly to the right of the local MWL for their study.

Water from the three springs sampled for the present study plots directly on the local MWL (Figure 3). Lack of deviation from the line suggests that the water discharged from these springs did not originate as surface water in a lake or wetland but instead as direct groundwater recharge. These findings are consistent with our conceptual model of short, rapid flow to the springs.

Table 4. Stable isotope sampling results

| Location | Sample ID | Sample Date | Deuterium | Oxygen-18 (δ ‰) | Tritium (enriched) (TU) | |
|----------------|-----------|-------------|-----------|-------------------------|-------------------------|-----|
| Mink River | Door - 1 | 11/30/06 | -71.98 | -10.40 | 8.9 ± | 1 |
| Three Springs | Door - 2 | 11/29/06 | -71.74 | -10.36 | 8.9 ± | 0.9 |
| Lime Kiln Road | Door - 3 | 12/01/06 | -70.14 | -10.30 | 9.3 ± | 0.9 |
| Mink River | Door - 1 | 04/02/07 | -74.35 | -10.76 | 10.9 ± | 0.9 |
| Three Springs | Door - 2 | 04/02/07 | -74.21 | -10.83 | 11.1 ± | 0.9 |
| Lime Kiln Road | Door - 3 | 04/02/07 | -69.43 | -10.15 | 11 ± | 0.9 |

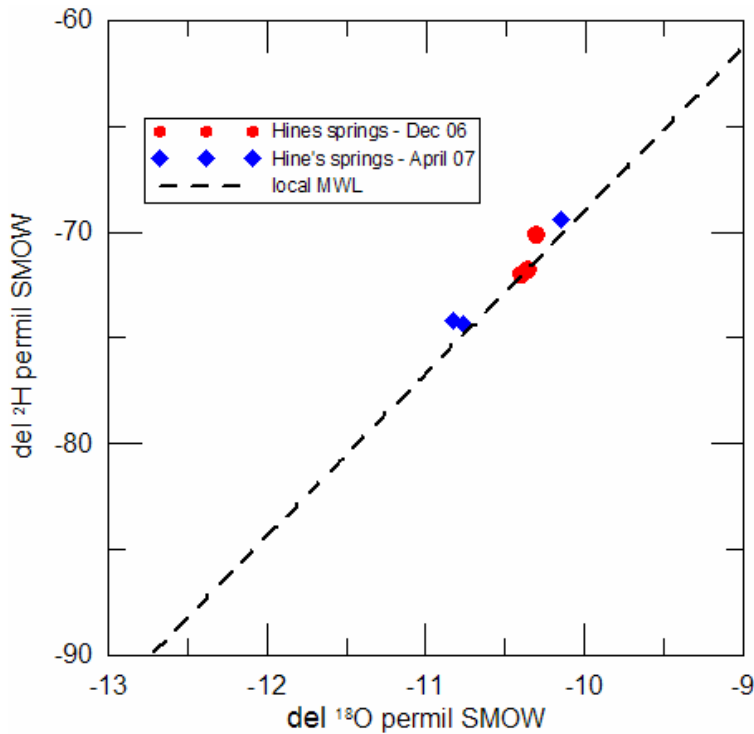


Figure 3. Oxygen-18 versus deuterium contents for water samples collected from springs at three HED sites. All analyses plot along the meteoric water line (MWL), consistent with groundwater recharged directly from recent precipitation.

Estimated groundwater flow rates

Previous studies of groundwater movement in Door County (for example, Rayne, Bradbury, and Muldoon, 2001) have shown that groundwater flow rates are generally rapid, and estimated velocities of 10's of feet per day (ft/day) are not uncommon. The simple groundwater flow models constructed for this study are not intended to be used for transport-time predictions. They simulate the fractured dolomite aquifer in Door County as a porous medium and neglect the rapid and complex groundwater flow paths that undoubtedly occur through fracture conduits and minor karst features. Nevertheless, comparisons of model-simulated flow rates and groundwater travel times with transport data acquired from a recent tracer test in Door County suggest that the models give reasonable estimates of flow rates, and by extension are appropriate tools for delineating contributing areas to the Hine's emerald areas.

In late 2007 a dye tracer test was performed at a site called Plum Bottom, located near Egg Harbor, WI on the western (Green Bay) side of Door County and about equidistant between Sturgeon Bay and Fish Creek. The purpose of the test was to determine the source of contamination of a supply well located at a restaurant. Two different fluorescent dyes were injected into the restaurant's septic system, and dye concentrations were monitored at downgradient wells for several months (Alexander, Green, and Alexander, 2008). The dyes were detected at two wells located 2700 and 3000 feet horizontally downgradient of the injection point. The first detection of the dye in these wells occurred between 83 and 90 days after injection, giving an approximate horizontal groundwater flow rate of 32-33 ft/day. It is important to understand that these numbers

apply to the horizontal distance between the injection and detection points and not to the actual complex flow path followed by the water.

For comparison, linear flow velocities predicted by the models developed for this project range from 1 to 43 ft/day, with maximum groundwater travel times from recharge to the HED sites ranging from 260 days to 48 years. At six sites (Washington Island, Mink River, Three Springs, North Bay, Bailey's Harbor Swamp, and Kellner Fen) the estimated maximum travel times are less than two years and estimated horizontal flow velocities are in the range of 10-40 ft/day, similar to the 32 ft/day value from the tracer experiment. These estimates are based on the calibrated hydraulic conductivity and hydraulic gradient obtained from each GFLOW model and use an estimated effective porosity of 0.005, as selected by Rayne, Bradbury, and Muldoon (2001).

Summary and Conclusions

This study has estimated contributing areas for groundwater recharge potentially effecting eleven Hines emerald dragonfly habitats in Door County. The areas range in size from 0.4 to 11.4 square miles, and some areas overlap. The estimated areas are based on relatively simple groundwater models constructed and calibrated using existing information and a small amount of new field data. The scope of this project did not permit extensive new data collection, and the need to evaluate eleven sites prohibited expending substantial resources at any single site. However, the estimated areas in this report are hydrogeologically reasonable and should be considered in future land-use decisions. In particular, the delineated areas provide an outer bound for areas contributing water to each HED site. It is likely that specific points within each area, such as open fractures, shallow bedrock pavements, or small sinkholes, might be critical input points for groundwater flowing to each critical HED habitat, but locating those specific points was beyond the scope of the present study. Geochemical and isotopic data collected from groundwater at three of the HED sites are consistent with the conceptual model of relatively rapid recharge and rapid groundwater movement (10's of ft/day) to the springs. These data reinforce the idea that the springs are vulnerable to local land-use changes.

The area delineations in this report are intended to provide resource managers with a starting point for protecting the downgradient Hine's emerald habitats. Such protection includes maintaining both the water balance and water quality in the areas. New demands on groundwater, or new industry or construction within the contributing areas and buffer zone should be considered to pose a risk to the Hine's emerald dragonfly. Further data collection and modeling may be required to answer specific land-use questions. The models and data generated in this study are intended to provide a resource and starting point for further work of this sort.

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Appendix A
Maps of HED Sites

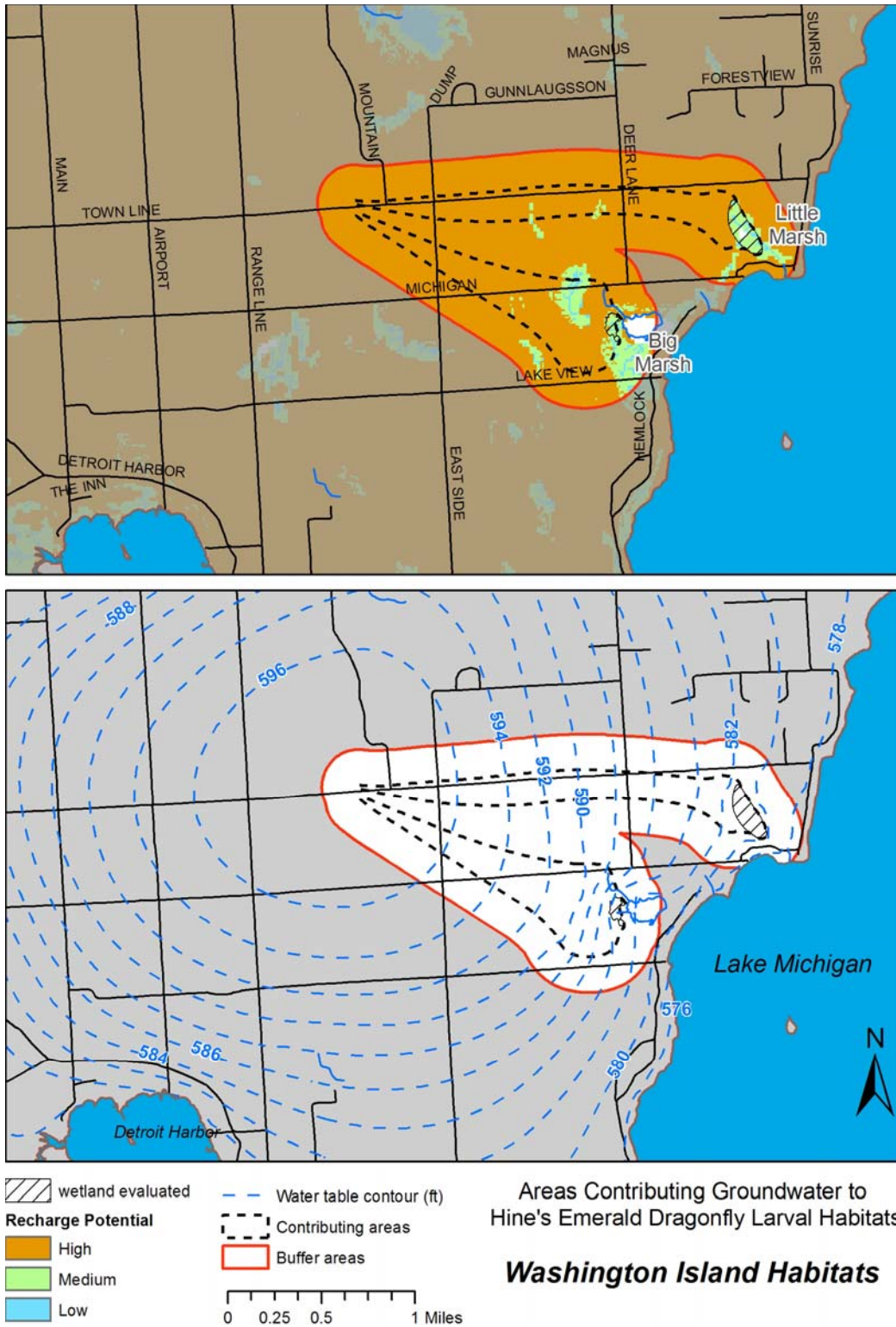


Figure A3. Contributing areas for larval sites on Washington Island.

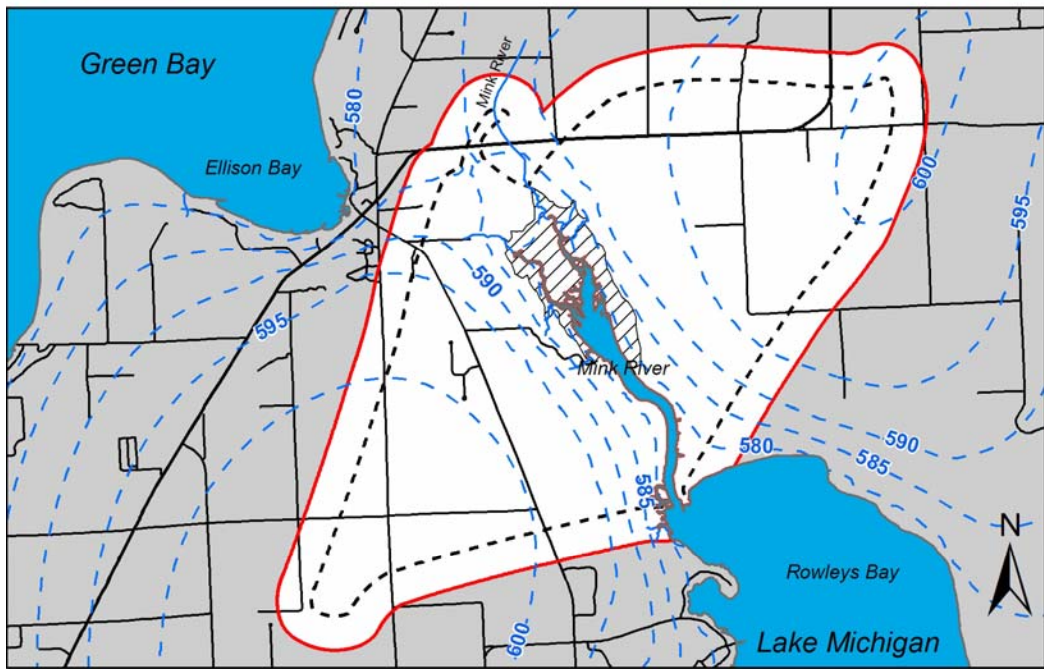
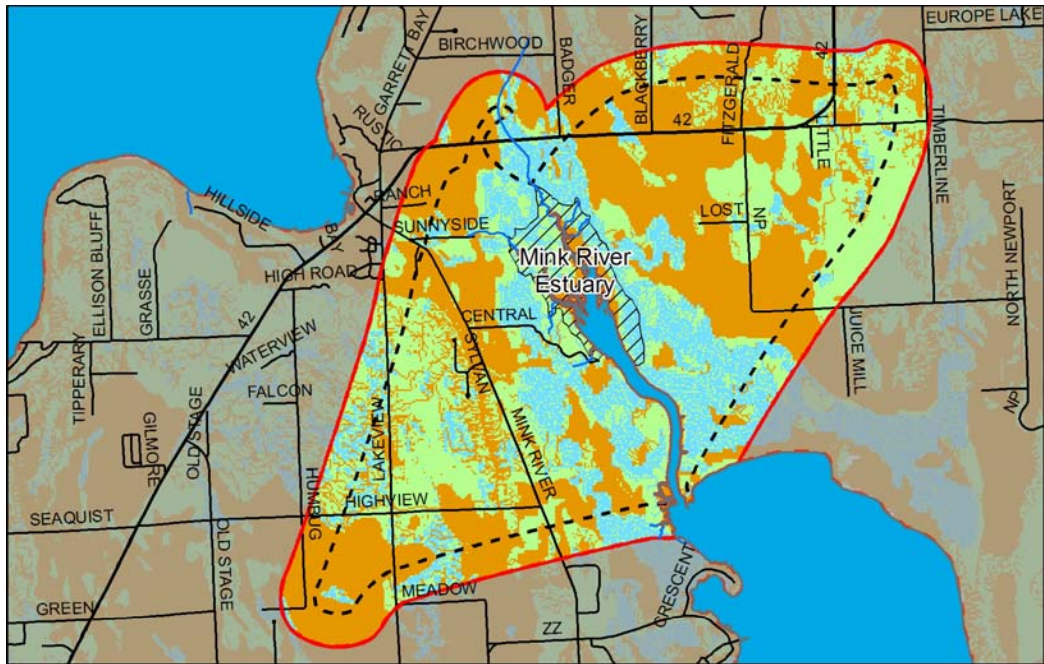


Figure A4. Contributing areas for larval sites along the Mink River

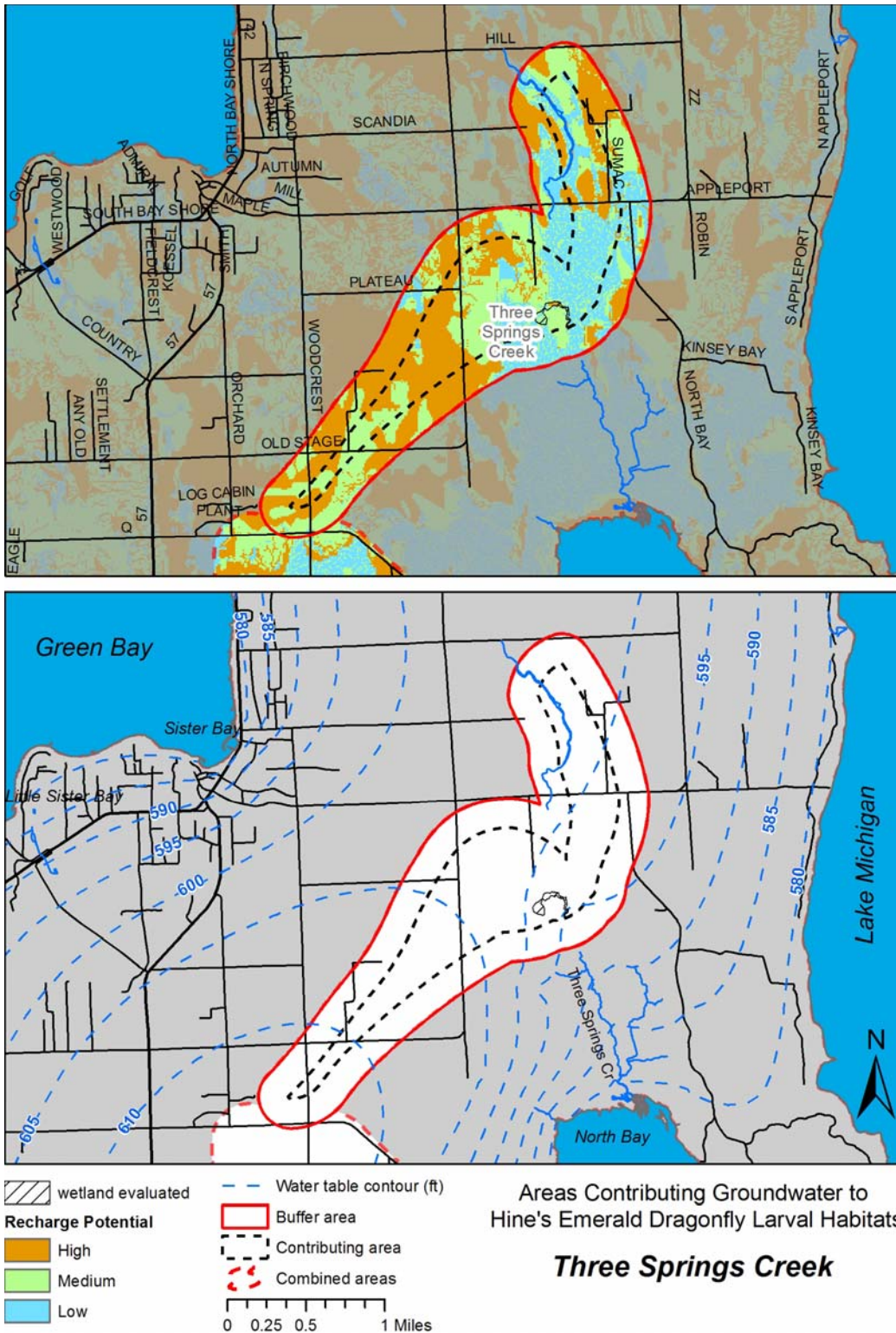


Figure A5. Contributing areas for larval sites along Three Springs Creek

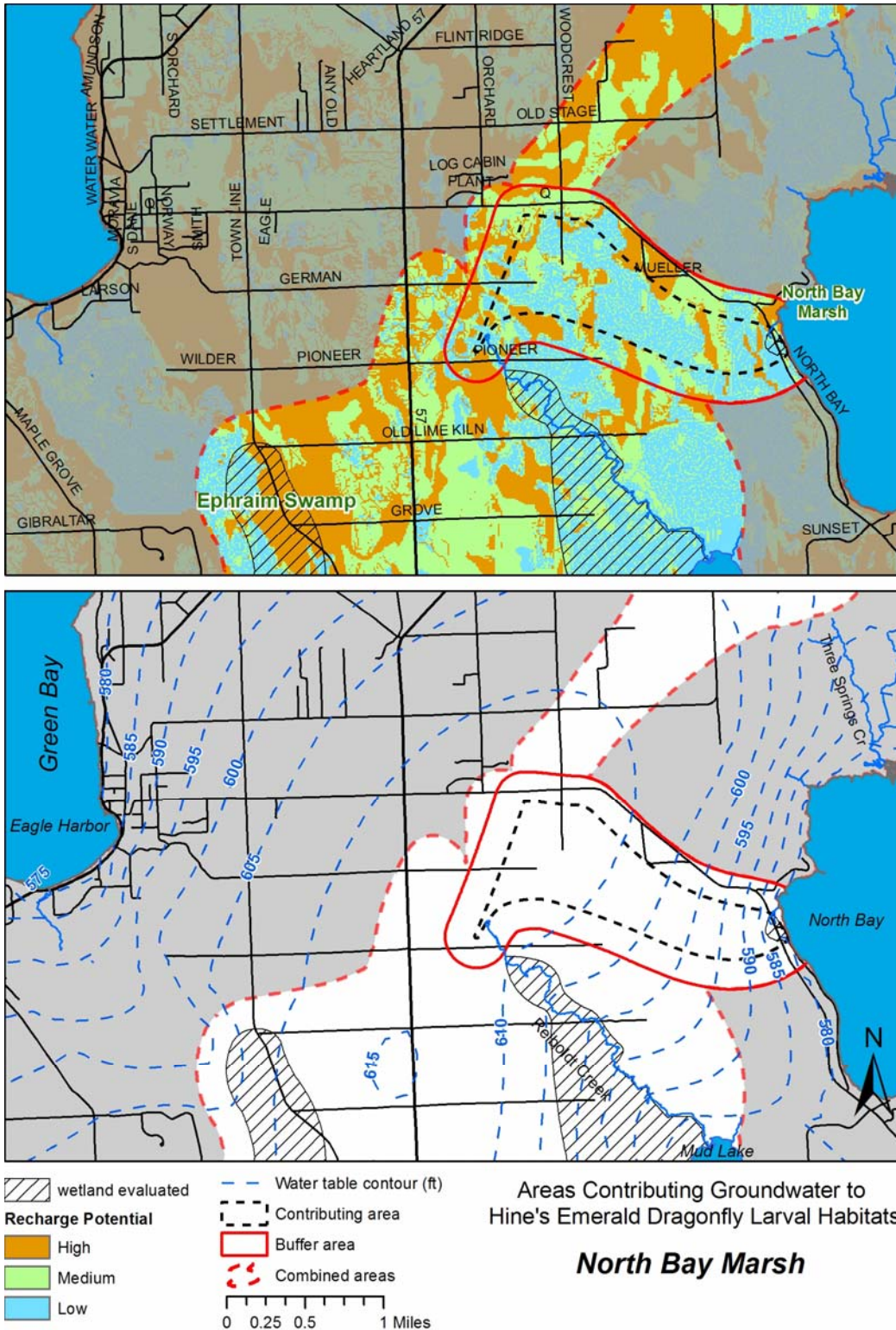


Figure A6. Contributing areas for larval sites near North Bay Marsh

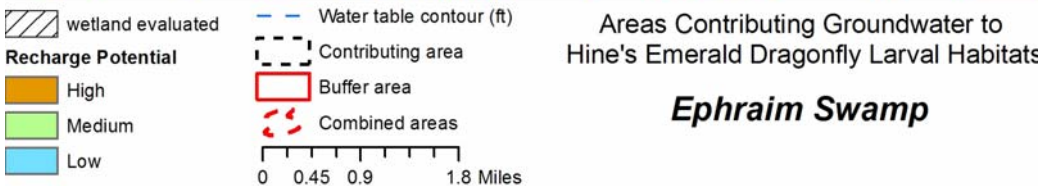
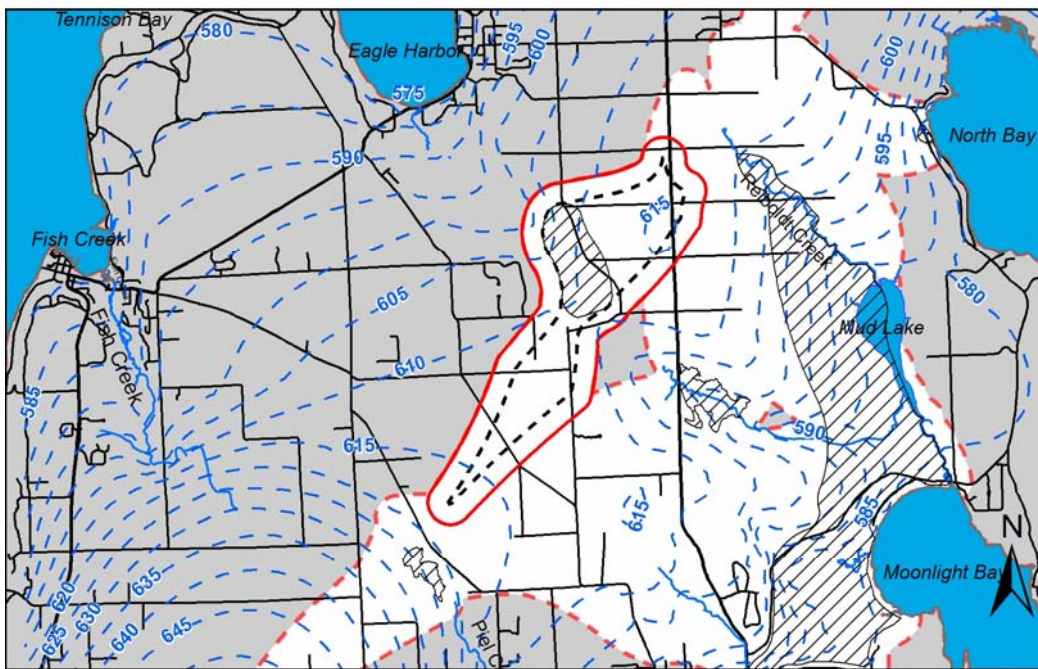
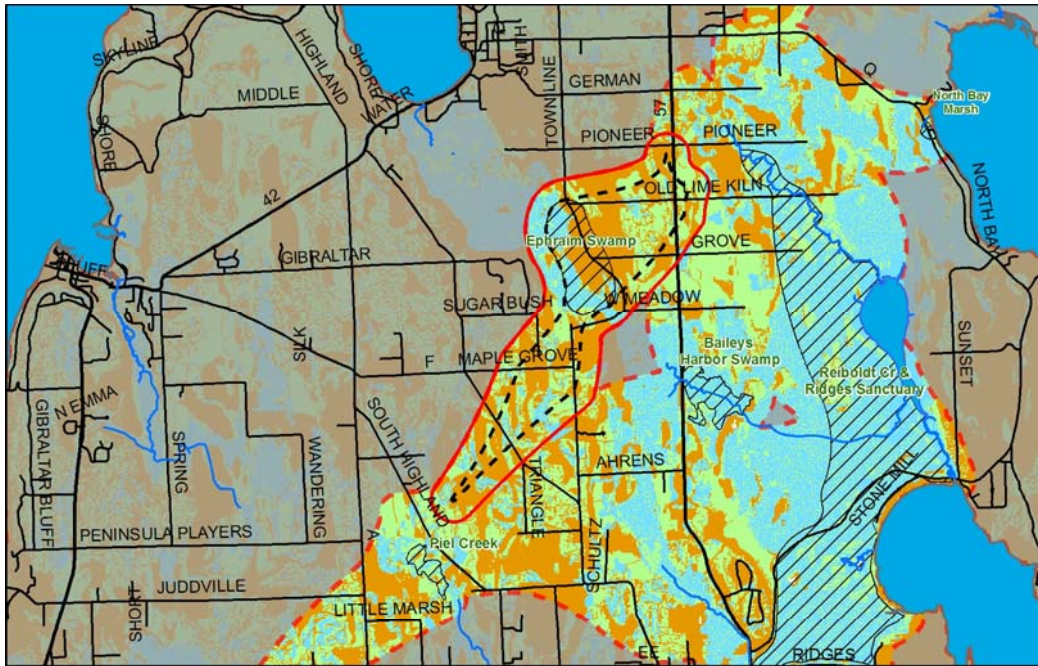
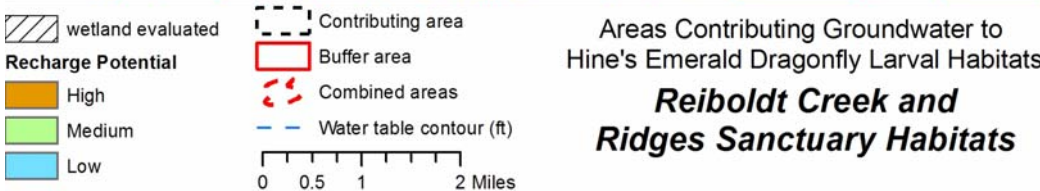
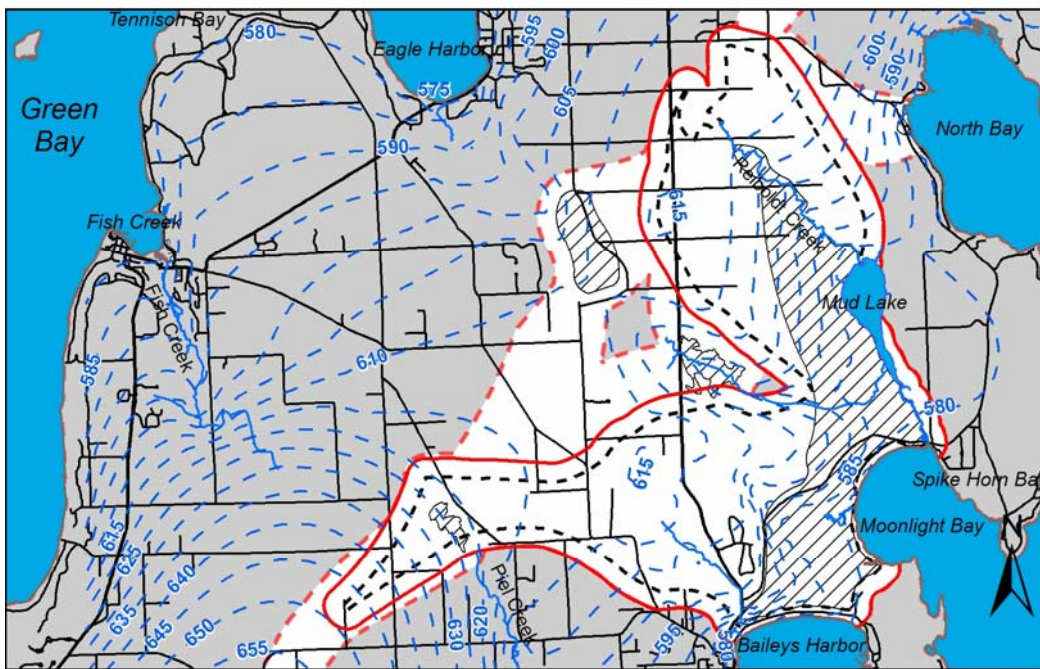
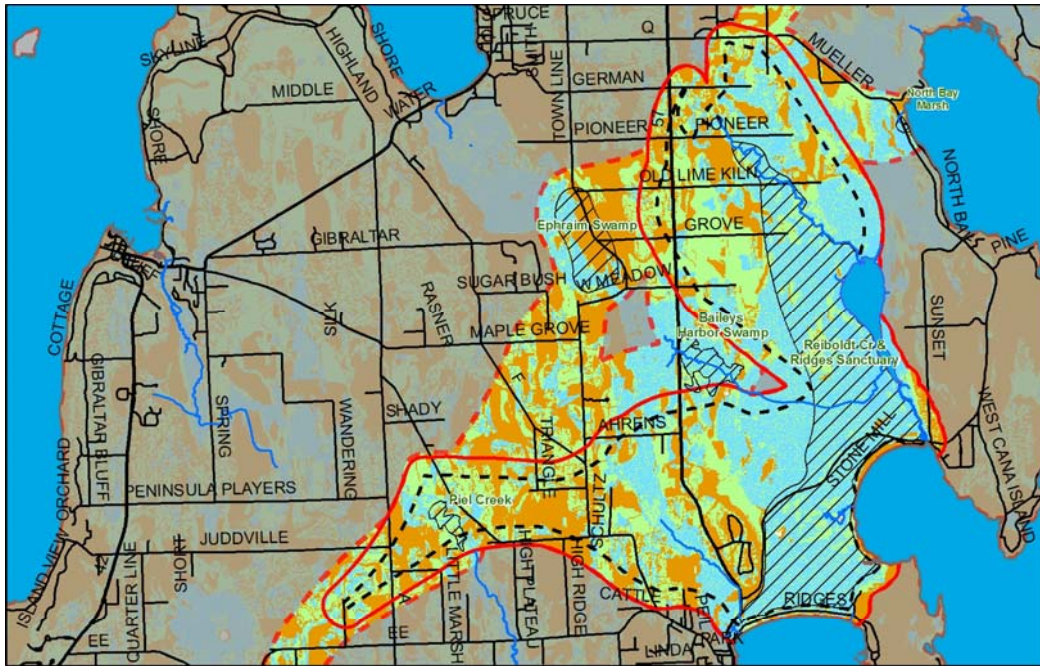


Figure A7. Contributing areas for larval sites near Ephraim Swamp



Areas Contributing Groundwater to
Hine's Emerald Dragonfly Larval Habitats
**Reiboldt Creek and
Ridges Sanctuary Habitats**

Figure A8. Contributing areas near Reiboldt Creek and the Ridges Sanctuary

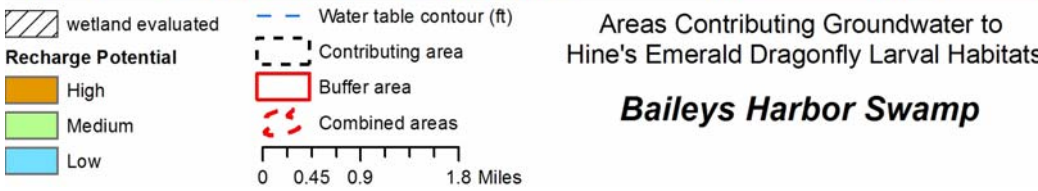
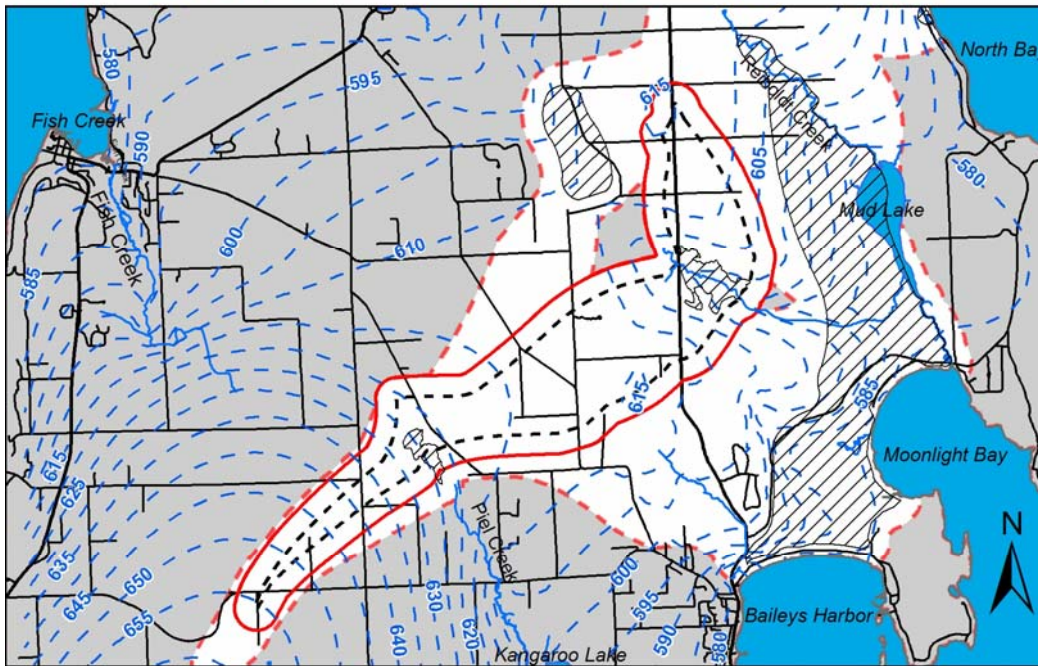
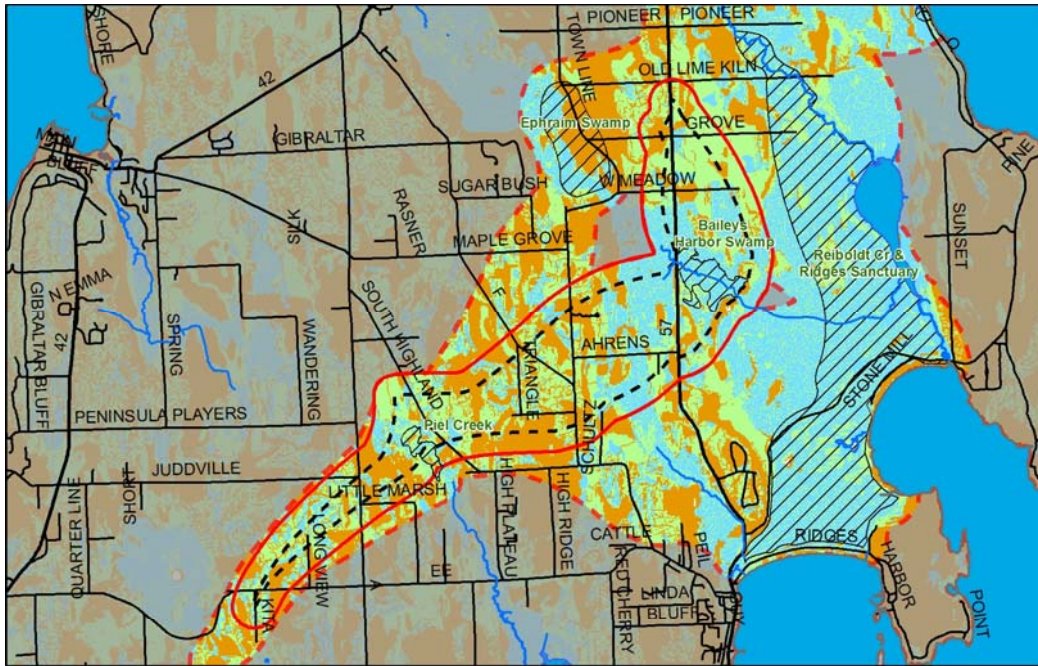


Figure A9. Contributing areas near Baileys Harbor Swamp

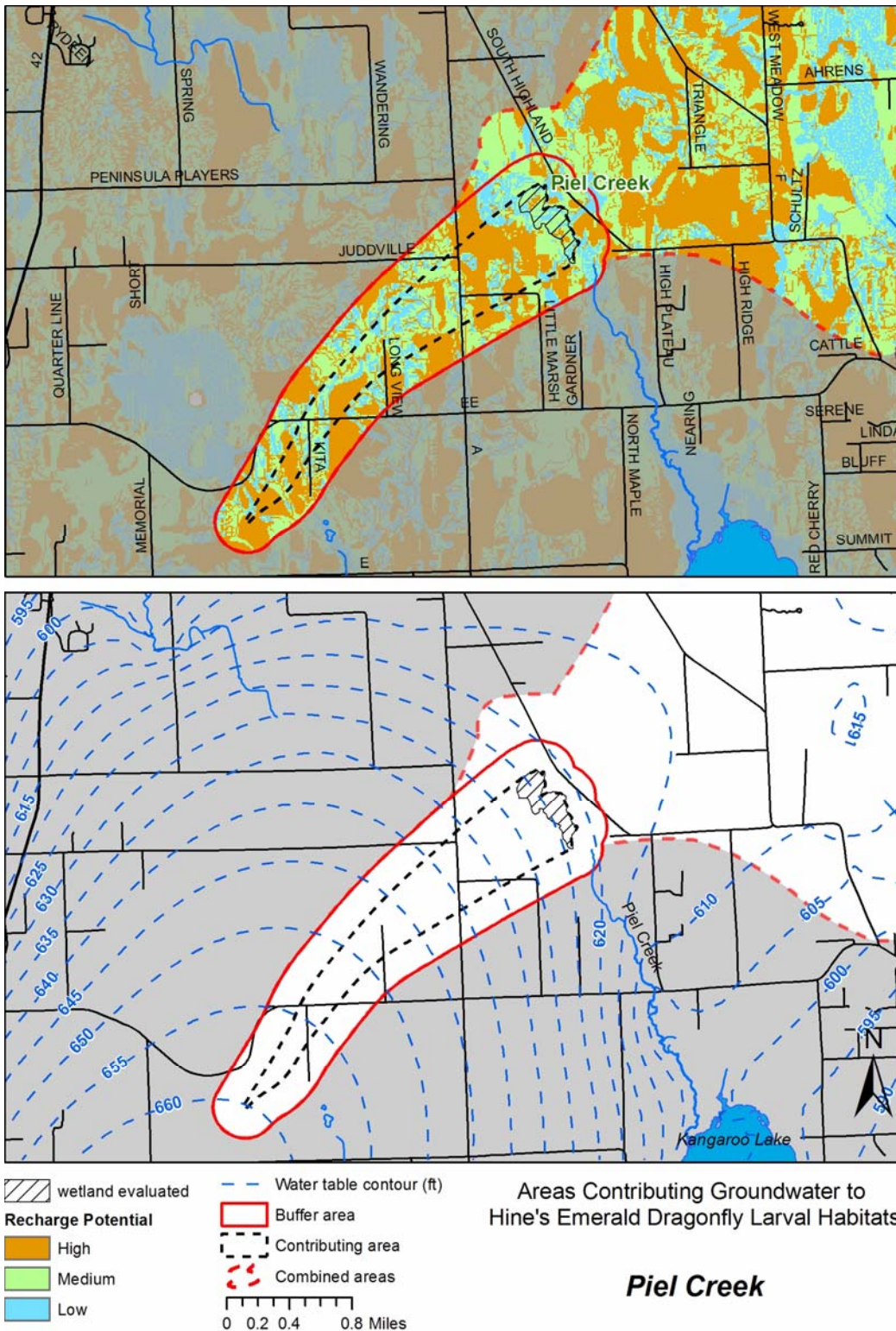


Figure A10. Contributing areas near Piel Creek

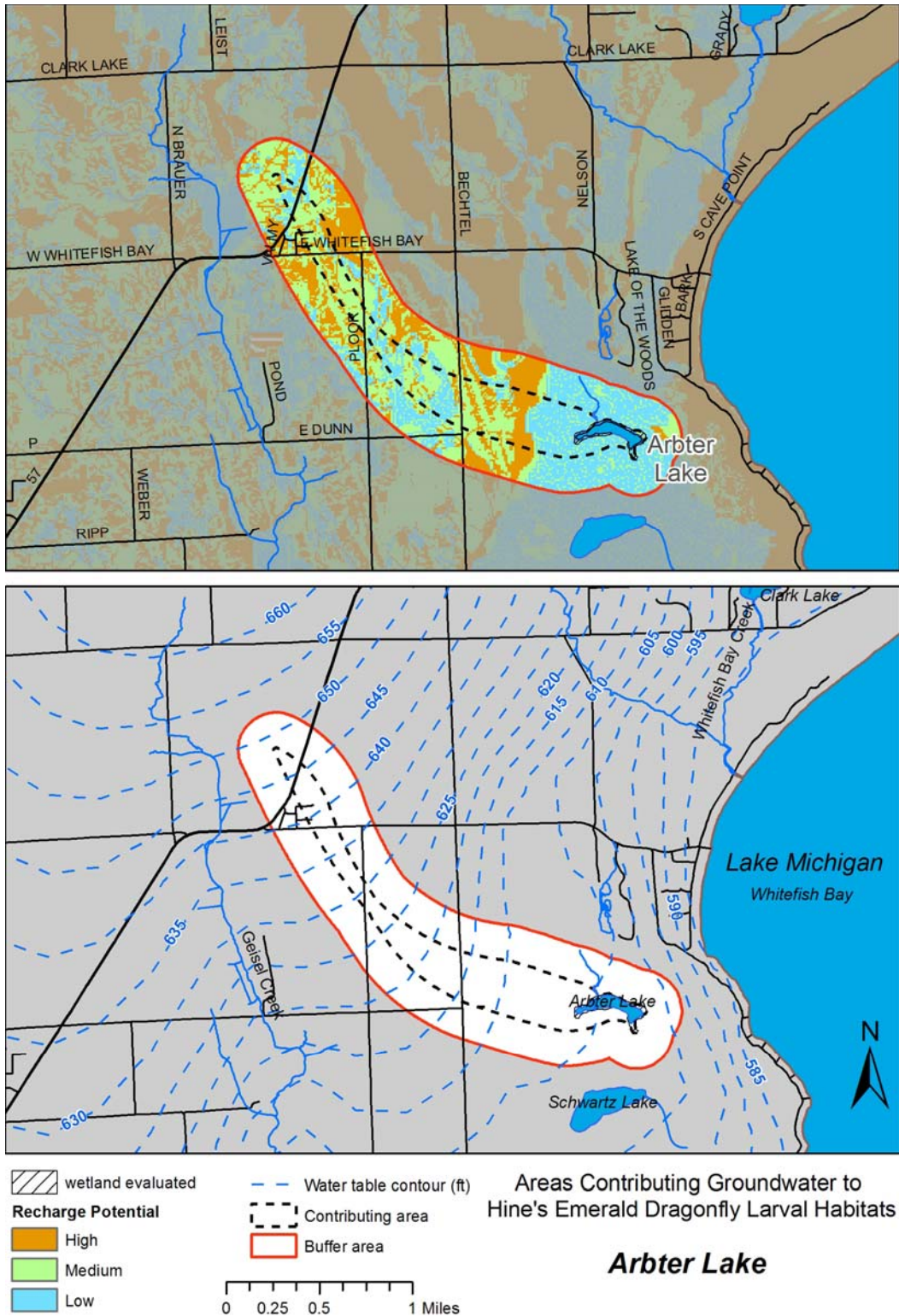


Figure A11. Contributing area for larval sites at Arbter Lake

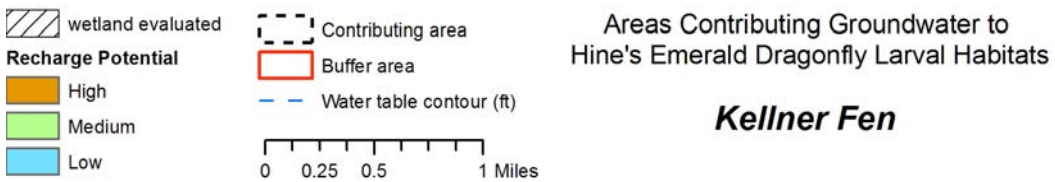
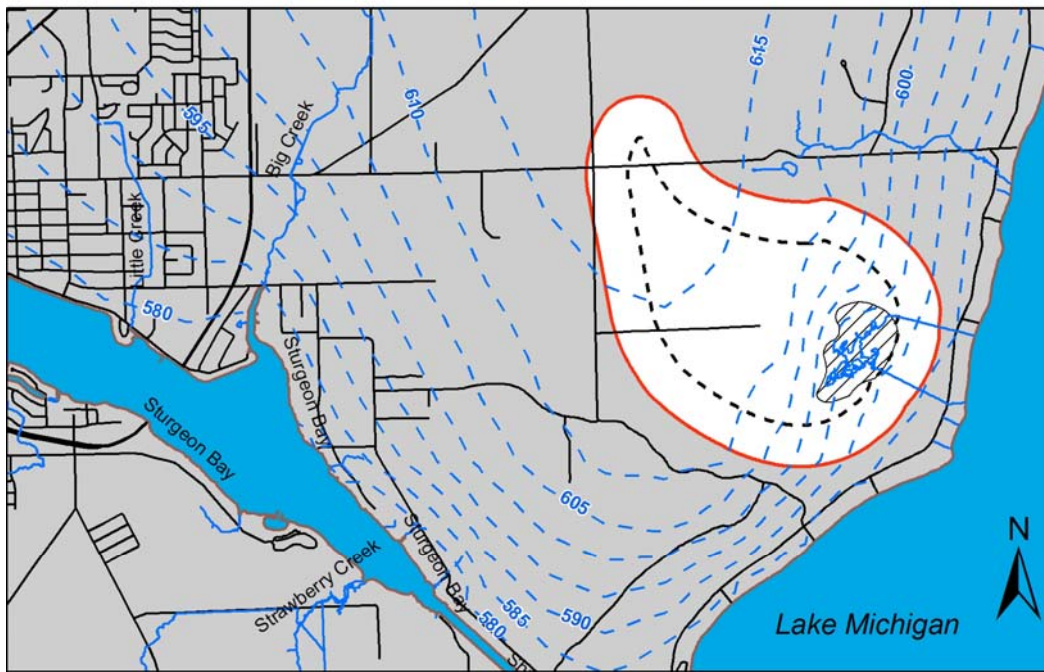
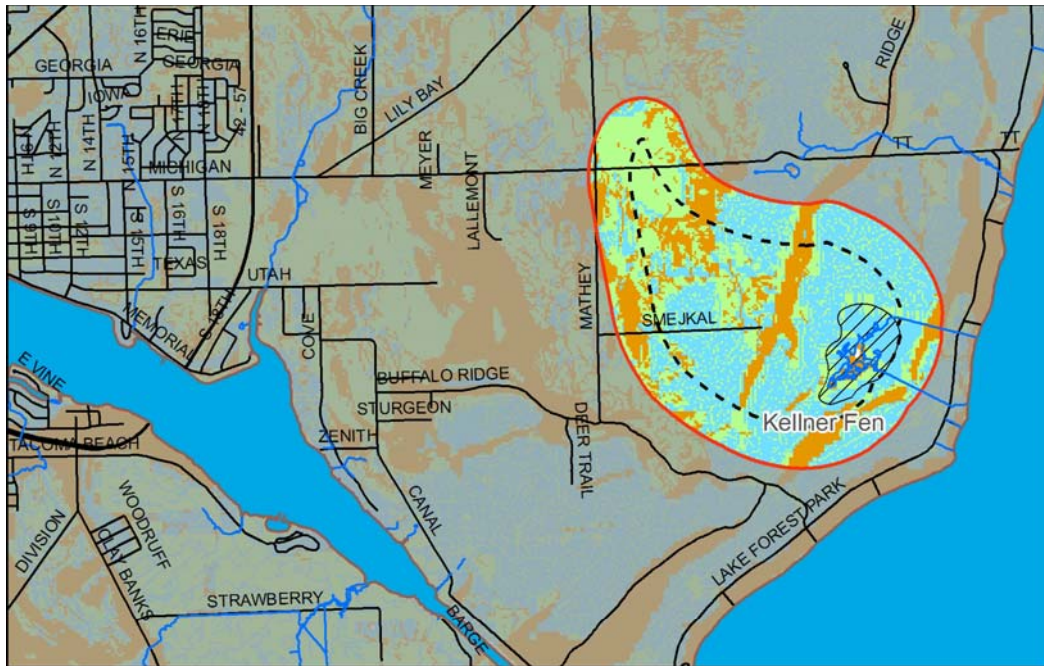


Figure A12. Contributing areas for larval sites near Kellner Fen

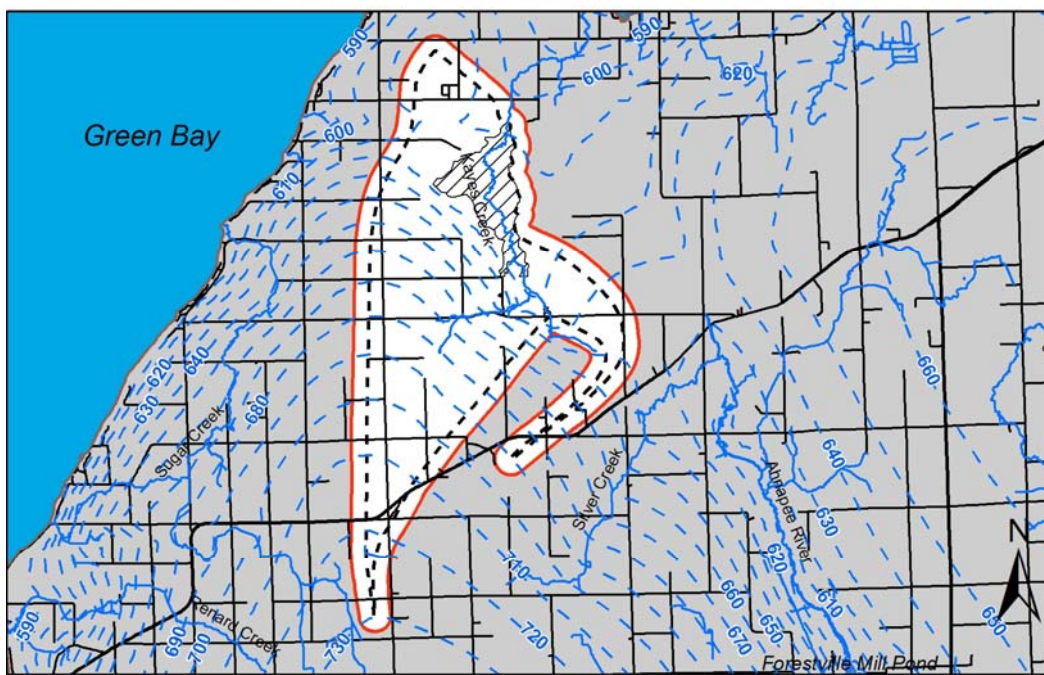
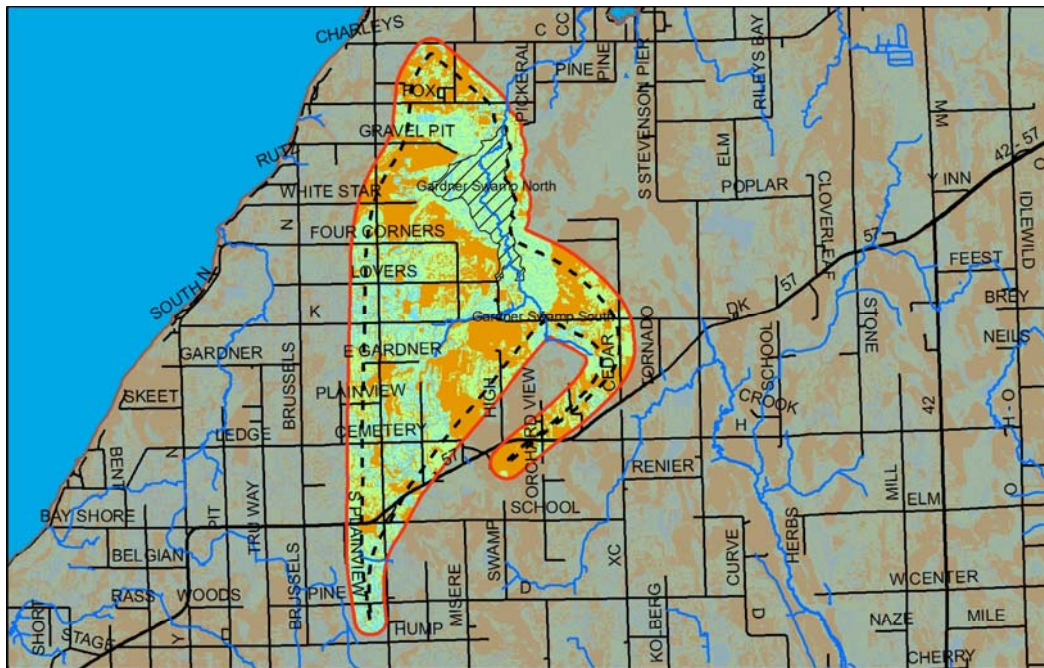


Figure A13. Contributing areas for larval sites near Gardner Swamp

Appendix B: Geophysical Survey

Door County Hine's Emerald Dragon Fly Geophysics Surveys

David Hart – Wisconsin Geological and Natural History Survey

May 24, 2007

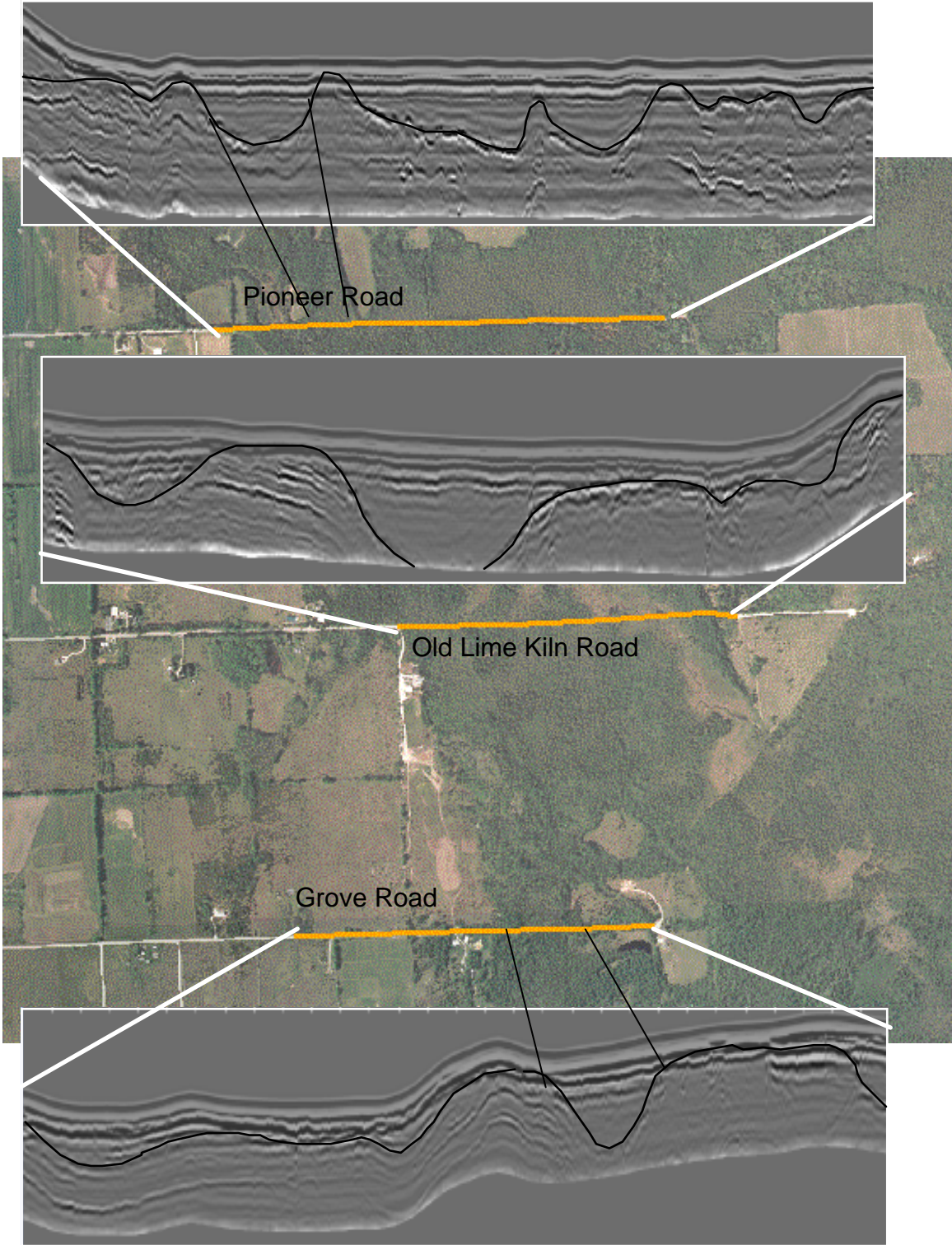
Ground Penetrating Radar (GPR)

GPR makes use of electromagnetic pulses that are sent into the ground and waits for responses that arrive in the form of reflected signals. A reflection occurs when the wave crosses a change in dielectric properties such as those found at the water table, bedrock surface, voids or different soil or rock layers. In this study, we sought to identify the bedrock surface. The limitation of this methodology is that the depth of penetration of the electromagnetic wave is controlled by the presence of highly conductive soils (e.g., saturated clays) that absorbs the energy and prevents the generation of reflection signals. Identifying a reflection and correlating it to a surface, such as the bedrock, may also be difficult. There were no good geologic controls available such as borings along the surveys lines and so the results should be verified by drilling if more certainty is required.

For this study, the data were collected using a GSSI SIR-3000 radar system with an 80 MHz antennae towed by hand and behind a pickup (Figure 1). This system gave a depth of penetration of around 30 feet, depending on the sediments and underlying bedrock. We collected data along three transects on Grove, Old Lime Kiln and Pioneer Roads as shown in Figure 2. The data for the three transects were post-processed by applying an automatic gain and distance and elevation corrections (rubberbanding). The reflections interpreted to correspond to the bedrock surface were marked on the three transects with dark lines. That reflection varies in depth from near 0 to over 20 feet in depth. If those reflections accurately represent the bedrock surface, there is significant variation in the depth to bedrock in the study area. A possible correlation between the deep reflection (possibly bedrock surface) and forest cover has been delineated by the lines between the GPR transects and the air photos for reflection “valleys” on Pioneer and Grove Roads.



Figure 1. Photos of the antenna and radar systems.



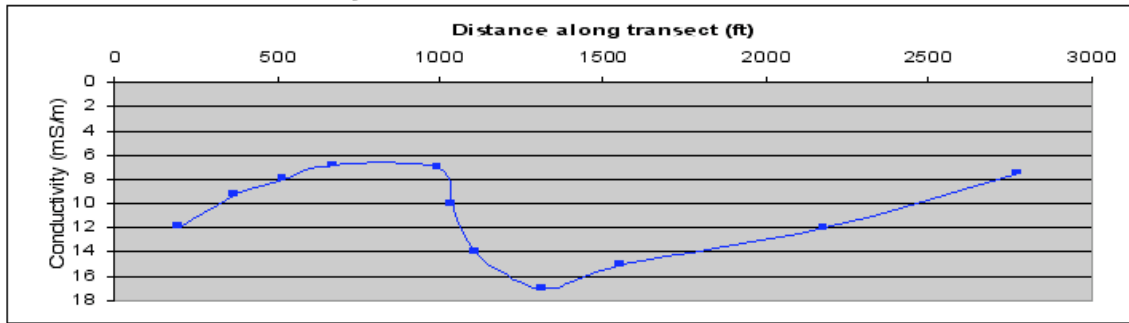
GPR Lines
Vertical Scale
20 feet

Electromagnetic Survey

We also conducted an electromagnetic survey to corroborate the results of the GPR survey. The electromagnetic method induces a current in the ground with a transmitter coil and senses the induced currents with a receiver coil. If the subsurface is a good conductor of electricity, then the induced current is larger and gives a larger signal to the receiver coil. A poor conductor gives a smaller signal to the receiver coil. Saturated soils, sands, and gravels are good conductors of electricity through the water in their pores. Clays are also very good conductors. Dolomite has few well-connected pores and so is not a good conductor. We made use of this difference of electrical conductivity between the sediment and the dolomite bedrock to provide an independent check on the depth to bedrock predicted by the GPR surveys.

We used an EM-31 conductance meter and recorded the conductance along the Old Lime Kiln Road transect. The EM-31 meter senses and averages the conductivities of all the materials beneath it to a depth of around 20 feet. If there is mostly bedrock beneath the EM-31, then the conductivity will be low, if there is mostly sediment, then the conductivity will be higher. A mix of 10 feet of sediment over bedrock will give an intermediate value. Figure 3 is a plot of the EM-31 measured conductivities along the Old Lime Kiln Road transect. Below that EM-31 plot is the GPR transect for comparison. In general, the agreement is quite good. At around 1000 feet on the transect, the conductivity increases, suggesting a greater depth to bedrock. At the same point, the GPR reflection also decreases to a depth slightly more than 20 feet, also suggesting a greater depth to bedrock. Both the EM-31 conductivity and GPR reflection then show a more gradual increase along the transect. The correlation between the EM-31 conductivities and the GPR reflection are not exactly one-to-one because the EM-31 does not linearly average the subsurface conductivities but is most sensitive to the material approximately 1.5 meters below the ground surface.

EM-31 Conductivity Results



Ground Penetrating Radar Results

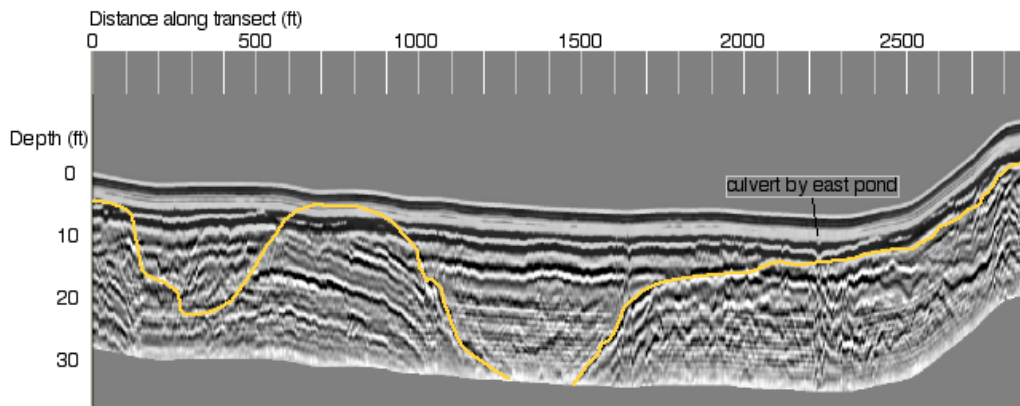


Figure 3. EM-31 conductivity and GPR compared on Old Lime Kiln Road. Both length scales are the same.

Geophysics Conclusions

Ground penetrating radar surveys were conducted on three East-West transects county roads, Pioneer, Old Lime Kiln, and Grove roads. The approximate lengths of the transects were 3000 feet. An electromagnetic survey was conducted along Old Lime Kiln road. The results of that survey support the conclusions of the GPR survey. These surveys all suggest that the depth to bedrock varies along these transects from near 0 to more than 20 feet with sediment filled bedrock valleys. If this conclusion will drive some further investigation or action, we recommend confirmation of the interpreted depths to bedrock by drilling or Geoprobe surveying in selected locations.