# Vashon-Maury Island
# Hydrologic Modeling

## Technical Report

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# Executive Summary

The Vashon-Maury Island Water Resources Evaluation (VMI WRE) is a seven-year project begun in 2003 by King County Water and Land Resources Division under the guidance of the Vashon-Maury Island Groundwater Protection Committee. The VMI WRE is intended to develop an understanding of current water resource conditions on the island, assess potential future conditions accounting for future pressures on water resources, and develop a long-term monitoring program for tracking conditions. This report presents the results of the second phase of modeling, which included the development of a time-varying, integrated groundwater-surface water model and an assessment of the impacts of possible future build-out and climate change scenarios on water resources. Information generated from the scenarios evaluated will be used by King County, the Vashon-Maury Island Groundwater Protection Committee, and others as they assess long-term sustainability of the island's water resources, develop a long-term monitoring program to track conditions, and consider possible future management actions.

The model was constructed using the MIKE SHE and MIKE 11 codes developed by DHI Water and Environment. MIKE SHE is a numerical hydrologic model that simulates all of the major components of the land-based phases of the hydrologic cycle, while MIKE 11 is a one-dimensional hydrodynamic surface water model that represents river and stream flows and is dynamically coupled with the runoff and groundwater components of MIKE SHE. Site-specific parameters used to construct the model included land use, precipitation, evapotranspiration, geologic and hydrogeologic parameters, well locations, and pumping and withdrawal rates. Several parameters were assumed to vary based on season, including precipitation, evapotranspiration, pumping, and withdrawal rates. The model output generally agrees well with previous evaluations of water resources, and the model calibration was acceptable for understanding the general flow direction, magnitude, and location of the water resources and assessing potential areas of concern (lower water levels and/or less base flow) based on future scenarios given the challenges of representing the complex conditions of the area such as subsurface flows to saltwater, steep bluffs, and heterogeneous geologic subsurface conditions. The model output is not intended to represent predictions of actual future conditions at any specific location at any specific time.

Following calibration, the model was evaluated for historical data, two possible future pumping scenarios representing additional development on the island associated with population growth, four possible future climate change scenarios representing possible changes in temperatures and precipitation, and four possible future scenarios that combined the development and climate conditions. The model outputs from these various scenarios were compared in order to provide estimates of the potential impacts of additional pumping and climate change.

The results for the future scenarios show projected decreases in recharge, groundwater levels, and stream summer baseflows under all of the future scenarios that were evaluated. Groundwater levels were projected to decline from between 0.3 feet to 5.9 feet depending on the scenario, the location, and the aquifer in question. The largest projected decreases in groundwater levels were found to occur surrounding Group A water supply wells under

combined increased pumping and climate change conditions. Stream summer baseflows were projected to decline between 0.1 and 4.5 percent in the creeks evaluated, depending on the scenario and the creek in question. The largest decline in summer stream baseflows was for Judd Creek under the 2075 climate scenario from the ECHAM climate model and the A2 emissions scenario. The ECHAMS – A2 scenarios represent a mid range precipitation and temperature change condition from among the various climate change scenarios that were considered.

SECTION 1

# Introduction

## 1.1 Overview

Vashon-Maury Island (VMI) is an island that lies in the Puget Lowland encompassing about 37 square miles. All drinking water sources on the island (springs, surface water, and groundwater) are supplied by precipitation. Groundwater is the portion of precipitation that soaks into the ground and gets stored in underground geological water systems called aquifers. Every groundwater system is unique and dependent upon external factors such as the rate of precipitation, the interaction of groundwater with the streams and other surface water bodies, and the rate of evapotranspiration. These external factors all contribute to the overall water budget. Understanding the water budget for Vashon-Maury Island and how it changes in response to human activities and climate changes is important in determining the amount of drinking water that can be used on a sustainable basis.

A long-term plan that describes and evaluates the different components of the VMI water budget is being implemented to address needs and concerns identified by residents of Vashon-Maury Island including the VMI Groundwater Protection Committee and King County staff. Much interest has been expressed over the years in the sustainability of the water supply on the island. This work documents the development of a coupled surface-ground water model and analysis of scenarios that evaluate the effects of additional water extraction and climate change on island water supplies.

## 1.2 Study Area

Vashon-Maury Island is located in the Puget Lowland within the boundaries of King County, Washington situated southwest of Seattle and north of Tacoma. The island encompasses approximately 36 square miles of which 29 square miles are on the Vashon portion of the island and 7 square miles on the Maury portion of the island. The topography of Vashon-Maury Island varies from sea level to elevations in excess of 460 feet based on U.S. Geological Survey topographic maps. The shoreline extent of Vashon-Maury Island is just over 58 miles, most of which lies beneath steep, slide-prone slopes. The island has numerous (>70) stream basins. Two of these, Judd Creek (3,220 acres) and Shinglemill Creek (1,940 acres), are larger perennial streams with distinct subbasins, and all of the stream basins on the island drain into Puget Sound.

Precipitation is the primary source of recharge and can vary greatly across Vashon-Maury Island from 48 inches/yr on the western side of Vashon Island to 35 inches/year on the eastern side of Maury Island. All drinking water sources on the island (springs, surface water, and groundwater) are supplied by local precipitation. The majority of the residents of Vashon-Maury Island get their drinking water from public water systems that rely on groundwater

supplies. The population of Vashon-Maury Island is growing. The island population has grown steadily, approximately 2 percent per year, from 6,516 in 1970, to 7,377 in 1980, to 9,309 in 1990, to 10,100 in 2000. According to the Puget Sound Regional Council (PSRC), the population of VMI will continue to grow at a rate of 100 people per year. Potential population growth capacity has also been estimated by VMI resident Bob Powell in 2007 (http://dogpatch.com/kcprop/). These sources were considered in determining the additional amounts of water to be extracted in the model. Potential climate change scenarios for the study area were based on the climate change scenarios prepared by the University of Washington Climate Impacts Group for the Climate Change subcommittee of the Regional Water Supply Planning process (http://www.govlink.org/regional-water-planning).

## 1.3 Project Background

In 2005, the King County Department of Natural Resources and Parks (DNRP) completed a groundwater modeling study of VMI as part of a VMI Water Resources Evaluation, an effort aimed at assessing the quantity of water resources available on the island and understanding the threats to its sustainability. This initial phase of modeling was a three-dimensional model that describes the basic flow patterns of groundwater and provides annual average estimates of water supply for Vashon-Maury Island. The Phase I modeling report was published in October 2005 (King County, 2005).

This Phase II modeling work involves refining the Phase I groundwater model and linking it to a surface water model. New software (called MIKE SHE) was purchased in late 2005 to address the integration of surface water and groundwater. Completion of this Phase II model will give King County the ability to evaluate the potential impacts to groundwater supplies caused by potential changes in climate and assess the impacts from potential population growth by extracting more water from existing wells and adding new wells to the existing well network.

While the Phase I work provided a solid foundation for understanding the groundwater resources on the island, several limitations and recommendations for future work were identified including the need to refine the hydrostratigraphy and aquifer properties used in the model, reduce the uncertainty surrounding the boundary conditions used in the model (particularly the recharge boundary), perform a transient simulation, and expand and improve the model calibration. In order to refine the ability to simulate historical groundwater conditions on the island and improve the ability to model future conditions scenarios, DNRP began developing a transient integrated hydrologic model using DHI's MIKE SHE code and the existing MODFLOW model as a starting point.

Subsequent staff changes at DNRP resulted in a lack of resources available to complete the MIKE SHE modeling. In order to facilitate the completion of the work, DNRP contracted with DHI in 2008 to complete the construction and calibration of the model and evaluate a series of future conditions scenarios. This report describes the results of this initiative including the following general activities:

- Adding additional processes to the model including evapotranspiration, overland flow, channel flow, and unsaturated flow;

- Calibrating the model to transient observed streamflow and groundwater observation data;
- Evaluating a series of future conditions scenarios with the model involving changes in climate and groundwater pumping;
- Documenting the limitations of the model and making additional recommendations for subsequent work.

## 1.4 Goals and Objectives

The goal of this work is to build and maintain a comprehensive model of VMI that evaluates groundwater and surface water quantity and quality. An additional goal is to have a tool to evaluate the island-wide water resources under various climate change and land-use scenarios for assessing sustainability issues.

The objectives of this modeling work are:

1. To build and maintain a comprehensive model of VMI that evaluates groundwater and surface water quantity;
2. To identify all the data necessary to assess the island wide water balance;
    a. Continue monitoring the necessary data for water resource assessment;
    b. Identify data gaps and potential ways to collect this data;
3. To assess the sustainability of the water resources under various land-use and climate change scenarios, and;
4. To coordinate these activities with the Vashon-Maury Island Groundwater Protection Committee and the citizens of Vashon-Maury Island to help monitor the island's resources.

## 1.5 Historical Water Resources Review

### 1.5.1 Vashon-Maury Island Water Resources Report

In 1983, the first major report of island resources was completed and is commonly referred to as the "Carr Report" (Carr/Associates, Inc., 1983). This report concluded that precipitation is the only source of recharge to the island aquifers. This finding was significant at the time, as many people then believed the island's water supply came from distant sources such as the Olympic or Cascade Mountains.

The Carr Report documented that the island's water supply is obtained primarily from wells and springs. In addition, the report developed a water budget for the island based on measured precipitation and stream flows.

The water budget estimated that the island receives an average of 38 inches of precipitation annually. Half of the total annual precipitation received (19 inches) was calculated to be lost to direct evaporation or transpiration by plants (evapotranspiration). Another 14 inches of the

total annual precipitation was calculated to be lost via direct surface runoff to streams, and only 5 inches of total annual precipitation was estimated to infiltrate and recharge the groundwater.

### 1.5.2 Vashon-Maury Island Groundwater Management Plan

The Groundwater Management Plan for Vashon-Maury Island was completed in 1998 (VMI GWAC, 1998). The VMI Groundwater Management Plan built upon the Carr Study and incorporated many new management strategies to protect the island's groundwater quantity and quality.

While preparing the plan, additional measurements of precipitation, temperature and stream flows were collected to refine the water budget for the island. The new water budget concluded there were approximately 16.4 in/yr of water available to recharge the aquifers. This estimate was significantly (3.4 times) higher than the Carr Report which only estimated a total recharge of approximately 5 in/yr.

### 1.5.3 Water Resources Evaluation

In 2001, King County Department of Natural Resources and Parks began a groundwater monitoring program to assess the current status of the groundwater quantity and quality on the island. Ambient monitoring had not been done on the island since the data collection for the VMI Groundwater Management Plan was completed in 1992.

The Water Resources Evaluation (WRE) project was launched in 2004 to monitor all water resources on the island (precipitation, surface water, and ground water). The effort to establish an accurate water balance for the island is a priority for the Groundwater Protection Committee (GWPC). King County is assessing water availability by developing a water budget-based model at the request of the GWPC. The WRE includes two modeling efforts utilizing the new monitoring along with all the other necessary data to better assess the island's overall water balance. The WRE water balance is being prepared to resolve the differing estimates of groundwater availability calculated from the water budgets prepared in the 1983 Carr Report and the 1998 GWMP. To calculate aquifer recharge, the WRE water balance uses the following formula. Precipitation minus evapotranspiration and surface water runoff equals aquifer recharge. Aquifer discharge is estimated by calculating spring flow, stream base-flow, and well pumpage with the remaining flow discharging to Puget Sound via submarine groundwater pathways.

In the first phase of modeling, WRE staff created an island-wide (steady-state) groundwater flow model to better assess the available water resources. This model used new data gathered by the WRE in addition to the data collected by earlier studies. The effort highlighted the fact that ground and surface water quantity data was not readily available or well monitored on the island. The Phase I modeling effort produced a new estimated aquifer recharge (12.8 in/yr) that was between the two previous study results. Much of the water use data for the smaller (Group B) public water systems and the domestic wells was estimated based on regional water use patterns.

SECTION 2

# Model Development

## 2.1 Model Algorithms

The Vashon-Maury Island Hydrologic Model was constructed using the MIKE SHE and MIKE 11 codes developed by DHI Water & Environment, Inc (DHI, 2008). MIKE SHE is numerical hydrologic model that simulates all of the major components of the land-based phases of the hydrologic cycle (Figure 1). These components include evapotranspiration (ET), overland flow, unsaturated flow, and groundwater flow. For each of these processes, MIKE SHE offers several different approaches which range from simple, lumped, and conceptual to advanced, distributed, and physically based. Simple and advanced approaches may be combined, enabling the most appropriate model to be constructed in order to meet the demands of a given project while considering computational and data availability constraints.

The VMI MIKE SHE model was dynamically linked to the one-dimensional hydrodynamic surface water model, MIKE 11, for a representation of surface water flow and the interactions between the surface water and groundwater systems. Table 1 summarizes the model components used for the VMI model and the method used (or governing equation) for each, and Table 2 summarizes the model inputs and parameters required for each component. A general explanation of how these components work in MIKE SHE and MIKE 11 is given below, and information on data sources follows in Section 2.2.

### 2.1.1 Evapotranspiration

The evapotranspiration (ET) module in MIKE SHE uses meteorological and vegetative data to simulated ET, and includes methods for simulating evaporation from interception storage in the canopy, evaporation from the soil surface, transpiration of water by plant roots based on soil moisture in the unsaturated zone, and transpiration from groundwater if the rooting depth exceeds the thickness of the unsaturated zone (DHI, 2008). The VMI MIKE SHE model uses a Two-Layer Water Balance Method for simulating ET which divides the unsaturated zone into an upper rooting zone, from which ET can occur, and lower zone below the rooting zone, where ET does not occur.

The simulated ET is based on the specification of potential ET (PET). For each ET time step, the model tries to meet the PET or determines to what degree the PET can be met from four different storages: the canopy, ponded water, the unsaturated zone, and the saturated zone, and limits each of these components based on the simulated available water in each of these storages. The method also allows for upward movement of water from the saturated zone to the rooting zone to occur as a result of rooting zone ET demand. The primary input parameters include PET, and Leaf Area Index (LAI) and Rooting Depth (RD) data for the various vegetation types in the model.

Table 1: Simulation modules, processes, and methodologies used in the VMI MIKE SHE model.

| **Model Component** | **Processes Simulated** | **Methodology** |
|---|---|---|
| MIKE SHE OL | Overland sheet flow. water depths, depression storage | Two-dimensional diffusive wave approximation of the St. Venant equations |
| MIKE 11 | River and lake hydraulics, flows and water-levels | 1-dimensional fully dynamic wave approximation of the St. Venant equations |
| MIKE SHE UZ and ET | Flow and water content in the unsaturated zone, ET, infiltration, groundwater recharge | Two-layer water balance method |
| MIKE SHE SZ | Groundwater flow and storage changes | Finite-difference method |

### 2.1.2 Overland Flow

The VMI model uses an explicit finite difference method for simulating overland flow. It solves a two-dimensional diffusive wave approximation of the Saint Venant equations to calculate surface flow in the x- and y- directions and water depths for each grid cell of the model domain. The overland flow algorithm interacts with the channel flow, the unsaturated zone, and the saturated zone components of the model. The primary input parameters include a description of the topography, and Manning's roughness coefficients (n) and detention storage values ($S_D$) for the various land cover categories used in the model. Although this option was not used in the VMI model, it is possible to use a 'paved area option' to send a fraction of the generated overland flow from pervious areas directly to streams represented in the model.

### 2.1.3 Unsaturated Flow

The unsaturated flow component of the VMI model uses a Two-Layer Water Balance Method that functions in conjunction with the ET component of the model. This method uses a simple mass-balance approach to represent the unsaturated zone, and accounts for interception storage changes, surface ponding, and water content in the root zone, infiltration, evapotranspiration, and groundwater recharge. Volumetric moisture contents at saturation ($\theta_S$), field capacity ($\theta_{FC}$), and wilting point ($\theta_{WP}$) are used to calculate the average moisture content in the soil, which is linearly dependent on the depth of the water table. The difference between the moisture content at saturation and at field capacity ($\theta_S$-$\theta_{FC}$) provides an estimate of the storage capacity of the soil; while the difference between the moisture content at field capacity and at the wilting point ($\theta_{FC}$ - $\theta_{WP}$) provides an estimate of the amount of water available for transpiration within the rooting zone.

Table 2: Required input data for each component of the VMI MIKE SHE model.

| Model Component | Required Input Data |
|---|---|
| Precipitation | Distribution of precipitation rates |
| MIKE SHE OL | Topographic map, land use map, distribution of Manning's roughness coefficients, distribution of detention storage, initial water depths |
| MIKE 11 | Channel network, cross section geometries, Manning's roughness coefficients, boundary conditions, initial conditions |
| MIKE SHE UZ and ET | Distribution and rates of potential ET, soil map, saturated hydraulic conductivities, soil moisture contents at saturation, field capacity, and wilting point, leaf area index, rooting depth |
| MIKE SHE SZ | Aquifer geometries, hydraulic conductivities, specific yields, storage coefficients, pumping well locations, depths, and abstraction rates |

Infiltration to the unsaturated zone is controlled by a time-invariant maximum infiltration rate that can be spatially distributed according to soil types. The specified infiltration rate is a calibrated effective parameter rather than a physical soil property. Because it is an effective parameter the value must be sufficient to represent average response of the unsaturated zone in an area. The actual infiltration to the unsaturated zone is the minimum of the amount of ponded water available, the infiltration rate times the time step, or the available storage volume in the unsaturated zone.

### 2.1.4 Groundwater Flow

The VMI model uses a three-dimensional finite-difference approach for representing the groundwater system that is very similar to MODFLOW. The finite difference algorithm calculates flow by describing the spatial and temporal variations of the dependent variable (hydraulic head) mathematically using a three-dimensional Darcy equation solved numerically by an iterative implicit finite difference technique. The method utilizes the preconditioned conjugate gradient groundwater solver developed by the USGS. The saturated zone component of flow interacts with the other components in MIKE SHE primarily by using flow terms from the other components implicitly or explicitly as source or sink terms.

### 2.1.5 Channel Flow

MIKE 11 is a one-dimensional hydrodynamic modeling tool used to analyze water movement in a stream network including flow through structures and other hydraulic features. The MIKE 11 component of the VMI model solves the fully dynamic wave approximation of the Saint Venant equations for one-dimensional unsteady flows. The MIKE 11 model is integrated with the MIKE SHE model, and MIKE SHE acts as a dynamic boundary condition for that exchanges overland flows and groundwater baseflows with MIKE 11.

### 2.1.6 Anthropogenic Influences

The VMI model also takes into account anthropogenic influences such as groundwater abstraction, septic system return flows, and irrigation. Groundwater pumping and septic system return flows were handled using the pumping module in MIKE SHE, which extracts or injects (for the case of return flows) water from/to the saturated zone. The pumping rate is specified using time series files linked to the well locations. The irrigation module in MIKE SHE was also used for the VMI model. The model applies water to the land surface in the model for the cells that are coded as irrigated at a specified rate using a time series file that is linked to the irrigation areas.

## 2.2 Input Data

### 2.2.1 Model Domain and Simulation Period

The VMI MIKE SHE model domain (i.e. the spatial boundary) includes all of VMI, and represents the island using approximately 4,000 500-ft by 500-ft square grid cells (each cell is approximately 6 acres). This grid resolution was selected in order to allow for a refinement of the MODFLOW model grid which operated on a 1,000-ft square grid but not exceed the resolution of the available input data or result in unmanageable computational times. The overland flow, unsaturated flow, groundwater flow and evapotranspiration calculations are each computed for every 500-ft square grid cell, however, the channel flow calculations occur at node locations on the stream network rather then on a grid-cell basis.

The simulation period used for the VMI model was from 10/1/2001 – 9/30/2004. In order to begin the simulations with realistic initial conditions the model used a 'hot start' file whereby simulated conditions at the end of a previous simulation were used as the initial conditions in the final simulation in order to allow the model to reach a dynamic equilibrium with the simulated processes and responses and reduce the sensitivity of the results to the assumed initial conditions. The climate change scenarios were evaluated over a longer timeframe from 10/1/1927 – 10/1/2003 which is discussed in greater detail in Section 4 of this report.

### 2.2.2 Climate Data

Precipitation records on VMI are incomplete for the modeled time period and thus it was not possible to develop a continuous precipitation timeseries for the model using island data. Instead, the climate data used in the VMI model is based on the nearby Sea-Tac gauging station (~ 6 mi to the east of the island) operated by the National Weather Service. In order to account for differences in precipitation between Sea-Tac and VMI and to account for spatial variation in precipitation across the island, an annual isohyetal map for the island was used to scale the Sea-Tac record. The annual isohyetal map was generated by King County using VMI precipitation data from 2005 through 2007. The area between each 1" annual isohyetal contour on the island was used to define 14 precipitation polygons for the island. Each polygon was assigned to a precipitation timeseries by scaling the daily Sea-Tac record by a constant factor in order to bring the long-term mean annual precipitation into agreement with the values indicated by the isohyetal data (Figures 2 and 3). A single daily potential evapotranspiration (PET) timeseries was developed using a modified Penman-Monteith formulation and the Sea-Tac temperature records (Figure 4). A 19-step procedure was used for performing this calculation as described in Appendix A (after Duke et al., 2008). Climate data for the potential climate change scenarios were based on the climate change scenarios prepared for the SeaTac weather station by the Climate Change subcommittee of the Regional Water Supply Planning process.

### 2.2.3 Land Cover

Land cover is one of most important inputs in MIKE SHE as variations in vegetation types can significantly affect many of the relevant processes such as overland flow, evapotranspiration, and infiltration. In MIKE SHE, vegetation-based properties like the leaf area index and the rooting depth (discussed in the following sections) are assigned based on vegetation types in the land cover map. In order to account for the variations in vegetation properties across the island, a polygon shapefile (the 2002 King County GIS dataset) showing the major land cover categories on the island was used in the model. The models used six land cover categories as defined in the GIS dataset: coniferous forest, mixed forest, herbaceous vegetation, shrub/scrub vegetation, low-density urban, and high-density urban (Figure 5).

### 2.2.4 Vegetation Properties

Two parameters describing the characteristics of the vegetation were assigned to each of the six land cover categories described above. These parameters are the Leaf Area Index (LAI) and the Rooting Depth (RD). The LAI is defined as the (area of leaves)÷(area of the ground) and can vary between 0 and 7 (dimensionless ratio) depending on the vegetation type. In MIKE SHE this parameter exerts a strong control over the rate of evapotranspiration. Site specific values of the LAI and the RD were not available, thus values were assigned based on literature values from similar vegetation types and adjusted during calibration. Table 3 shows the minimum and maximum values for the LAI and the RD used for each of the six land cover categories used in the model.

Table 3: Minimum and maximum Leaf Area Index (LAI) and Rooting Depth (RD) values (units of feet) used in the VMI MIKE SHE model.

| Land cover | LAI (min) | LAI (max) | RD (min) | RD (max) |
|---|---|---|---|---|
| High-density Urban | 2.0 | 2.0 | 0.8 | 0.8 |
| Low-density Urban | 1.0 | 2.0 | 1.5 | 1.5 |
| Herbaceous Vegetation | 0.5 | 3.0 | 1.0 | 2.5 |
| Shrub/Scrub Vegetation | 1.6 | 2.6 | 3.4 | 3.4 |
| Coniferous Forest | 5.5 | 5.5 | 3.5 | 3.5 |
| Mixed Forest | 2.3 | 5.3 | 3.7 | 3.7 |

### 2.2.5 Irrigation

Irrigated areas were included in the model based on a shapefile showing the agricultural parcels on the island. The parcels are divided into three categories: horticulture, pasture, and mixed (Figure 6). Irrigation rates for each of the three categories were based on the irrigation pumping rates determined for the MODFLOW study; however, the steady-state pumping rates used in the MODFLOW model were converted to transient rates by applying a representative annual distribution to the total rates. This distribution was based on expected seasonal variations in demand for irrigation. The irrigation season was assumed to begin in May and extend through October and rates were set to ramp up from May to a peak in July and September and then ramp back down through October (Figure 7).

### 2.2.6 Overland Flow Parameters

Along with the topography, a distribution of Manning's roughness coefficients (n) is the main input to the overland flow component of the model. A spatial distribution of roughness coefficients was developed based on the land cover map described in Section 2.2.4. No site-specific coefficients were available, so standard literature values were used as the basis for determining the initial coefficient values for each land cover category and final values were determined during calibration (AASHTO, 2005; DIDM, 2000; HCSS, 2005; McCuen, 2004). It is important to note that while the modeled 'n' values bear some resemblance to typical 'n' values that would be used in, for example floodplain calculations in a surface water model, the choice of values is highly grid-scale dependent. Since the overland flow component of the model operates on a 500-ft by 500-ft grid, the model representation of the topography is highly generalized. This results in a situation whereby artificial roughness and/or smoothness is introduced by the large flat topographic grid cells, and the larger the cells become the more magnified this effect becomes. The final values used in the model range from 0.06 for high-density urban areas to 0.14 for mixed forest areas (Table 4).

Table 4: Overland Manning's roughness coefficients (n) used in the VMI MIKE SHE model.

| Land cover | Manning's n |
|---|---|
| High-density Urban | 0.06 |
| Low-density Urban | 0.07 |
| Herbaceous Vegetation | 0.08 |
| Shrub/Scrub Vegetation | 0.11 |
| Coniferous Forest | 0.13 |
| Mixed Forest | 0.14 |

### 2.2.7 Channel Flow Data

Channel flow was handled by the MIKE 11 model which was dynamically linked to the MIKE SHE model. The primary input data for this model included the stream network, boundary conditions, and channel geometry data. The stream network was generated based on a hydrography shapefile and includes Judd Creek, Shingle Mill Creek, and 15 additional streams on the island (Figure 8). Boundary conditions in MIKE 11 are required for all unconnected ends of branches. In the VMI MIKE 11 model, all of the upstream boundaries are closed (i.e. no-flow boundaries). This is because water is introduced to the stream network via overland flow, interflow, and baseflow that is simulated via MIKE SHE so it is not necessary to define an upstream inflow hydrograph. The downstream boundary of each branch was set to a constant water level approximately 1-ft above the thalweg elevation. Surveyed cross sectional data was unavailable, thus a standard triangular channel cross section, 6.6-ft wide by 3.2-ft deep was used and the thalweg elevations were extracted from a LiDAR dataset of the island (King County GIS data).

### 2.2.8 Soils

In order to account for the variations in soil characteristics across the island, the National Resource Conservation Service's Soil Geographic Database (SSURGO, 2008) was used to develop a soil distribution for the model. Approximately 80% of the island is covered by two soil series (Alderwood and Everett-Alderwood) and an additional 10 soil series cover the remainder of the island (Figure 9). The required model input parameters for each soil type include the soil moisture content at saturation ($\theta_S$), field capacity ($\theta_{FC}$), wilting point ($\theta_{WP}$), and saturated hydraulic conductivity (Ksat). Initial values of these parameters were taken from the SSURGO database and final values were determined through model calibration (Table 5).

### 2.2.9 Aquifer Geometries and Properties

The upper surface of the model was defined by re-sampling a LiDAR dataset of the island to the model grid resolution of 500-ft. The lower surfaces of each model layer were imported from the existing MODFLOW model. The MODFLOW surfaces were based on geologic mapping and borehole log interpretations performed by the Pacific Northwest Center for Geologic Mapping Studies (GeoMapNW) in 2004.

Table 5: Soil properties used in the VMI MIKE SHE model ($K_{sat}$ values are in units of ft/s).

| Soil type | $\theta_S$ | $\theta_{FC}$ | $\theta_{WP}$ | $K_{sat}$ |
|---|---|---|---|---|
| Alderwood | 0.32 | 0.14 | 0.11 | 4.9E-05 |
| Alderwood-Kitsap | 0.39 | 0.26 | 0.19 | 3.2E-05 |
| Bellingham | 0.43 | 0.30 | 0.13 | 6.2E-06 |
| Coastal Beaches | 0.26 | 0.06 | 0.05 | 3.0E-04 |
| Everett | 0.32 | 0.13 | 0.10 | 5.2E-04 |
| Everett-Alderwood | 0.32 | 0.13 | 0.10 | 2.9E-04 |
| Pits | 0.26 | 0.06 | 0.05 | 1.8E-04 |
| Indianola | 0.30 | 0.16 | 0.12 | 6.6E-04 |
| Kitsap | 0.26 | 0.06 | 0.05 | 1.6E-05 |
| Norma | 0.33 | 0.22 | 0.12 | 9.2E-05 |
| Ragnar-Indianola | 0.30 | 0.12 | 0.07 | 5.2E-04 |
| Seattle | 0.67 | 0.40 | 0.13 | 3.0E-05 |

A few of the hydrogeologic units were handled differently than they were in the MODFLOW model however. Specifically, the upper most units (Qvr and Qal) were handled as a lens in the MIKE SHE model rather then a continuous model layer. This was done in order to represent the discontinuous nature of these deposits more realistically in the model. The representation of these materials as a lens means that where the lens is present, the hydrogeologic properties assigned to the lens become embedded in the underlying layer via a weighted mean for horizontal conductivity (K) and a harmonic-weighted mean for vertical K. The other major difference from the MODFLOW model is that in the MODFLOW model the Qva was represented as two model layers because of numerical stability considerations inherent to MODFLOW, whereas in the MIKE SHE model these layers were combined. Although it was not done for this study, the two Qpff layers could also be combined which would likely have a limited impact on the results but potentially help to reduce computational times. The MIKE SHE model thus contains eight layers and one lens which represent four aquifers and four aquitards (Table 6).

Associated with each model layer and lens are the horizontal and vertical hydraulic conductivity values ($K_h$ and $K_v$, respectively). Values for each of these parameters were initially taken from the MODFLOW model and final values were determined through model calibration (Table 6).

### 2.2.10 Groundwater Boundary Conditions

The model used a zero-flux (no-flow) boundary around the perimeter of the model for all layers except for Layer 2 (Qva) and Layer 5 (QAc). Both of these layers used a constant fixed head boundary condition. A fixed head boundary of 124.7-ft NAVD88 was used for the Qva in order to represent springs that discharge around the perimeter of the island. This boundary was not included in the MODFLOW model but was added as part of the calibration process which is

Table 6: Model layers and hydraulic conductivity values.

| Layer | Unit | Layer Type | Kh (ft/day) | Kv (ft/day) |
|---|---|---|---|---|
| Lense | Qvr | Aquifer | 1710 | 17.1 |
| Layer 1 | Qvt | Aquitard | 2.5 | 0.005 |
| Layer 2 | Qva | Aquifer | 9.9 | 2.5 |
| Layer 3 | Qpff | Aquitard | 0.01 | 0.001 |
| Layer 4 | Qpff | Aquitard | 0.01 | 0.001 |
| Layer 5 | QAc | Aquifer | 9.9 | 1.0 |
| Layer 6 | QBf | Aquitard | 1.0 | 0.005 |
| Layer 7 | QBc | Aquifer | 20.1 | 2.0 |
| Layer 8 | Qc | Aquitard | 1.0 | 1.0 |

described in Section 3. The value represents an elevation in the lower portion of the Qva layer. A fixed head boundary of 23-ft was used for the QAc in order to represent the subsurface ischarge to Puget Sound. This boundary condition was placed in the overlying Qpf layer in the MODFLOW model. The position and value of this boundary in the MIKE SHE model was determined as part of the calibration process.

A drainage boundary condition was included in order to represent springs that discharge on the island. The locations where this boundary condition was included were based on a shapefile of known spring locations on the island. As part of the calibration process, the number of cells where drainage boundaries were included was expanded to include the full perimeter of the island as well as interior areas where springs have been identified (Figure 10). A drainage level of 0.03-ft below land surface and a drainage time constant of 1.0 x $10^{-7}$ seconds was used. The drainage level represents the level at which the groundwater levels must reach in order to generate drain flow, and the time constant along with the difference between the groundwater level and the drain level controls the rate of discharge exiting the drainage boundaries. The drain level and drainage time constant values were determined through the calibration process.

Existing pumping well locations and screening depths were taken from the MODFLOW model. This includes a total of 787 pumping wells including the Group A (large public water system wells), Group B (small public water system wells), agricultural, and industrial wells (Figure 11). Pumping rates were also taken from the MODFLOW model, however, the steady-state pumping rates used in the MODFLOW model were converted to transient rates by applying a representative annual distribution to the total rates. The total annual withdrawal volumes are the same as in the Phase I MODFLOW model. This distribution was based on metering of historical abstraction rates and accounts for the seasonal variations in demand whereby the highest pumping rates occur in the summer months and the lowest rates occur in the winter months. The 'summer' months from May to October now use 61% of the annual total (see Table 7).

Table 7: Monthly distribution of pumping used to reflect increased 'summer' demand. Percentages based on the VMI Group A Water Systems monthly usage totals.

| Month | % of Annual Total |
|---|---|
| Jan | 6.5% |
| Feb | 6.0% |
| Mar | 6.0% |
| April | 6.5% |
| May | 7.0% |
| June | 7.5% |
| July | 9.5% |
| Aug | 12.5% |
| Sept | 13.9% |
| Oct | 10.5% |
| Nov | 7.5% |
| Dec | 6.5% |

Recharge resulting from discharge from septic systems was included in the VMI model by adding a series of shallow injection wells with an injection depth of 3.2-ft (Figure 12). The injection wells were distributed based on a shapefile of parcels located outside of the Vashon Sewer District and the rates were taken from the MODFLOW model; the rates were not given a seasonal distribution as was done for the abstraction rates but instead were kept constant.

**SECTION 3**

# Model Calibration & Results

## 3.1 Available Data and Calibration Approach

The goal of the calibration for the VMI MIKE SHE model was to compare and calibrate the results of the model against as much data as possible to gain a solid understanding of the model's performance and identify any deficiencies in the model's representation of the hydrology of the island. The types of data available for calibration and comparison include overall water budgets, streamflow hydrographs, and groundwater head observations.

Several previous studies have estimated one or more components of the water budget including a study by Carr/Associates (1983), the Groundwater Management Plan (GWMP, VMI GWAC, 1998), and the MODFLOW study (King County, 2005). The goal for comparing the simulated water budget components with those from these previous studies was not necessarily to try and match the previous estimates but rather to serve as a means of gauging the reasonableness of the simulated values in this model and understand how they are similar or different from previous estimates.

Daily streamflow data was available at two locations on the island, Judd Creek and Shingle Mill Creek (Figure 8). Given that the primary objectives of the study relate to groundwater supply and demand questions, less emphasis was placed on the surface water calibration than was placed on calibration of the groundwater component of the model. Additionally, the surface water component of the model utilizes hypothetical cross section data rather then surveyed cross sections, thus we would not expect to be able to achieve a highly detailed surface water calibration especially with respect to higher flow conditions. The primary goal of the surface water calibration was to closely match the simulated baseflows with the measured data and a limited emphasis was placed on matching higher flows.

Groundwater observation data was available at 34 locations on the island (Figure 13). Most of these observation records contained less than 10 measurements during the simulation period, however, nine wells contained 10 or more measurements and three wells contained 25 or more measurements (Table 10). Most of the observations are from the upper two layers of the model (Qvr+Qvt and Qva), ten measurements are from layer five (QAc), and two are from layer seven (QBc) (Table 10).

There is some uncertainty about which unit is represented by some of the observations. For example, in some cases the observation depths suggest that the wells are completed within one of the confining units. Given that most of these wells are active production wells, it is unlikely that they are actually completed in a confining unit and differences between the model's representation of the model cell unit elevations and the true elevations likely account for this phenomenon. For these wells, it was assumed that the observation data actually represents the closest aquifer layer above or below the stated observation depth. In some instances, the over- and under-lying aquifers were approximately equidistant from the stated observation depth; for

these cases, the model results were used as a guide for determining which layer to assign to the observations. The process used to make this determination was to compare the observed heads to the simulated heads in both the over- and under-lying aquifers and make a decision based on the relative magnitudes of the calibration errors. This was a somewhat subjective process, however it was generally fairly obvious which was the correct layer when, for example, calibration errors were reduced at most wells in a given layer following a given calibration run but errors increased at one of the wells in question, this was used as an indication that the well in question actually represented observations from the alternative layer.

## 3.2 Performance Metrics

A series of statistical measures were used in order to compare and calibrate the model simulated streamflows and hydraulic heads against the observed values.

The following commonly used statistics were selected:

- Total Percent Volume Error

$$TE = \frac{\sum_t Calc_{i,t}}{\sum_t Calc_{i,t} - \sum_t Obs_{i,t}} \times 100$$

- Mean Error

$$ME_i = \frac{\sum_t (Calc_{i,t} - Obs_{i,t})}{n}$$

- Mean Absolute Error

$$MAE_i = \frac{\sum_t | Calc_{i,t} - Obs_{i,t} |}{n}$$

- Root Mean Square Error

$$RMSE_i = \frac{\sqrt{\sum_t (Calc_{i,t} - Obs_{i,t})^2}}{n}$$

where:

$Obs_{i,t}$ are the observed values at location i and time t,

$Calc_{i,t}$ is the model simulated value at location i and time t, and

n is the number of observations.

The percent volume error provides a measure of the overall over- or under-prediction of streamflows over the full simulation period. The mean error provides a measure of how well-predicted each of the individual simulated values are relative to the observed values and gives information about the model's tendency to over-predict or under-predict individual values

based on the sign of the error. The mean absolute error and the root mean square error provide measures of the overall quality of the match between simulated and observed values with no consideration of over-prediction versus under-prediction.

## 3.3 Parameter Selection

When working with a highly parameterized model like MIKE SHE, it is critical to identify which parameters are most sensitive so that the calibration effort can be focused on a subset of the available model parameters. An additional consideration is the degree to which a given parameter is known. For those parameters that are well-constrained by measurements or detailed studies there is less justification for making adjustments. On the other hand, some parameters are based on limited or no site-specific information or are known to vary widely. For this later group of parameters, there is significantly more leeway with which to make adjustments. For any parameter, however, it is important to consider the upper and lower bounds of reasonable values to ensure that all model parameter values remain realistic.

A series of test simulations were performed at the beginning of the calibration process where adjustments were made to a large list of parameters and the sensitivity of the model in terms of the overall water balance and hydraulic heads was evaluated. The outcome of this process was a list of parameters that became the focus of the remaining calibration effort. The following parameters were selected:

### Riverbed Leakage Coefficient

This parameter regulates the exchange of water between the groundwater and channel flow components of the model.

### Soil Moisture Contents

This set of parameters influences the amount of ET, infiltration, and groundwater recharge and indirectly affects the timing and magnitude of runoff.

### Saturated Hydraulic Conductivity (Soils)

This parameter controls the infiltration rate and indirectly affects the rate of groundwater recharge, ET, and runoff.

### Manning's Coefficients

This parameter controls the timing and magnitude of runoff.

### Horizontal and Vertical Hydraulic Conductivity

These parameters control the rate of groundwater flow and affect the simulated hydraulic heads.

### Drain Levels and Time Constants

These parameters control the rate and magnitude of drain flow and affect the simulated hydraulic heads and streamflows.

The remaining model parameters were either found to have only a limited influence on the model results or are so well constrained that making any significant adjustments is unjustifiable.

In addition to adjusting these model parameters, the influence of the results on the choice of groundwater boundary conditions was also explored as part of the calibration process. Specifically, the sensitivity of the results to which layers were represented as constant head boundaries and which layers were represented with no flow boundaries was investigated as were the values for the constant head boundaries. Which cells to include as drain cells was also explored because of the uncertainty associated with the distribution of springs on the island.

## 3.4 Calibration and Existing Conditions Results

### 3.4.1 Overall Water Budget

Table 8 shows the simulated average annual water budget for the full model area over the three year simulation period (water years 2002-2004), and compares the various water budget terms with estimates from the Phase I modeling study and other previous estimates. While these comparisons are useful to get a general idea of how various estimates of the water budget terms vary, it is important to note that the time periods evaluated in each study were different and thus some of the differences reflect variations in climate conditions rather than real or assumed differences in process magnitudes.

The following general equations can be used to help interpret the MIKE SHE values in Table 8:

- Groundwater Recharge = Precipitation + Irrigation + Septic Return Flow – Actual ET – Runoff
- Groundwater Discharge = Baseflow to Streams + Pumping + Springflow + Outflow to Sound
- Groundwater Recharge = Groundwater Discharge +/- Change in Groundwater Storage

These equations apply to the MIKE SHE water budget terms but not necessarily to the terms from the other studies where some of the component terms such as irrigation and septic return flow were not considered and some terms were not reported such as the change in groundwater storage.

The simulated ET is slightly higher then previous estimates at 45% of the incoming precipitation versus previous estimates of 38-44%. The simulated runoff represented 25% of the incoming precipitation which is in the middle of the range of previous estimates. Groundwater recharge was 31% of the incoming precipitation which is slightly higher then the MODFLOW estimate and in the middle of the range of all the previous estimates. Septic return flows and groundwater pumping agree closely with the MODFLOW estimates by design as these components of the model were simply adopted from the MODFLOW model.

Baseflow discharge to streams on the island represented 10% of the incoming precipitation and was significantly higher than the MODFLOW estimate, but in the middle of the range of all the previous estimates. The springflow estimate agreed well with the MODFLOW estimate at 0.3%

Table 8: Simulated water budget components and comparison with estimates from previous studies.

| | MIKE SHE Model (this study) | | MODFLOW Model (Johnson, 2005) | | GW Mgmt. Plan (VMI GWPC, 1998) | | Carr Report (Carr, 1983) | |
|---|---|---|---|---|---|---|---|---|
| | inches/yr | % of precip | inches/yr | % of precip | inches/yr | % of precip | inches/yr | % of precip |
| Precipiation | 43.8 | 100% | 38.7 | 100% | 44.1 | 100% | 38.1 | 100% |
| ET | 19.9 | 45% | 16.7 | 38% | 17.5 | 40% | 19.1 | 44% |
| Runoff | 11.1 | 25% | 9.2 | 21% | 10.3 | 23% | 14.3 | 33% |
| Irrigation | 0.3 | 1% | - | - | - | - | - | - |
| Septic Return Flow | 0.4 | 1% | 0.3 | 1% | - | - | - | - |
| Groundwater Recharge | 13.5 | 31% | 12.8 | 29% | 16.4 | 37% | 4.8 | 11% |
| Baseflow to Streams | 4.3 | 10% | 1.4 | 3% | 10.0 | 23% | 3.8 | 9% |
| Pumping | 0.6 | 1% | 0.6 | 1% | - | - | - | - |
| Springflow | 0.3 | 1% | 0.3 | 1% | - | - | - | - |
| Outflow to Sound | 7.6 | 17% | 10.5 | 24% | 6.3 | 14% | 1.0 | 2% |
| Change in Groundwater Storage | 0.7 | 2% | - | - | - | - | - | - |

Notes: The "-" symbol indicates a value that was either not computed or not reported.

of the incoming precipitation. Groundwater outflow to Puget Sound represented 17% of the incoming precipitation which is towards the high end of the previous estimates though significantly lower then the MODFLOW estimate.

### 3.4.2 Surface Water Calibration and Results

As discussed above, the focus of the streamflow calibration was to closely match baseflow conditions and a limited emphasis was place on matching conditions during higher flows. In order to evaluate the model's performance during baseflow conditions the period from July 15th through August 15th was chosen because an examination of the observed and simulated streamflow data indicated that this period contained few if any runoff events. Predominantly baseflow conditions likely extend through October in most years, however some runoff events occurred in late August and September (particularly in 2004) and thus the shorter period was chosen in order to more accurately isolate baseflow conditions. The model does a good job of predicting summer baseflow conditions for Shingle Mill Creek, and the percent streamflow volume error is 8% (Table 9 and Figure 14). During the rainy season, the model tends to over-predict baseflow conditions and under-predict peak flows. Additionally, the model simulates small runoff events in the late Spring and late Fall periods that do not appear in the observed data. The overall volume error for the three year simulation is an over-prediction of 31%.

The calibration for Judd Creek is much poorer with the model over-predicting summer baseflows during the July 15th to August 15th period by 43% (Table 9 and Figure 15). Rainy

season baseflows are under-predicted and the runoff events are severely under-predicted. The overall volume error for the three year simulation is an under-prediction of 41%.

The poor representation of runoff events particularly in Judd Creek may be the result of several factors. One possibility relates to the model's coarse representation of the surface topography. A large proportion (61%) of the runoff generated by the model does not discharge to the surface water component of the model but instead discharges to the model's external boundaries. While some runoff likely does leave the boundaries of the island as distributed overland flow rather then channelized flow, the model may be over-estimating this component of the runoff because the 500-ft cell size is too coarse of a resolution to accurately capture the overland flow paths and direct the generated runoff towards the stream channels in the model. A second possibility is that the model is not accurately accounting for the increased runoff associated with impervious areas. Separate soil properties were not used for impervious areas and the 'paved area option' in MIKE SHE, which routes a pre-defined fraction of the generated runoff directly to surface water features in the model, was not used. The lack of explicit representation of impervious areas in the model may mean that the simulated runoff from areas with a high proportion of impervious surfaces is under-predicted. A third possibility is that the scaled precipitation data from the SeaTac station is under-predicting precipitation on Vashon-Maury Island in some cases.

The use of generalized cross sectional data as opposed to surveyed cross sections likely affects the model's ability to accurately predict both runoff and baseflow conditions as well. The simulated surface water/groundwater exchange in the model is driven by the simulated water-level gradients between the surface water system and the adjacent groundwater elevations; without proper surveyed stream channel geometries, it is not reasonable to expect that the model can realistically simulate surface water stages.

### 3.4.3 Groundwater Calibration and Results

The simulated hydraulic heads in Layer 1 (Qvr and Qvt) indicate that groundwater generally follows topography in this surficial layer with steep gradients occurring along the coastlines of the island and hydraulic heads decreasing from 250 to 400-ft in the interior portions of the island to 0 to 100-ft along the coast (Figure 16). A southwest by northeast oriented groundwater divide runs along the length of the island located roughly equidistant between the east and west coasts in the southern portion of the island and closer to the western coast in the northern portion of the island. A prominent east-west oriented divide in the north-central portion of the island divides groundwater flowing to the north towards the Shingle Mill Creek drainage and groundwater flowing to the south towards the Judd Creek drainage (Figure 16). A northwest by southeast oriented divide south of Judd Creek divides groundwater flowing northeast towards Judd Creek and groundwater flowing southwest and southeast towards the Fisher and Christenson Creek drainages. In the southern portion of the island another east-west oriented divide divides flow to the north towards the Fisher and Christenson Creek drainages and flow to the south towards Tahlequah Creek and Puget Sound (Figure 16).

Groundwater flow directions in Layer 2 (Qva) follow the same general patterns as in Layer 1 but with much shallower gradients. Heads in the interior of the island generally range from 200 to 300-ft and decrease to 100 to 150-ft towards the coastline, and on Maury Island, heads are

Table 9: Comparison of simulated and observed streamflow volumes in units of million cubic meters for the full simulation period and for the summer baseflow period (July 15th – Aug. 15th).

| | Shingle Mill Creek | | Judd Creek | |
|---|---|---|---|---|
| | Total | 7/15 - 8/15 | Total | 7/15 - 8/15 |
| Observed | 420 | 14.7 | 557 | 12.9 |
| Simulated | 551 | 15.8 | 328 | 18.4 |
| % Error | 31% | 8% | -41% | 43% |

between 100 and 150-ft most everywhere (Figure 17). Heads are much more uniform in the deeper QAc and QBc aquifer layers (Layers 5 and 7) where heads range from 50 to 100-ft over a large area in the central portion of Vashon Island and decrease to between 0 and 50-ft in all directions (Figures 18 and 19). In Layer 7, the heads immediately adjacent to the coastline decrease to between -50 and 0-ft (Figure 19).

The groundwater calibration focused on minimizing the mean errors (ME), mean absolute errors (MAE), and root mean square errors (RMSE) at each of the 34 calibration wells. The overall ME at all 34 wells was -4.0-ft and the overall MAE was 19.4-ft. Although it is difficult to directly compare these results with the previous MODFLOW results because the modeling approaches are quite different with the MIKE SHE model being a transient integrated model and the MODFLOW model being a steady-state stand-alone groundwater model, the comparison is still useful to gain a general picture of how the MIKE SHE model is performing relative to the MODFLOW model. This comparison suggests that the overall performance of the MIKE SHE model is significantly better then that of the MODFLOW model, and that the ME is 0.5-ft lower and the MAE is 16.9-ft lower (Table 10).

The ME and MAE values in Layer 1 (Qvr and Qvt) range from -29.2 to 20.9-ft and 4.9 to 29.2-ft respectively, and the overall Layer 1 ME and MAE values are -7.0-ft and 15.9-ft respectively (Table 10). For Layer 2 (Qva), the ME and MAE values range from -47.4 to 28.8-ft and from 10.9 to 47.4-ft respectively. The overall layer 2 MAE was reduced by 15.2-ft relative to the MODFLOW results (Table 11). For Layer 5 (QAc), the ME and MAE values range from -12.5 to 31.9-ft and from 0.2-ft to 31.9-ft respectively, and the overall layer 5 values for these statistics are 4.6 and 10.1-ft which represents a reduction in the MAE of 14.8-ft relative to the MODFLOW model (Tables 10 and 11). There are only two wells available in Layer 7 (QBc) and the overall ME and MAE values are -3.4-ft and 41.8-ft which is a 5.1-ft higher ME then what was achieved with the MODFLOW model (Tables 10 and 11).

Table 10: Groundwater calibration statistics.

| Well Name | Well Number | Layer | # of Obs. | ME | MAE | RMSE |
|---|---|---|---|---|---|---|
| Baker Klemka #2 | 1-A | 1 | 7 | 3.9 | 4.9 | 5.5 |
| Davison Clegg | 1-B | 1 | 7 | -29.2 | 29.2 | 29.5 |
| Harper | 1-C | 1 | 8 | 5.9 | 5.9 | 6.8 |
| Jansen | 1-D | 1 | 8 | 20.9 | 20.9 | 20.9 |
| Misty Isle Farm | 1-E | 1 | 7 | -11.7 | 11.7 | 11.8 |
| Nyberg | 1-F | 1 | 7 | -22.5 | 22.5 | 22.7 |
| Sunnyslope | 1-G | 1 | 13 | -16.1 | 16.1 | 16.3 |
| **Layer 1 Mean** | | | | **-7.0** | **15.9** | **16.2** |
| | | | | | | |
| Abel | 2-A | 2 | 3 | -14.4 | 14.4 | 14.4 |
| Anderson | 2-B | 2 | 2 | -35.0 | 35.0 | 35.0 |
| Baker Klemka #1 | 2-C | 2 | 1 | 17.9 | 17.9 | 17.9 |
| Coulson | 2-D | 2 | 3 | -11.6 | 11.6 | 11.6 |
| Crockett | 2-E | 2 | 11 | -10.9 | 10.9 | 10.9 |
| Headley | 2-F | 2 | 6 | -33.6 | 33.6 | 33.7 |
| Heights Water #1 | 2-G | 2 | 25 | -21.3 | 21.3 | 21.3 |
| Heights Water #2 | 2-H | 2 | 21 | -47.4 | 47.4 | 47.4 |
| Johnson | 2-I | 2 | 8 | 26.9 | 26.9 | 27.0 |
| Kuperberg | 2-J | 2 | 23 | 28.8 | 28.8 | 28.8 |
| Luana Water | 2-K | 2 | 7 | -13.3 | 13.3 | 13.5 |
| Meeker | 2-L | 2 | 34 | -25.5 | 25.5 | 25.6 |
| Needle Creek | 2-M | 2 | 36 | 20.5 | 20.5 | 20.5 |
| Turner | 2-N | 2 | 2 | -32.1 | 32.1 | 32.1 |
| Wolff | 2-O | 2 | 9 | 23.6 | 23.6 | 23.6 |
| **Layer 2 Mean** | | | | **-8.5** | **24.2** | **24.2** |
| | | | | | | |
| Beardsley | 5-A | 5 | 16 | -1.3 | 1.9 | 2.6 |
| Bogaard | 5-B | 5 | 7 | -6.5 | 6.5 | 6.6 |
| Gold Beach #1 | 5-C | 5 | 2 | -7.0 | 7.0 | 8.8 |
| Oellien | 5-D | 5 | 5 | 16.9 | 16.9 | 21.4 |
| Perla | 5-E | 5 | 6 | 7.7 | 7.7 | 7.9 |
| Putnam | 5-F | 5 | 2 | 7.9 | 7.9 | 7.9 |
| Sage | 5-G | 5 | 3 | 0.0 | 0.2 | 0.2 |
| Svinth | 5-H | 5 | 6 | 31.9 | 31.9 | 31.9 |
| White #1 | 5-I | 5 | 1 | -12.5 | 12.5 | 12.5 |
| White #2 | 5-J | 5 | 5 | 8.9 | 8.9 | 9.4 |
| **Layer 5 Mean** | | | | **4.6** | **10.1** | **10.9** |
| | | | | | | |
| Heights Water #3 | 7-A | 7 | 20 | 38.4 | 38.4 | 38.4 |
| Rodriques | 7-B | 7 | 5 | -45.2 | 45.2 | 45.3 |
| **Layer 7 Mean** | | | | **-3.4** | **41.8** | **41.8** |

Table 11: Comparison of the groundwater calibration statistics (ME = Mean Error, and MAE = Mean Absolute Error) between the MIKE SHE and MODFLOW models for the island-wide aquifer layers.

| | MIKE SHE | | MODFLOW | |
|---|---|---|---|---|
| **Layer** | **ME** | **MAE** | **ME** | **MAE** |
| 2 - Qva | -8.5 | 24.2 | -14.1 | 39.4 |
| 5 - QAc | 4.6 | 10.1 | -8.2 | 24.9 |
| 7 - QBc | -3.4 | 41.8 | 23.3 | 36.7 |
| **All Layers** | **-4.0** | **19.4** | **-4.5** | **36.3** |

SECTION 4

# Scenario Analysis

## 4.1 Scenario Descriptions

This modeling work included an assessment of the impacts of possible future build-out and climate change scenarios on water resources. Each of the scenarios types are summarized below and Table 12 provides a matrix of all of the model scenarios.

### 4.1.1 Future Pumping Scenarios

Two future condition groundwater pumping scenarios were evaluated with the calibrated model. Scenario 1 involved uniformly increasing pumping rates at all of the existing wells by 15% with no additional wells added. This represents a population increase of about 1000 people which is a ~9% increase of the 2000 population. According to the Puget Sound Regional Council (PSRC), the population of VMI will continue to grow at a rate of 100 people per year.

Scenario 2 involved the addition of new exempt wells in areas of the island where future development may occur. The new well locations were determined in part by zoning build-out projections done by B. Powell prepared in 2007 (http://dogpatch.com/kcprop/). All of the new wells were placed within Layer 2 (Ova). A total of 423 new wells were added to the model with a mean annual pumping rate of 523 gallons/day which was distributed throughout the year in the same manner as was done for the existing wells (Figure 20). These pumping rates represent demands for a doubling of the number of exempt wells with a per capita water demand of 266 gallons/day. This represents a population increase of about 2000 people which is a ~18% increase of the 2000 population. In order to evaluate the impacts of these two scenarios, the results were compared against the baseline results described in the calibration section of the report.

### 4.1.2 Climate Change Scenarios

The climate change scenarios are based on statistically-downscaled and bias-corrected Global Climate Model data produced by the University of Washington Climate Impacts Group. The climate change scenarios were prepared for the Climate Change subcommittee of the Regional Water Supply Planning process (http://www.govlink.org/regional-water-planning). The data used in the analysis are based on the output from the ECHAM climate model and the A2 emissions scenario (IPCC, 2001). This scenario represents a mid range precipitation and temperature change condition from among the various climate change scenarios that were considered. The available downscaled data includes daily maximum and minimum temperature and daily precipitation for four future periods of interest. The four periods of interest are three decades in length and are centered on the following years: 2000, 2025, 2050, and 2075, and the data are downscaled based on the historical records for the SeaTac gaging station.

In order to implement these climate projections in the model, the downscaled precipitation data was distributed across the island by scaling the precipitation record using the same isohyetal dataset used for the baseline model (see Section 2.2.2). A single daily potential evapotranspiration (PET) timeseries was developed using the Penman-Monteith formulation and the projected minimum and maximum temperature records similar to what was done for the baseline model (see Appendix A). The scenarios were evaluated with the model for a 76-yr period (water years 1927 to 2003). The four periods of interest (2000, 2025, 2050, & 2075) were evaluated with separate model runs. Because of the inherent differences between climate model derived climate data and historical data, the results from the 2000 climate change simulation (Scenario 3) were used as the baseline against which to evaluate the impacts of the 2025, 2050, and 2075 climate change scenario results (Scenarios 4 through 6).

### 4.1.3 Climate Change & Future Pumping Scenarios

In addition to evaluating the future pumping scenarios and the climate change scenarios separately, the future pumping conditions implemented in Scenarios 1 and 2 were combined with the 2000 and 2050 climate change scenarios in order to investigate the combined impacts of projected increases in groundwater pumping and climate change. The results from these four scenarios (Scenarios 7 through 10) were evaluated against the 2000 climate change scenario (Scenario 3) in order to evaluate the combined impacts of increased pumping and climate change. Table 12 provides a matrix of all of the model scenarios that were evaluated and the baseline against which the results were compared.

## 4.2 Scenario Results

### 4.2.1 Increased Pumping Scenario

The impacts of Scenario 1 were evaluated in terms of the change in the mean hydraulic heads under the increased pumping condition relative to the baseline simulation. The changes in Layer 1 (Qvr and Qvt) were very minimal (<0.1-ft) throughout the island. The changes in Layer 2 (Qva) were also generally less than 0.1-ft except in a few isolated areas such as the southwest portion of Vashon Island and the central-eastern portion of Maury Island where decreases of up to 0.35-ft occurred (Figure 21).

Changes in Layer 5 (QAc) were more significant with a localized area in the northwest portion of Vashon Island experiencing decreases of up to 1.9-ft, a large area in the east-central portion of the island experiencing decreases of up to 0.4-ft, and a large area in the north-central portion of Maury Island experiencing decreases of up to 0.2-ft (Figure 22). The patterns of change in Layer 7 (QBc) were similar to what was seen for Layer 5, with decreases of up to 0.6-ft occurring over a fairly large area along the central-west coast of Vashon Island, decreases of up to 2.2-ft over a large area in the east-central portion of the island, and decreases of up to 0.5-ft in the north-central portion of Maury Island (Figure 23). The areas experiencing declines in head under

Table 12: Scenario matrix.

| Scenario Name | Scenario Type | Description | Results Compared Against |
|---|---|---|---|
| Baseline | Historical Conditions | 3-yr simulation used for calibration and to represent existing conditions | - |
| Scenario 1 | Future Pumping | 3-yr simulation with a 15% increase in pumping at existing wells; used to represent the impacts of increased pumping | Baseline |
| Scenario 2 | Future Pumping | 3-yr simulation with new wells added; used to represent the impacts of build-out pumping | Baseline |
| Scenario 3 | Climate Change | 76-yr simulation using the 2000 GCM datasets; used to provide a baseline for evaluating the impacts of climate change | - |
| Scenario 4 | Climate Change | 76-yr simulation using the 2025 GCM datasets; used to represent the impacts of climate change | Scenario 3 |
| Scenario 5 | Climate Change | 76-yr simulation using the 2050 GCM datasets; used to represent the impacts of climate change | Scenario 3 |
| Scenario 6 | Climate Change | 76-yr simulation using the 2075 GCM datasets; used to represent the impacts of climate change | Scenario 3 |
| Scenario 7 | Future Pumping Plus Climate Change | 76-yr simulation using the 2000 GCM datasets with a 15% increase in pumping at existing wells; used to represent the combined impacts of climate change and increased pumping | Scenario 3 |
| Scenario 8 | Future Pumping Plus Climate Change | 76-yr simulation using the 2000 GCM datasets with new wells added; used to represent the combined impacts of climate change and build-out pumping | Scenario 3 |
| Scenario 9 | Future Pumping Plus Climate Change | 76-yr simulation using the 2050 GCM datasets with a 15% increase in pumping at existing wells; used to represent the combined impacts of climate change and increased pumping | Scenario 3 |
| Scenario 10 | Future Pumping Plus Climate Change | 76-yr simulation using the 2050 GCM datasets with new wells added; used to represent the combined impacts of climate change and build-out pumping | Scenario 3 |

Scenario 1 correspond closely to individual Group A and Group B production wells or clusters of wells completed in the QAc and QBc units (Figure 24).

### 4.2.2 Build-out Scenario

The impacts of Scenario 2 were evaluated in terms of the change in the mean hydraulic heads under the build-out pumping condition relative to the baseline simulation. The changes in Layer 1 (Qvr and Qvt) were less then 0.1-ft throughout the island. Decreases in Layer 2 heads of between 0.1 and 0.25-ft occurred over large areas of Vashon Island and the northern and western portions of Maury Island. Scattered areas experienced larger decreases of up to 0.9-ft but generally less then 0.5-ft (Figure 25). The areas that experienced changes greater then 0.1-ft corresponded closely with the new wells that were added for this scenario to represent the build-out condition (see Figures 20 and 25). The changes in Layers 5 and 7 were less than 0.1-ft

throughout the island which is not surprising given that the new wells were all place in the shallow Qva layer.

The impacts of the scenario were also evaluated in terms of the percent change in total streamflow and baseflow (defined as flow between July 15th and August 15th). These results indicate that build-out pumping conditions may result in very minor declines in total streamflow and baseflow in Shingle Mill Creek and Judd Creek of between <0.1% and 0.3% (Table 13).

### 4.2.3 Climate Change Scenarios

The impacts of the 2025, 2050, and 2075 climate change scenarios were evaluated in terms of the change in the overall water budget under each scenario relative to the 2000 climate change scenario. Precipitation decreased slightly (by 0.2-in/yr) in the 2025 scenario, and increased by 0.6 and 1.3-in/yr in the 2050 and 2075 scenarios respectively (Table 14). Evapotranspiration increased by 0.8, 1.0, and 1.6-in/yr in the 2025, 2050, and 2075 scenarios respectively (Table 14). Runoff decreased by 0.7-in/yr in the 2025 scenario and by 0.2-in/yr in the 2050 and 2075 scenarios, and changes in baseflow were very minimal (0.1-in/yr or less). The net result in terms of groundwater recharge was that the increases in precipitation were largely offset by the increases in evapotranspiration such that recharge decreased by only 0.3-in/yr in the 2025 scenario and by 0.1-in/yr in the 2050 and 2075 scenarios (Table 14). This represents a 1.8% reduction in recharge in 2025 and a 0.8% reduction in 2050 and 2075.

The impacts of the climate change scenarios were also evaluated in terms of the change in the mean hydraulic heads under 2025, 2050, and 2075 scenarios relative to the 2000 scenario. The changes in Layer 1 (Qvr and Qvt) in the 2025 scenario were the most significant of all of the layers and all of the climate change scenarios. The average island-wide change in the mean hydraulic head was a decrease of 1.1-ft. The declines were largest in the southern and northern portions of Vashon Island, in the central portion of the island on either side of the Judd Creek drainage, and along the southern coastline of Maury Island, and the maximum decrease was 5.2-ft (Figure 26). The changes in Layer 2 (Qva) were much smaller with a decrease of 0.1- to 0.25-ft over the majority of the island. Localized areas experienced larger decreases of 0.25- to 0.50-ft, and a few very small areas experienced small increases of up to 0.2-ft (Figure 27). The changes in the deeper aquifer layers (QAc and QBc) were less then 0.1-ft throughout the island.

The 2050 climate change scenario resulted in an average Layer 1 (Qvr & Qvt) decrease in hydraulic head of 0.4-ft. Large portions of the island experienced decreases of 0.50 to 1.0-ft (Figure 28). Decreases on Maury Island were somewhat larger then on Vashon Island with a significant portion of the island experiencing decreases of 1.0- to 2.0-ft with a maximum decrease of 2.9-ft (Figure 28). Changes in Layer 2 (Qva) were generally less then 0.1-ft except for a few areas such as the northwestern coastal areas and the south-central portion of Vashon Island, and the northern portion of Maury Island which experienced decrease of between 0.1- and 0.3-ft (Figure 29). The changes in the deeper aquifer layers (QAc and QBc) were less then 0.1-ft throughout the island

Table 13: Summary of the percent change in streamflow (total flow and baseflow) for Shingle Mill Creek and Judd Creek for each scenario.

| Scenario # | Description | Shingle Mill Creek | | Judd Creek | |
|---|---|---|---|---|---|
| | | Total Flow | Baseflow (7/15 - 8/15) | Total Flow | Baseflow (7/15 - 8/15) |
| Scenario 1 | Increased Pumping at Existing Wells | 0.0% | 0.0% | 0.0% | 0.0% |
| Scenario 2 | Build-out Pumping | -0.1% | 0.0% | -0.2% | -0.3% |
| Scenario 3 | 2000 Climate Change | NA | NA | NA | NA |
| Scenario 4 | 2025 Climate Change | -4.1% | -2.3% | -4.0% | 0.3% |
| Scenario 5 | 2050 Climate Change | -1.5% | -0.9% | -1.5% | -0.2% |
| Scenario 6 | 2075 Climate Change | -1.0% | -2.0% | -1.5% | -4.5% |
| Scenario 7 | Scenario 1 with Scenario 3 | -0.1% | -0.1% | -0.1% | -0.2% |
| Scenario 8 | Scenario 2 with Scenario 3 | -0.4% | -0.5% | -0.2% | -0.2% |
| Scenario 9 | Scenario 1 with Scenario 5 | -1.6% | -1.0% | -1.6% | -0.5% |
| Scenario 10 | Scenario 2 with Scenario 5 | -1.9% | -1.4% | -1.6% | -0.5% |

Notes: 'NA' stands for not applicable.

Unlike the 2025 and 2050 scenarios, the Layer 1 (Qvr and Qvt) hydraulic heads increased in many areas of Vashon Island under the 2075 scenario. The increases are generally between 0.1- and 0.25-ft with a few areas experiencing increases of up to 0.4-ft (Figure 30). These areas experiencing increases are dispersed throughout the southern, central-eastern, and northern portions of the island. Scattered areas elsewhere on the island, and a contiguous area in the central portion of the island experienced decreases of 0.1- to 0.25-ft, and a few small isolated areas experienced larger decreases of up to 0.4-ft (Figure 30). On Maury Island, the heads decreased by 0.1- to 0.25-ft over much of the island and by 0.25- to 0.50-ft over a subset of this area. In the central portion of the island, a small area experienced larger decreases of up to 1.5-ft. Changes in the Layer 2 (Qvr & Qvt) heads were generally less then 0.1-ft, a few areas experienced decreases of 0.1- to 0.3-ft (Figure 31). The changes in the deeper aquifer layers (QAc and QBc) were less then 0.1-ft throughout the island.

Table 14: Water budget comparison (in units of in/yr) for the four climate change scenarios.

| | 2000 | 2025 | 2050 | 2075 |
|---|---|---|---|---|
| **Precipiation** | 50.3 | 50.2 | 51.0 | 51.6 |
| **ET** | 23.1 | 23.8 | 24.1 | 24.7 |
| **Runoff** | 13.8 | 13.1 | 13.5 | 13.5 |
| **Recharge** | 13.8 | 13.5 | 13.7 | 13.7 |
| **Baseflow** | 4.8 | 4.7 | 4.7 | 4.7 |

Notes: The 2000 climate change simulation was used as the baseline against which to evaluate the impacts of the 2025, 2050, and 2075 scenarios.

The impacts of the climate change scenarios were also evaluated in terms of the percent change in total streamflow and baseflow in Shingle Mill Creek and Judd Creek (defined as flow between July 15$^{th}$ and August 15$^{th}$). These results indicate that under climate change conditions, total streamflows may decrease by 1.0% to 4.1%, and baseflows may decrease by up to 4.5% (Table 13).

### 4.2.4 Future Pumping Plus Climate Change Scenarios

The impacts of the combined future pumping and climate change scenarios (Scenarios 7-10) were evaluated in terms of the change in the mean hydraulic heads under each scenario relative to the 2000 climate change simulation results (Scenario 3). When combined with the 2000 climate change scenario, both of the increased pumping scenarios show similar patterns and magnitudes of head declines as they did when evaluated as stand-alone future pumping scenarios, with slight increases in the magnitudes of the declines (Figures 32 through 36).

The results from the 2050 climate change plus increased pumping at existing wells scenario (Scenario 9) are very similar to the stand-alone 2050 climate change scenario results for Layer 1 (Qvr and Qvt) (see Figures 28 and 37). Heads decreased over large portions of the island by 0.5 to 1.0-ft and the average island-wide decline was 0.4-ft. Decreases on Maury Island were larger and the maximum decline was 2.9-ft (Figure 37). Changes in Layer 2 (Qva) were somewhat higher than under the stand-alone climate change scenario and large portions of the two islands experienced declines of 0.1 to 0.25-ft and a few areas experienced larger declines of up to 0.5-ft (Figure 38).

Unlike the upper layers where the declines in recharge were the primary cause of the declines in heads, the changes in the Layer 5 and 7 heads were due primarily to the increased groundwater abstraction. The layer 5 (QAc) heads declined by 0.25 to 1.0-ft over a large area in the central portion of Vashon Island and a localized area in the northwest portion of the island near the

coast experienced larger declines of up to 2.1-ft (Figure 39). The area experiencing declines of more then 0.25-ft increased substantially compared to the stand-alone increased pumping condition (see Figures 22 and 39) suggesting that the impacts of the increased pumping from the deeper wells on the island may be exacerbated under climate change conditions. The same situation is true for Layer 7 where heads declined by 0.5- to 1.0-ft over a large area in the central portion of the island and by up to 2.5-ft locally (Figure 40) and the area experiencing significant declines expanded relative to the stand-along pumping scenario (see Figures 23 and 40).

The results from the 2050 climate change plus build-out pumping scenario (Scenario 10) are also very similar to the stand-alone 2050 climate change results for Layer 1 where heads decreased between 0.5 and 1.0-ft over large portions of the island, the average island-wide decline was 0.4-ft, and declines on Maury Island were as high as 2.9-ft (see Figures 28 and 41). Changes in Layer 2 were larger then in either the stand-alone build-out or stand-alone 2050 climate change scenarios and heads declined by 0.25 to 0.50-ft over large portions of Vashon Island and the mean and maximum head changes were 0.2 and 1.1-ft respectively (Figure 42). Heads changed by less then 0.1-ft over most of the island in Layer 5 with the exception of a moderate sized area in the north-central portion of the island where heads declined between 0.1 and 0.25-ft (Figure 43). Changes in Layer 7 were less than 0.1-ft everywhere.

A summary of all of the mean and maximum head changes in all of the scenarios is provided in Table 15.

The impacts of the combined pumping and climate change scenarios were also evaluated in terms of the percent change in total streamflow and baseflow in Shingle Mill Creek and Judd Creek (defined as flow between July 15th and August 15th). These results indicate that under combined 2050 climate change and increased pumping conditions, total streamflows may decrease by up to 1.9%, and baseflows may decrease by up to 1.4% (Table 13).

Table 15: Summary of the mean change in hydraulic heads for each layer and each scenario (units are feet).

| Scenario # | Description | Layer 1 (Qvr & Qvt) | | Layer 2 (Qva) | | Layer 5 (QAc) | | Layer 7 (QBc) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean Head Change | Max Head Change | Mean Head Change | Max Head Change | Mean Head Change | Max Head Change | Mean Head Change | Max Head Change |
| Scenario 1 | Increased Pumping at Existing Wells | - | - | - | -0.4 | -0.1 | -1.9 | -0.2 | -2.2 |
| Scenario 2 | Build-out Pumping | - | - | -0.1 | -0.9 | - | - | - | - |
| Scenario 3 | 2000 Climate Change | NA | NA | NA | NA | NA | NA | NA | NA |
| Scenario 4 | 2025 Climate Change | -1.1 | -5.2 | -0.1 | -0.5 | - | - | - | - |
| Scenario 5 | 2050 Climate Change | -0.4 | -2.9 | -0.1 | -0.3 | - | - | - | - |
| Scenario 6 | 2075 Climate Change | - | -1.5 | - | -0.3 | - | - | - | - |
| Scenario 7 | Scenario 1 with Scenario 3 | - | - | - | -0.4 | -0.5 | -2.1 | -0.3 | -2.4 |
| Scenario 8 | Scenario 2 with Scenario 3 | - | -0.2 | -0.2 | -0.9 | - | - | - | - |
| Scenario 9 | Scenario 1 with Scenario 5 | -0.4 | -2.9 | -0.1 | -0.5 | -0.2 | -2.1 | -0.3 | -2.4 |
| Scenario 10 | Scenario 2 with Scenario 5 | -0.4 | -2.9 | -0.2 | -1.1 | - | -0.2 | - | - |

Notes: 'NA' refers to not applicable and the "-" symbol indicates no change or changes less than 0.1-ft.

**SECTION 5**

# Discussion and Conclusions

## 5.1 Summary of Results

In general the water budget terms simulated with the VMI MIKE SHE model agree well with previous estimates. The MIKE SHE results suggest that ET is slightly higher then previous estimates at 45% of the incoming precipitation, and that groundwater recharge is somewhat higher then the MODFLOW estimate at 13.5 in/yr or 31% of the incoming precipitation. The model also suggests that baseflow is significantly higher than the MODFLOW estimate and that the groundwater outflow to Puget Sound is significantly lower than the MODFLOW estimate at 17% of the incoming precipitation versus 24% in the MODFLOW model.

The model did a reasonably good job of estimating the observed streamflows in Shingle Mill Creek. The model represents summertime baseflow conditions quite well in this creek, but under-predicts flows during runoff events. The model does not predict streamflows nearly as well in Judd Creek, where runoff events are significantly under-predicted and baseflows are significantly over-predicted.

The groundwater calibration represents a significant improvement over what was achieved with the MODFLOW model with overall ME and MAE values that are 0.5- and 17-ft lower then the MODFLOW values of these calibration statistics respectively. However, calibration errors are still quite high at some locations in each of the aquifer layers.

The scenario results suggest that increasing pumping by 15% at existing well locations on the island may result in declines in the mean groundwater heads of up to 0.5-ft in the Qva aquifer and up to 2.0-ft in the QAc and QBc aquifers. Under a build-out pumping scenario, where additional wells are completed within the Qva, mean heads in the Qva may decrease by up to 0.9-ft. Stream baseflow may also decrease slightly under the build-out pumping scenario by up to 0.3%.

The climate change scenarios suggest that both mean annual precipitation and evapotranspiration will increase over the next century, and that runoff and baseflow will decrease slightly. The net result in terms of groundwater recharge is that relatively small declines in mean annual recharge will occur. These changes in recharge are predicted to have some impacts to groundwater heads in upper aquifers on the island however, and the impacts are shown to decrease over time with the largest effects seen in the 2025 scenario and the smallest effects seen in the 2075 scenario. In the 2025 scenario, mean annual heads declined by up to 5.2-ft in the Qvt & Qvr units (Layer 1) and by 0.5-ft in the Qva unit (Layer 2). By 2075, however, these maximum declines were reduced to 1.5- and 0.3-ft respectively, and some areas are predicted to experience an increase in mean annual heads. Total streamflow was shown decrease by 1.0% to 4.1% under climate change conditions and baseflow was shown to decrease by up to 4.5%.

When the pumping scenarios are evaluated in combination with 2050 climate change conditions, the effects of increasing pumping at existing wells on the island is predicted to be

magnified with predicted maximum declines in mean annual heads of 2.1-ft and 2.4-ft in the QAc and QBc aquifers respectively. Similarly, when the build-out pumping condition is evaluated under 2050 climate change conditions, the impact of the increased pumping is predicted to result in slightly larger declines in the mean annual heads in the QAc aquifer, with maximum head declines of up to 1.1-ft. Total streamflow was shown to decrease by up to 1.9% under combined 2050 climate change and increased pumping conditions, and baseflow was shown to decrease by up to 1.4%

## 5.2 Model Limitations and Uncertainty

It is likely that the MIKE SHE estimates of the various water budget components are more accurate than the previous estimates because the major relevant processes that dictate the water budget are explicitly simulated in the model rather then derived purely through the calibration process or estimated from empirical relationships as they were in the previous studies.

The higher baseflow estimate simulated with the MIKE SHE model may be a more accurate estimate because the baseflow response was calibrated by comparing simulated streamflows with measured streamflow data which was not done in any comprehensive manner for the previous estimates. That being said, the model over-predicts summertime streamflows significantly in Judd Creek which suggests that the baseflow estimate may be too high. The outflow to Puget Sound term is still poorly constrained and it is difficult to postulate as to if the MIKE SHE value represents a more realistic estimate than the previous studies because no data is available with which to quantify this term and the value was derived purely from the calibration process.

The poor representation of runoff events in the model (particularly for Judd Creek) may be the result of several factors. One possible explanation is that the model's representation of the surface topography is too coarse to accurately route runoff towards the stream network. A second possibility is that the lack of an explicit representation of impervious areas has resulted in an under-prediction of runoff production from areas containing a large proportion of impervious surfaces. A third possibility is that the scaled SeaTac precipitation data used in the model under-predicts the actual precipitation that occurred on the island.

The use of generalized cross sectional data as opposed to surveyed cross sections likely has a lot to do with the model's ability to accurately predict both runoff and baseflow conditions as well. The simulated surface water/groundwater exchange in the model is driven by the simulated water-level gradients between the surface water system and the adjacent groundwater elevations; without proper surveyed stream channel geometries, it is not realistic to expect that the model is accurately simulating surface water stages.

The groundwater calibration results are encouraging in the sense that they represent a significant improvement over the calibration achieved with the MODFLOW model. That being said, the calibration errors are still quite high and are as large as 30- to 40-ft at some locations in each of the aquifer layers. Large errors at some of the well locations occurred in the MODFLOW model as well, and these errors suggest that the model's representation of the hydrostratigraphy (which was for the most part simply adopted from the MODFLOW model) may be lacking in its representation of the true geometries of the major deposits on the island.

One of the inherent difficulties in representing the hydrostratigraphy on the island in a numerical model is the relatively rapid decline in thickness of the Qvt and Qva units that occurs near the margins of the island and the discontinuous nature of these deposits (and the Qvr unit) on the island. Representing the complex geometries of these units in a finite-difference model like MODFLOW or MIKE SHE is challenging because of the constraint of needing to have grid cells of uniform dimensions with constant upper and lower elevations, the inability to have a spatially discontinuous model layer, and the numerical instabilities that can occur when large changes in layer thickness occur over short distances.

A constant head boundary condition was used in Layer 2 (Qva) to allow outflow to occur from this layer. This modification resulted in significant improvements in the model calibration, and the modification is justified because springs and seeps likely do occur where the Qva is exposed along the perimeter of the island. The value for this constant head boundary is, however, difficult to constrain with the available observation data and the use of a constant head boundary for this layer is somewhat problematic in that that it does not prohibit inflow from occurring which is clearly unrealistic given that the boundary is located above sea level. Small inflows do occur in the current model, however the net flux across the boundary was outwards for every day during the simulation so this is not a major issue. The use of a seepage face boundary condition would be a more appropriate representation of this boundary because it allows outflow to occur but prevents any inflow. This type of boundary condition is not, however, available in the current version of the MIKE SHE model.

The interaction of the deeper layers in the model with Puget Sound is very difficult to represent accurately within the current modeling framework and it is also difficult to evaluate how well it is represented due to a lack of available observation data in these deeper units. Groundwater flow at this freshwater/saltwater interface is likely significantly influenced by variable density phenomenon which can not be simulated in the MIKE SHE model but which are likely important for dictating the groundwater dynamics in these deeper layers.

## 5.3 Recommendations for Future Work

The current VMI MIKE SHE model provides a solid foundation for understanding the water resources on Vashon-Maury Island, and the current study helped to identify several key areas where the model's representation of the island hydrology could be improved through future work. One such area concerns data availability. Two primary data deficiencies include the lack of surveyed channel cross section data for any of the streams on the island, and the lack of continuous climate records on the island.

The use of characteristic cross sections used in the current version of the model makes it difficult to accurately simulate stream discharges and surface water/groundwater interactions, and the collection of surveyed stream channel cross sections would allow the existing surface water component of the model to be refined and likely result in an improved calibration of the model to measured streamflow data.

The current model uses precipitation data and temperature data (to generate potential evapotranspiration) from the Sea-Tac climate station. This record was used to distribute

precipitation across the island using an isohyetal coverage and may in fact do a reasonably good job of representing the climate on the island. Given the importance of precipitation in driving this hydrology model, future work should utilize the on-going climate data being collected on the island as part of WRE activities.

There are several additional areas where the current model can be improved. The grid resolution of the current model appears to be adequate for representing most of the hydrologic processes on the island with the exception of overland flow. The large proportion of overland flow that discharges to the model boundaries instead of to the stream network suggests that the model's representation of the topography is not adequately capturing the runoff flow paths. This phenomenon is also exerting a strong influence on the model's ability to reproduce discharge patterns during runoff events and in general the model significantly under-predicts runoff-generated discharges. This problem can likely be resolved relatively easily by refining the model grid to a finer resolution in order to better represent the surface topography; however this refinement must be balanced with the need to maintain reasonable computational run times.

As discussed above, a more appropriate boundary type for Layer 2 (Qva) would be a seepage face boundary condition which would allow a constant head to be used but force all exchange across the boundary to be out of the model domain. This boundary type was not used because it is not among the available boundary condition options in MIKE SHE, however, in future phases of the work, this boundary type could be added to the model code.

The pumping used in the MIKE SHE model is similar to what was used in the MODFLOW model when looking at total annual extraction volumes. This work improved the representation of pumping by using transient pumping rates that consider the timing of increased demand, however many of the withdraw rates are estimations (King County, 2005) and may not reflect actual usage patterns. Additional data collection of all type of water usages is recommended.

The MIKE SHE model calibration represents a significant improvement over the calibration achieved with the MODFLOW model, however the relatively large calibration errors at many of the observation locations suggest that the model's representation of the hydrostratigraphy on the island may be lacking. There are several possible reasons for this; one is that the available borehole log data may not be comprehensive enough to allow for an accurate interpolation of the stratigraphic surfaces. A second possibility is that the interpolation process itself is lacking, and a third possibility is that the surfaces are reasonably accurate but they simply can't be represented with enough accuracy using a finite-difference scheme which requires uniform rectilinear grid cells with constant upper and lower elevations within each cell. In order to investigate the first two possibilities, a comprehensive review of the available borehole data and the interpolation into continuous model layers is warranted.

In addition to or instead of refining the MIKE SHE model, an alternative approach for future modeling work on the island would be to develop a finite-element groundwater model using a model code such as FEFLOW. Developing such a model may help with several of the above-mentioned issues. Firstly, unlike finite-difference models, a finite-element model uses a triangular mesh to represent the stratigraphic surfaces in the model. This allows for a much

better representation of complex geometries because the mesh can be refined (made finer) in areas where surface elevations vary widely over small distances, and be coarser in other areas where geometries are less variable so that the total number of model elements does not become to large and result in an unmanageable computational times. An additional advantage to using FEFLOW, is that it already includes the ability to use a seepage face boundary condition.

FEFLOW also includes the capability of simulating variable density groundwater flow which is not possible in the MIKE SHE model but which is likely an important component of the groundwater dynamics in the deeper aquifer layers where the freshwater/saltwater interface would be expected to exert a strong control on the aquifer heads. Simulating these variable density effects would likely allow the discharge to Puget Sound term of the water balance to be better constrained. This term is a very significant component of the overall water balance and estimates of the term from the various studies on the island vary widely. Presumably an explicit representation of the density effects in these deeper layers would result in an improved calibration to the available observation data. Better representation of the aquifer surfaces using a triangular mesh would also presumably help to improve the calibration in the other model layers especially if it was combined with a review and refinement of the borehole interpolations.

It is important to note, that the development of a finite-element model would not mean that the MIKE SHE model would become obsolete. MIKE SHE is arguably the best model code available for dynamically simulating all of the relevant hydrologic processes and for estimating spatially- and temporally-varying groundwater recharge surfaces, and the impacts of changes in climate on recharge. The current recharge estimates for both existing conditions and for the climate change scenarios could be used as the inputs to a finite-element groundwater model such that the two models would work in tandem for evaluating water resource scenarios whereby MIKE SHE would be used to evaluate changes in recharge and the finite-element model would then be used to evaluate the impacts of these changes in recharge on groundwater heads and storages.

The last suggestion for future work involves the climate change scenarios. The current work only evaluated the climate change impacts using the output from a single Global Climate Model (GCM) for a single emissions scenario. The climate change predictions from the various leading GCMs and from the various emissions scenarios that have been evaluated with the GCMs vary widely and the International Panel on Climate Change (IPCC) recommends using an ensemble of models and emission scenarios for climate change impact evaluations. It is recommended that additional climate change scenarios be evaluated in order to investigate the range of possible climate change impacts on water resources of the island. Additionally, several Regional Climate Models (RCMs) of the Pacific Northwest which utilize GCM outputs as boundary conditions have been developed. In some cases, these RCMs may make provide more spatially realistic predictions of future climates than the GCMs, and their predictions may be more accurate because the reduced domains of the RCMs allow for the resolution of finer-scale climatic processes then what is possible using a GCM. Additionally, the use of RCM data may allow future climate predictions specific to Vashon Island to be used instead of relying on predictions from the Sea-Tac station.

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# Appendix A – Methodology used to Compute Potential ET from Temperature Data (after Duke et al., 2008)

**Data Required:**

Elevation, metres [m]
Latitude, degrees [°]
Minimum Temperature, degree Celsius [°C]
Maximum Temperature, degree Celsius [°C]
Classification as Coastal or Interior
Classification as Arid or Humid
Julian day

**Assumed data or constants:**

| | |
|---|---|
| Wind speed | 2 m/s |
| Albedo or canopy reflection coefficient, $\alpha$ | 0.23 |
| Solar constant, $G_{sc}$ | 0.082 $MJ^{-2}min^{-1}$ |
| Interior and Coastal coefficients, $K_{Rs}$ | 0.16 for interior locations<br>0.19 for coastal locations |
| Humid and arid region coefficients, $K_o$ | 0 °C for humid / sub-humid climates<br>2 °C for arid / semi-arid climates |

**Definitions:**

$ET_o$ = reference evapotranspiration [mm $day^{-1}$],
$R_n$ = net radiation at the crop surface [MJ $m^{-2}$ $day^{-1}$],
G = soil heat flux density [MJ $m^{-2}$ $day^{-1}$],
T = mean daily air temperature at 2 m height [°C],
$u_2$ = wind speed at 2 m height [m $s^{-1}$],
$e_s$ = saturation vapour pressure [kPa],
$e_a$ = actual vapour pressure [kPa],
$e_s - e_a$ = saturation vapour pressure deficit [kPa],
$\Delta$ = slope vapour pressure curve [kPa $°C^{-1}$],
$\gamma$ = psychrometric constant [kPa $°C^{-1}$].

**Procedure:**

1. Calculate mean air temperature, T [°C]

$$T = \left( \frac{T_{\min} + T_{\max}}{2} \right)$$

2. Calculate actual vapour pressure, $e_a$ [kPa]
   Use minimum temperature and adjustment factor depending on climate classification humid or semi-arid.

$$e_a = 0.6108 \ \exp\left[\frac{17.27\,(T_{\min} - K_o)}{(T_{\min} - K_o) + 237.3}\right]$$

   where:
   $K_o$ = 0 °C for humid and sub-humid climates
   $K_o$ = 2 °C for arid and semi-arid climates

   Stations are classified as coastal and interior, interior stations are considered semi-arid, while coastal stations are considered to be humid.

3. Calculate saturated vapour pressure for $T_{max}$, $e_{(Tmax)}$ [kPa]

$$e_{(T_{\max})} = 0.6108 \ \exp\left[\frac{17.27 \ T_{\max}}{T_{\max} + 237.3}\right]$$

4. Calculate saturated vapour pressure for $T_{min}$, $e_{(Tmin)}$ [kPa]

$$e_{(T_{\min})} = 0.6108 \ \exp\left[\frac{17.27\,T_{\min}}{T_{\min} + 237.3}\right]$$

5. Calculate saturated vapour pressure, $e_s$ [kPa]

$$e_s = \left(\frac{e_{(T_{\min})} + e_{(T_{\max})}}{2}\right)$$

6. Calculate inverse relative distance Earth-Sun, $d_r$ [rad]

$$d_r = 1 + 0.033 \ \cos\left(\frac{2\,\pi}{365}\,J\right)$$

   where:
   J = Julian day

7. Convert latitude to radians, $\psi$ [rad]

$$\varphi(rad) = \frac{\pi}{180}\,lat(°)$$

   where:
   lat = latitude of station in degrees

8. Calculate solar declination, δ [rad]

$$\delta = 0.409 \sin\left(\frac{2\,\pi}{365}\,J - 1.39\right)$$

where:

J = Julian day

9. Calculate sunset hour angle, $\omega_s$ [rad]

$$\omega_s = \arccos\left[-\tan(\varphi)\,\tan(\delta)\right]$$

10. Calculate extraterrestrial radiation, $R_a$ [$MJm^{-2}$ $day^{-1}$]

$$R_a = \frac{24 \times 60}{\pi} G_{sc}\; d_r\; \left[\omega_s\,\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right]$$

where:

$G_{sc}$ = solar constant = 0.082 $MJm^{-2}$ $min^{-1}$

11. Calculate clear sky solar radiation, $R_{so}$ [$MJm^{-2}$ $day^{-1}$]

$$R_{so} = \left(0.75 + 2 \times 10^{-5}\, z\right) R_a$$

where:

Z = elevation of climate station above sea level [m]

$R_a$ = Step 10

12. Calculate solar radiation, $R_s$ [$MJm^{-2}$ $day^{-1}$]
Use adjustment factor $K_{Rs}$ depending on station location, coastal or interior

$$R_s = K_{Rs}\,\sqrt{(T_{\max} - T_{\min})}\; R_a$$

where:

$K_{Rs}$ = 0.16 for interior locations

$K_{Rs}$ = 0.19 for coastal locations

13. Calculate net longwave radiation, $R_{nl}$ [$MJm^{-2}$ $day^{-1}$]

$$R_{nl} = \sigma\;\frac{(T_{\max} + 237.15)^4 + (T_{\min} + 237.16)^4}{2}\;\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$$

where:

σ = 4.903 x $10^{-9}$ $MJK^{-4}m^{-2}day^{-1}$

14. Calculate net solar radiation, $R_{ns}$ [$MJm^{-2}$ $day^{-1}$]

$$R_{ns} = (1 - \alpha)\; R_s$$

where:

α = 0.23

15. Calculate net radiation, $R_n$ [$MJm^{-2}$ $day^{-1}$]

$$R_n = R_{ns} - R_{nl}$$

16. Calculate slope vapour pressure, Δ [kPa □$C^{-1}$]

$$\Delta = \frac{2504 \ \exp\left(\frac{17.27\,T}{T + 237.3}\right)}{\left(T + 237.3\right)^2}$$

17. Calculate atmospheric pressure, P [kPa]

$$P = 101.3 \ \left(\frac{293 - 0.0065\,z}{293}\right)^{5.26}$$

where:

z = elevation above sea level [m]

18. Calculate psychometric constant, γ [kPa □$C^{-1}$]

$$\gamma = 0.665 \times 10^{-3}\,P$$

where:

P = Step 17

19. Calculate evapotranspiration, $ET_o$

$$ET_o = \left[\frac{0.408\,\Delta\,R_n + \gamma\ \left(\frac{900}{T + 273}\right)\ u_2\ (e_s - e_a)}{\Delta + \gamma\ \ (1 + 0.34\,u_2)}\right]$$

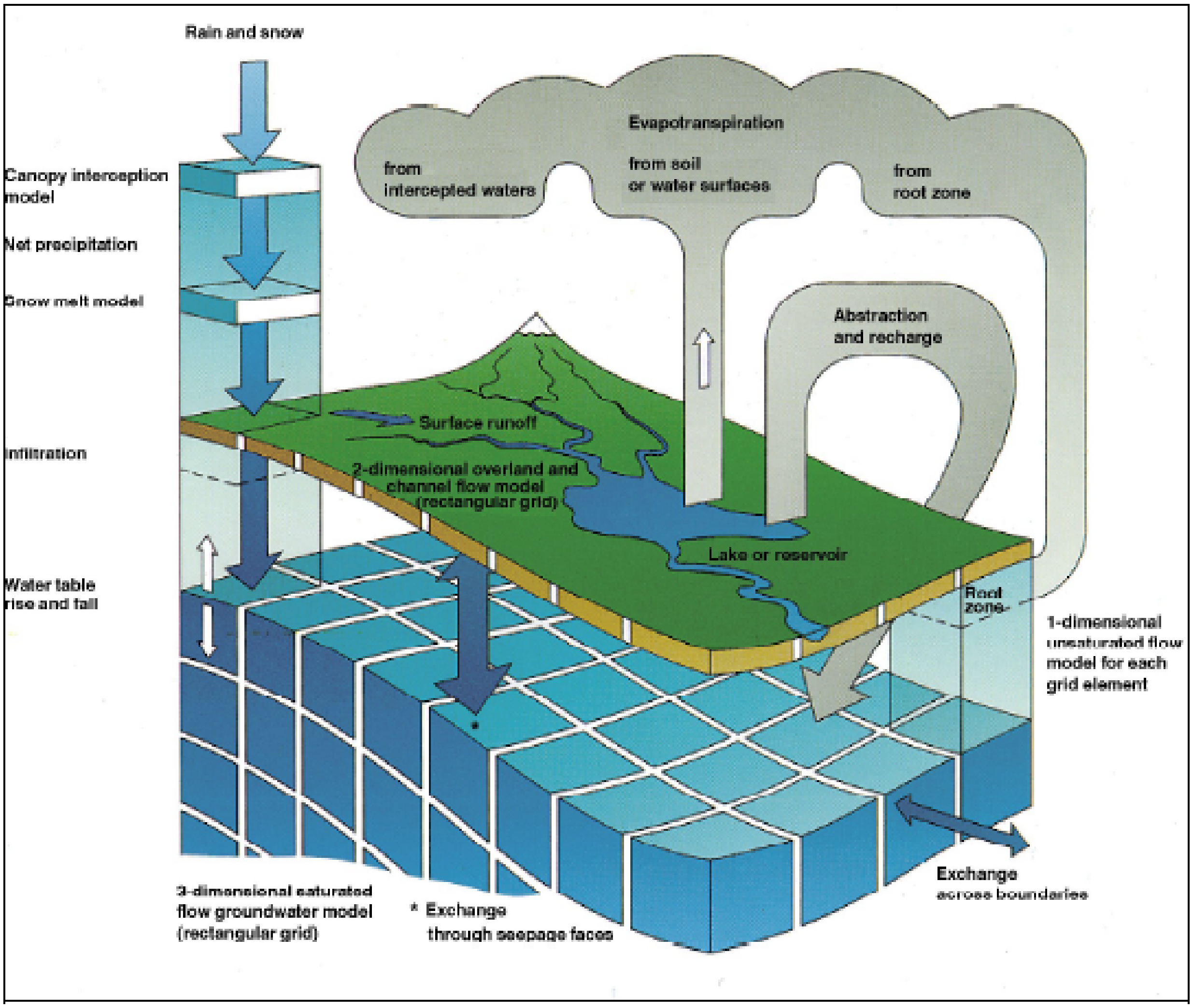


Figure 1: Structure of the MIKE SHE/MIKE11 integrated modeling system.

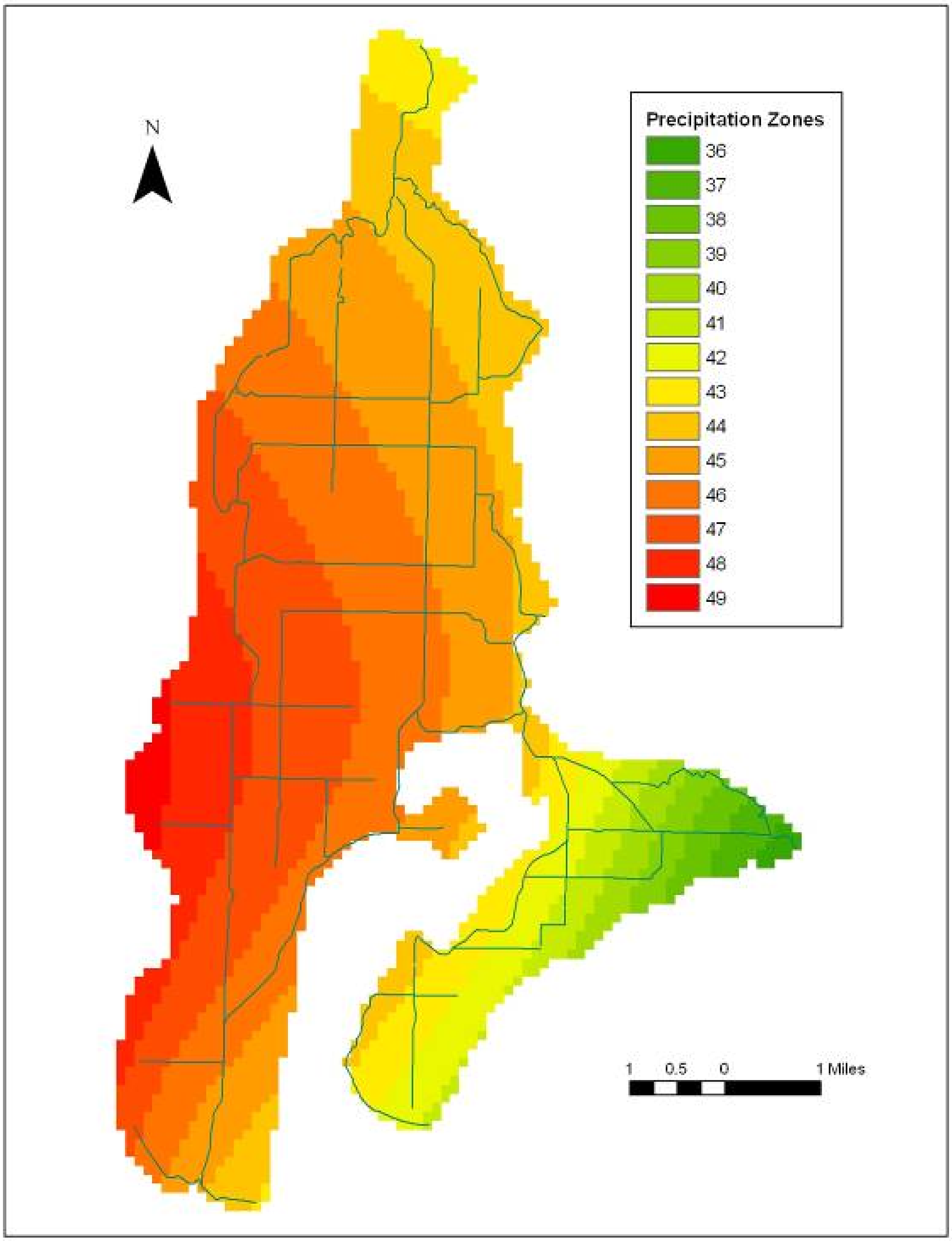


Figure 2: Precipitation zones used in the VMI MIKE SHE model. Zone numbers represent mean annual precipitation values from the isohyetal data in inches.

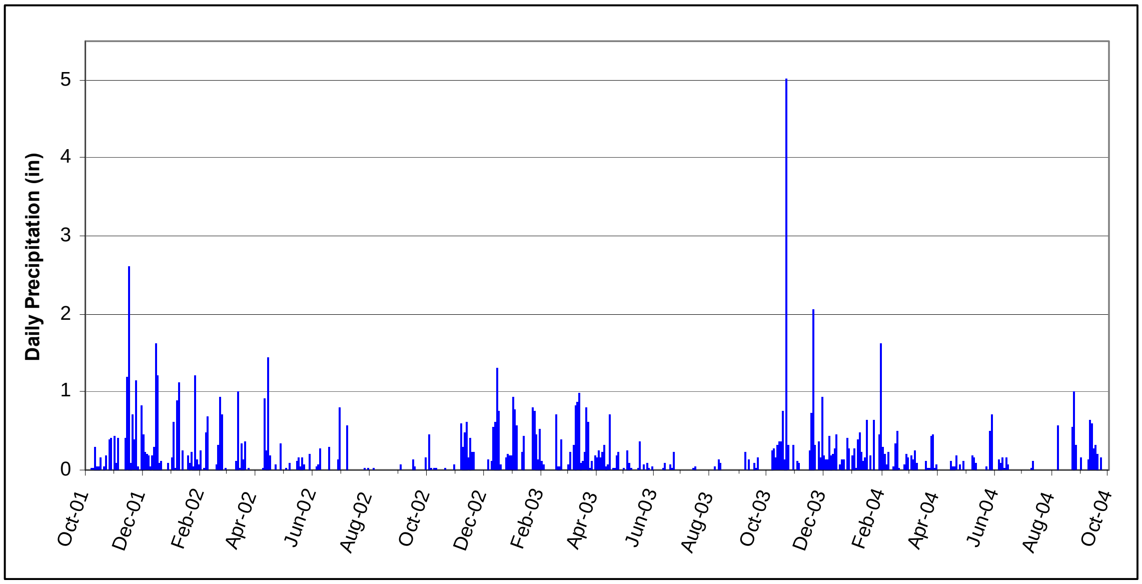


Figure 3: Un-scaled Sea-Tac precipitation record used in the VMI MIKE SHE model.

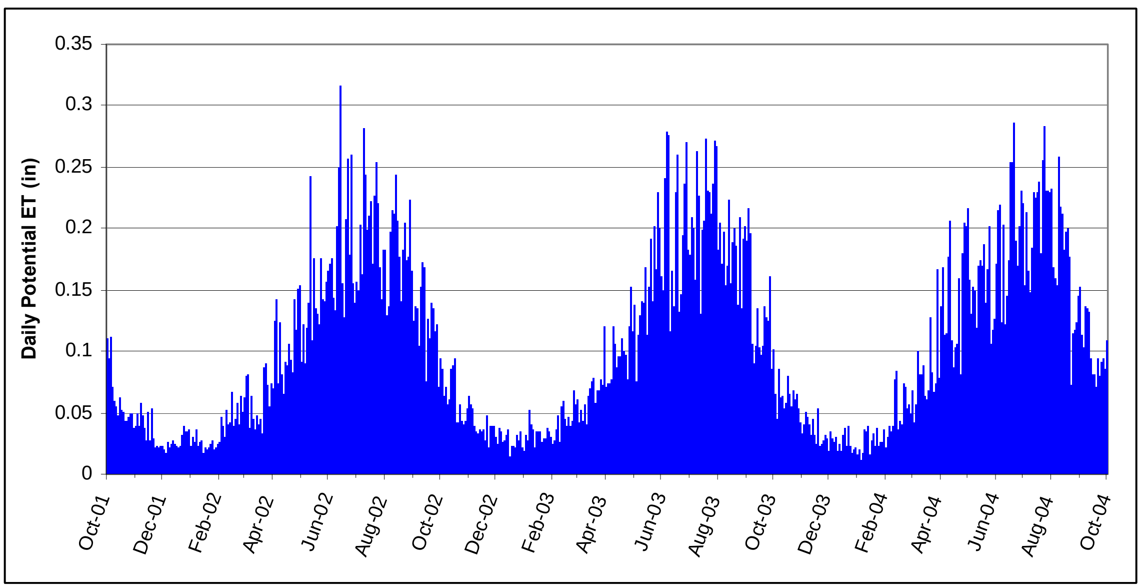


Figure 4: Potential evapotranspiration (PET) record used in the VMI MIKE SHE model.

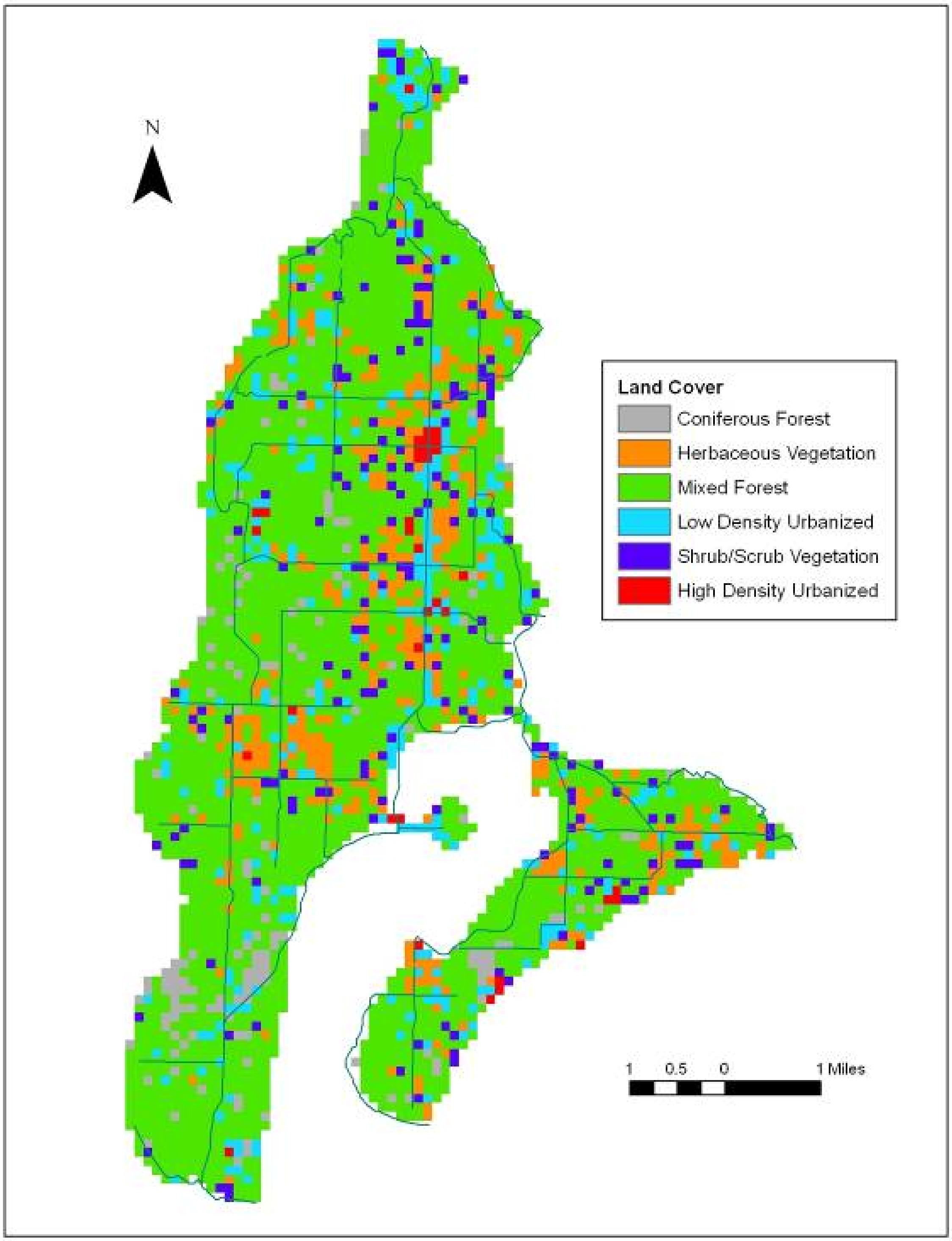


Figure 5: Land cover map used in the VMI MIKE SHE model based on the 2002 King County GIS dataset.

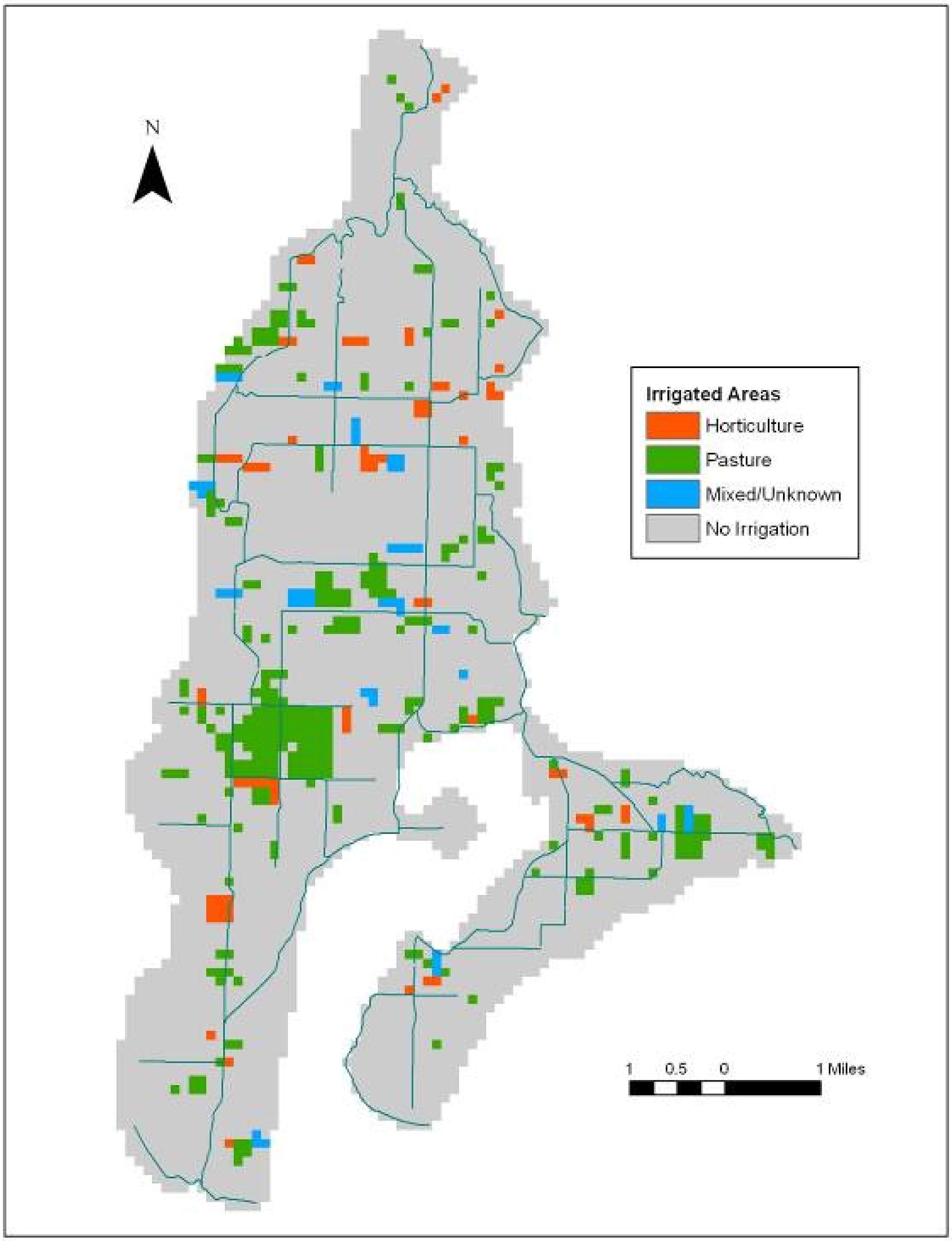


Figure 6: Irrigated areas in the VMI MIKE SHE model based on the King County GIS dataset.

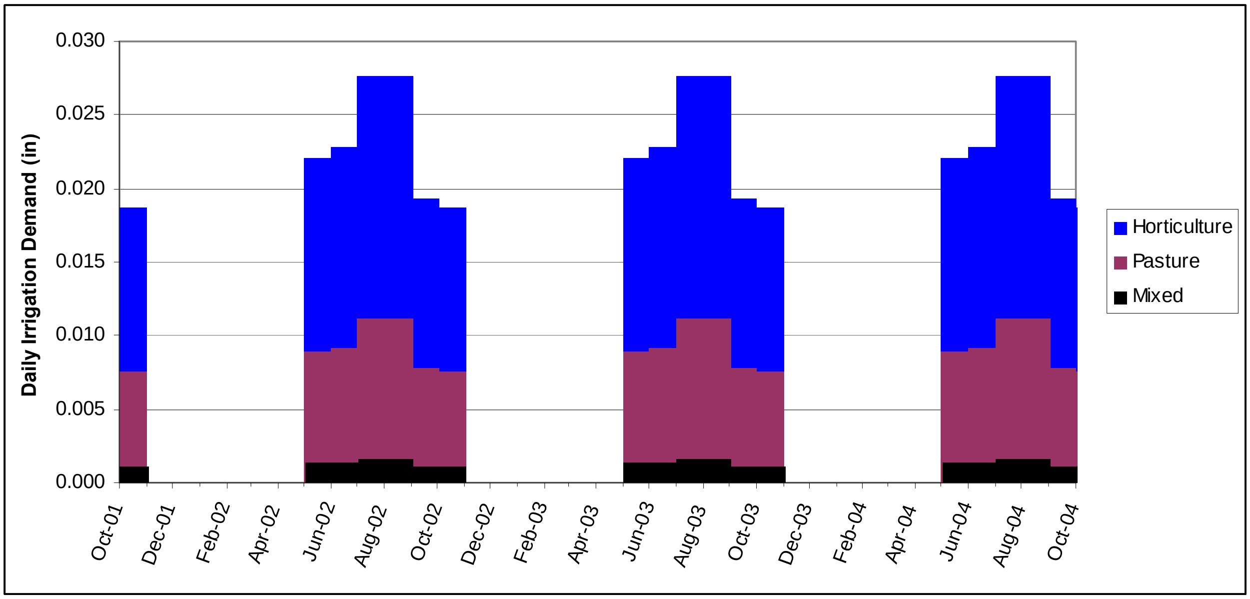


Figure 7: Irrigation demands used in the VMI MIKE SHE model.

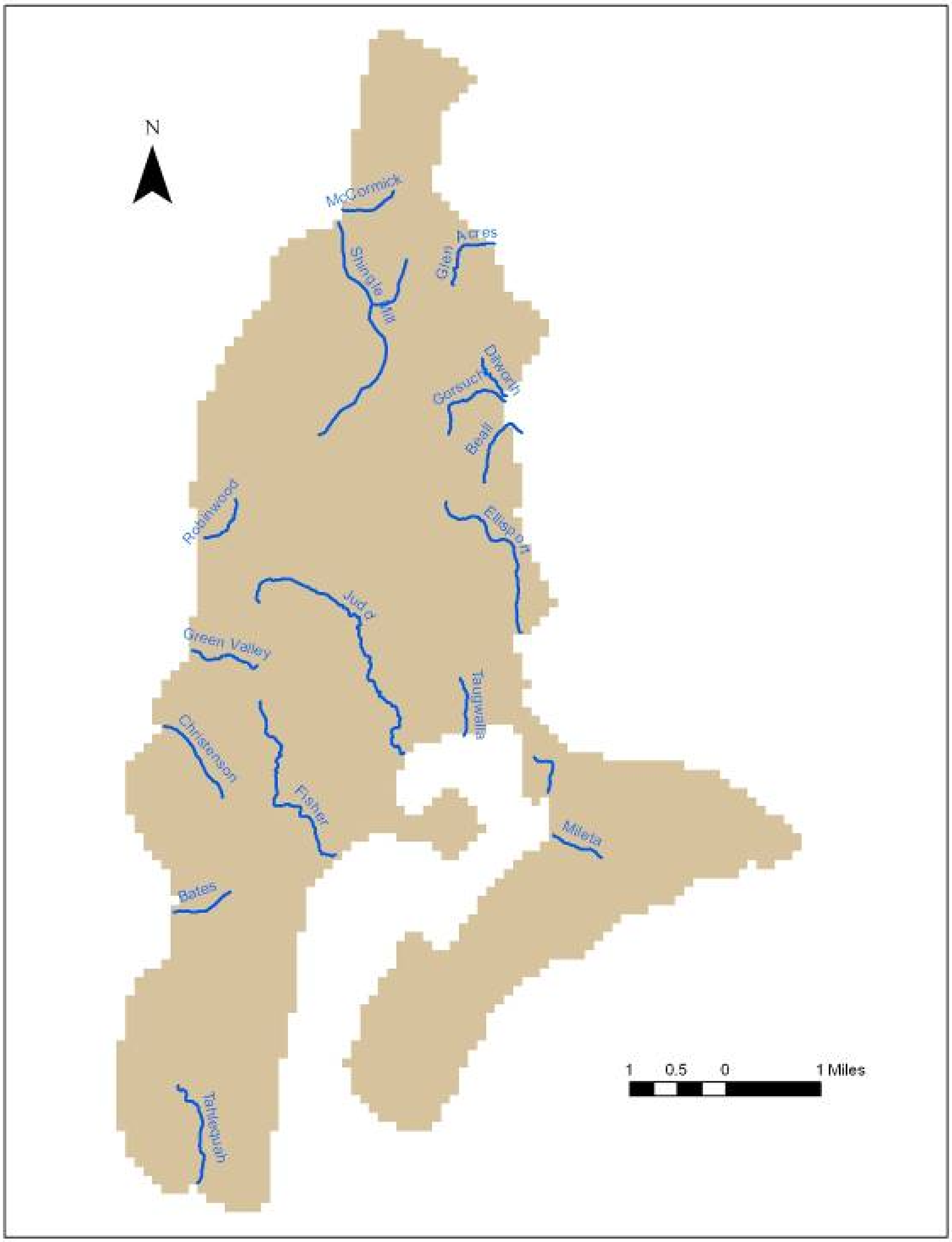


Figure 8: Stream network used in the VMI MIKE SHE model based on the King County GIS dataset.

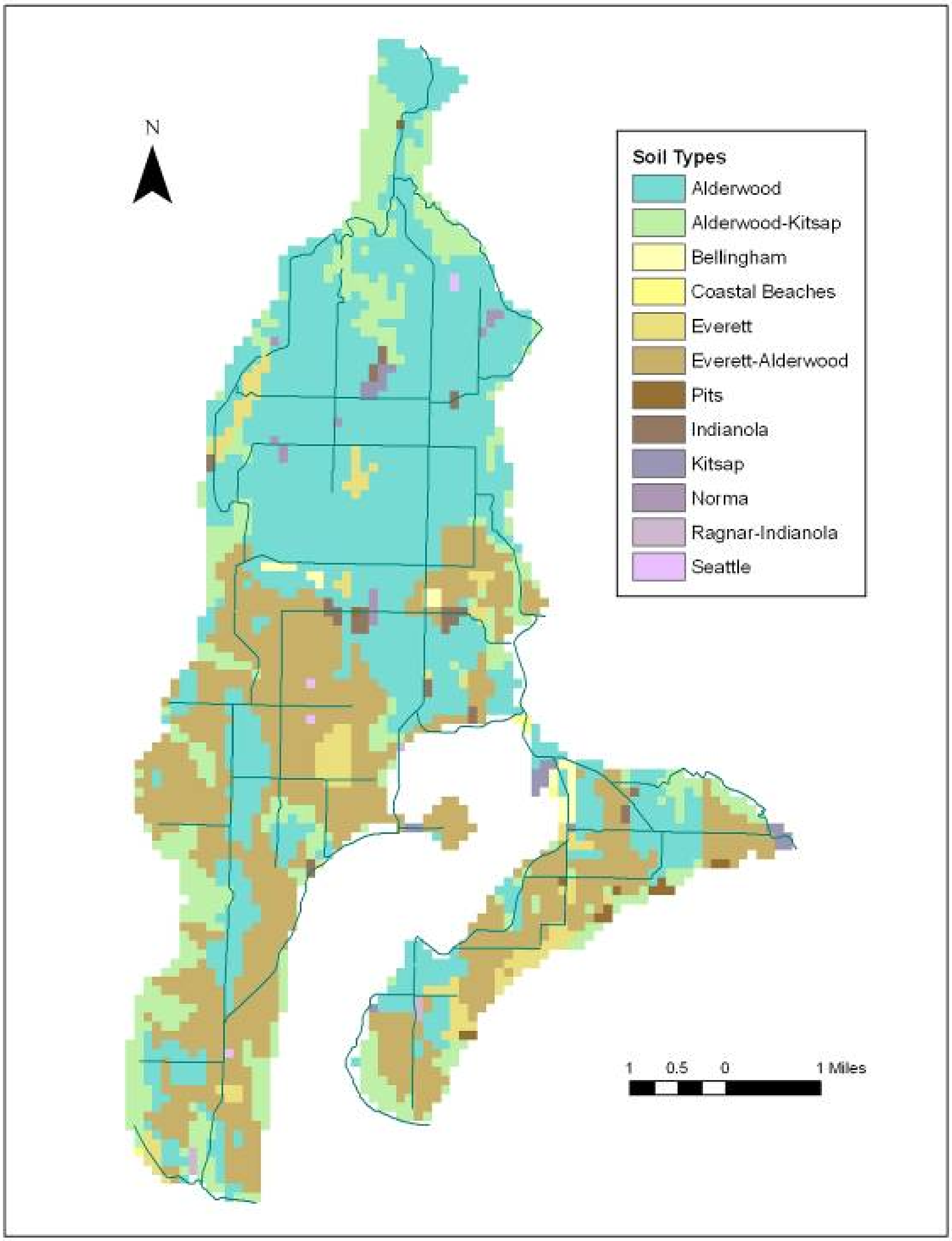


Figure 9: Soil types used in the VMI MIKE SHE model based on the USDA GIS dataset (SSURGO, 2008).

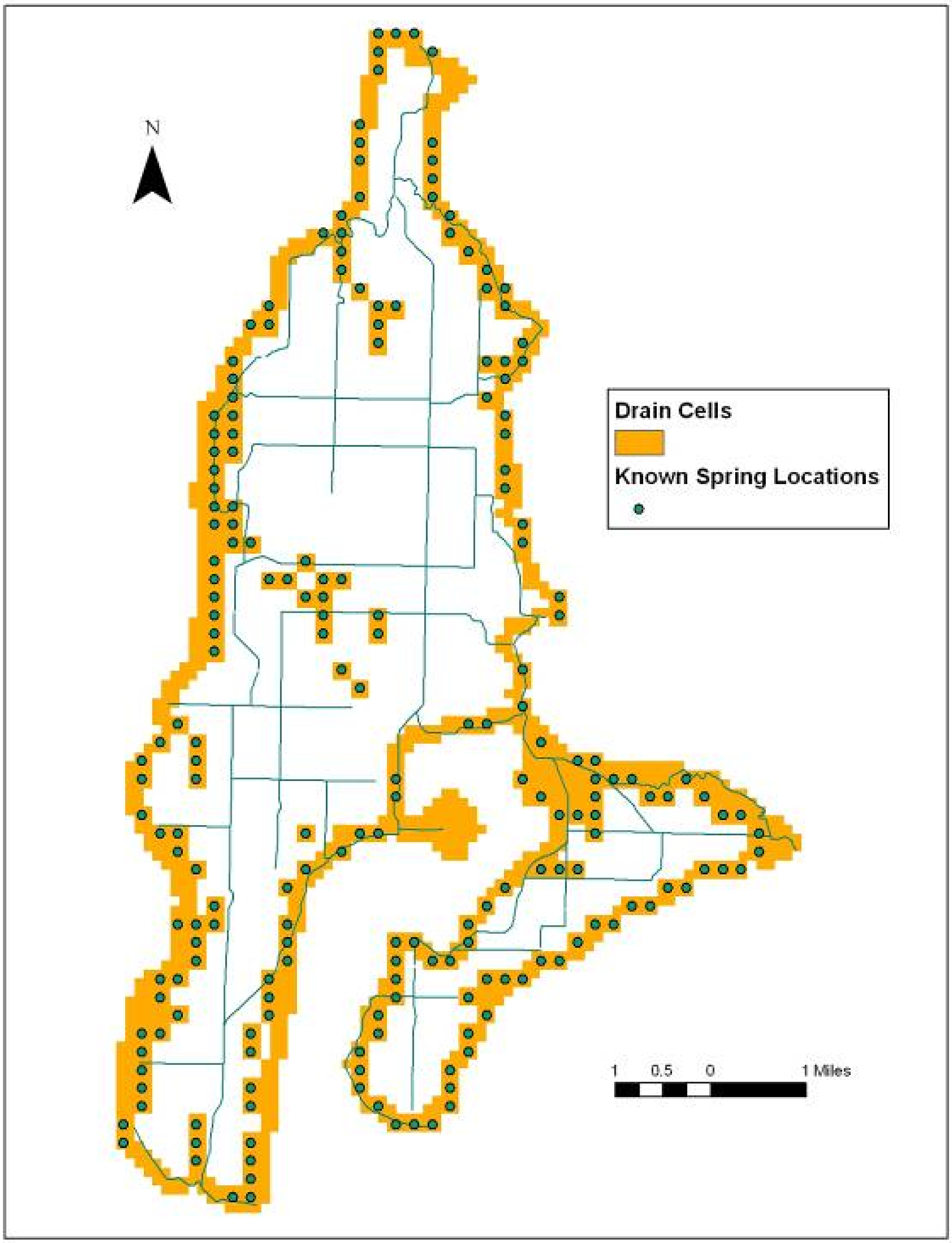


Figure 10: Drain cells used in the VMI MIKE SHE model to represent spring flow shown with the King County GIS dataset of known spring locations.

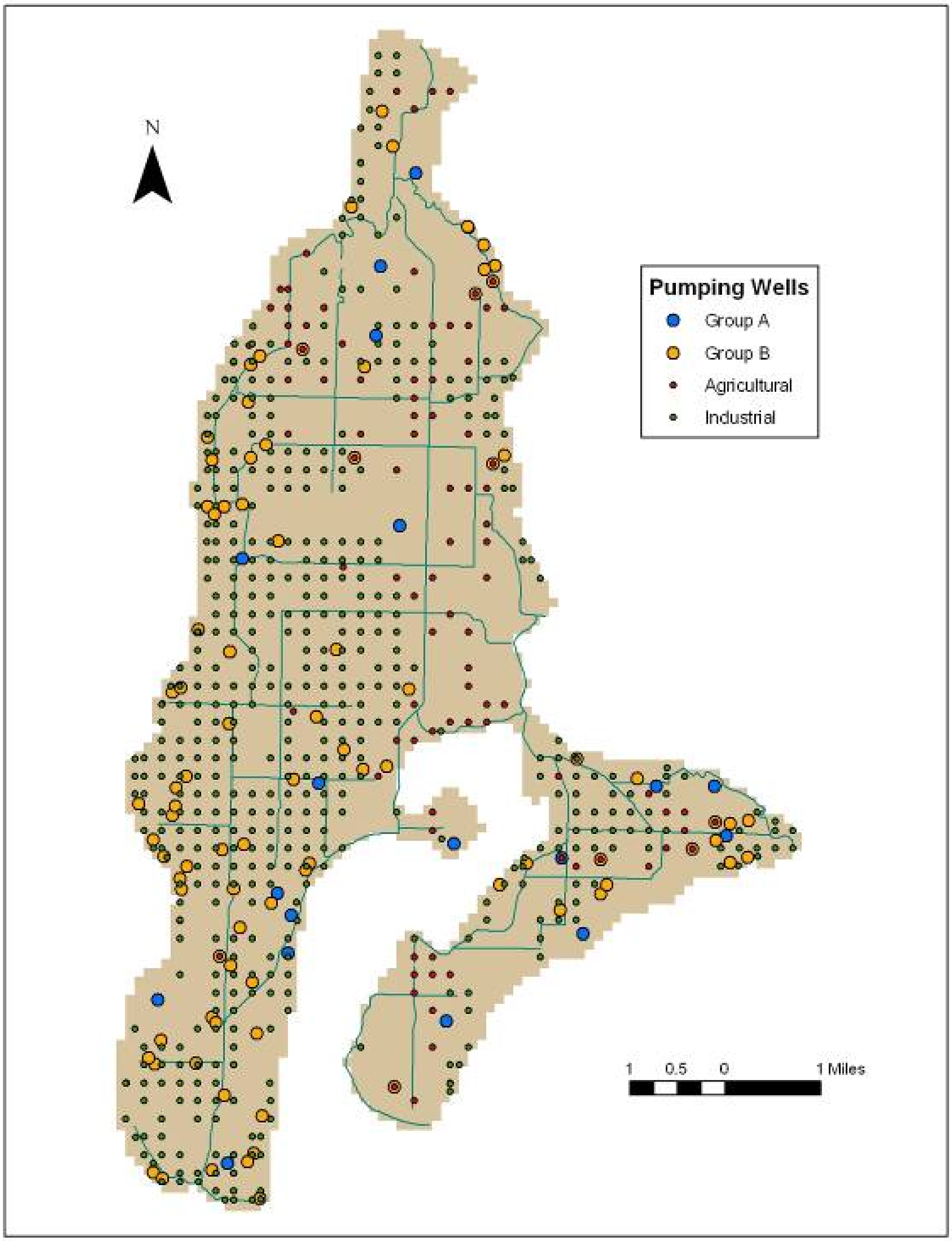


Figure 11: Pumping wells in the VMI MIKE SHE model based on the King County GIS dataset.

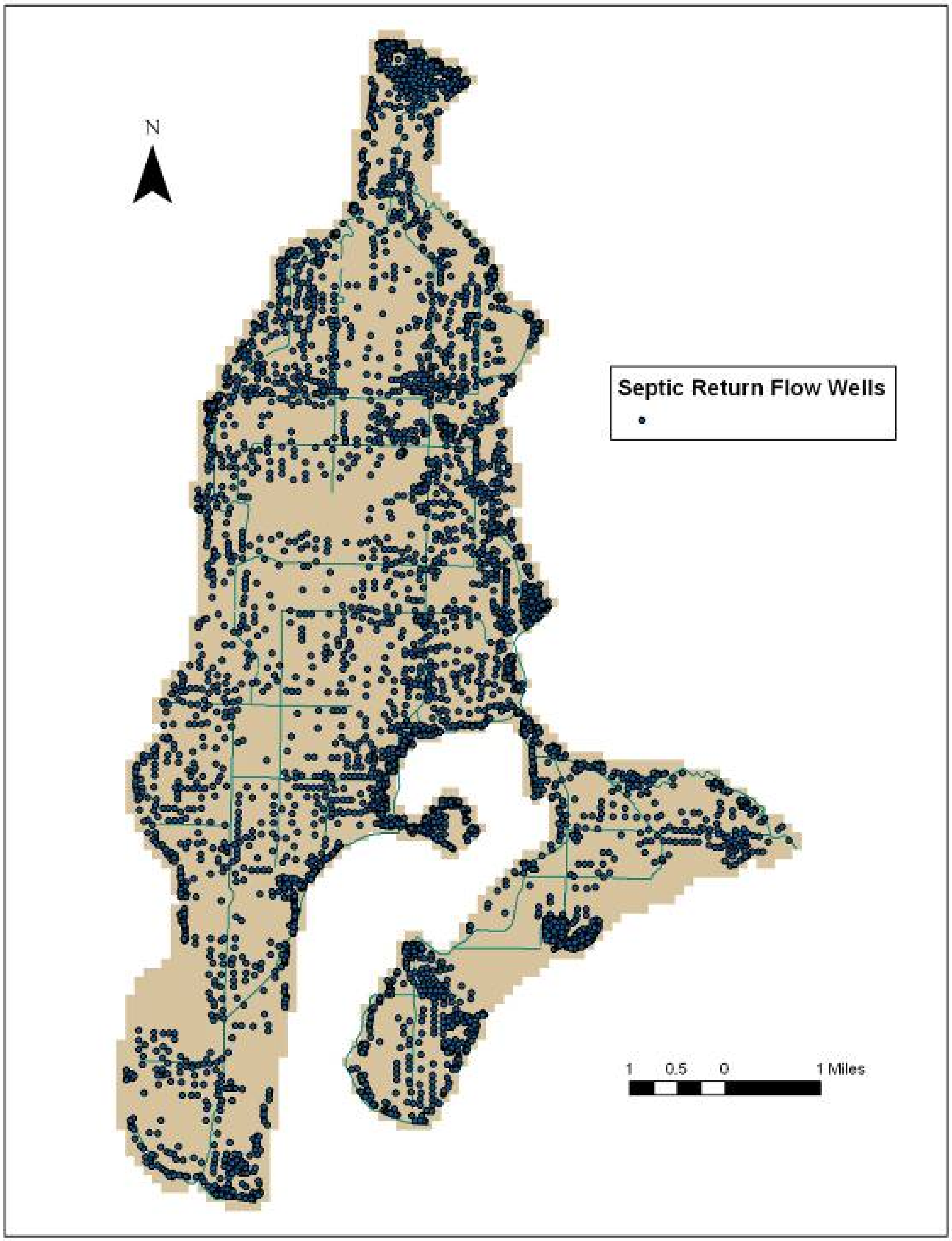


Figure 12: Septic return flow injection wells in the VMI MIKE SHE model based on the King County  GIS dataset.

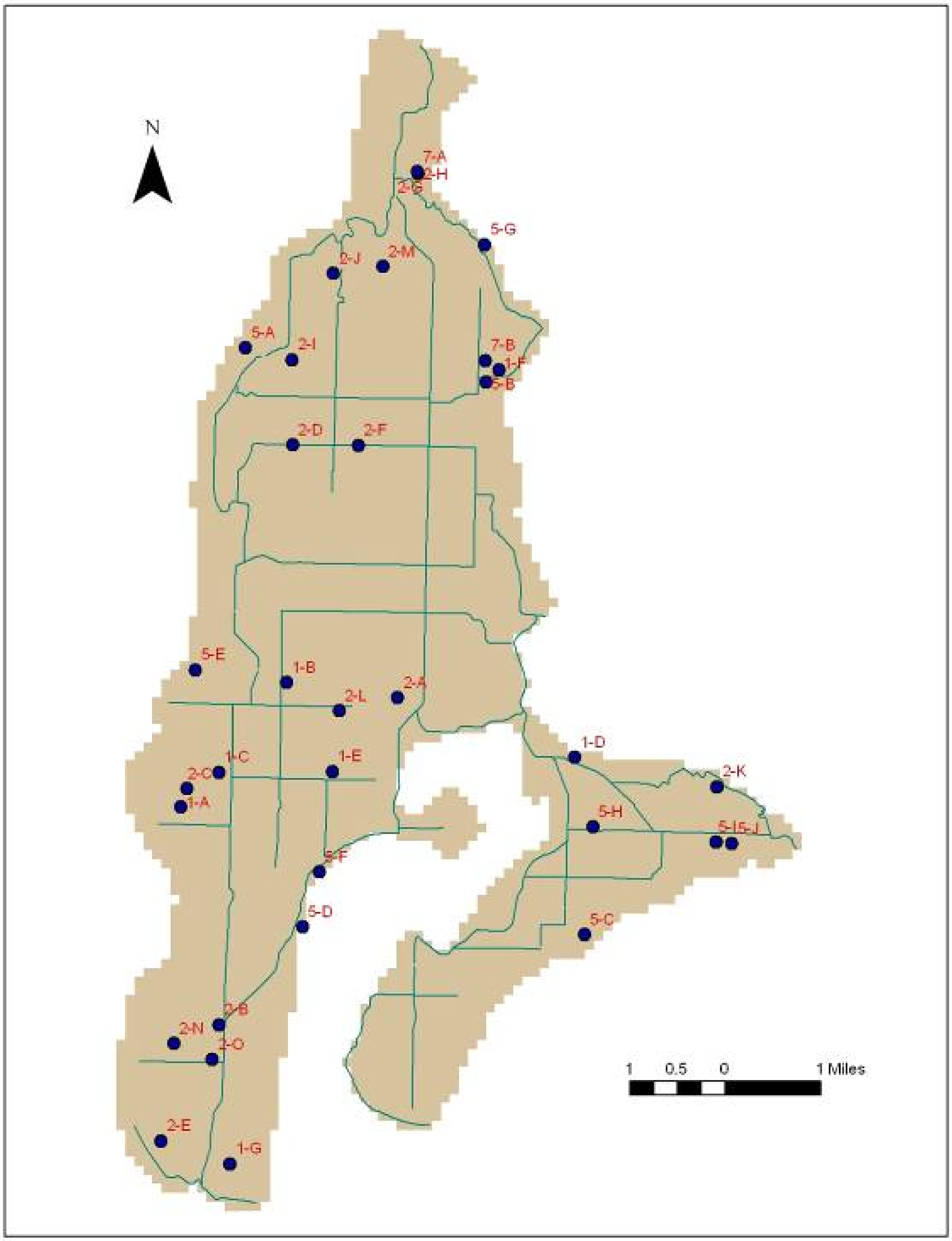


Figure 13: Groundwater observation wells used for calibration. Labels are linked to Table 10 and label numbers indicate the model layer.

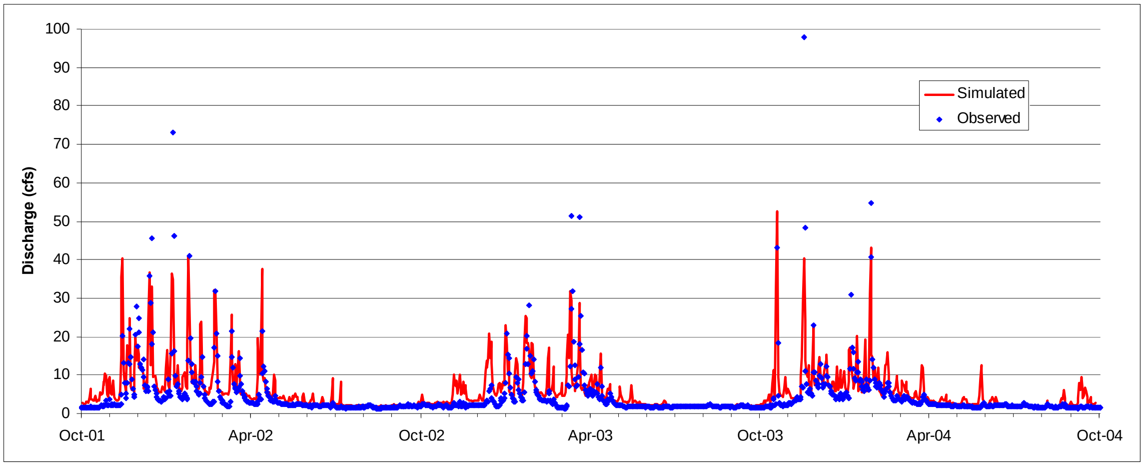


Figure 14: Hydrograph comparison for the Shingle Mill Creek calibration.

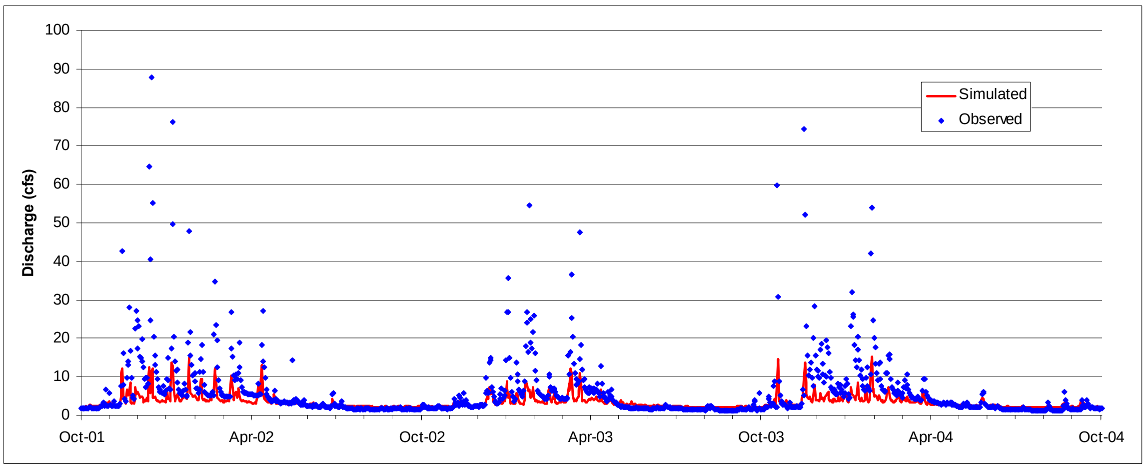


Figure 15: Hydrograph comparison for the Judd Creek calibration.

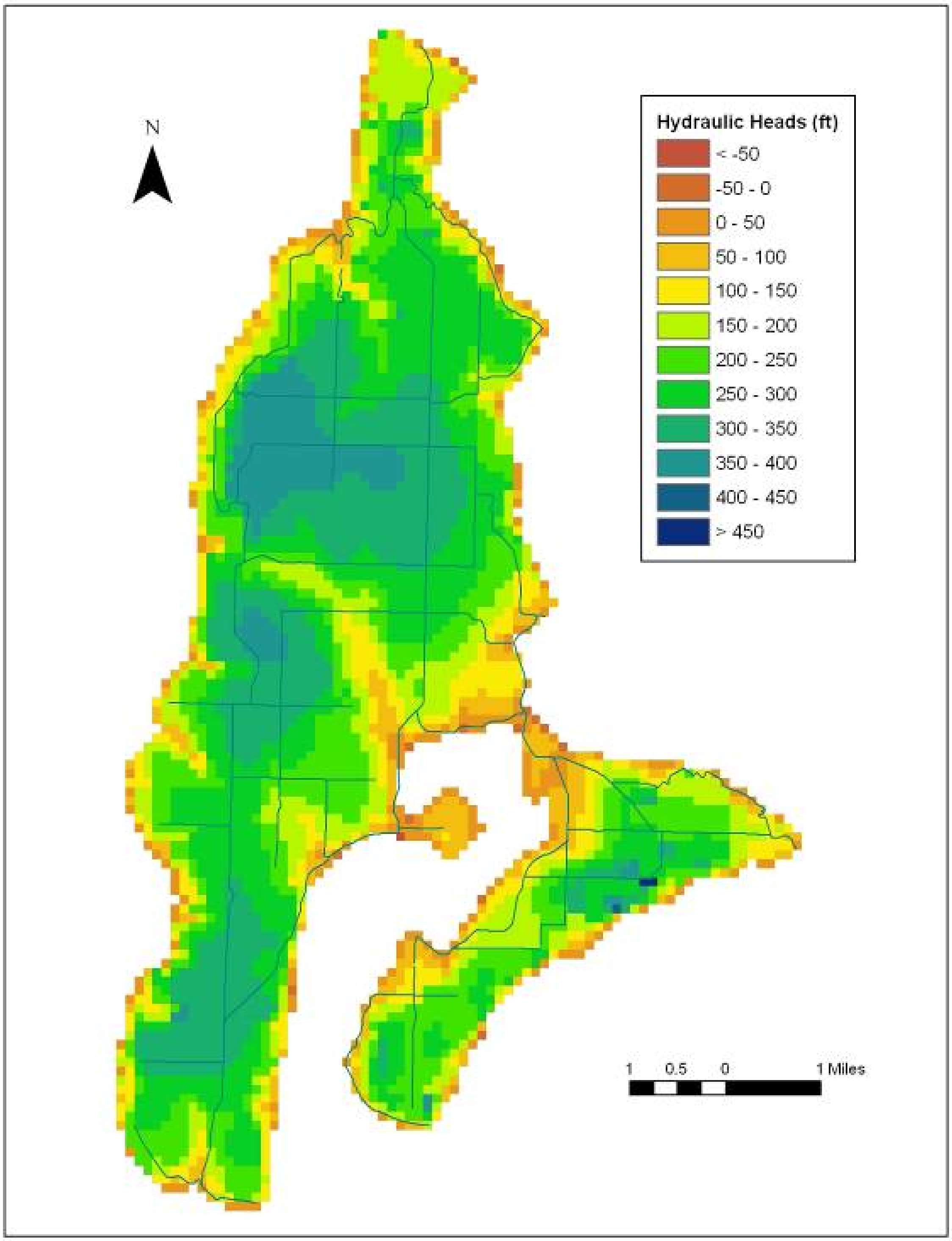


Figure 16: Simulated mean hydraulic heads in Layer 1 (Qvr and Qvt )

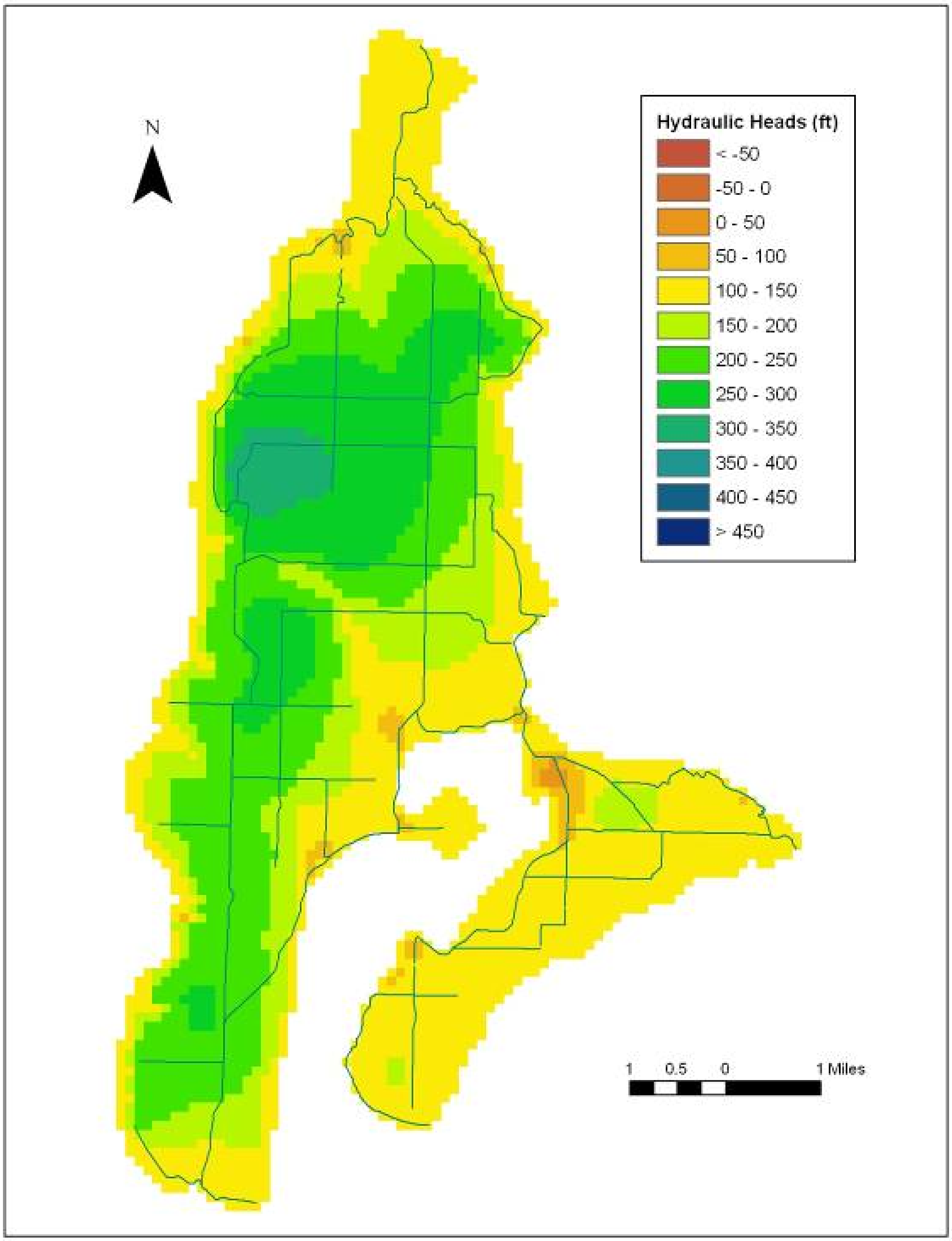


Figure 17: Simulated mean hydraulic heads in Layer 2 (Qva).

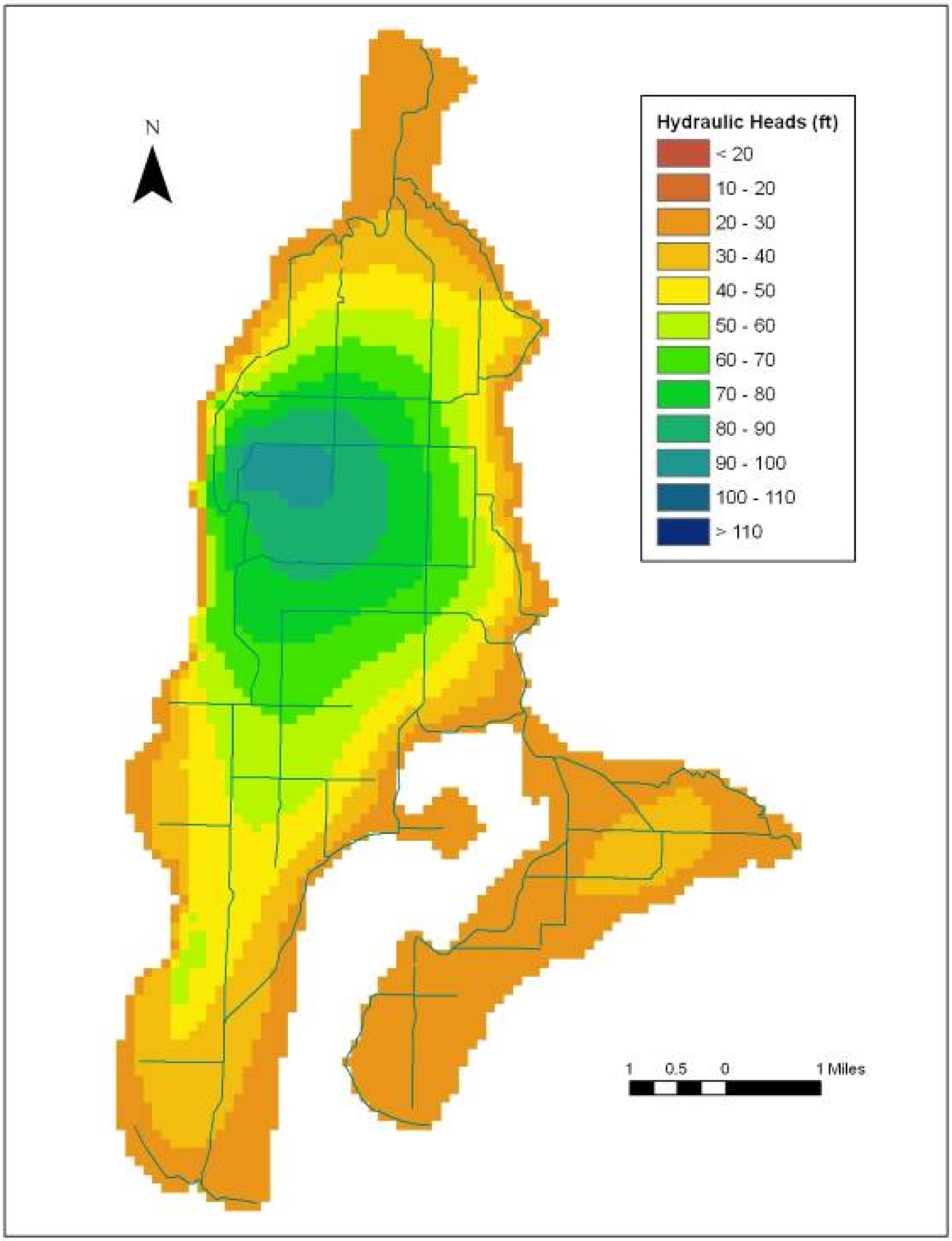


Figure 18: Simulated mean hydraulic heads in Layer 5 (QAc).

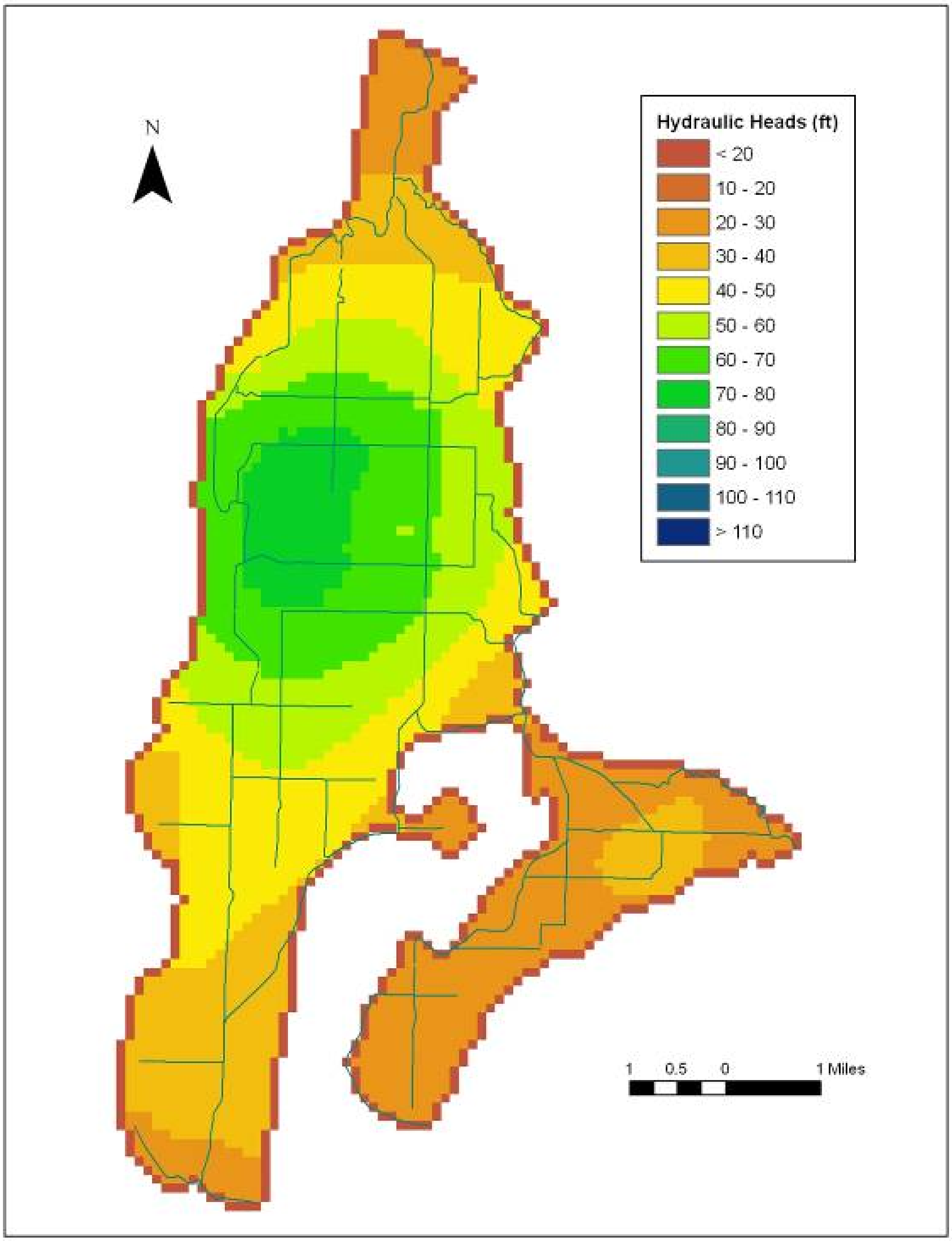


Figure 19: Simulated mean hydraulic heads in Layer 7 (QBc).

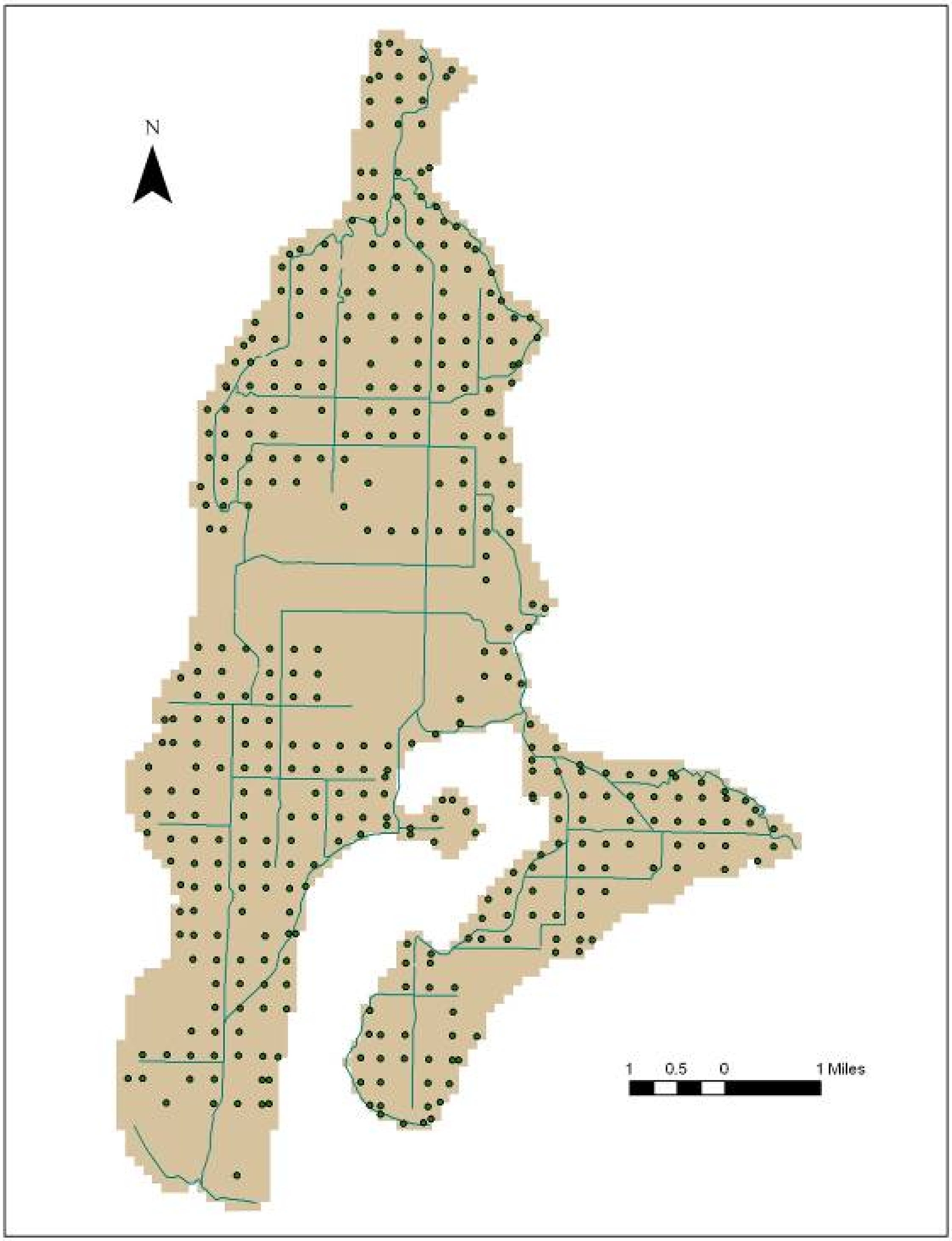


Figure 20: New exempt wells (423) included in Scenarios 2, 8, & 10 to represent build-out conditions.

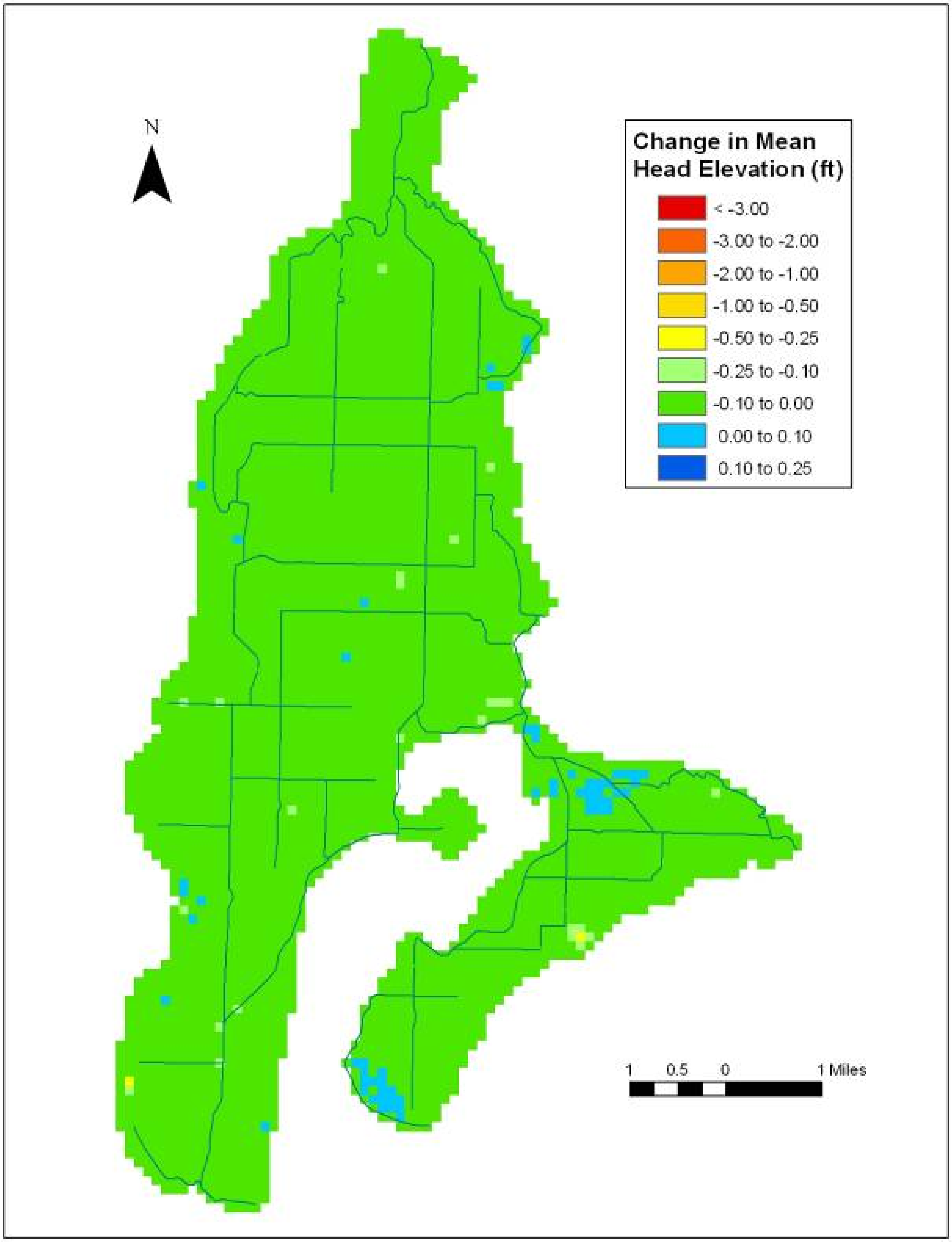


Figure 21: Change in the mean hydraulic heads in Layer 2 (Qva) under Scenario 1.

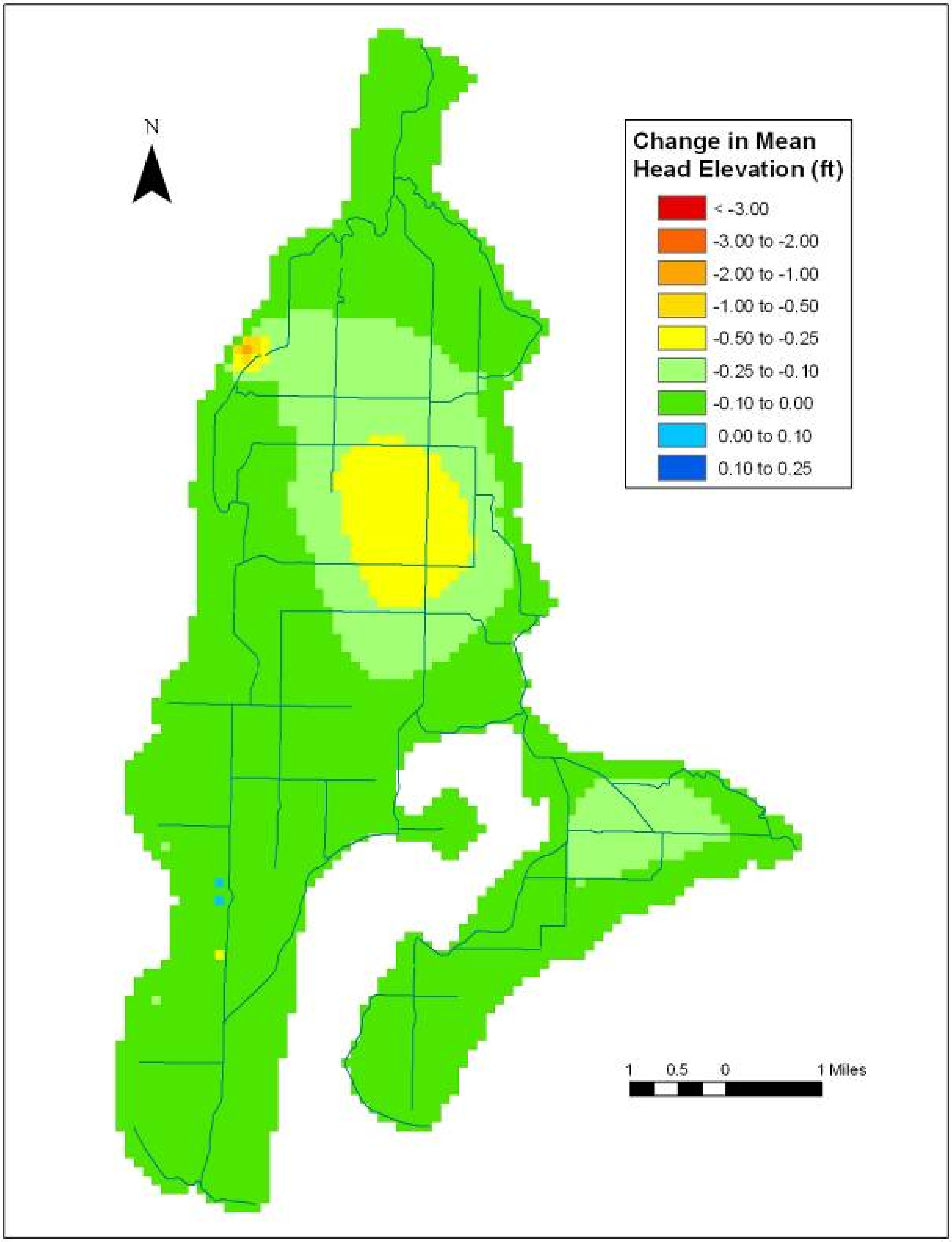


Figure 22: Change in the mean hydraulic heads in Layer 5 (QAc) under Scenario 1.

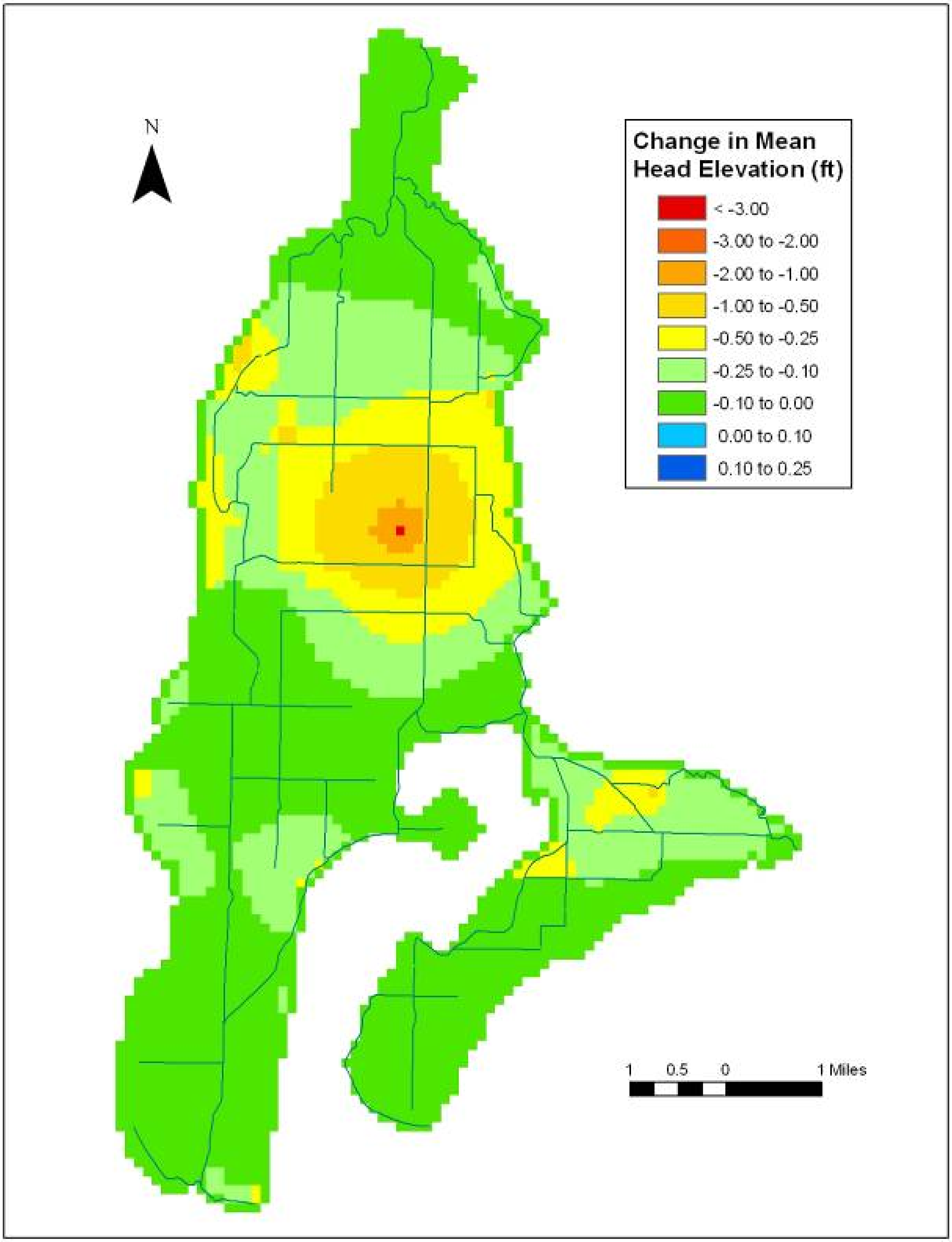


Figure 23: Change in the mean hydraulic heads in Layer 7 (QBc) under Scenario 1.

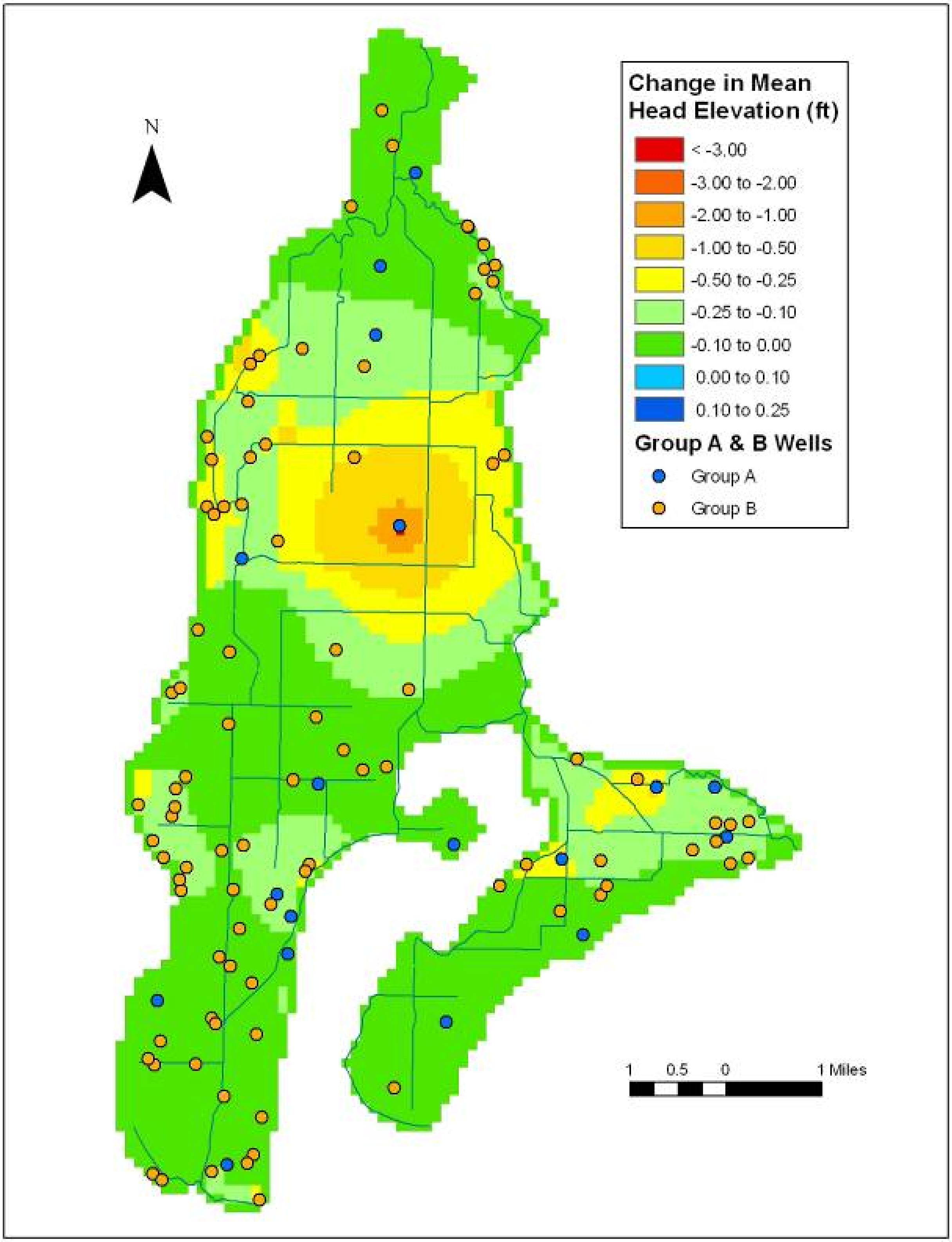


Figure 24: Change in the mean hydraulic heads in Layer 7 (QBc) under Scenario 1 relative to the locations of Public Water System Group A and B production wells.

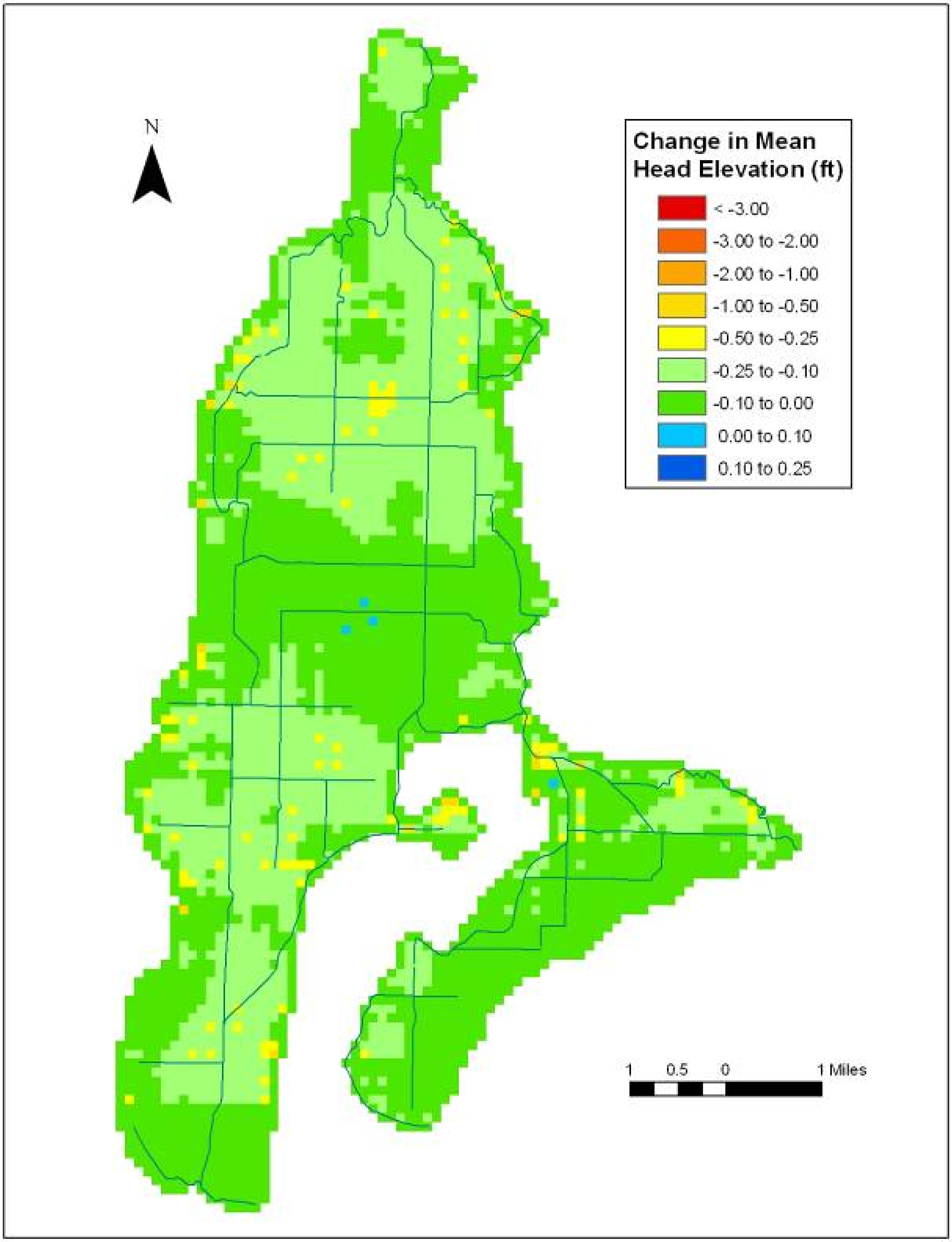


Figure 25: Change in the mean hydraulic heads in Layer 2 (Qva) under Scenario 2.

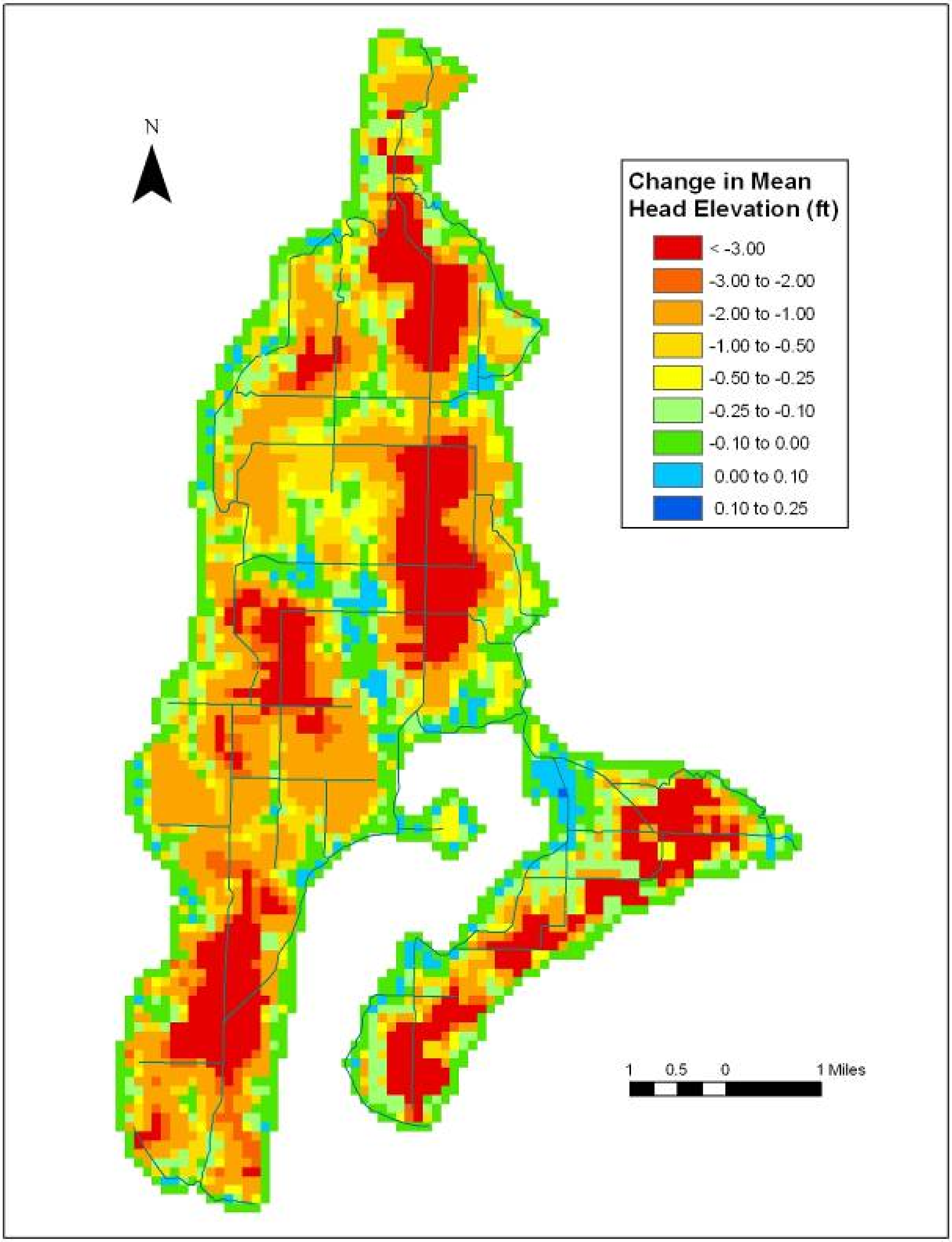


Figure 26: Change in the mean hydraulic heads in Layer 1 (Qvr and Qvt) under Scenario 4 – 2025 Climate Change.

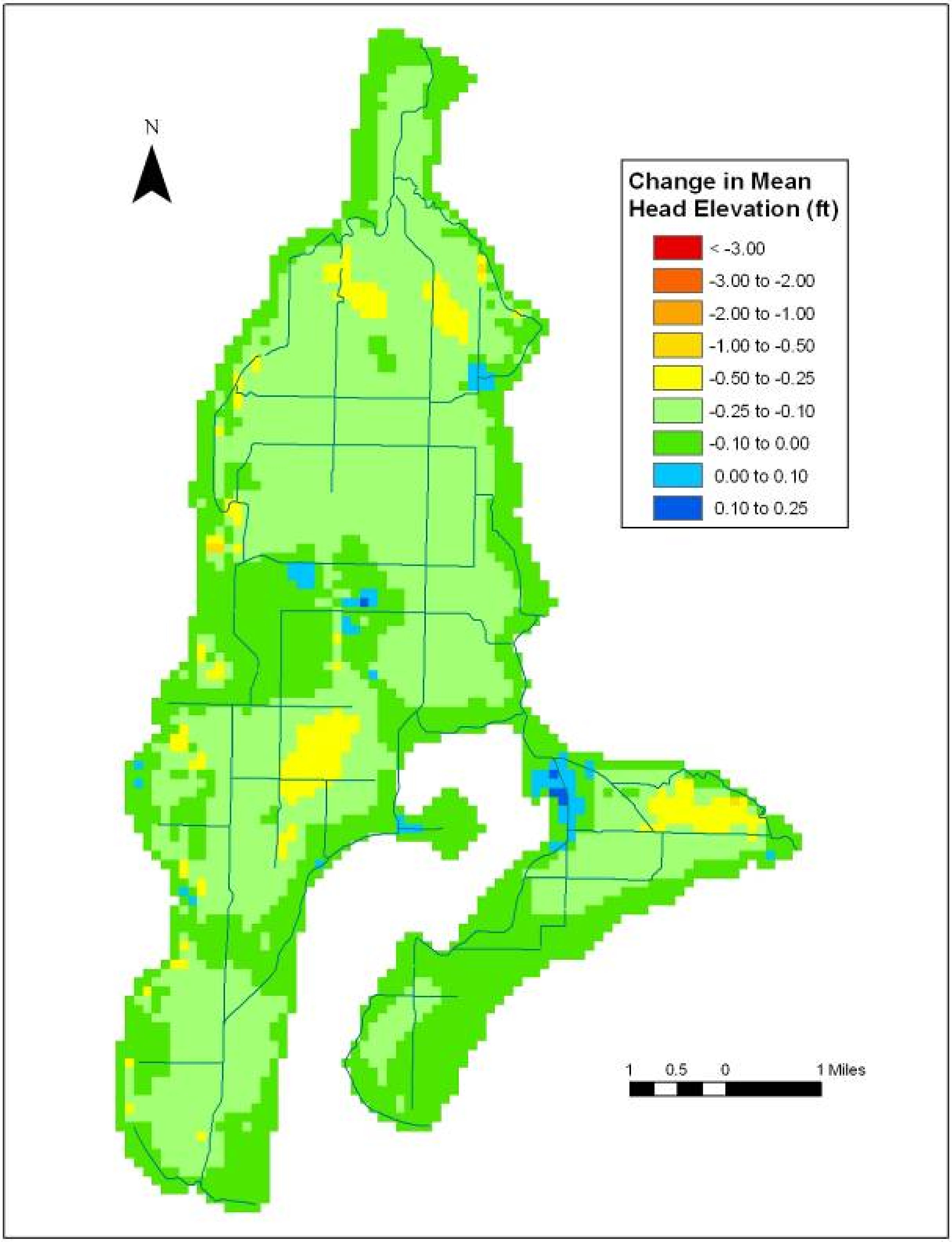


Figure 27: Change in the mean hydraulic heads in Layer 2 (Qva) under Scenario 4 – 2025 Climate Change.

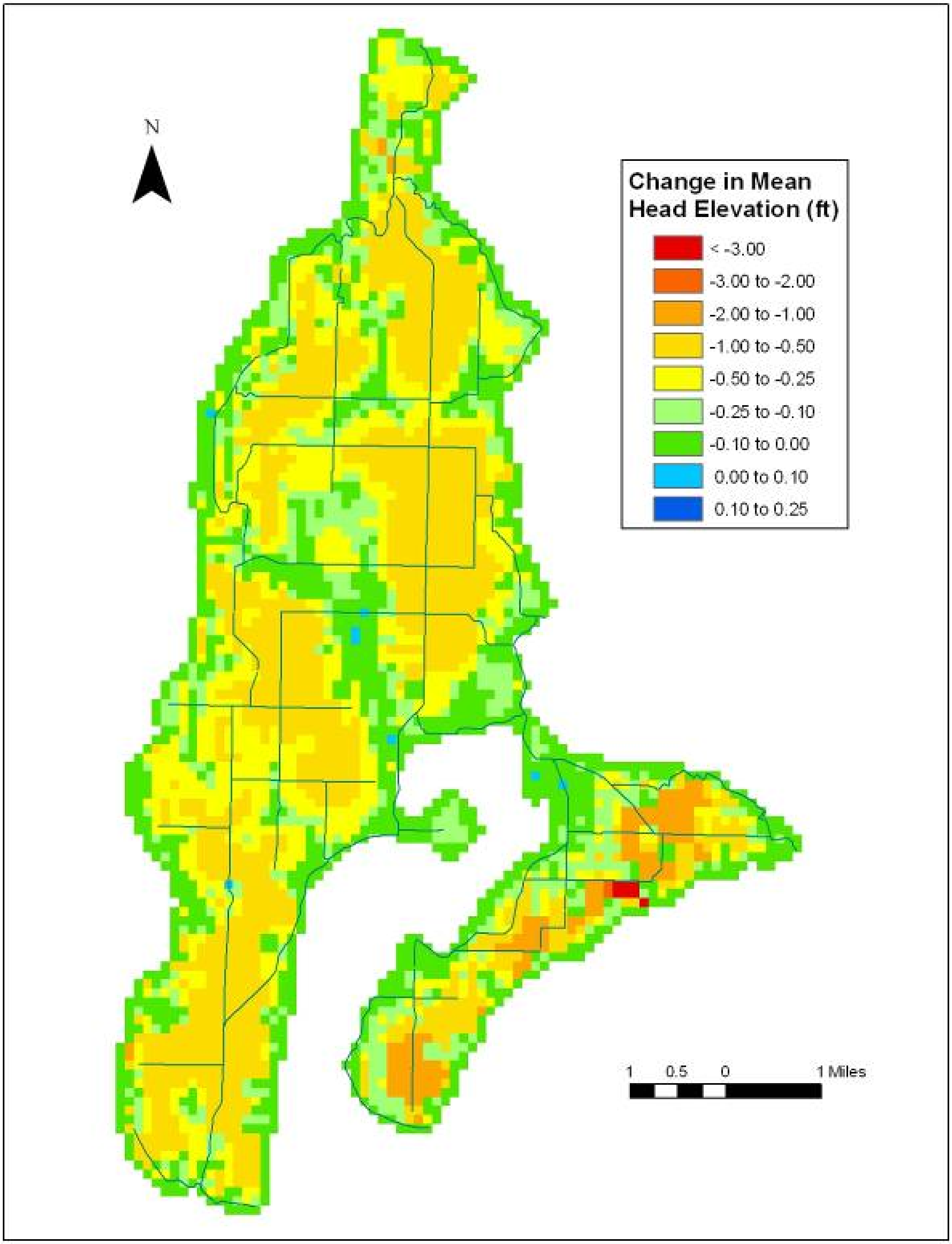


Figure 28: Change in the mean hydraulic heads in Layer 1 (Qvr and Qvt) under Scenario 5 – 2050 Climate Change.

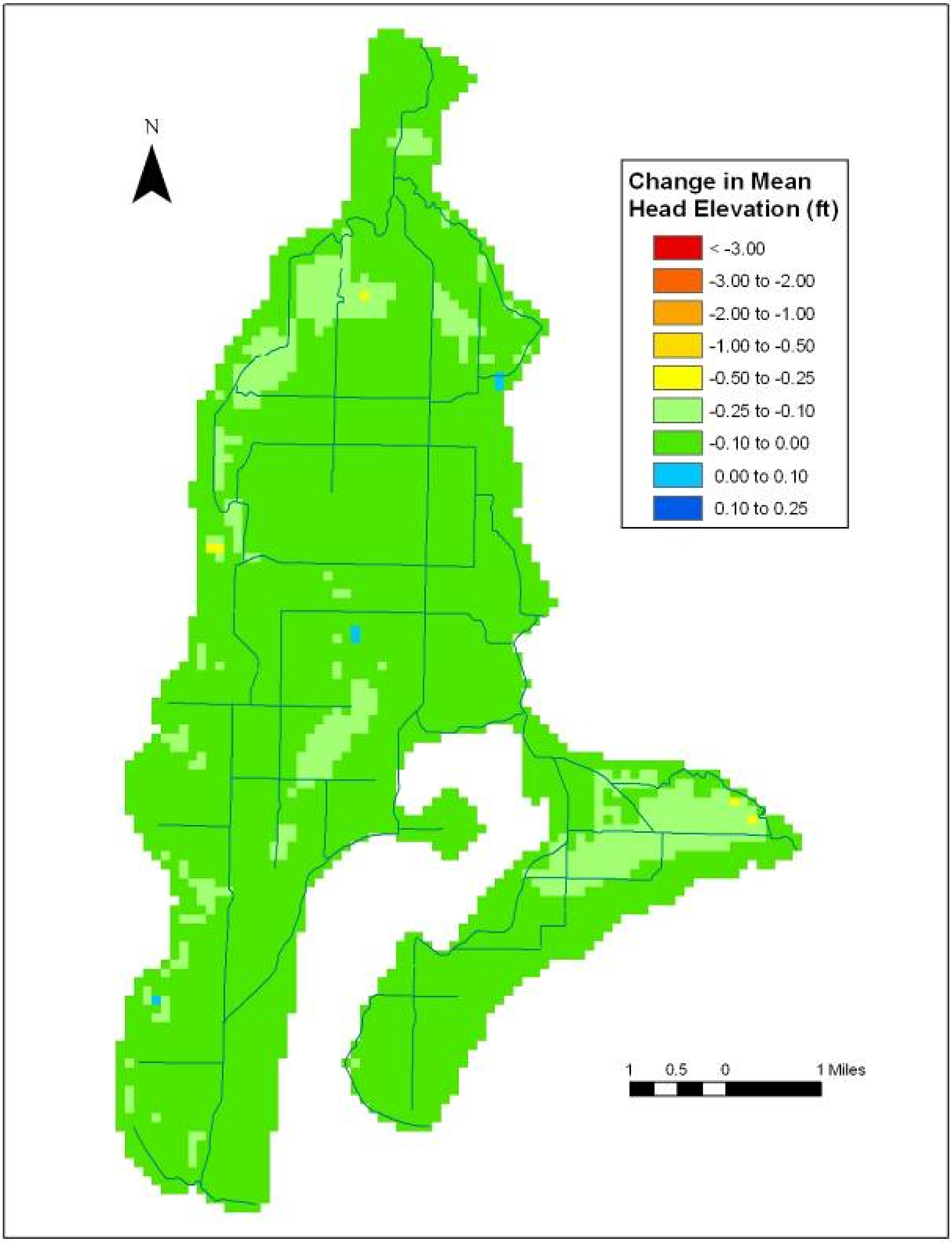


Figure 29: Change in the mean hydraulic heads in Layer 2 (Qva) under Scenario 5 – 2050 Climate Change..

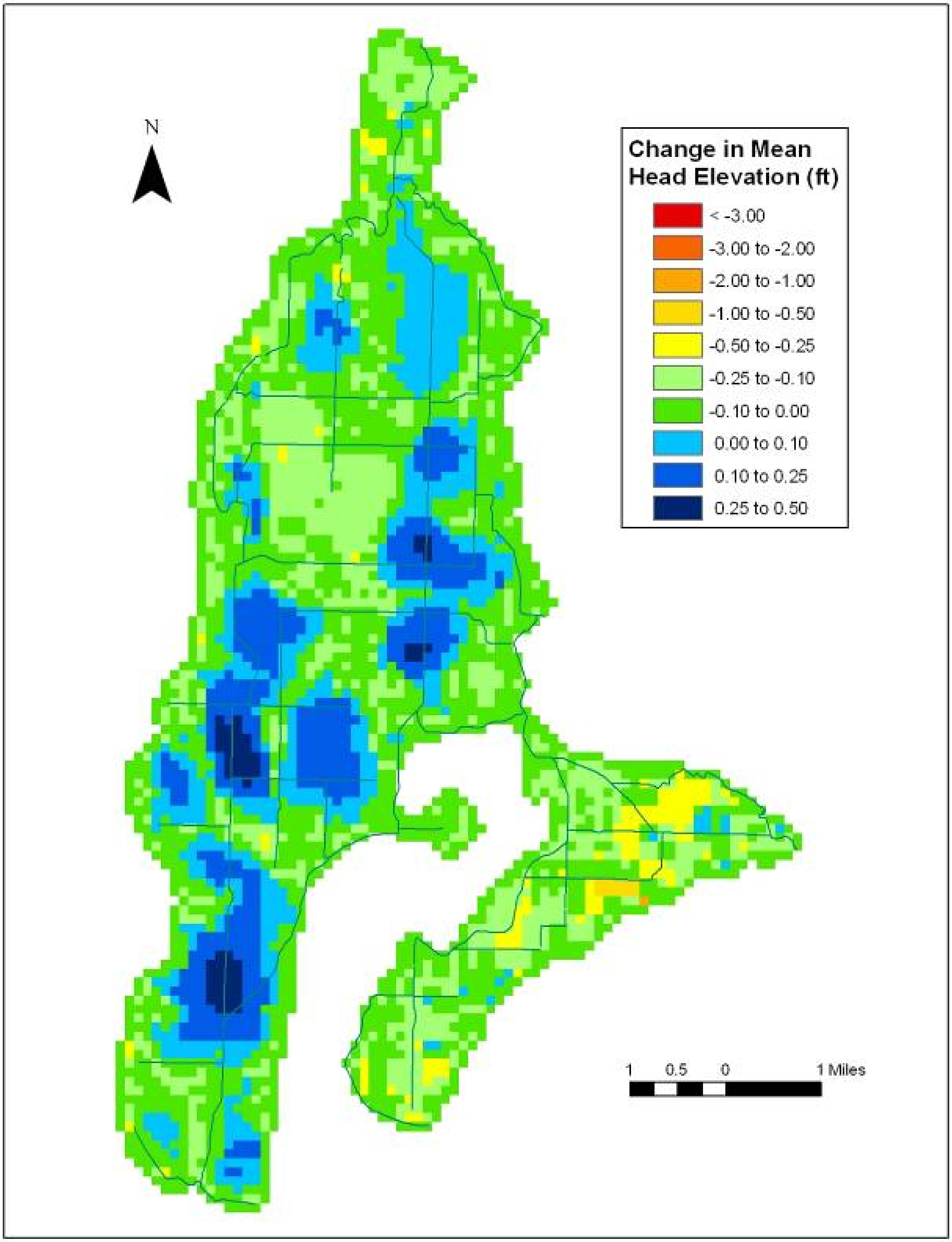


Figure 30: Change in the mean hydraulic heads in Layer 1 (Qvt & Qvr) under Scenario 6 – 2075 climate change.

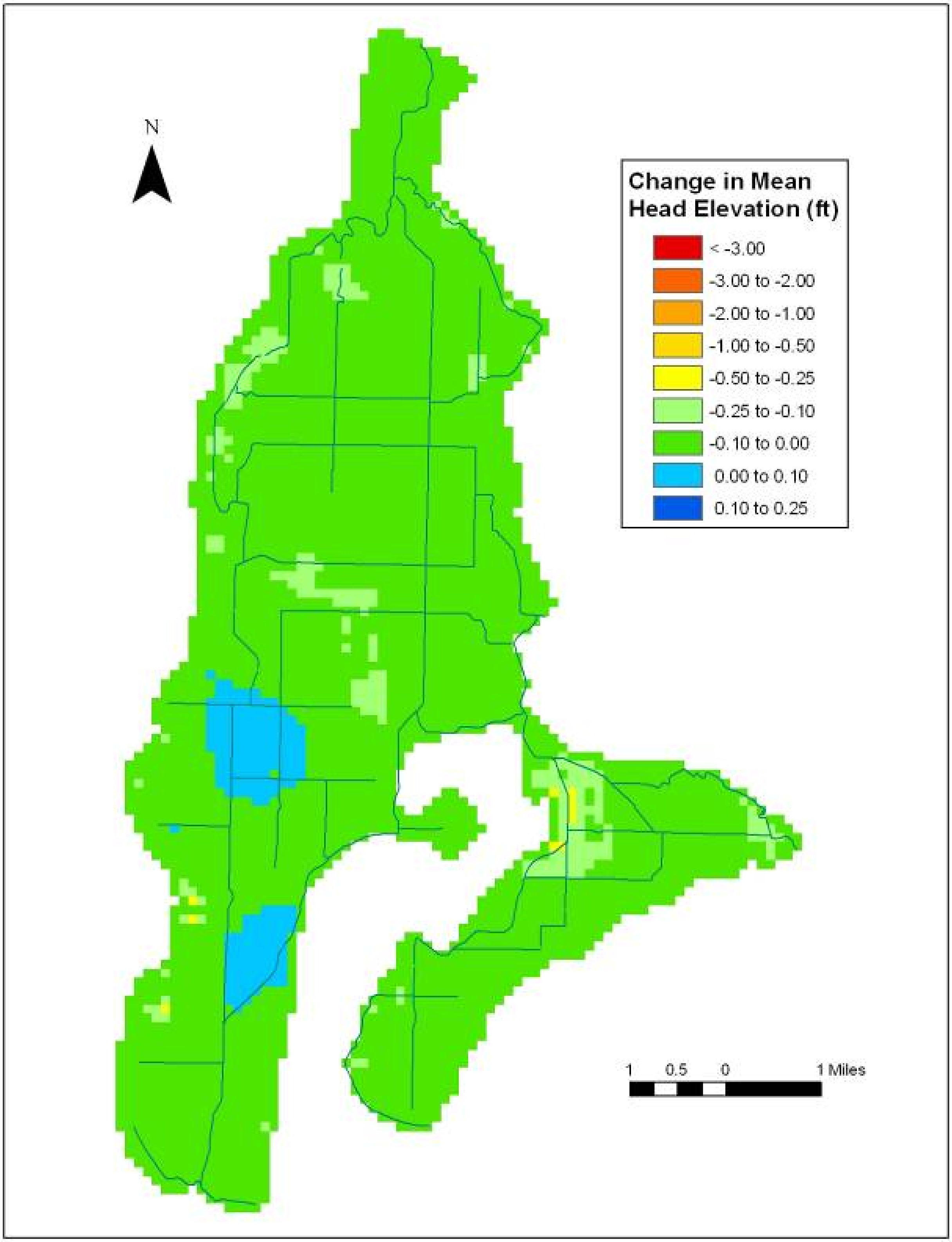


Figure 31: Change in the mean hydraulic heads in Layer 2 (Qva) under Scenario 6 – 2075 climate change.

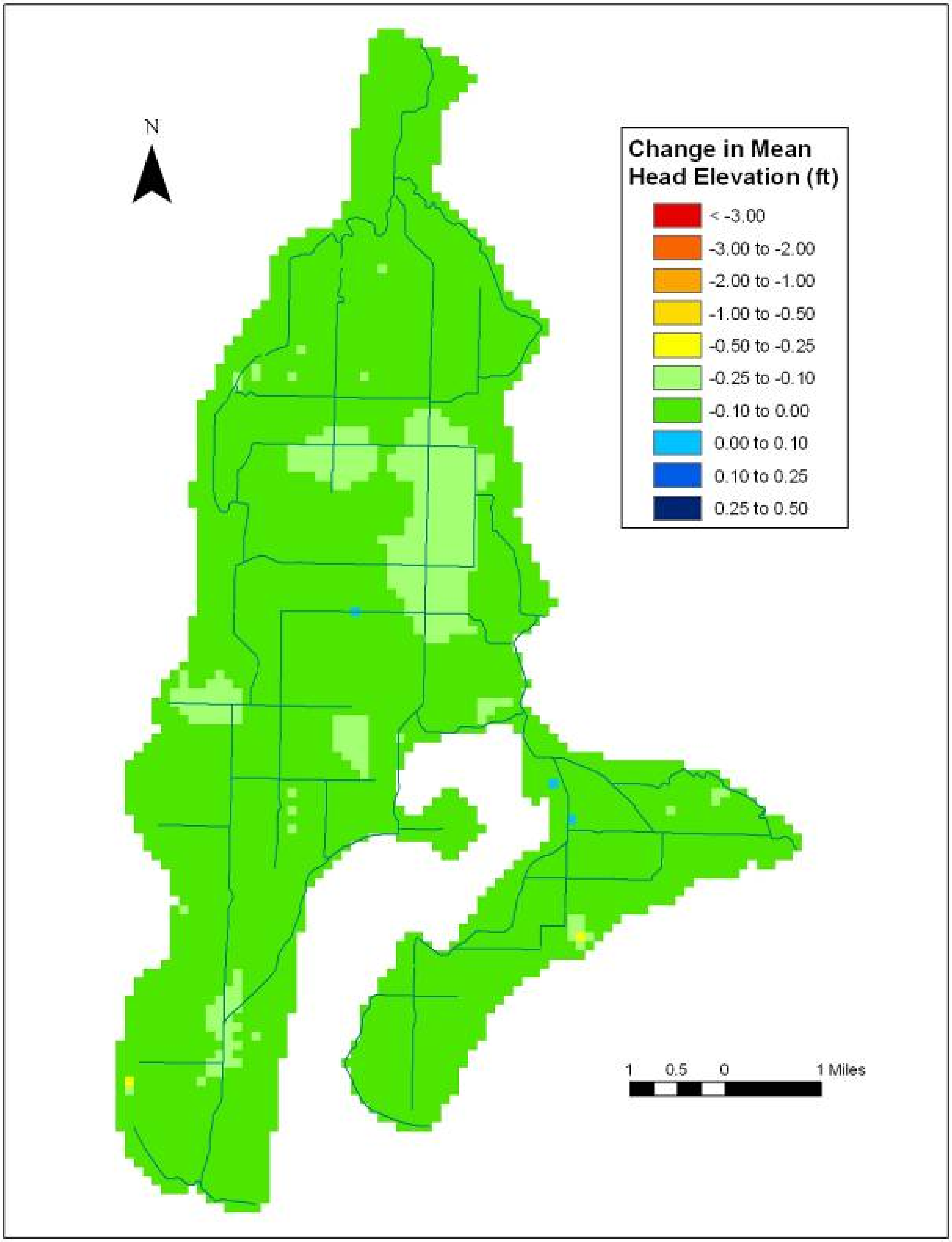


Figure 32: Change in the mean hydraulic heads in Layer 2 (Qva) under Scenario 7 – Increased Pumping with 2000 climate change.

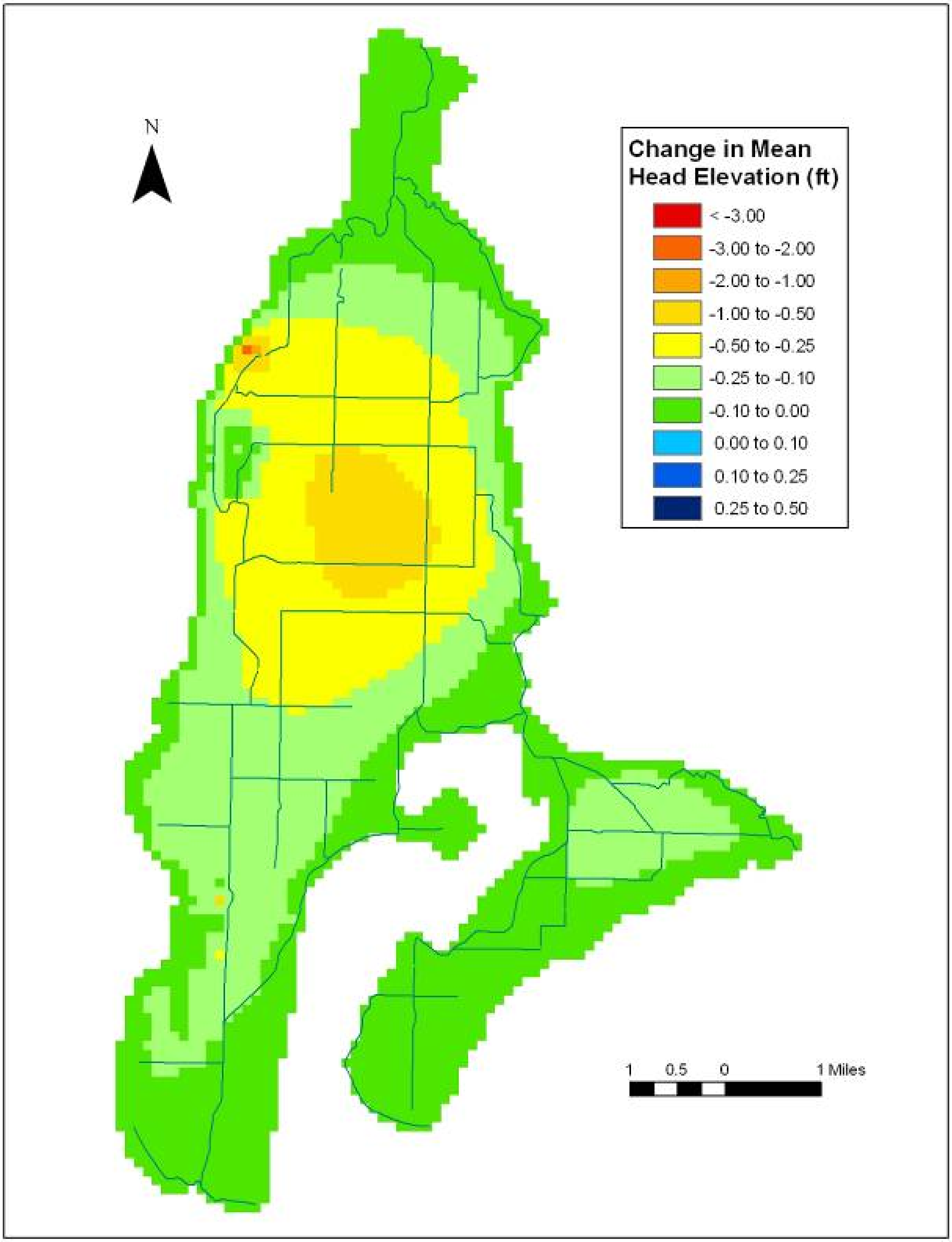


Figure 33: Change in the mean hydraulic heads in Layer 5 (QAc) under Scenario 7 – Increased Pumping with 2000 climate change.

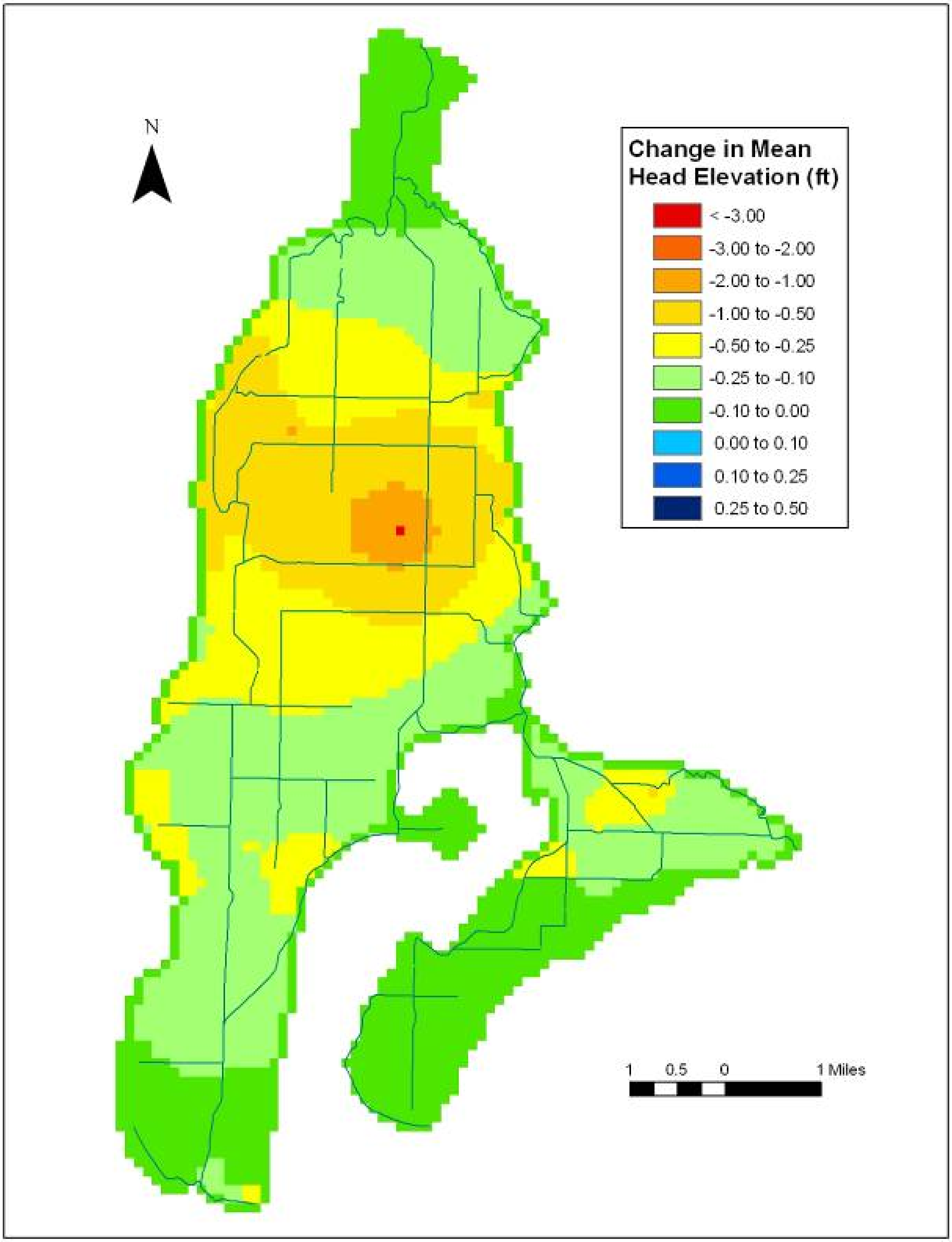


Figure 34: Change in the mean hydraulic heads in Layer 7 (QBc) under Scenario 7 – Increased Pumping with 2000 climate change.

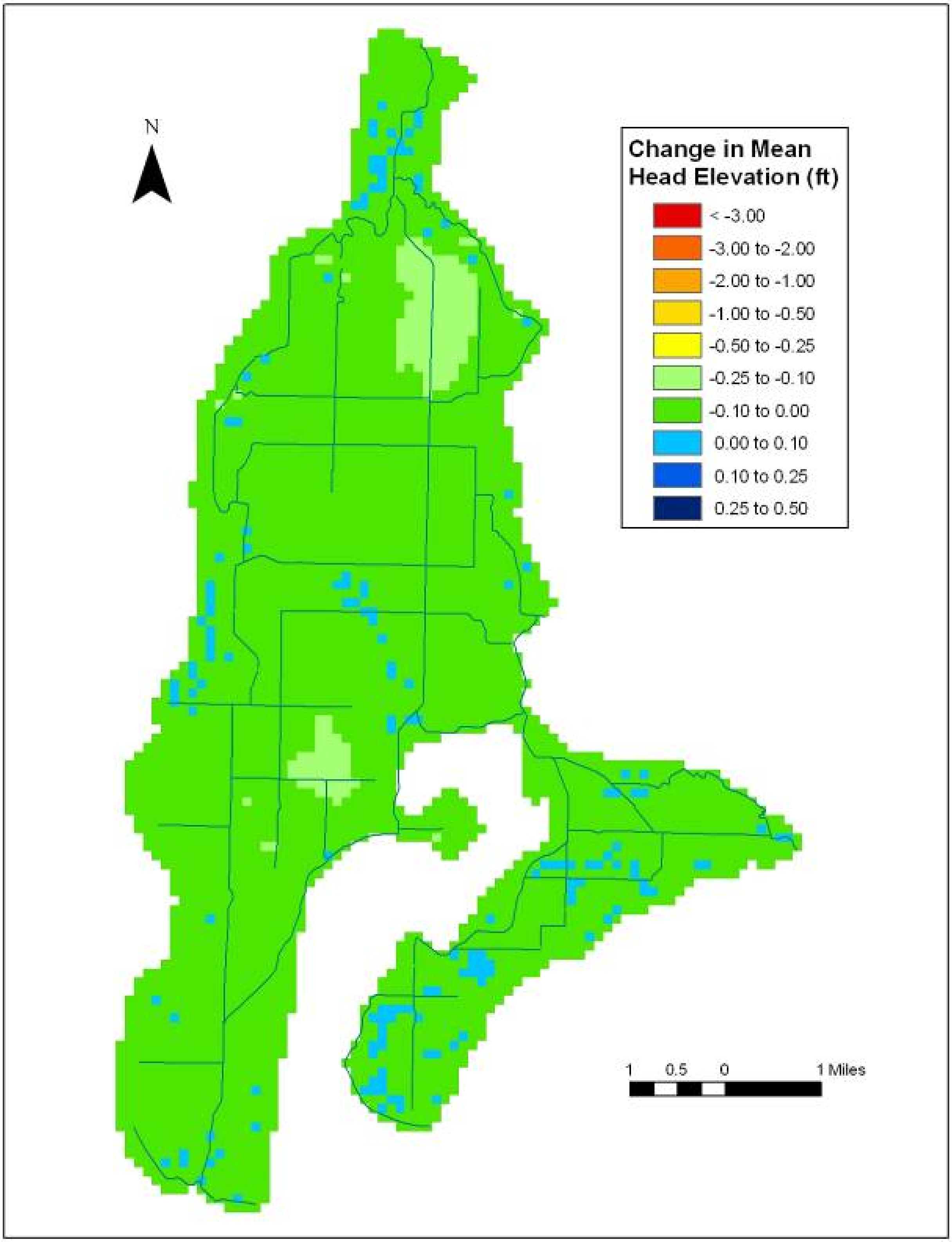


Figure 35: Change in the mean hydraulic heads in Layer 1 (Qvr and Qvt) under Scenario 8 – New Wells with 2000 climate change.

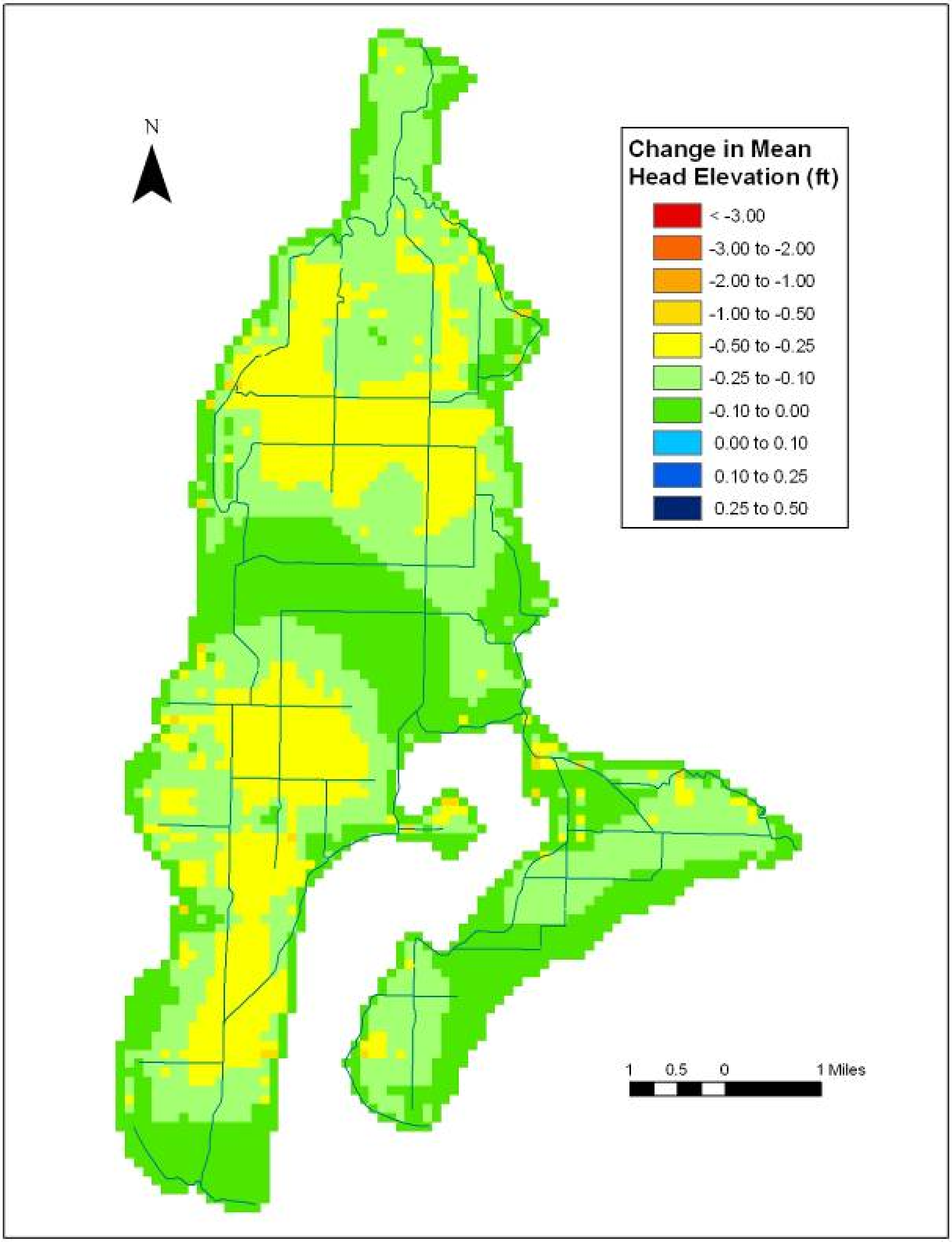


Figure 36: Change in the mean hydraulic heads in Layer 2 (Qva) under Scenario 8 - New Wells with 2000 climate change.

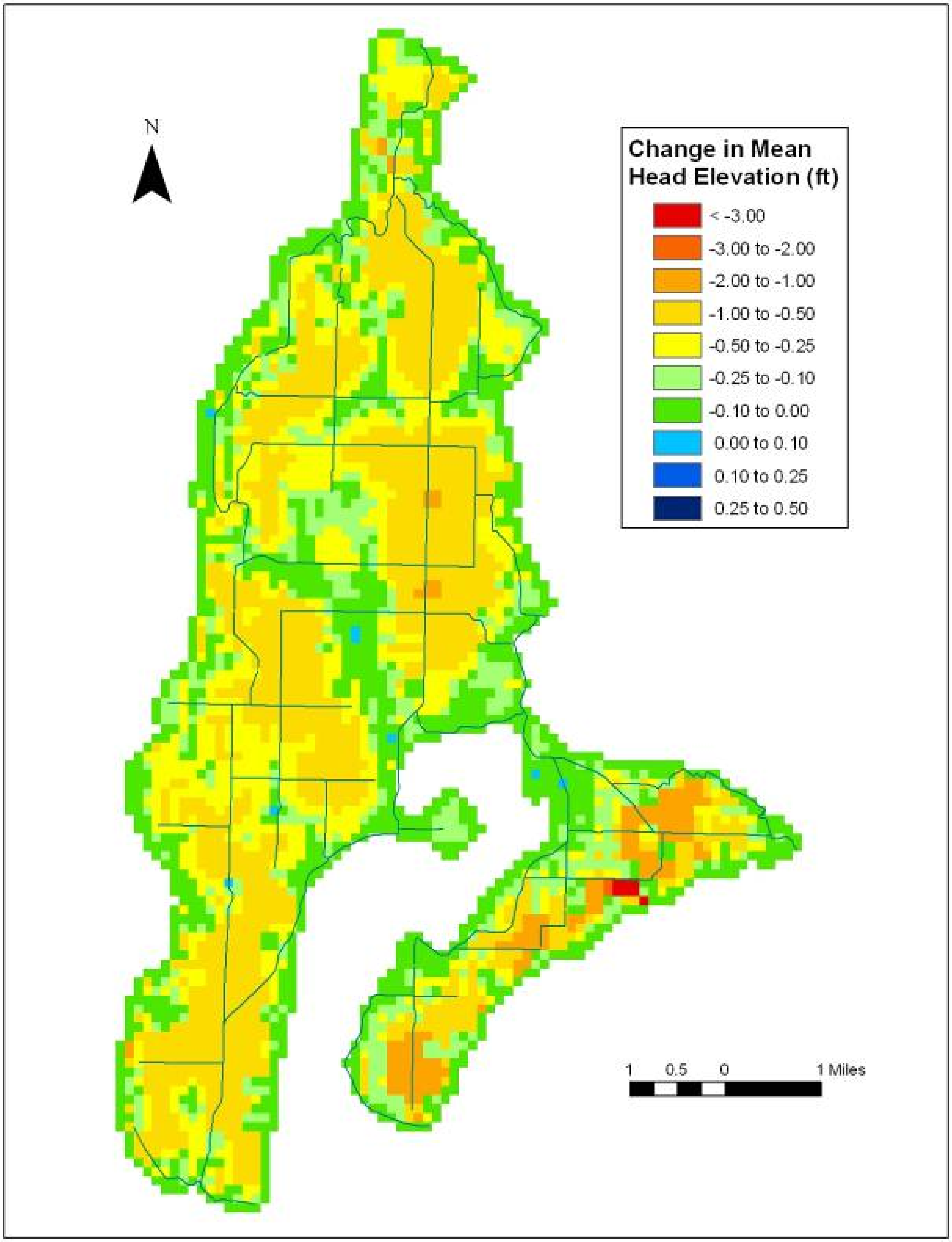


Figure 37: Change in the mean hydraulic heads in Layer 1 (Qvr and Qvt) under Scenario 9 – Increased Pumping with 2050 climate change.

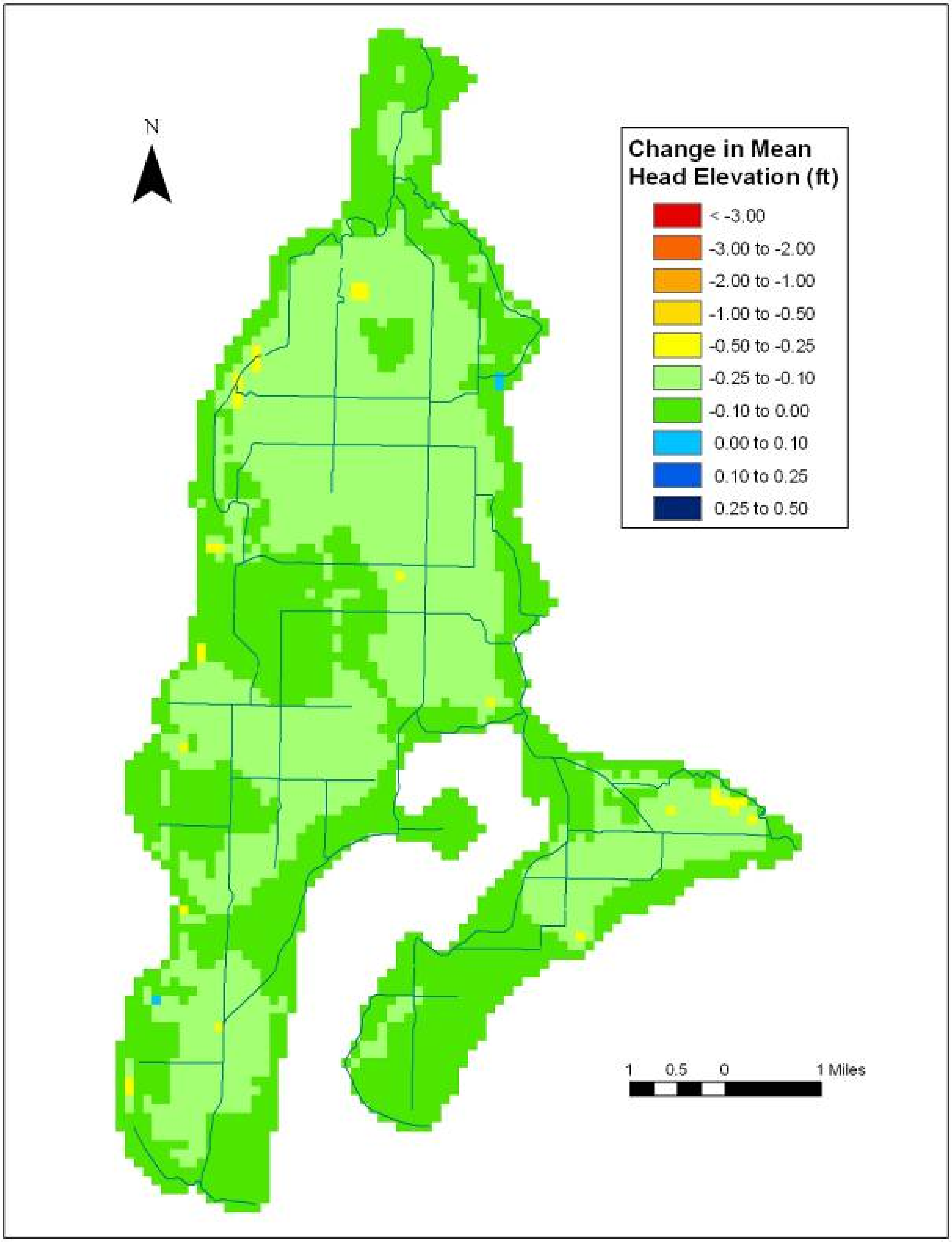


Figure 38: Change in the mean hydraulic heads in Layer 2 (Qva) under Scenario 9 – Increased Pumping with 2050 climate change.

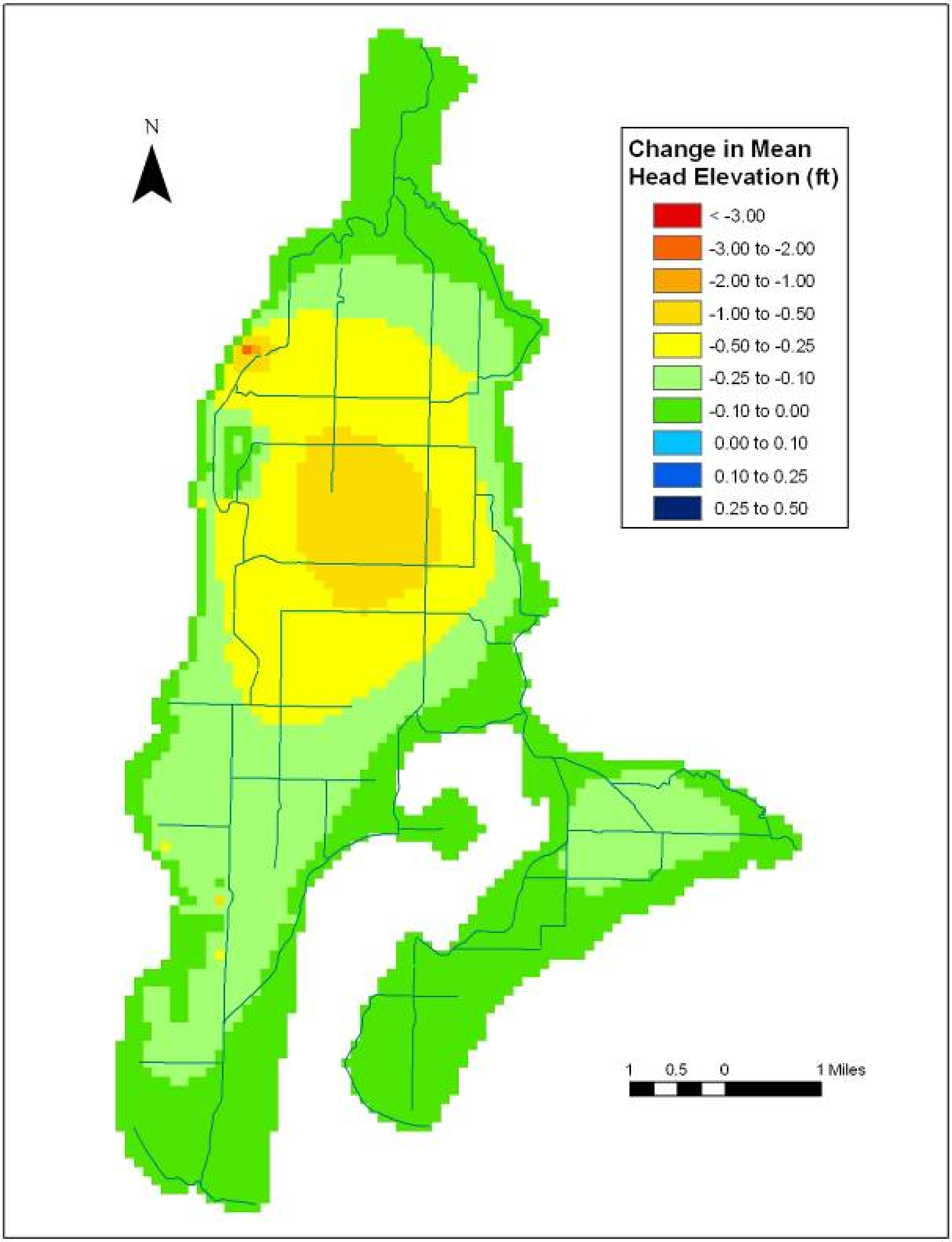


Figure 39: Change in the mean hydraulic heads in Layer 5 (QAc) under Scenario 9 – Increased Pumping with 2050 climate change.

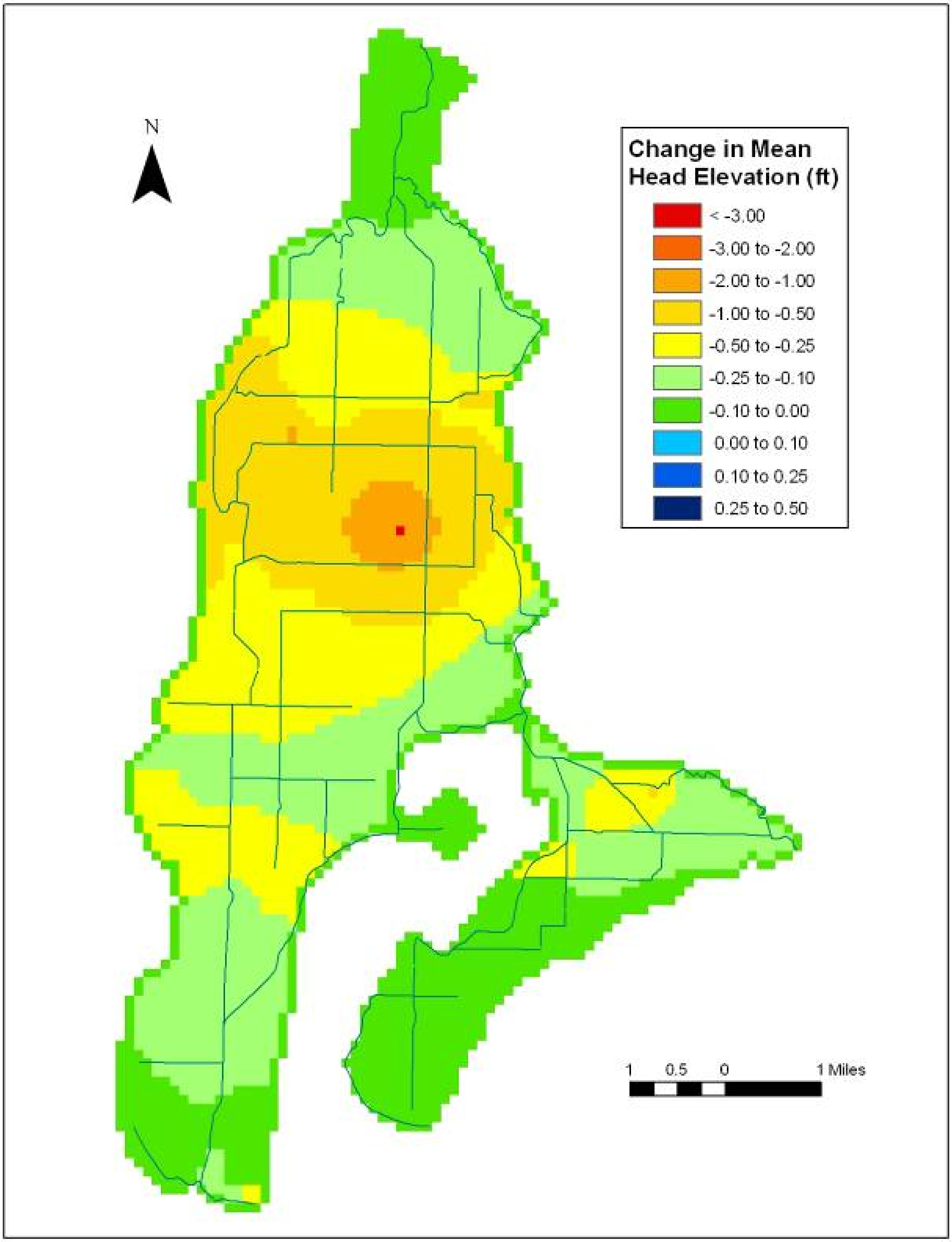


Figure 40: Change in the mean hydraulic heads in Layer 7 (QBc) under Scenario 9 – Increased Pumping with 2050 climate change.

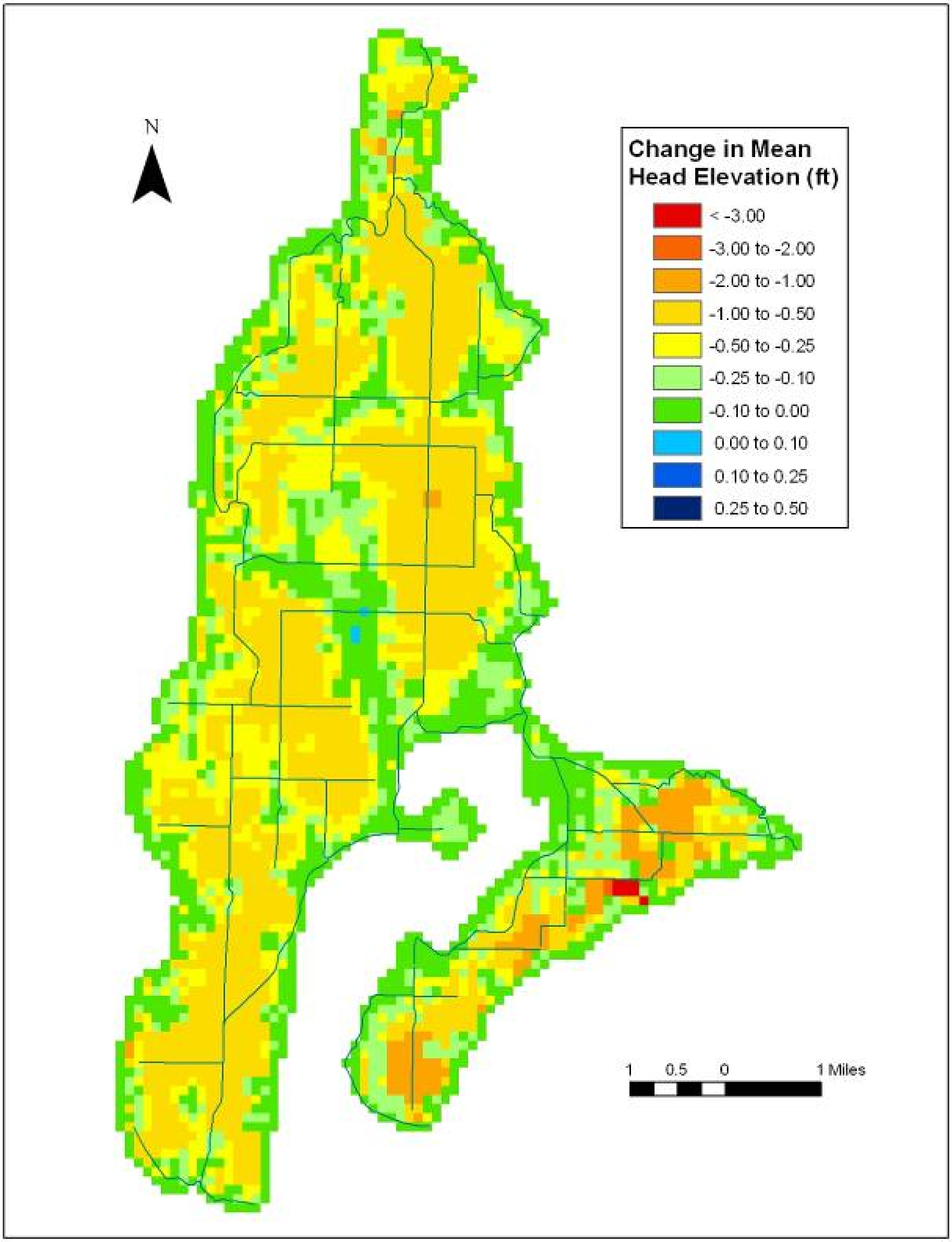


Figure 41: Change in the mean hydraulic heads in Layer 1 (Qvr and Qvt) under Scenario 10 – New Wells with 2050 climate change.

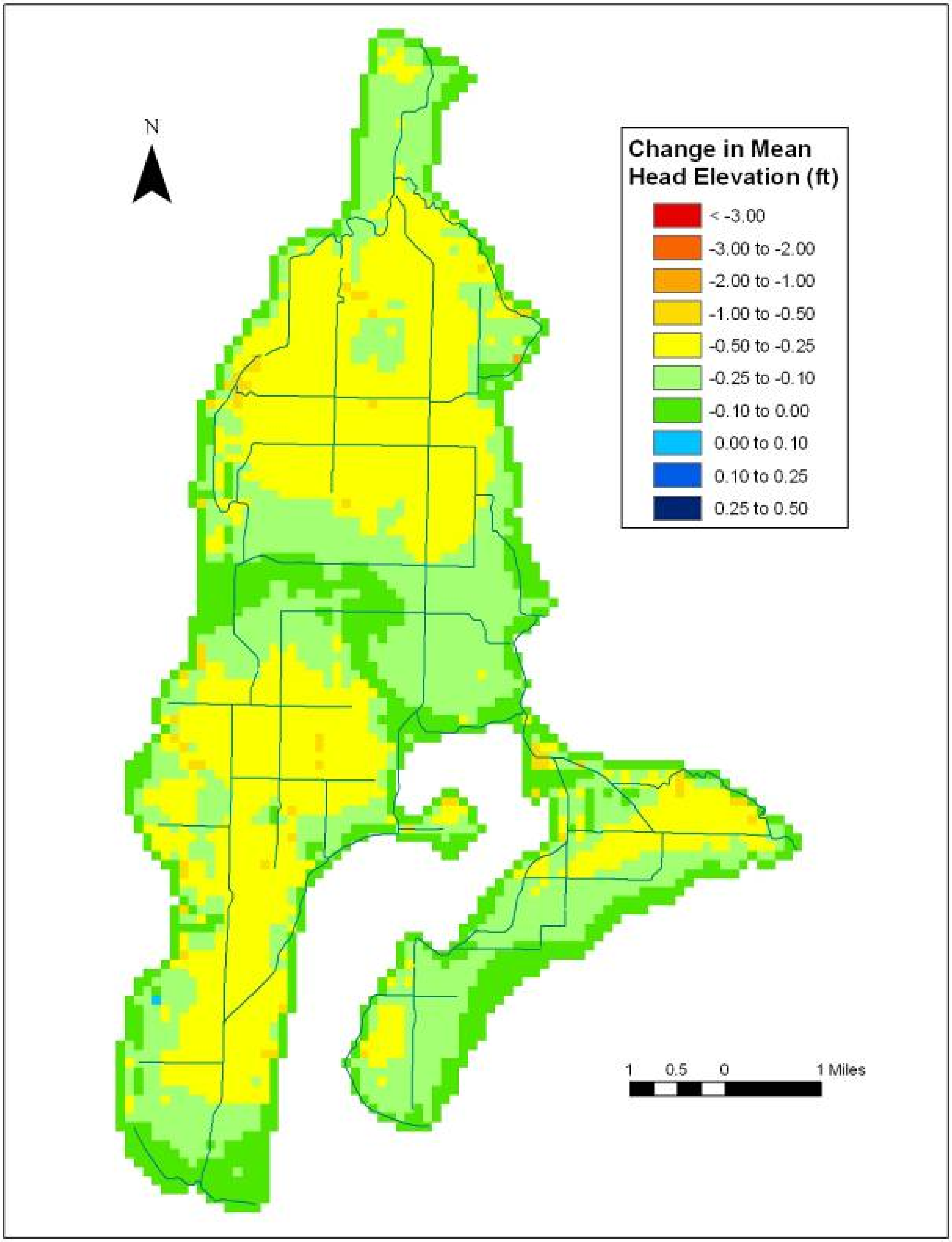


Figure 42: Change in the mean hydraulic heads in Layer 2 (Qva) under Scenario 10 – New Wells with 2050 climate change.

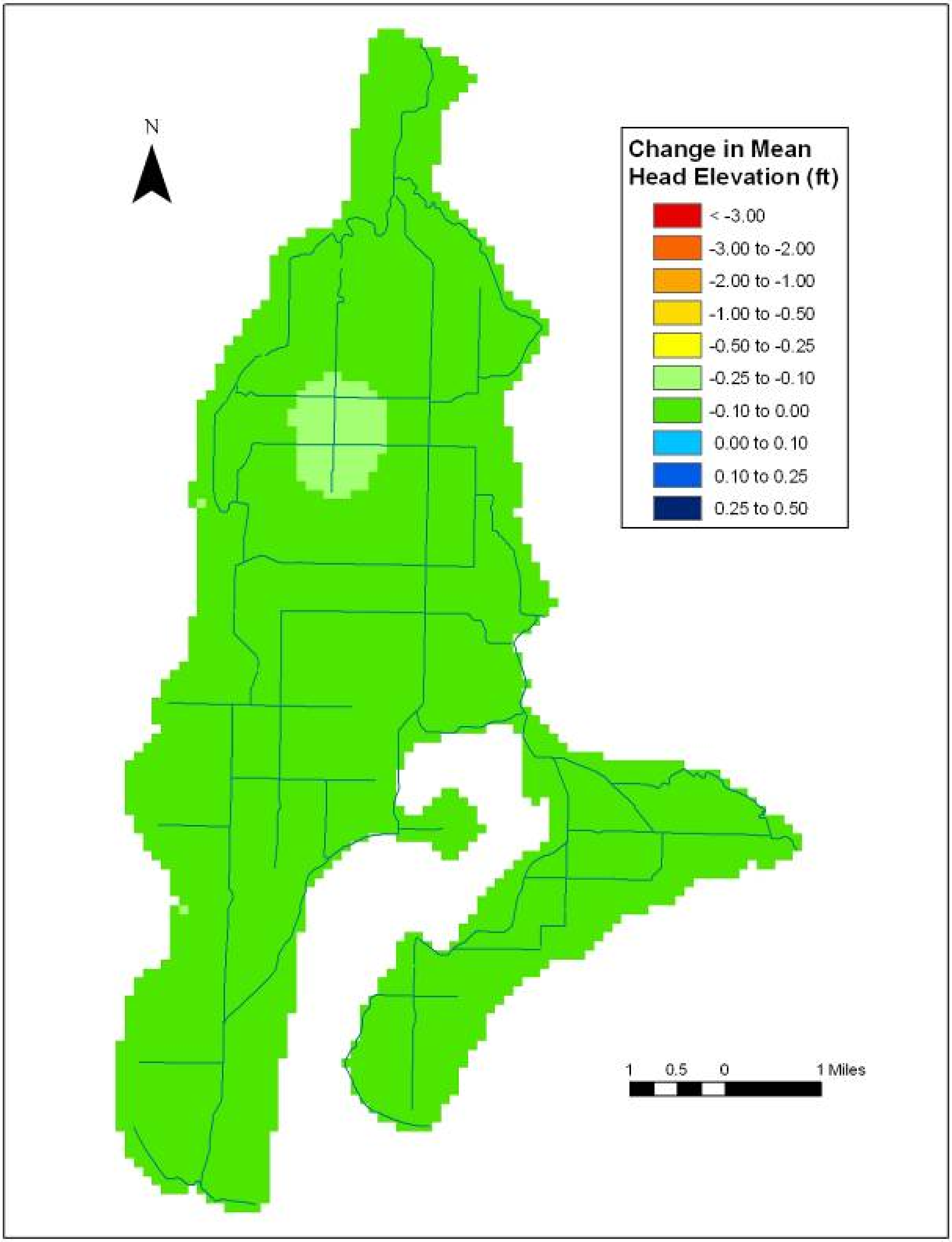


Figure 43: Change in the mean hydraulic heads in Layer 5 (QAc) under Scenario 10 – New Wells with 2050 climate change.