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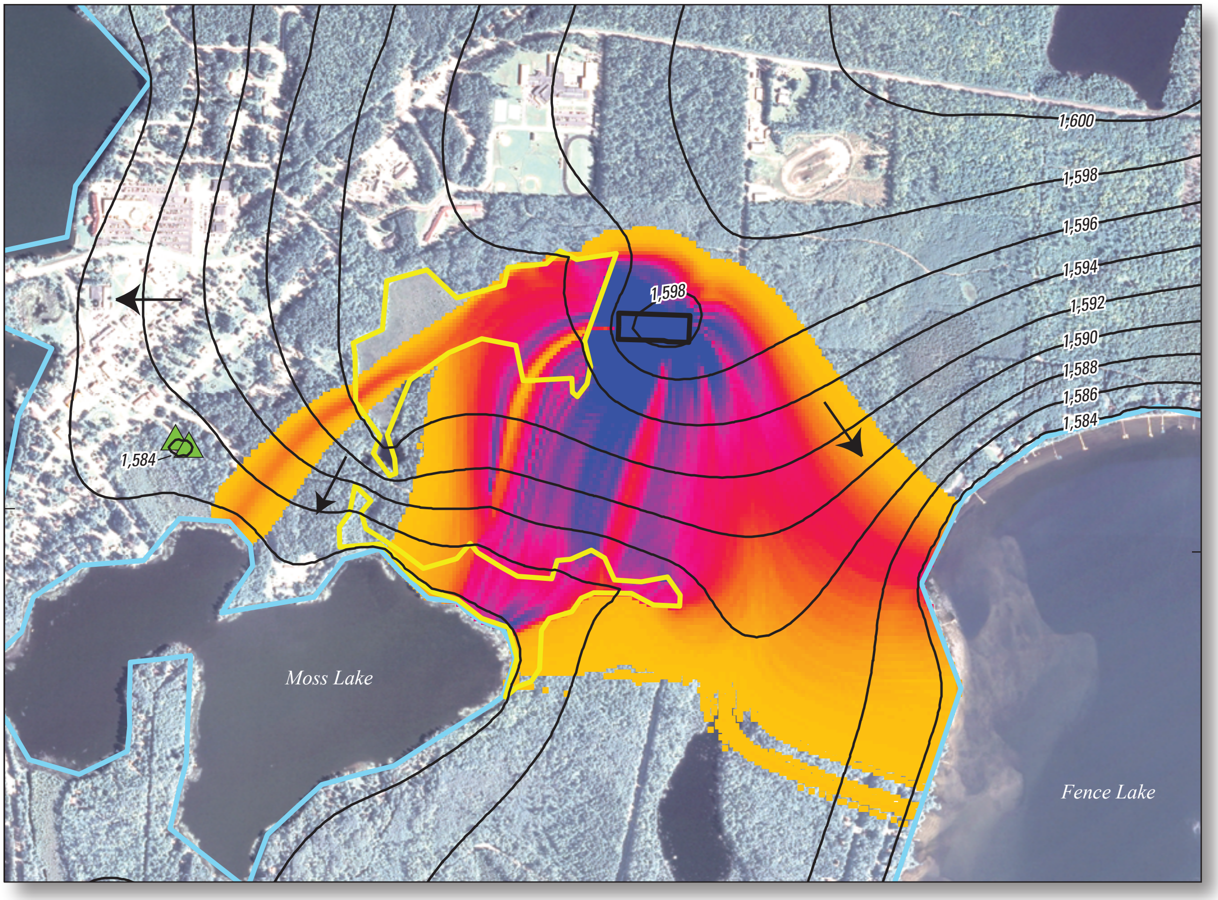
Simulation of the Probabilistic Plume Extent for a Potential Replacement Wastewater-Infiltration Lagoon, and Probabilistic Contributing Areas for Supply Wells for the Town of Lac du Flambeau, Vilas County, Wisconsin



Open-File Report 2020–1032

U.S. Department of the Interior
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Cover. Simulated probability of the plume extent for a scenario with wastewater discharged from proposed infiltration lagoons north of the lined treatment lagoons, Town of Lac du Flambeau, Vilas County, Wisconsin (figure 2 of this report).

Simulation of the Probabilistic Plume Extent for a Potential Replacement Wastewater-Infiltration Lagoon, and Probabilistic Contributing Areas for Supply Wells for the Town of Lac du Flambeau, Vilas County, Wisconsin

By Paul F. Juckem and Michael N. Fienen

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1927 (NAD 27).

Abbreviations

GFLOW	groundwater flow computer model
USGS	U.S. Geological Survey

Simulation of the Probabilistic Plume Extent for a Potential Replacement Wastewater-Infiltration Lagoon, and Probabilistic Contributing Areas for Supply Wells for the Town of Lac du Flambeau, Vilas County, Wisconsin

By Paul F. Juckem and Michael N. Fienen

Abstract

An existing two-dimensional, steady-state groundwater-flow model of the shallow groundwater-flow system of the Lac du Flambeau Reservation in Vilas County, Wisconsin, originally developed by the U.S. Geological Survey, was used to simulate the potential for wastewater from a proposed relocation of a wastewater lagoon to contaminate the Lac du Flambeau Band of Lake Superior Chippewa's drinking-water-supply wells. This simulation was completed by the U.S. Geological Survey in cooperation with the Lac du Flambeau Band of Lake Superior Chippewa and Indian Health Service. The simulated scenarios consisted of removing wastewater infiltration from existing lagoons and re-applying that infiltration at the proposed location. Two analyses were performed for the scenarios. First, the probable extent of the plume discharging from the proposed infiltration lagoons was mapped with a Monte Carlo algorithm that used uncertainty identified during the calibration process to simulate thousands of possible outcomes. Second, the Monte Carlo method was again used to simulate a probabilistic contributing area for the Tribe's nearby "Main Pumphouse" supply wells. The purpose of the simulations was to evaluate the potential for infiltrated wastewater to be captured by the public-supply wells.

Most features of the previously developed model remained unchanged, including calibrated parameters such as hydraulic conductivity and recharge. Thus, the same covariance distributions that were generated during calibration of the regional model (Juckem and others, 2014) remained unchanged and were used to inform the Monte Carlo simulations for the scenario simulations described in this report. The reader is encouraged to read the full report by Juckem and others (available at https://doi.org/10.3133/sir20145020) for a detailed description of the model design and calibration, as well as a description of the Monte Carlo method, its limitations, and the original results.

Results for these new scenarios indicate that the probabilistic plume extent for the proposed infiltration lagoons does not reach the Main Pumphouse wells using pumping rates and wastewater volumes estimated for 2010. Similarly, the contributing area for the Main Pumphouse wells does not capture water from within the proposed infiltration lagoon footprint. However, at higher pumping rates and wastewater volumes, as projected by the Tribe for about 2035, the contributing area for the Main Pumphouse wells do include particles that originated within the proposed lagoon footprint, albeit at low probabilities. That is, for a few of the thousands of simulations that represented a range of calibration-informed parameter covariances, some amount of infiltrated wastewater was captured by the Main Pumphouse wells under projected 2035 conditions.

Introduction

The Lac du Flambeau Band of Lake Superior Chippewa (referred to hereafter as "the Tribe") and the Indian Health Service have been working to identify a new location for wastewater infiltration lagoons for the Town of Lac du Flambeau on the Lac du Flambeau Reservation in Wisconsin. Previous work involving the construction and calibration of a regional groundwater flow (GFLOW; Haitjema, 1995) model (Juckem and others, 2014) illustrated that the probable wastewater plume extent from the existing lagoons overlapped with the contributing area for drinking-water supply wells (pumped wells; fig. 1) at the "Main Pumphouse" site and elevated the water table near Moss Lake, thereby limiting the thickness of the unsaturated zone below the infiltration lagoons. New simulated scenarios were needed to evaluate the likelihood that the wastewater plume from a proposed set of infiltration lagoons would reach the Main Pumphouse wells. A second method, the area contributing recharge method, also was used to evaluate the potential that the wells would capture water that originated within the footprint of the proposed infiltration lagoons.

Purpose and Scope

This report describes the modifications to the original GFLOW model (Juckem and others, 2014) and results from the simulation of new model scenarios of two-dimensional, steady-state, groundwater flow through the shallow hydrologic system near the Town of Lac du Flambeau, Wisconsin. The purpose of these scenarios was to evaluate the probability that the Main Pumphouse wells would capture infiltrated wastewater from the proposed relocation of the infiltration lagoons. This evaluation was accomplished by simulating the probabilistic contributing area to the Main Pumphouse wells under 2010 and projected 2035 pumping rates, and the probabilistic wastewater plume extent for the proposed set of infiltration lagoons using parameter covariance matrices developed during calibration of the original GFLOW model. The probabilistic contributing area and plume extent scenarios combine thousands of plausible model simulations, or realizations, into individual maps that when combined convey the uncertainty associated with the model, and are preferable for informing risk management decisions in that they highlight rather than hide the range of possible outcomes. The model theory, construction, calibration of the underlying regional model, and methods for simulating probabilistic contributing areas and plume extents were fully described by Juckem and others (2014). The scope of the evaluations described in this report are limited to uncertainty ranges informed during the original model calibration (Juckem and others, 2014) because no additional groundwater data were collected in the area of interest, and the underlying model was not recalibrated. Computer model files for the scenarios described in this report have been archived and made available by Juckem (2020).

Physical Setting

The regional and local settings were described by Juckem and others (2014); important features of the local setting are shown in figure 1 and briefly described here. The Town of Lac du Flambeau (hereafter, Town) is in western Vilas County, Wisconsin, and surrounded by several lakes that form the headwaters of the Bear River, a tributary to the Flambeau River (not shown in figures). The groundwater-flow system near the Town is bounded by Pokegama and Long Interlaken Lakes to the west, Moss Lake to the south, and Fence Lake to the east. Locally, groundwater generally flows in a southwesterly direction from an upland area northeast of the Town toward Long Interlaken Lake (fig. 2). The area is underlain by a permeable sand and gravel aquifer, which is underlain by a relatively continuous layer of clay-rich till (Attig, 1985; Batten and Lidwin, 1996), and relatively impermeable crystalline bedrock (Attig, 1985) that forms the base of the groundwater-flow system. The sand and gravel aquifer has a high horizontal hydraulic conductivity (Juckem and others, 2014).

Data Sources

No new data were collected or incorporated into this effort; the location of the proposed infiltration lagoons was provided by the Indian Health Service (Matthew Zoch, written commun., December 7, 2018).

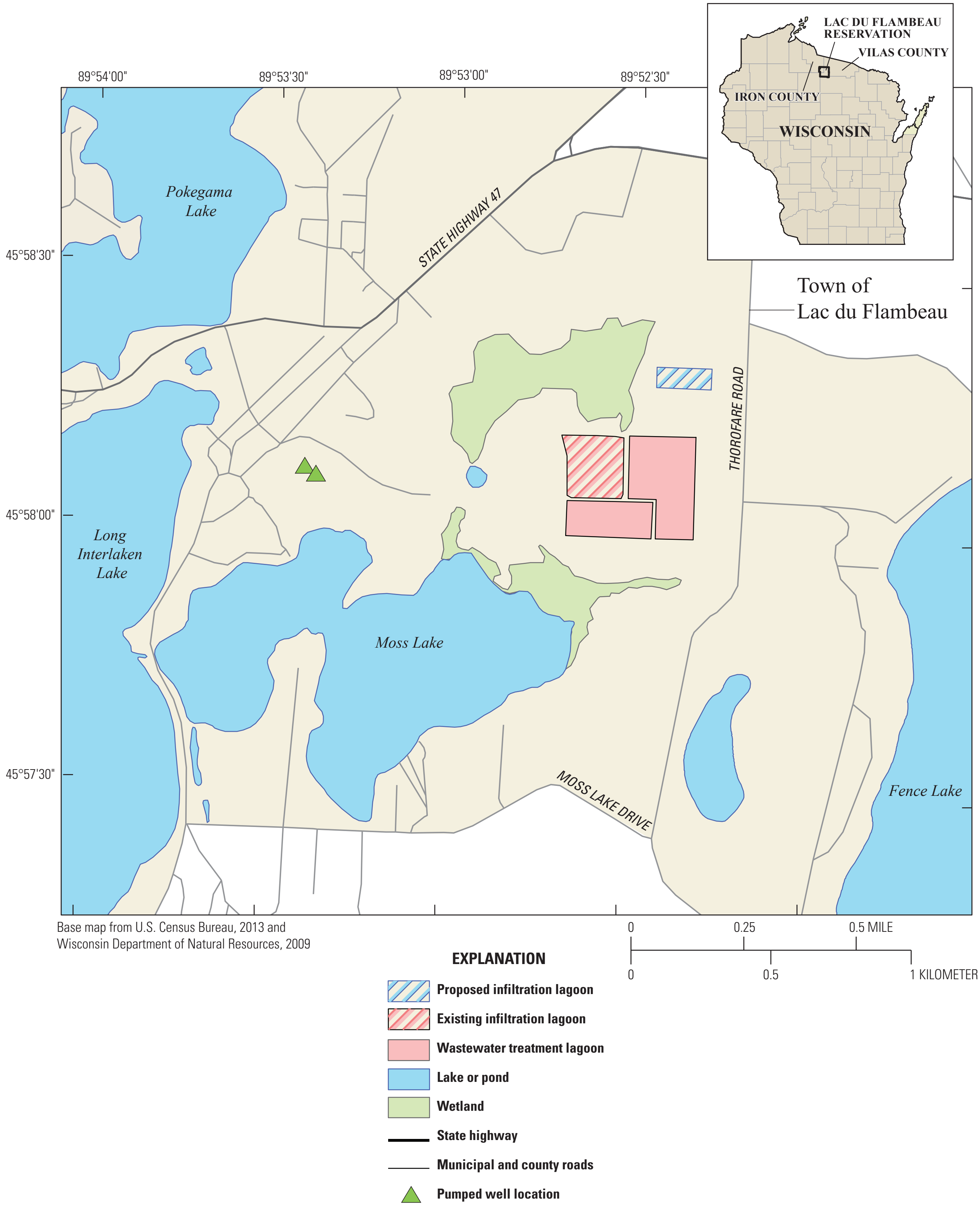

Figure 1. Location of the Town of Lac du Flambeau, the existing wastewater treatment and infiltration lagoons, and the proposed location for replacement infiltration lagoons, Vilas County, Wisconsin.

Methods

An analytic-element groundwater-flow model, developed with the computer program GFLOW (Haitjema, 1995), was used to simulate the groundwater system and its interaction with surface-water features. A complete description of analytic elements is beyond the scope of this report, but additional information on analytic element modeling can be found in a review of applications of the method by Hunt (2006) and a detailed discussion of the underlying concepts and mathematics by Haitjema (1995). Juckem and others (2014) described development and application of a GFLOW model for the Lac du Flambeau Reservation, and a brief overview of important features of the model are highlighted here.

An infinite aquifer is assumed in analytic element modeling. To construct an analytic element model, features important for controlling groundwater flow (for example, wells and surface-water features) are entered as singular mathematical elements (wells) or strings of elements (linesinks). The amount of detail specified for the features depends on distance from the area of interest and the purpose of the model. Each element is represented by an analytic solution. The effects of these individual solutions are added together to form a solution for any location in the simulated groundwater-flow system. In the GFLOW code used here, the analytic elements are two dimensional and are used only to simulate steady-state conditions (water levels that do not vary with time).

Hydraulic conductivity and recharge values calibrated by Juckem and others (2014) were not changed for the simulations described in this report. Similarly, the distribution of parameters used to evaluate uncertainty and probability through the Monte Carlo method were identical to those used by Juckem and others (2014). The scenario simulations described in this report differ from previous scenarios in that the wastewater infiltration lagoons were moved to a new proposed location north of the lined treatment lagoons (fig. 1). Pumping rates from the Main Pumphouse wells also matched the values used by Juckem and others (2014) to simulate 2010 ("current") and 2035 ("future") conditions, as estimated by the Tribe. Similarly, following the methods of Juckem and others (2014), the volume of simulated wastewater applied to the proposed infiltration lagoons was provided by the Tribe, and then adjusted for precipitation onto and evaporation off the surface area of the lagoons.

Simulation of the Wastewater Plume Extent from Proposed Infiltration Lagoons

The horizontal extent of the wastewater plume downgradient from the proposed infiltration lagoons was simulated using particle tracking, with particles starting at the water table within the infiltration lagoons and traced to a terminal surface-water body or well. The method considered only advective flow from the sources; no attempt was made to evaluate the transport of contaminant mass or concentration. That is, source concentrations, dispersion, sorption, and geochemical reactions were all ignored. Instead, results were posed in terms of the probability that one or more particles would flow through a synthetic grid cell in the area downgradient from the lagoons. A synthetic grid was introduced for mapping purposes because analytic element methods do not rely upon grid-based solutions, yet a uniform mesh was needed to evaluate the density of particle path lines over small areas, or pixels, for each of the thousands of realizations. Monte Carlo techniques were used to estimate the probable horizontal extent of the wastewater plume given a range of parameter values that were informed by covariance matrices developed during the calibration process and variance estimates for parameters that were fixed during calibration (Juckem and others, 2014). The range of model parameter values were sampled using a Latin Hypercube approach (Starn and Bagtzoglou, 2012) to construct thousands of possible parameter realizations for the Monte Carlo simulations.

The horizontal extent of the probable wastewater plume was evaluated according to whether one or more particles passed through individual cells, or pixels, of the synthetic grid that covered the aquifer in the area of interest (see Juckem and others, 2014 for additional details). The method is susceptible to the level of detail used to represent the synthetic grid and the number of particles released from the wastewater source (Juckem and Fienen, 2013), as both influence the density of particle path lines that cross individual cells of the grid. For this plume extent scenario, particles were placed 33 feet (10 meters) apart within the infiltration lagoon area, and the synthetic grid used a 33-foot cell spacing. Because of the method's sensitivity to particle and grid resolution, results for source tracking of the wastewater plume are considered to be qualitative only. Nonetheless, areas with extreme probabilities (grid cells at the ends of the color spectrum for the "Probability of plume extent") are expected to be less sensitive to the number of particles and level of discretization than areas with less definitive outcomes (grid cells near the middle of the color spectrum).

Wastewater infiltrated from the proposed wastewater infiltration lagoons flows radially away from the lagoons, and then flows predominantly west toward a wetland located between the proposed lagoons and the Main Pumphouse wells, south toward a wetland adjacent to Moss Lake, and east toward Fence Lake as it integrates with the regional groundwater flow system (fig. 2). Most of the infiltrated wastewater discharges to the wetlands west and south of the lagoons. However, some of the infiltrated wastewater is simulated as having a moderate probability of flowing beneath the wetland between the lagoons and the Main Pumphouse wells before discharging to Moss Lake. Groundwater flow is simulated and shown below the wetlands because of their relatively higher simulated sediment resistance compared with the adjacent drainage lakes. That is, the calibrated resistance was 24 days for wetlands and 1 day for drainage lakes, with both values being varied around their calibrated values for the Monte Carlo analysis based on the covariances computed for each parameter during the calibration process (Juckem and others, 2014). This flow pattern indicates that there may be a low to moderate probability that some wastewater could flow beneath the wetland toward the Main Pumphouse wells (fig. 2). While wastewater does not appear to intersect the Main Pumphouse wells, it is important to recognize some limitations of the model. Specifically, tracking of wastewater through the groundwater system is halted when the water discharges into a wetland or lake. That is, the possibility remains that some wastewater that discharges to the wetland west of the proposed lagoon could, in reality, move within the wetland as surface water and then re-infiltrate into the aquifer and possibly reach the wells. This pathway, along with other sources of uncertainty, such as seasonal variability, were not simulated, and therefore impart an additional degree of uncertainty that could not be quantified with the simulations described in this report.

Simulation of Areas Contributing Recharge to the Main Pumphouse Wells

Areas contributing recharge to the Main Pumphouse wells were delineated by forward tracking of particles from the water table to the wells; this, in combination with Monte Carlo techniques, enabled maps to be produced showing the probability of capture for the well nest. That is, a range of model parameter values were sampled using a Latin Hypercube approach (Starn and Bagtzoglou, 2012) to construct thousands of parameter realizations. For every realization, or combination of parameter values, the model was re-solved and simulated particle tracks were evaluated as to whether each particle was or was not captured by a pumped well. After completing all realizations, the percentage of realizations for which a particle was captured by a well was computed for each particle. The starting location for each particle was then plotted on a map, with the color code indicating the percentage of realizations, or probability, that the particle would be captured by a nearby well (figs. 3 and 4). Particles were started on a 82-foot (25-meter) resolution grid upgradient from the Main Pumphouse wells, except within areas simulated as lakes and wetlands because surface-water flow within these features cannot be tracked in GFLOW, and groundwater/surface-water interaction between the aquifer and these features occurs along the perimeter analytic elements that define them in the model. Steady-state (no change over time) pumping conditions were used to simulate two scenarios—a scenario with pumping rates that reflect 2010 conditions, and a high-pumping scenario in which the rate was set at the expected water demand for 2035, as estimated by the Tribe. Per the methods of Juckem and others (2014), pumping rates for individual wells were estimated as a percentage of the total water demand for the Town based on the maximum pumping capacity of each well.

The results of the Monte Carlo simulations show a relatively sharp spatial contrast from areas of high probability of capture to low probability of capture for the Main Pumphouse wells under 2010 and 2035 pumping scenarios (figs. 3 and 4). This sharp gradation in probability is a result of the simulated steady-state conditions, as well as the well-constrained groundwater-flow patterns that result from the presence of regionally important boundary conditions (for example, Fence, Long Interlaken, and Pokegama Lakes; fig. 1). That is, the large lakes that occupy much of the Reservation have strong control over groundwater-flow directions, and reasonable changes to modeling parameters (for example, hydraulic conductivity and lake bed resistance) have only moderate capacity to modify the flow patterns near these large lakes. Most of the area contributing recharge to the Main Pumphouse wells is downgradient from a large wetland that extends between the wells and the proposed wastewater infiltration lagoons. In the model, surface water infiltrates from the wetland along its western border, enters the aquifer, and flows toward the wells. Probability of capture was not shown inside the wetland because the wetland was simulated as a boundary condition (a lake element), and therefore no particles were started within the wetland area. That is, water in the simulated wetlands and lakes was assumed to be fully mixed, so the origin of water discharging from the wetland into the aquifer is indiscernible for particle-tracking purposes. In other words, surface-water movement is not simulated *within* lakes or wetlands represented by lake elements in GFLOW, although groundwater movement is simulated below them. Given these features of the model, figures 3 and 4 show that groundwater recharged in areas east of the wetland has a low to moderate probability of being captured by the Main Pumphouse wells. Indeed, a few particles originate at the mounded water table beneath the proposed infiltration lagoons for the 2035 scenario, which illustrates a small potential for the Main Pumphouse wells to capture infiltrated wastewater if pumping and associated wastewater volumes increase to meet projected future demand.

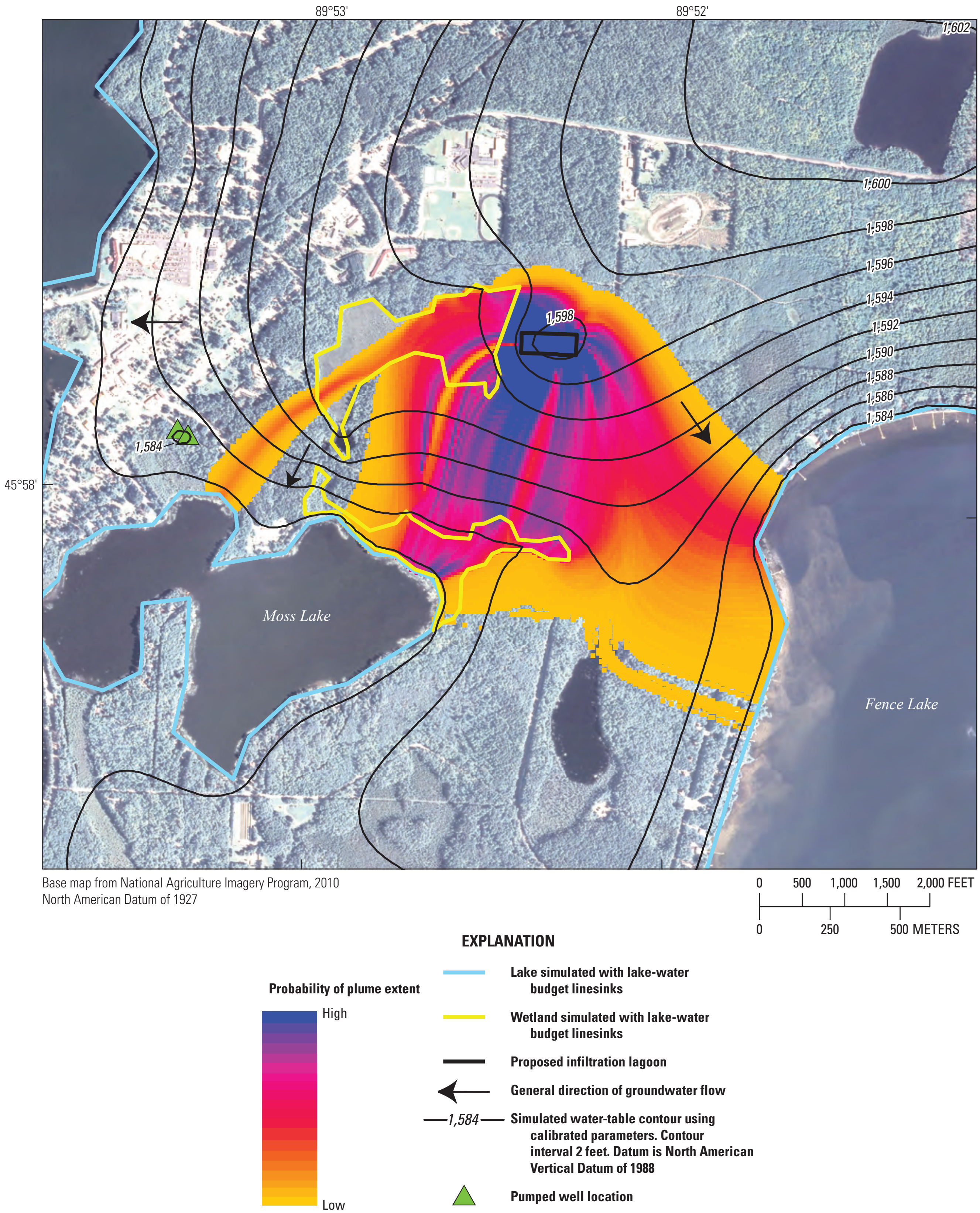

Figure 2. Simulated probability of the plume extent for a scenario with wastewater discharged from proposed infiltration lagoons north of the lined treatment lagoons, Town of Lac du Flambeau, Vilas County, Wisconsin.

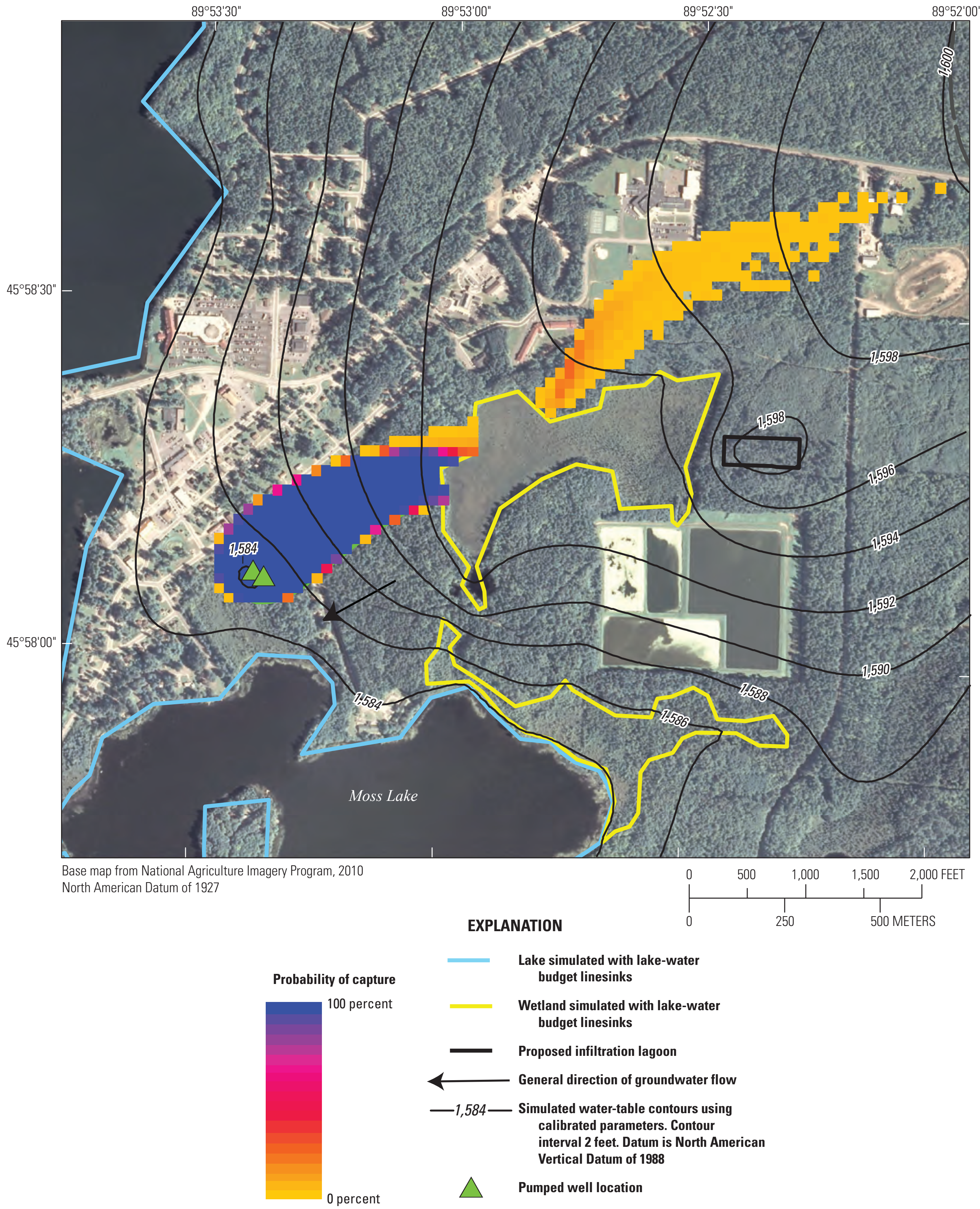

Figure 3. Simulated probabilistic areas contributing recharge to the Main Pumphouse wells, pumping at the 2010 estimated rate, with wastewater discharged from proposed infiltration lagoons north of the lined treatment lagoons, Town of Lac du Flambeau, Vilas County, Wisconsin.

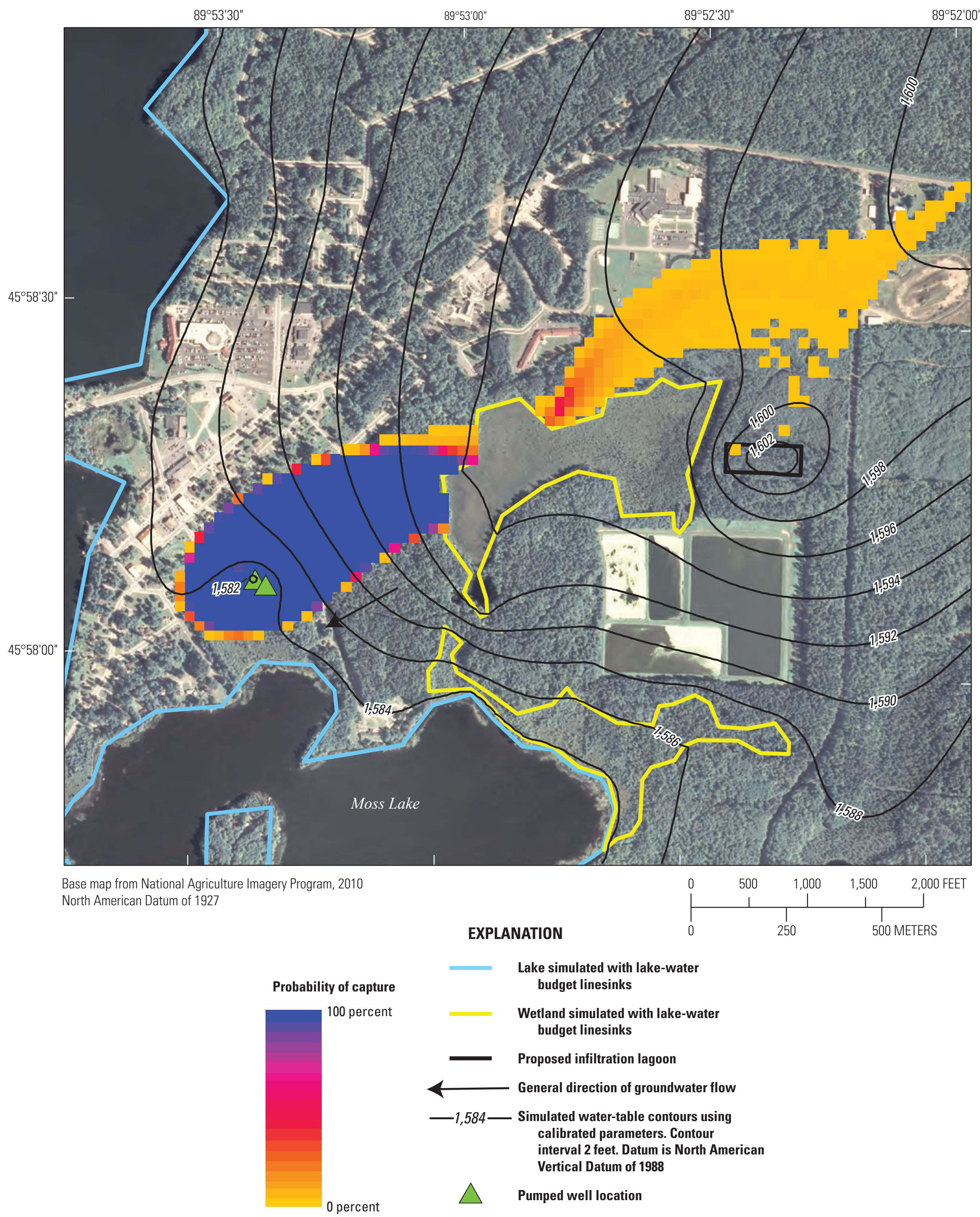

Figure 4. Simulated probabilistic areas contributing recharge to the Main Pumphouse wells, pumping at the 2035 estimated rate, with wastewater discharged from proposed infiltration lagoons north of the lined treatment lagoons, Town of Lac du Flambeau, Vilas County, Wisconsin.

Assumptions and Limitations

Given the relatively coarse nature of the unconsolidated sediments, relatively high net annual precipitation, and groundwater-flow patterns being controlled by the surrounding lakes, the groundwater and surface-water systems were assumed to have a close hydrologic connection in the modeled area. Therefore, elevations of surface-water features were assumed to be representative of the groundwater system. A two-dimensional model was assumed to be appropriate for the larger model domain because the groundwater-flow system is thin and areally extensive. Finally, steady-state simulations were also assumed appropriate for this study because hydraulic conductivity is high and distances between surface-water features are relatively small; these characteristics help dampen the effects of periodic transient stresses applied to the system (Haitjema, 1995). Steady-state simulations can be expected to result in an estimate of the higher range of system response to a hydrologic stress because they are not mitigated by groundwater release from storage.

Limitations of the model arise from these assumptions; specifically, local three-dimensional flow and transient system response expected near wells, infiltration lagoons, and shorelines of surface-water features are not represented. In addition, local features of the groundwater system (for example, local variations in hydraulic conductivity and recharge) are only approximated by using large zones. These limitations add to the uncertainty associated with estimating areas contributing recharge to wells and mapping wastewater plume extents (Franke and others, 1999). However, the Monte Carlo methods that were used for this study take uncertainty associated with parameter values partially into account. Other uncertainties resulting from the model structure were not evaluated (for example, alternative distributions of parameters or alternative conceptual models); therefore, some additional uncertainty in simulated results is expected beyond that presented in this report. In particular, results of Monte Carlo simulations for tracking of wastewater from the infiltration lagoons are sensitive to user-specified settings. These settings include the number of simulated particles (138) and the resolution of the synthetic grid (33 feet). Consequently, the wastewater infiltration tracking simulation (fig. 2) is considered qualitative and should be used with caution for informing management decisions; the methods used to assess areas contributing recharge to wells (figs. 3 and 4) are less sensitive to user-specified settings and are therefore considered more quantitative.

Summary

The Lac du Flambeau Band of Lake Superior Chippewa and Indian Health Service have been working to identify a new location for wastewater infiltration lagoons for the Town of Lac du Flambeau on the Lac du Flambeau Reservation in Wisconsin. Previous work by the U.S. Geological Survey involving the construction and calibration of a regional groundwater flow (GFLOW) model (available at https://doi.org/10.3133/sir20145020) illustrated that the probable wastewater plume extent from the existing infiltration lagoons overlapped with the contributing area for drinking-water supply wells at the “Main Pumphouse” site. New simulation scenarios were needed to evaluate the probability that the wastewater plume from a proposed set of infiltration lagoons would reach the Main Pumphouse wells. This report describes scenario simulations for the proposed wastewater infiltration lagoons that are based on the original field work and model development. The model was used for scenario simulations to estimate the probable extent of infiltrated wastewater from the proposed lagoons and probable areas contributing recharge to the Main Pumphouse wells for pumping rates estimated for 2010 and 2035.

Major conclusions from this study include the following:

A qualitative Monte Carlo assessment of the wastewater plume extent was simulated by evaluating the probability that each forward-tracked particle from within the proposed infiltration lagoons would intersect an individual cell of a synthetic grid applied across the downgradient aquifer. Results show that wastewater infiltrated from the proposed lagoons flows west and south before discharging to local wetlands, and east as it integrates with the regional groundwater-flow system upgradient from Fence Lake. No mathematical particles of infiltrated wastewater reached the Main Pumphouse wells during the simulation; instead, most of the infiltrated wastewater discharged to the nearby wetlands where tracking of the wastewater is halted in the model.

Simulated results of the wastewater-plume-extent scenario are sensitive to the number of mathematical water particles used to represent infiltrating wastewater and the level of detail in the synthetic grid used for the probability analysis. Therefore, simulated probabilities of wastewater plume extents are qualitative only. Moreover, the Monte Carlo methods used in this study to evaluate uncertainty associated with parameter values do not allow for evaluation of alternative distributions of parameters or alternative conceptual models, and therefore, some level of additional uncertainty beyond the simulated results is unavoidable. Nonetheless, the uncertainty analyses were developed from the basis of a physically based groundwater-flow model and covariances developed through calibration to extensive target datasets.

Areas contributing recharge to the Main Pumphouse wells were delineated by tracking simulated particles from the water table to wells in combination with Monte Carlo techniques, which produced maps of the probability of capture for the wells. Simulations were performed with estimates of 2010 and 2035 pumping rates. The simulations show a relatively sharp spatial contrast from areas of high probability of capture to areas of low probability of capture for the Main Pumphouse wells under both pumping scenarios. Most of the area contributing recharge to the Main Pumphouse wells is downgradient from a large wetland between the wells and the proposed wastewater infiltration lagoons. Results show

show no infiltrated wastewater from the proposed lagoons being captured by the Main Pumphouse wells under 2010 pumping conditions. However, a few particles of water originating from near or within the proposed infiltration lagoons were captured by the wells for the 2035 scenario when higher pumping rates and increased wastewater volume, as estimated by the Lac du Flambeau Band of Lake Superior Chippewa, were simulated.

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